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Proceedings of a Workshop on the

Durability of Structural Panels

Pensacola, Florida
October 5–7, 1982

Edited by
Eddie W. Price

Proceedings of a Workshop on the

DURABILITY OF STRUCTURAL PANELS

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Presented by the

Southern Forest Experiment Station

and

Auburn University

FOREWORD

Wood is a biological material that is subject to deterioration from natural elements and organisms. To counteract the deterioration, wood may be treated or utilized in a protective manner. But wood is often used with the knowledge that a certain amount of deterioration will occur and the structure will remain functional. Also, when one type of wood product is being replaced with another wood product, for instance, plywood replacing solid lumber, concern is expressed about the durability of the product and appropriate evaluation techniques.

During the 1960's, the development of the southern pine plywood occurred and the product durability, particularly the bond durability, was often debated. Today, a group of structural panels is being proposed to be utilized in roof, walls, and floor sheathing applications. Panel types in this group are referred to as waferboards, flakeboards, strandboards, OSB (oriented structural boards), structural particleboards, etc. Individual companies will also select tradenames for marketing purposes for their product. In general, all the products are manufactured with a phenol-formaldehyde resin and wood particles of sufficient size to obtain the required structural properties. A large percentage of the wood particles usually has a length to thickness ratio greater than 50 and often greater than 100. Also being proposed are materials with a combination of veneer and wood particles.

The development of these structural panels has taken several years and many individuals. But, durability and evaluation techniques are still a major concern of the industry, scientists, and users. For certain panel types, particularly those utilizing a mixture of southern hardwoods, the durability of the proposed panel has delayed the industrial expansion.

Therefore, the Southern Forest Experiment Station proposed a Workshop on the durability of structural panels. Auburn University scientists had worked with the Forest Service scientists in developing an understanding of dimensional stability and were invited to assist in sponsoring the Workshop. The economic situation at the planned meeting dates, October 5-7, 1982, limited the travel of several individuals. However, the meeting was attended by 26 individuals, 22 papers were presented, and 20 papers included in the Proceedings. The Workshop concluded with a half-day discussion on the research needs. A summary of this discussion is given as the final presentation of the Proceedings.

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DURABILITY[1/]

Otto Suchsland[2/]

Abstract.--After an examination of the popular concept of durability, the relationship between product cost and product durability is explored. Most wood product standards are not explicit on durability or service life. The durability of particleboard is believed to be limited by swelling stresses that may lead to permanent strength reduction.

DEFINITION AND POPULAR CONCEPTS OF DURABILITY

Many a speech has been launched in the proper direction with a quotation from Webster's Dictionary. Webster's definition of durability, however, is so general that it becomes ambiguous, particularly when applied to man-made materials and structures:

> "Durability is the ability to exist for a long time with retention of original qualities, abilities, or capabilities."

Taken literally, it doesn't seem to apply to anything, because almost nothing retains its original quality for a long period of time.

Even if we allow that Webster may have meant maximum retention of original qualities; we will have to deal with the term 'a long time' (fig. 1).

If an astronomer would declare that, based on newest scientific evidence, the level of life sustaining solar heat radiation was diminishing at a much faster rate than had previously been anticipated, some of us might feel a little uneasy.

With regard to the durability of solar radiation, our concept of 'a long time' is that of a very long time, indeed, preferably exceeding our comprehension.

If, on the other hand, an automobile muffler lasts for three or four years (in Michigan), we consider that a fairly good durability record.

We have different durability expectations for different products:

Cathedrals, national monuments;
Highway, automobiles, boats;
Houses;
Books;
Photographic prints.

Many other products we discard long before they have lost a significant part of their original qualities (fashion, technical obsolescence).

The success of a product in existing while retaining its original properties and qualities depends of course on the environment.

This environment could be the earth's atmosphere with its varying physical and biological conditions or it could be an artificial environment like the interior of a combustion engine or the interior of a chemical reactor vessel. In many cases, this environment is predictable or stable, in others it is not. For instance, the Acropolis was built for eternity. It had no trouble maintaining its original quality during the first 2000 years. Now, it is being threatened by air pollution caused by automobile emission.

DURABILITY AND COST

When we talk about durability, we normally mean future durability, not past durability. We are interested in predicting durability, or in terms of Webster's definition, in predicting the 'quality - time' curve. To be able to predict durability requires either patience or test procedures that accelerate at a known rate the effect of the environment on product quality. Once a 'quality - time' curve has been established, we can often control durability meaningfully (fig. 2). If the length of time during which the quality of a product is acceptable is too short for various reasons, we can either raise the original quality level or modify the product characteristics in such a way that the rate of deterioration is reduced.

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7, 1982.

2/Professor, Department of Forestry, Michigan State University, East Lansing, MI.

Such modifications normally are associated with additional manufacturing costs. In those cases predictability must be accurate in order to allow an evaluation of the trade-offs. Examples of this process are automobile tires and batteries. This is a delicate field and involves guarantees and monetary compensation for premature failure.

The durability of a system is often limited by the durability of one of its elements (fig. 3). If the weak link can readily be replaced, the durability of the system can be greatly increased. The cost of replacements of the elements must be weighed against the cost of using superior elements with greater durability to begin with.

THE DURABILITY OF WOOD STRUCTURES (HOUSES)

Life expectancy of houses differs greatly in different parts of the world and at different times. This tied to social customs, traditions, mobility, etc.

In this country we have a relatively low expectancy for homes certainly not much in excess of 100 years. We are therefore willing to incorporate materials which might be considered less than permanent and in another time or at a different location might have been or might be called entirely unsuitable.

The house may be considered a system of components with different durabilities or different durability requirements:

Basement and foundations are expected to be most durable because they are difficult to replace and their failure would jeopardize the entire system.

The roof normally has a limited life. It is easy to replace. More durable options are available (tiles) but require stronger structural members for support of the greater weight and therefore are more costly.

Structural members (studs, joists, trusses, etc.) are actually overdesigned to allow for known time factors. Normally indefinite service is assumed.

Plywood panels. Standards are not explicit on durability or service life. However, extensive service records are available. Under conditions of appropriately limited exposure, indefinite service is assumed. The distinction between 'interior' and 'exterior' types is not directly related to durability.

Particleboard panels. Standards are not explicit on durability or service life. Experience is limited. The use of 'exterior' resins does not necessarily impart the same resistance to moisture as it does in the case of plywood.

Fiberboard (siding). Well developed accelerated testing procedures and records are available. Many products are guaranteed in terms of service life (15 years). Real service expectation is probably considerably longer. Fiberboard siding appears to be a truly exterior product.

DURABILITY OF PARTICLEBOARD

Among the reasons for the absence of explicit life expectancies or guarantees are these:

- Great variety of products in terms of densities, species, construction, resin types, resin contents, etc.
- Constant technological change and improvements of particleboard design and manufacturing methods.
- Uncertainty as to minimum engineering requirements.
- Relatively few long range exposure test results.

One of the few long range exposure test results has been reported by a British researcher. (J. M. Dinwoodie. Today's adhesives: their properties and performance. First International Particleboard Symposium, Hamburg 1978. Proceedings: Particleboard - Today and Tomorrow.) Figure 4 illustrates some of these results. The continuous decline of this particular property, regardless of the resin type is remarkable and alarming. Dinwoodie formulates these conclusions:

> "It is now beginning to look as if none of the resin bonded particleboards are suitable for long term external conditions such as wall cladding ...."
> ".... it is very doubtful if high external performance of any particleboard, with the possible exception of cement bonded boards, can be guaranteed for a long period of time."

These are certainly important conclusions which should inject a shot of caution into our efforts of replacing exterior plywood with structural particleboard.

There is in the literature no clear statement with regard to the exact mechanics of these strength reductions. They are, no doubt, the result of a complex combination of many factors and interactions.

The swelling and shrinkage of the particles, however, due to moisture uptake and loss, in particular the cyclic moisture content changes experienced during exterior exposure, must rank highly on the list of such factors. Figures 5 and 6 illustrate the consequences of such dimensional changes. Both lateral and thickness swelling of the particles are likely to result in glue line stresses particularly when glue lines become brittle with age.

It is clear that the geometry of the particle must have an important effect on these swelling stresses. Smaller particles result in more uniform particle distribution and narrower overlaps and therefore in reduced swelling stresses. Fiber furnishes may have certain advantages here.

I am sure that my highly qualified fellow speakers will further elucidate this subject. I shall, therefore, at this time beat a quick retreat into the shadows of the back rows... which brings me to the wood stove (fig. 7):

> This picture can make a philosopher of you. Just imagine that you are sitting in front of a stove like this, in a cabin in northern Michigan, at 25 degrees below zero, contemplating the stove's durability.

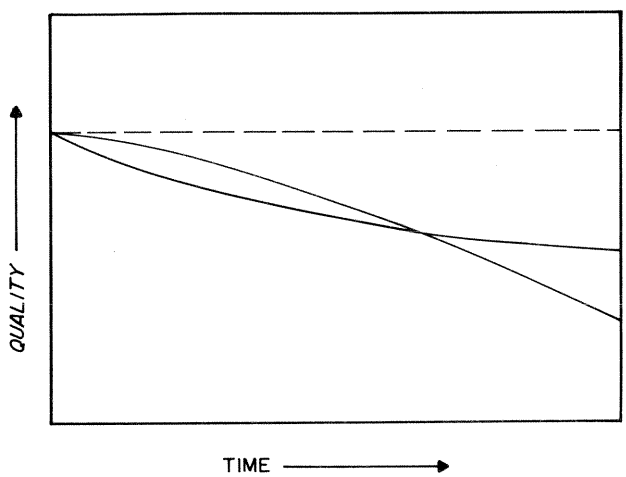

Figure 1.--Quality - time curves illustrating concept of durability.

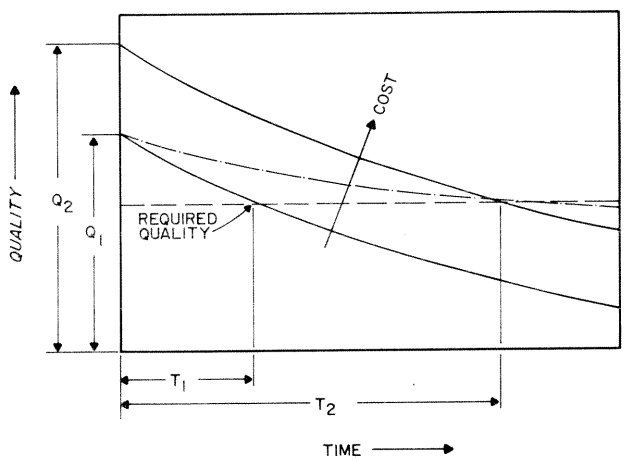

Figure 2.--Quality - time curves showing various modifications of durability.

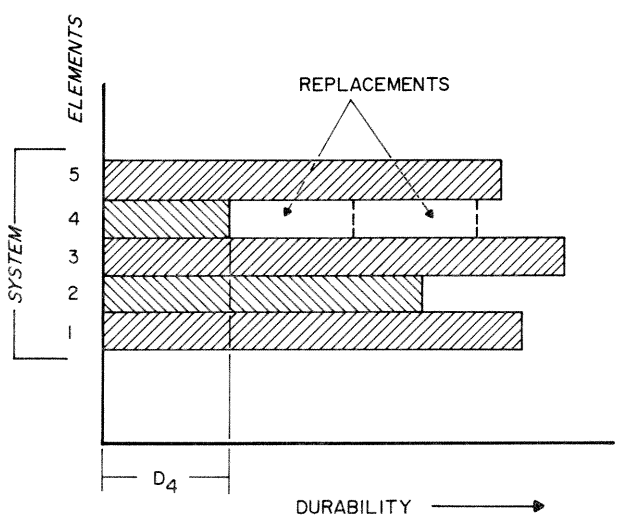

Figure 3.--Durability of system consisting of elements with different durabilities.

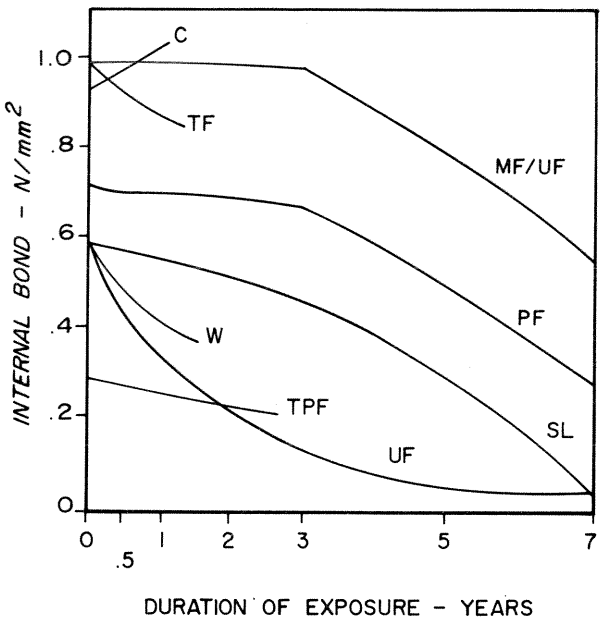

Figure 4.--Internal bond of various particleboard types as function of exposure time.

C = Cement binder
TF = Tannin - formaldehyde binder
MF/UF = Melamine- and urea-formaldehyde binder
PF = Phenol-formaldehyde binder
W = Waferboard
TPF = Tannin-phenol-formaldehyde binder
SL = Sulphite liquor binder
UF = Urea-formaldehyde binder

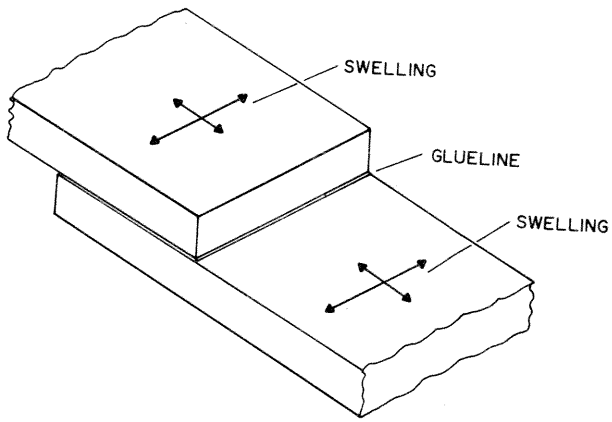

Figure 5.--Illustration of stresses due to swelling and shrinkage in the plane of the board of particles.

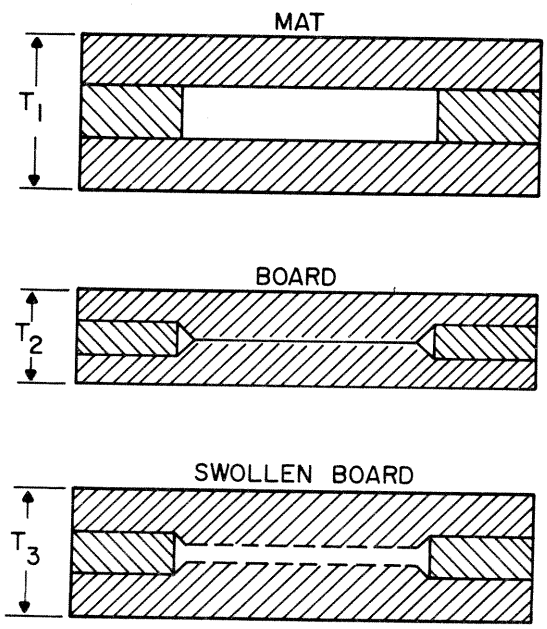

Figure 6.--Illustration of stresses due to swelling and shrinkage perpendicular to the plane of the board of particles.

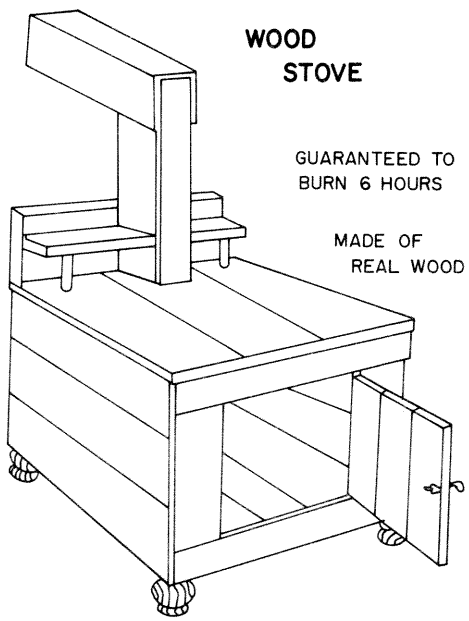

Figure 7.--The "wood" stove.

DURABILITY PROBLEMS ASSOCIATED WITH WOOD CONSTRUCTION[1]/

Don Percival[2]/

Abstract.--A few examples of durability associated with wood construction are presented. Most of the problems discussed are related to the inattention to recommended instructions and the application of the various elements of the structure.

INTRODUCTION

Durability problems associated with wood construction can best be discussed using samples of deterioration. Unfortunately, many of the pictorial illustrations presented at the Workshop are not in this written proceedings. However, anyone connected with wood construction will have similar experiences, and need only refer to their files for illustrations.

Even though this Workshop is primarily concerned with panel or reconstituted wood building products durability, general problems associated with light-frame construction will be discussed. This includes panel products and the framing elements.

The definition of durability is rather elusive and can mean many things to many people. From personal experiences over the years, durability, or the lack thereof, usually means a deterioration of an element of the structure requiring repair or replacement, reattachment, refinishing, etc., at some given period earlier identification stamp.
than expected. Other than repainting or refinishing, etc., a consensus might be interpreted as expecting the structure to outlast the mortgage. Some expect the house to last forever while others may prefer the structure to last ten years before replacement.

Most problems I have experience with are directly related to (1) the physics of moisture and humidity (Anderson and Sherwood 1974; Small Homes Council 1975; Sherwood and Hans 1979), and (2) inattention to recommended instructions and application of the various elements of the structure. Generally, the importance of controlling free water and moisture vapor is known. However with the increasing emphasis on energy conservation towards tighter construction and extensive use of insulation, the importance of controlling the moisture becomes paramount.

Sometimes, even when contractors or builders try to follow recommended instructions a definite lack of continuity between the product manufacturers and users exists. Some of the "newer" materials used in light-frame construction increase the need for additional attention to details and installation instructions and specifications. For instance, two common problems are associated with caulking and treating exposed areas. Along horizontal joints, some form of caulking often replaces the recommended flashing (fig. 1). If the caulking shrinks and cracks over time, water can saturate the edges and durability problems occur. Similarly, but not necessarily with panel products, soaking the cut ends and edges of pressure treated wood with the recommended wood preservative is rarely done (fig. 2). This practice requires the contractor to search for the treating chemical and plan for an application which can easily be "forgotten". Using treated wood for ground contact that was not treated for ground contact is often encountered. The practice may have resulted from the contractor's "inability" to correctly apply the information on an identification stamp.

As mentioned earlier, many of the problems associated with wood construction can be traced directly to poor construction practices or design. The trend to place the house close to the ground, mainly for aesthetic reasons, places the substructure in jeopardy. For instance, a slab and crawl space type house construction placed close to the ground places the wood substructure and siding at the grade line, or just above (fig. 3) Ground moisture, especially if the grade is running toward the house is easily accessible to the sill plates and band joists. Then, decay spores start to germinate and grow and the wood is susceptible to serious problems. The construction also allows the lower edges of wood siding and unprotected edges of reconstituted panel products to be subjected to splashing rain or standing snow and subsequent deterioration.

"Low" foundations also reduce the function of crawl space vents. Rain and surface ground water enter through the vents and collect in the crawl space area. This water on the ground cover eventually evaporates and migrates up into the house and is absorbed by the substructure members.

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7, 1982.

2/Research Professor of Wood Technology and Utilization, Small Homes Council, University of Illinois at Urbana-Champaign , One East St. Mary's Road, Champaign, IL 61820.

A properly installed ground cover does prevent crawl space moisture from moving up into the structure, but water on the cover will evaporate and be absorbed by the wood elements. Occurrences of joist decay have also been observed where paper covered insulation has been fastened between the joists (fig. 4). This practice definitely restricts moisture movement and holds it in the crawl space area. Eventually, the moisture content of the joists is raised to a dangerous level. Therefore, recommendations have been to insulate the foundation walls and/or provide proper crawl-space ventilation.

Grading of the fill around the foundation will settle over time. If not correctly graded, the settlement will cause surface water to drain toward the foundation. Subsequent regrading to create a slope away from the foundation will properly drain the water. However, when the house is already too close to grade, building up the grade for proper drainage will put the substructure and siding in jeopardy (fig. 5).

Although termite shields have proven to be ineffective as a barrier to subterranean termite infestation, the shield is proving to be an effective barrier against moisture migration through the cavities of hollow masonry and is in direct access to moisture migration. In this case, the shield functions as a barrier.

To conserve energy, houses are being built tighter with sill sealers, caulking, more precision construction, additional insulation, etc. Air leakage is reduced creating an increase in vapor pressure. Provisions must be made to dissipate this vapor from inside the house. From a study by Wetterman (1982), uncontrolled humidity in a house can lead to wood moisture related problems. For instance, a family of four can But an average 2,000 square foot house can safely hold only 5 to 7 pints of moisture laden air before it migrates to areas of less pressure. Unless dissipated by dehumidification equipment, air leakage or controlled ventilation, the vapor pressure will increase and moisture will enter the walls and ceiling. The excessive moisture can dampen the insulation of the framing lumber and eventually migrate to the sheathing and siding. Installation of an effective vapor barrier and controlled ventilation is essential. The vapor barrier should always be placed on the warm side of the wall, that is, between the insulation and the interior finish covering such as drywall gypsum board or plaster.

Control of interior vapor is especially important for homes covered with reconstituted board sidings. Most of these products are more vapor impermeable than the common resawn sidings. Condensed vapor, which has escaped through the walls, can be absorbed and held longer in the paneled siding. This can result in extractives bleeding through the finishes. General recommendations include (1) finishing the edges and ends of all wood siding materials, (2) the final finishes being compatible with the primer coats, and (3) vertical joints properly caulked and covered with batten strips. Unfortunately, these finishing recommendations are not always met because the painter usually appears after the carpenter has left the job. Also, the instructions for application and finishing are usually lost during construction; consequently, the recommendations are not always followed.

A controversy exists on whether or not to install a vapor barrier in the ceiling, however, the same law of physics affects moisture migration in the ceiling. That is, vapor pressure migrates to areas of less pressure and without a ceiling vapor barrier, the vapor can migrate to the attic. In addition, a loose fitting or improperly installed attic access opening is an easy path of escape for vapor. Again, controlling living area vapor pressure is essential to prevent buildup of moisture in the attic. Other problems can be caused in the attic with heavy applications of attic insulation closing off the soffitt vents. Colder surfaces of the roof framing and sheathing will cause vapor to condense on the surfaces and eventually be absorbed by the wood materials unless adequate ventilation is functioning correctly. This pick up of moisture by the wood framing along with the ceiling being absorbed by the attic moisture and lower chords of trusses or lower portion of ceiling joists can sometimes lead to phenomenon known as ceiling-floor partition separation (CFPS) (Percival, Suddarth, and Comus 1982). This is not usually considered a durability problem, per se, but some homeowners consider it a fault in the construction. Additional information about CFPS is detailed in other reports (Percival and Comus 1982; Percival, Suddarth, and Comus 1982).

Low slope roofs have also led to deteriorcially with wood shakes and shingles (fig. 6). The low slope slows down drainage allowing moisture backup in the shingles and deterioration to occur in less than expected longevity. However, properly sloped wood shingled roofs have lasted many years. Other types of shingles have also faced deterioration problems related to construction or insulation. For instance, asphalt shingles have shown early signs of deterioration with insulation installed between the rafters or the top chords or trusses.

Deterioration or lack of durability of wood products in light-frame construction are generally not considered a common problem. But, in most areas of the country and with questionable construction practices, deterioration examples are found. For wood deterioration problems that do occur, the fault can usually be traced to a lack of communication and understanding about the product, about its recommended application and end-use environment. Secondly, for house construction, generally the builder has the responsibility for seeing that the product specifications are understood and followed. Therefore, the house can end up as a finished product with built-in problems about to happen.

The recommendation for more codes or regulations is not implied in the previous comments. Hopefully, these comments will inspire all individuals concerned with wood products used in house or light-frame construction to be concerned with the completed structure, not just their particular product. The homeowner does not really care who is at fault when the siding deteriorated or his back porch decayed, only that they failed. He assumes that someone in the construction process has consulted the specifications and the job was properly performed.

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Figure 1.--Caulking incorrectly used instead of the recommended flashing.

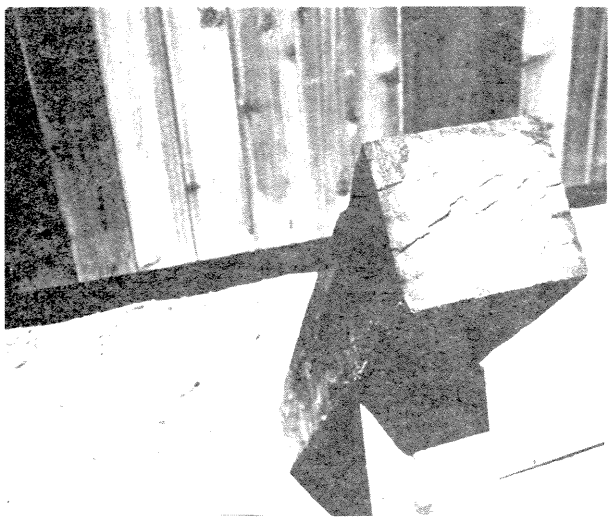

Figure 2.--Cut end of a treated timber not soaked prior to application.

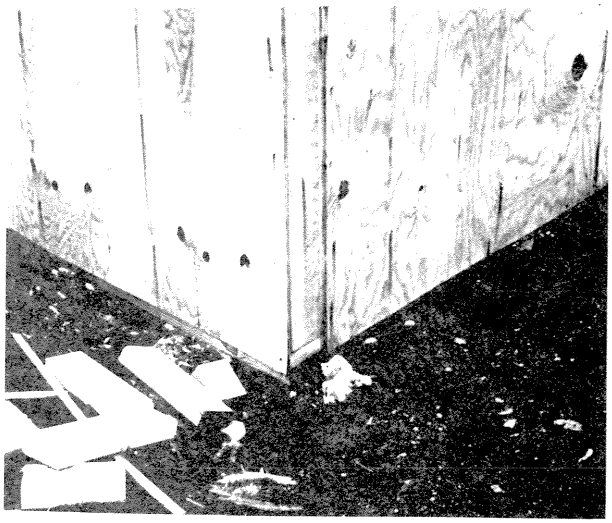

Figure 3.--A slope and crawl-space type house construction placed close to the ground allowing ground moisture accessibility to the wood substructure and siding.

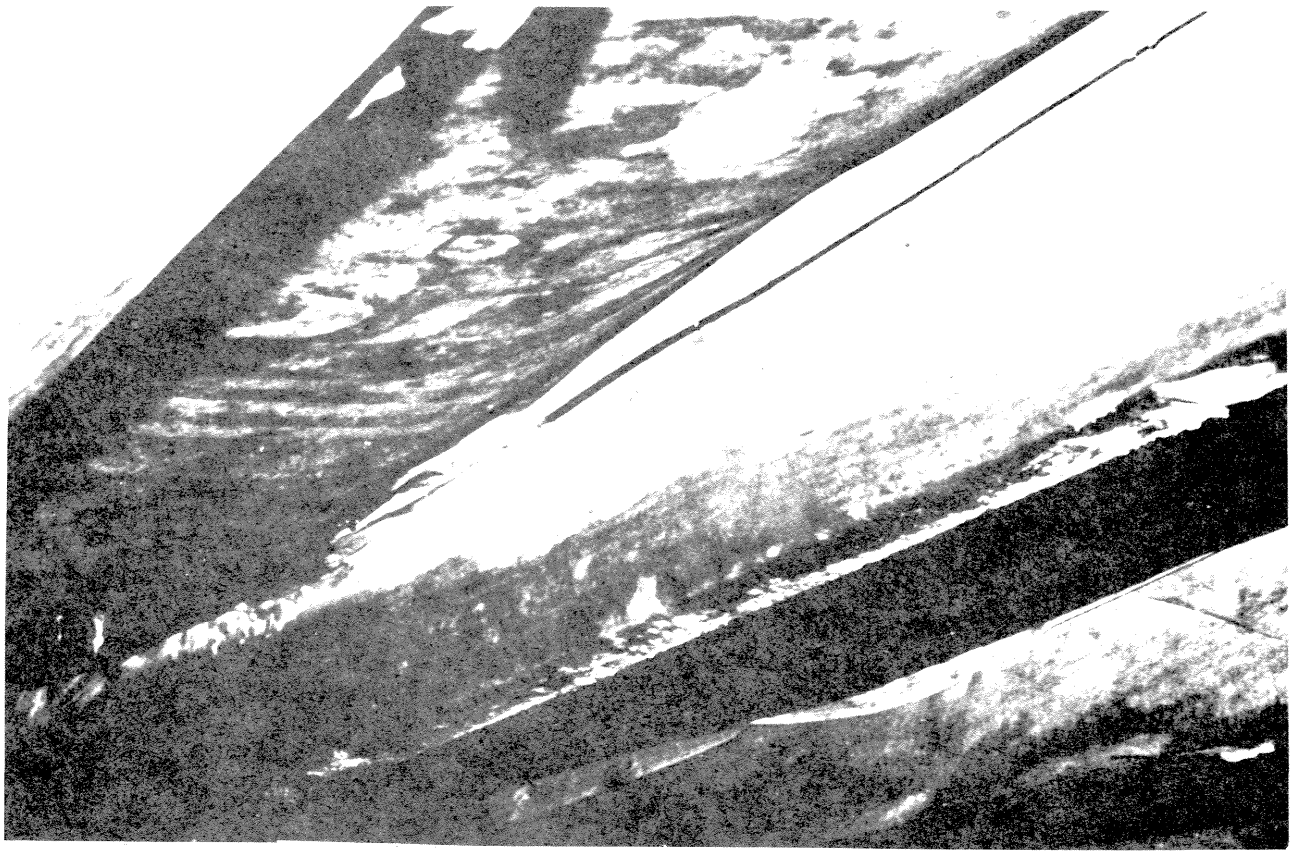

Figure 4.--Joist decay resulting from improper ventilation and insulation.

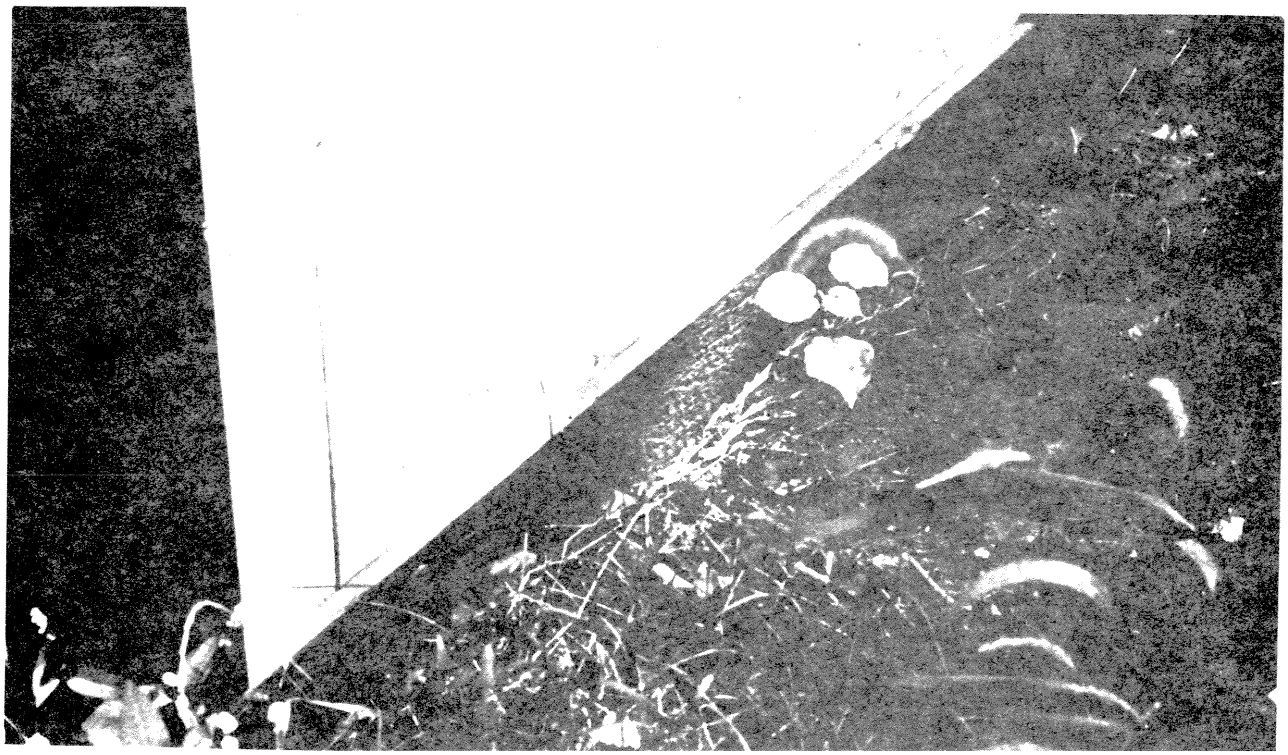

Figure 5.--The grade around the house improperly sloped.

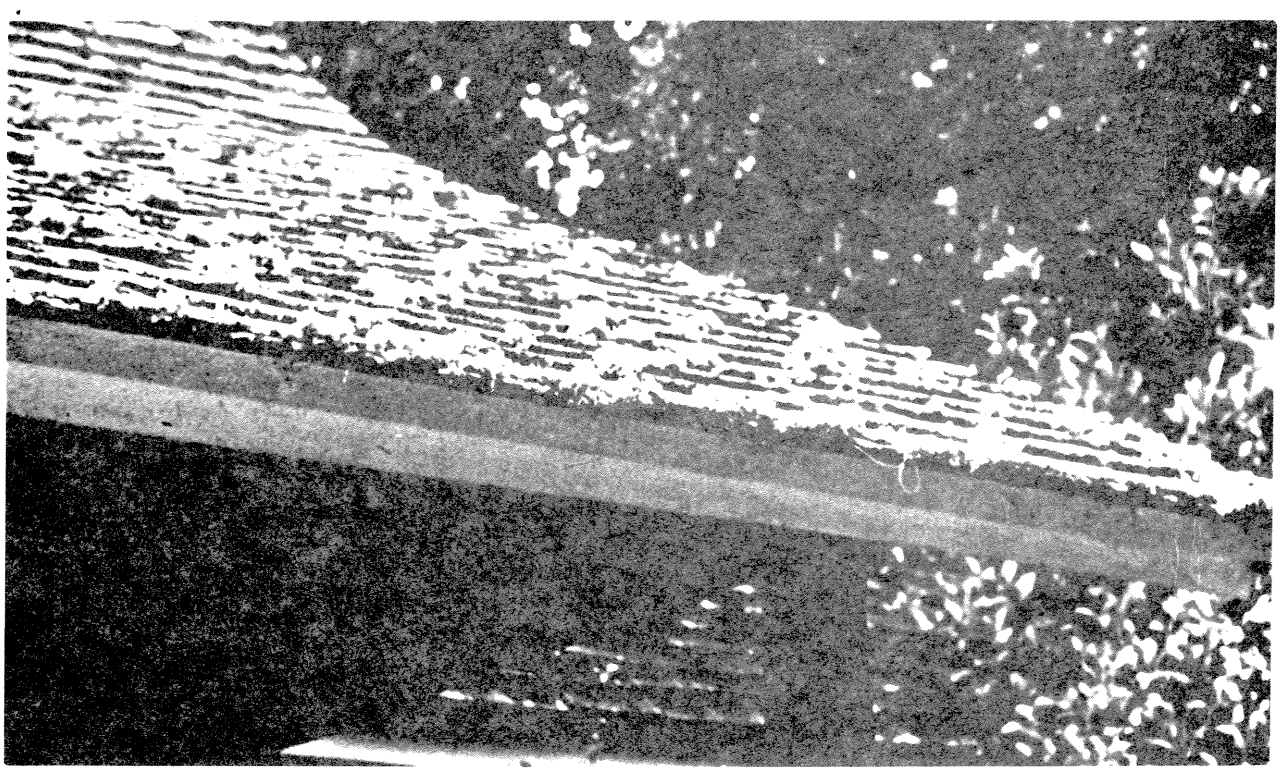

Figure 6.--Low slope roof allowing deterioration to occur in less than expected longevity.

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

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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-1.[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

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3/ The conditions used for treatment in a laboratory procedure are shown in the Appendix with the procedures numbered sequentially.

of 300 treatment hours.[4/] 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 compared 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)[5/] 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

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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:

$$\frac{dk}{dT} = \frac{E}{RT^2} \quad \text{or} \quad k = \frac{-E}{2.303RT}$$

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. Stamm (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 were 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 the 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 mm^2 (1 $in.^2$) from the specified 1,935 mm^2 (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 delmaination 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-, WAFER-, 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 Pinion (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, cycling between two 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 for 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 evaluating their durability. 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. There are definite needs to develop rapid wet tests that are better suited for control of mismanufacture.

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 x 25 mm (1 in. x 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 as required for 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 wet 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

of particleboard, and carried out lengthy and extensive experimentation. He was searching for test procedures that would account for the most important degrading mechanisms acting on a wood-adhesive system and that were also independent of the type of adhesive involved. Results from the laboratory testing procedures were compared with those from weathering exposures where samples were exposed for as long as 9 years to direct outdoor exposure, and also to protected outdoor exposure in both a stressed and unstressed condition. He concluded that neither the outdoor weathering tests nor a simple accelerated test in the laboratory were sufficient, alone, to provide a comprehensive assessment of the durability of a particleboard adhesive. Gressel suggested that proof of future serviceability could be established by use of four laboratory test methods, dispensing with outdoor weathering exposures. He categorizes these test procedures as being of two types: performance tests which permit the deliberate use of conditions that considerably exceed those found in the expected natural environment, and suitability tests that use climatic conditions that approximate those that might occur in service.

Each test is designed to provide a certain type of information relating to a specific degradation mechanism. None of these tests can be expected to be useful for control of mismanufacture, however.

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:

$$\text{Design stress} = \text{Mean stress} \times \text{Variability factor} \times \text{Exposure condition factor} \times \text{Quality control factor} \times \text{Duration of load factor} \times \text{Safety factor}$$

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.

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1964. Permanence/durability after Book II test data of naturally aged papers. Virginia Historical Society Bldg., Richmond, Va.

APPENDIX

A-1 (ASTM D 1037)
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-9 (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 (ASTM D 2898)

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 IB 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

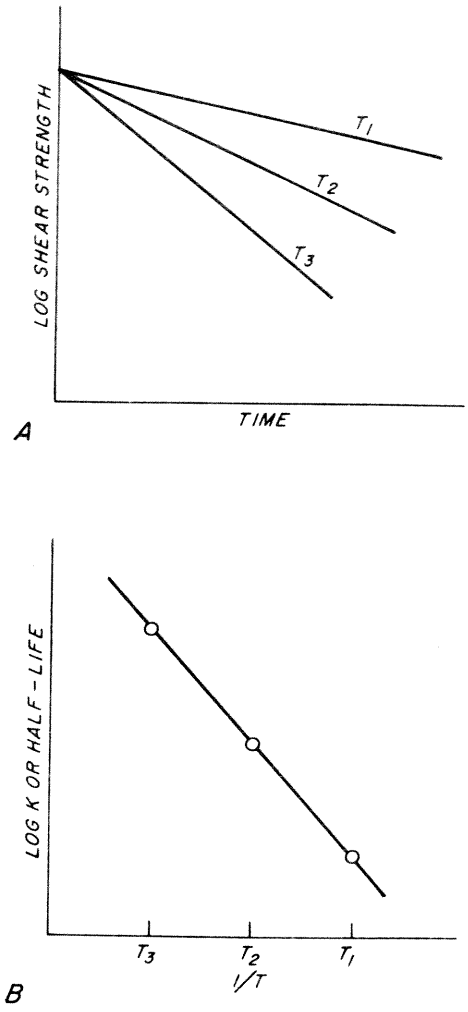

Figure 1.--Hypothetical treatment of shear strength data.

DURABILITY: ITS CONCEPTUALIZATION, CONSEQUENCES, AND CHARACTERIZATION[1/]

Jay A. Johnson[2/]

Abstract.--In this presentation the issue of composite panel durability is viewed from an overall framework: end-use requirements should be related to quality control tests which in turn should be related to process and raw material variables. A definition of durability is given which includes identifying failure events, agents, and their interactions responsible for material breakdown and the use of time as a measure of the degree of degradation. Examples are given to illustrate a few points and a plea is made to develop a quantitative information linkage system.

INTRODUCTION

Since this paper is part of a workshop, I don't feel compelled to follow a rigid format of a formal scientific paper. I do feel compelled, however, to let the reader know how I am going to string my thoughts together for this presentation. The menu of topics will be as follows: (1) message of the paper; (2) definition and general discussion of durability; (3) some thoughts on an overall perspective; (4) some examples of how to characterize durability concepts and finally; (5) I will summarize and make a plea for an integrated approach to the subject of durability.

MESSAGE

Consider a simplified view of the manufacturing process of a wood based product for a particular end-use (fig. 1). The material flow consists of assembling the raw material at the plant, sending this raw material through a series of unit operations which produces a final product and this is sent out to satisfy a need. The ultimate owner pays, up front, for the product and his expectation is that the product will continue to perform its function thereafter. The customer is apparently satisfied; the manufacturer makes a profit and all is right with the world. Right? Wrong!

To make sure the product continues to perform its function and that the manufacturer continues to make a profit, there is a need for an information flow in this system. The information flow can be segmented into four parts (fig. 1): the characterization of product performance, quality control, process control, and raw material characterization. It is important to recognize that the information flow is counter-current to the material flow. One needs to know what performance level the product needs to satisfy and for how long, then quality procedures are required which will provide indicators for future performance; they will distinguish between good and bad product. If bad product is detected, the unit operations must be adjusted and controlled within acceptable tolerances to rectify the problem. Changes in raw material characteristics need to be monitored and their contribution to product quality understood in order to intelligently deal with adjustments to stop making poorer quality product.

The durability question of structural panels is but one of the many performance requirements which must satisfy end-user needs and, consequently: (this is the message).

> There is a need for an information linkage system for product durability which will connect and interrelate raw material characteristics, processing variables and quality control tests to actual end-use service conditions,

and furthermore: (this is a mini-message).

> The information linkage system should be as quantitative as possible with product performance being the focal point of the system.

DEFINITION OF DURABILITY

A number of definitions of durability have been given at this workshop and I will probably duplicate the efforts of others, but nevertheless I do not want to be left out of this exercise.

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7, 1982.

2/Associate Professor, University of Washington, Seattle, WA.

The reason why one spends time defining a concept is not because of the glory and acclaim one will receive from the particular pearls of wisdom which will be written down, but because it is basically a good way to understand the nature of the problem.

A standard gimmick used to define a concept is to look the word up in the dictionary. So let's do that. (As though dictionary editors are experts on technical concepts such as durability.) What you find is something like: durability has something to do with the quality of being durable. Isn't that helpful? Reading on you find: it is the ability to last in spite of frequent use. That's better, but really no different than a common sense definition that my brother gave me: a durable product will last a long time. So much for dictionaries.

A number of good definitions are found in an ASTM publication dealing with durability of building materials (Sereda and Litran 1980). Definitions emerge from the papers in this document like: (1) the durability of a material is its ability to resist changes of its state; (2) durability has to do with the safe performance of a structure (or a portion of it) for its desired life expectancy; or (3) durability is a complimentary concept of reliability which is related to the probability of the successful operation of a device (or product) in a manner it was intended. This last idea is neat as it opens up the use of probability mathematics to help characterize durability.

I have concluded, after dabbling in the literature a bit, that to define a general concept like durability is not easy. Having said that I am going to try anyway. First, however, I will start with a TRUTH which I claim is self-evident, that is:

> A PRODUCT, in use, will be subjected to AGENTS which will INTERACT with the MATERIALS of which it is composed and change the STATE of the product from one form to another.

A general definition of durability follows from this truth:

> The DURABILITY of a product is an ATTRIBUTE related to the TIME taken for it to DEGRADE to the point where it fails to PERFORM its intended PURPOSE or FUNCTION.

Specific definitions of durability can be formulated once the agents have been identified, types of interactions known and failure events clearly defined.

A list of degradation factors (agents) has been put together by Frohnsdorff and Masters (1980) which include: WEATHERING (radiation, temperature, water, normal air constituents, air contaiminants, freeze-thaw cycles, and wind), BIOLOGICAL (micro-organisms, fungi and bacteria), STRESS (sustained and periodic loads), INCOMPATIBILITY (corrosion, chemical and physical degradation) and USE (normal wear and tear, abuse, faulty design). Obviously, the performance of structural wood panels would be influenced heavily by the first three categories.

For a given situation, such as panel products at the job site being subjected to driving rain and subsequently being dried by intense radiation from the sun, a number of the factors may be involved in the deterioration of the product. These factors need to be identified for a specific definition of durability.

The interactions of the agents with the material is usually very complex and difficult to understand theoretically, consequently, simulation (weathering tests) or "worse case" procedures (boil-dry-boil cycles, for example) are used to assess the rate of deterioration as indicators of durability. Methodologies for assessing durability generally consist of performing tests on products subjected to periodic "loads" of a degradation factor. The response of a measured "indicator" (strength, appearance, movement, etc.) is plotted over time.

Characterizing the responses is not as straightforward as one might think. Farhi (1980) discusses four types of behavior which conceivably could be encountered in durability studies (fig. 2). Very durable products are ones which degrade slowly so they virtually never slip below the threshold of acceptable performance (fig. 2a). The degradation may be rapid to begin with but level out above the threshold level; hence, the product would be durable but would show signs of decay (fig. 2b). The product may decay past the threshold level, but at least have a limited life expectancy (fig. 2c). Replacement strategies would be important here and providing the degradation was not rapid a safety factor concept would be employed. The behavior which would be the most difficult to design for would be one in which the degradation rapidly decelerates at a particular point in time (fig. 2d).

More work is needed in this area to understand the "physics" of the degradation processes. By doing fundamental studies, insight will be gained and better judgment of end-use performance should follow. The ingredients for dealing with the interactions then, must be: INSIGHT, UNDERSTANDING, AND JUDGMENT.

Finally, to finish up this section on definition, there is a need to be more specific about failure events. How long will a product like a structural panel "see" a certain "load" or level of a degradation factor?

If more information were available for the frequency of the "loads" (degradation factors) (i.e., rainfall, wet/dry cycles, etc.) then perhaps durability could be handled in a load/resistance format. This is shown schematically in figure 3. A safety index is defined once the durability resistance and the "load" distribution

are characterized. The manufacturer who can keep his product durability resistance distribution "tight" will be in a better position to provide product performance at reduced cost or greater profit.

Another question related to defining failure events that might be worth asking is: Are there specific sequences of events which must be satisfied before a failure will occur? This type of analysis can be done with a fault-tree approach, see, for example, Henley and Kumamoto (1981). Chances are that if this tool were used to identify problems in durability of structural panels, many of the sequences of events leading to failure would be related to installation problems or simple misuse of products for certain applications. The use of a fault-tree diagram has been used to assess problems related to fire in buildings.

PERSPECTIVES

Some time ago Stan Suddarth discussed some aspects of research needs in light-frame construction (Suddarth 1973). He mentioned a few things in particular about durability; i.e., moisture is one of the agents of importance in wood product durability, but he also brought up a few points of a general nature that I think are worth mentioning. Let me paraphrase a few pertinent points:

- Consumers lack an adequate understanding of the behavior of wood and wood products (widespread misconceptions exist about wood).
- The lack of adequate performance standards are an impediment to progress in light-frame construction.
- There is a need for a comprehensive design methodology (more emphasis on "how to" rather than "what to").
- Expected potentials might be gained by introducing probability concepts into design procedures since inherent variability of wood and wood products has penalized their utilization potential.

Although there has been some progress toward resolving some of the deficiencies pointed out by Stan, I think they still exist today. The area of durability of various wood products is particularly lacking in consumer understanding performance standards that adequately reflect end-use requirements, and design methodology which addresses durability.

What can be done about changing this state of affairs? Is there any need to making these changes? To answer these questions, consider the problem from a historical perspective:

Past

- Experience served as a guide.
- The test fence served as a simulation of end-use conditions; subjective judgment of durability.
- Simple test methods were developed (generally of the boil-dry-boil cycle type); tests easy to perform, results used as indicators of durability; useful for comparisons.
- Basically no incentive existed to develop more of a theoretical understanding.

Present

- Uncertain times: Will building practices change or remain the same?
- New generation of wood products emerging: waferboard, OSB, other (?).
- Uncertainty about: long-term performance; mismatch in end-use; proper application.

Future

- If no drastic change in product usage, then no major change in evaluation of durability.
- If, however, changes do occur (fewer housing starts, more discriminating consumer, more competition from non-wood materials), then there may be an incentive for better evaluation procedures.
- Quality may become an issue if demand decreases; less emphasis on supply.
- Costs can be lowered by being more efficient in the end-use application.
- Insight gained by understanding phenomena leading to increased durability may be beneficial in terms of spinning off new products.

I feel things will change; hence, I would say there is a need to do things different. As far as "what can be done?" I don't have any specific answers. The approach will have to vary from one application area to another but it is important that a central group, an ASTM committee perhaps, serve as a focusing body to deal with the problem from an overall perspective.

EXAMPLES

To be more specific about quantifying durability concepts, let me present a few examples. In my opinion, there are two broad categories of performance requirements for building materials: APPEARANCE and BEHAVIORAL. The first example, buckling of medium density siding (MDS), involves an appearance requirement for acceptable performance, whereas the other two examples that I have

selected--cyclic moisture testing and fracture mechanics characterization of delaminations--involve mechanical behavior.

Buckling of MDS Siding

A problem encountered with MDS in the field is one of excessive bowing of the siding. Water is always the culprit. Sometimes excessive rain is associated with the problem, sometimes an internal source of water is implicated; but moisture wherever it comes from, elongates the MDS material and induces a compressive load, since the siding is restrained by nails. If the load reaches a critical value, the MDS "buckles" or deforms laterally, causing an unwanted wavy appearance.

Inspired by others (Suchsland 1965, Spalt and Sutton 1968), the author has looked into this problem from a theoretical point of view and found that for a strip of MDS held between two fixed positions, but whose ends are free to rotate, the outward deflection of the strip, immersed in water, is given by:

$$\delta = \frac{2\ell}{\pi}\sqrt{\varepsilon - \varepsilon_{cr}} \quad \ldots\ldots\ldots\ldots\ldots \quad 1$$

where δ is the maximum lateral deflection, ℓ is the length of the strip, and ε is the free swelling strain of the material related to the amount of water absorbed. The deflection is proportional to the square root of the difference between the free swelling strain and the critical strain, ε_{cr}, at which buckling begins. It can be shown that the critical strain is given by:

$$\varepsilon_{cr} = k\left(\frac{h}{\ell}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots \quad 2$$

where h is the panel thickness thickness and k is an end condition constant.

Using twelve commercially available MDS products, the deflection of strips in a specially designed apparatus was measured and the results, as shown in figure 4, were obtained. Boards with low water absorption, and hence low linear expansion, had smaller deflections but the interesting aspect of these results is that they all fall along the theoretical prediction.

Here we have a situation where the appearance problem is related to water absorption. The "physics" is somewhat complex but is understood and is based on only a few variables. These can be manipulated to reduce the magnitude of the problem. Basically, one can make the product thicker, reduce the linear expansion or do both.

A more basic problem, however, is to determine how much reduction is necessary. Since there is no data on what the water "load" is on the MDS in the field, or whether it is externally or internally generated, then it is virtually impossible to know how to design the product. In fact, for certain parts of the country the weather conditions may make it impossible to reduce the level of response to that required for adequate "performance", i.e., little or no waviness.

This example illustrates how an understanding of a problem can help identify the important ingredients, but without an adequate knowledge of the end-use "loading" requirements only a costly "trial-and-error" approach can be taken relative to developing higher performance products The end-use side is not well understood and it is this aspect of the problem which needs work before a rational approach to the problem can be developed.

Cyclic Loading

When designing a structure, it is customary, if not mandatory, for codes to use "worse case" loading, i.e., the largest reasonable forces--snow, wind, etc.--which will act on the unit over its lifetime. For wood structures a "duration of load" factor is generally applied to account for the deterioration of strength due to these constantly imposed stress states. In addition, the structure also "sees" a number of other low grade cyclic loads: either mechanical or others (loads due to shrinkage and swelling resulting from changes in temperature and relative humidity). The question arises as to whether or not they can significantly deteriorate material performance. Historically, overdesign has, by and large, negated any problems but as new materials evolve will current test methods allow for optimization and still maintain adequate safety?

An interesting approach involving cyclic testing was taken by Okuma et al. (1980) in which urea-melamine particleboard was subjected to cyclic loading (fig. 5). Various stress levels were used with the material being both wet and dry. An index of resistance to cylcic loading was developed by forming a ratio between the number of cycles to failure in the wet condition to those in the dry, i.e.

$$\log r = \log N_w - \log N_d \quad \ldots\ldots\ldots\ldots \quad 3$$

Although this index is somewhat arbitrary, it is a useful concept in that it incorporates a number of factors: time (or cycles) to failure, load levels and the difference between wet and dry behavior. Obviously, this is useful for comparative purposes, but more importantly, information of this type can conceivably be useful in a design calculation. As a matter of fact, the authors state that a particleboard product which can withstand 3×10^5 cycles could be used in floors as this is roughly the number of "foot-steppings" the floor will receive in its lifetime!

The use of cyclic shrinkage and swelling loads has been used by Caster (1980) to evaluate glue bond performance relative to adhesive use in laminated building products. An automatic

boil test ABT was developed and used in conjunction with adhesive block shear strength tests. In this test, samples are immersed in boiling water for a short period of time, lifted out and subsequently dried in a high temperature environment. The whole process is handled automatically and at various times (cycles) the samples are removed and tested.

The degradation of sheer strength for various adhesive systems is shown qualitatively in figure 6. The results are plotted as percentage of dry strength. Clearly, within a few cycles the strength of urea systems decays to nothing.

Phenolic systems on the other hand decay slowly and actually parallel the degradation of wood. With these or suitably transformed plots (percent strength reduction versus log cycles, say), a slope could be used to characterize the degradation resistance of the system. Correlating these degradation indexes with end-use conditions (test fence results, for example) would establish a link between laboratory test results and real world experience. A limited amount of data has been collected on composite boards, shown in figure 7, and a similar pattern emerges.

There are a couple of difficulties with this approach which need to be pointed out. First, when one looks at the original data there is a lot of scatter. Some samples simply fall apart after a few cycles while their neighbors "hang tough", forever (fig. 8a). It sometimes appears that if a sample gets by the first few cycles, it is not affected as much by the succeeding cycles. Because of this problem perhaps a better way to analyze the results of these tests would be to plot cumulutative distributions of the strengths at various times. Then the lower 5% exclusion limit could be characterized as a function of the number of cycles (fig. 8b).

Second, since boiling and drying in a hot environment is a severe treatment which will never be "seen" by the structure ("We don't boil houses") one might ask if there are less drastic types of moisture loading that would be more appropriate. Controlled humidity cycles perhaps? I think this is an area where some interesting work could be done to develop new test methodology and correlate results to more realistic loading regimes.

Fracture Mechanics

The essential idea in the study of fracture is that energy is required to form new surface area and that "strong" materials are those which require a good deal of work to delaminate them (or "tear them asunder"). Now, anyone who has probed a piece of wood composite (particleboard, fiberboard, flakeboard, etc.) knows that the tensile strength, perpendicular to the surface, is very low and very variable. It should come as no surprise that the ubiquitous "IB" (internal bond) test, used by us practioners of performance evaluation, has associated with its highly variable results. This is due to the inherent HETEROGENEITY of the material we are evaluating. I think it is time we start incorporating this aspect into our testing methodology.

In figure 9, a schematic diagram is shown of a conceptual fracture specimen and hypothetical results. Using the load record and position of the crack tip it should be possible to determine fracture toughness at each point along the crack path. Instead of recording one measure of average performance per specimen (which is done in the IB test), a large amount of data could be obtained from one sample which then could be used to characterize the non-uniformity of the material. The obvious implications to regulating product performance consistency would follow if this type of information were available.

Some work has been done in this area by Wilson and his students at Oregon State University and Kyanka, Perkins and students at Syracuse University. This also is a fruitful area for research particularly, I think, when combined with cyclic loading either fatigue (mechanical) or cyclic shrinkage and swelling (moisture). Delamination of the newer structural composites (waferboard, oriented strand boards (OSB), etc.) is a durability concern and a fracture mechanics approach could provide considerable insight to the reasons why delaminations occur.

SUMMARY

There is nothing new in this presentation. I have tried to bring some diverse material together in an attempt to look at the problem of characterizing durability of wood composite materials. The problem is not well defined and a number of approaches are possible depending on the goals of the organizations dealing with the problems. Perhaps a too simplistic view would be to characterize the interested parties as:

INDUSTRY ..... with.....practical concerns

UNIVERSITIES... with.....theoretical interests

PUBLIC LABORATORIES...with....a "bridging the gap" role

If this were the case, then an INFORMATION LINKAGE SYSTEM could be developed in which the end-use performance is related to plant operating characterics which in turn is related to raw material characterization and the parties could contribute various types of information, basic or applied, to the overall system. In this way, a coordinated approach to the durability problem could evolve and its progress monitored until the goal of sufficient performance at lowest cost is achieved.

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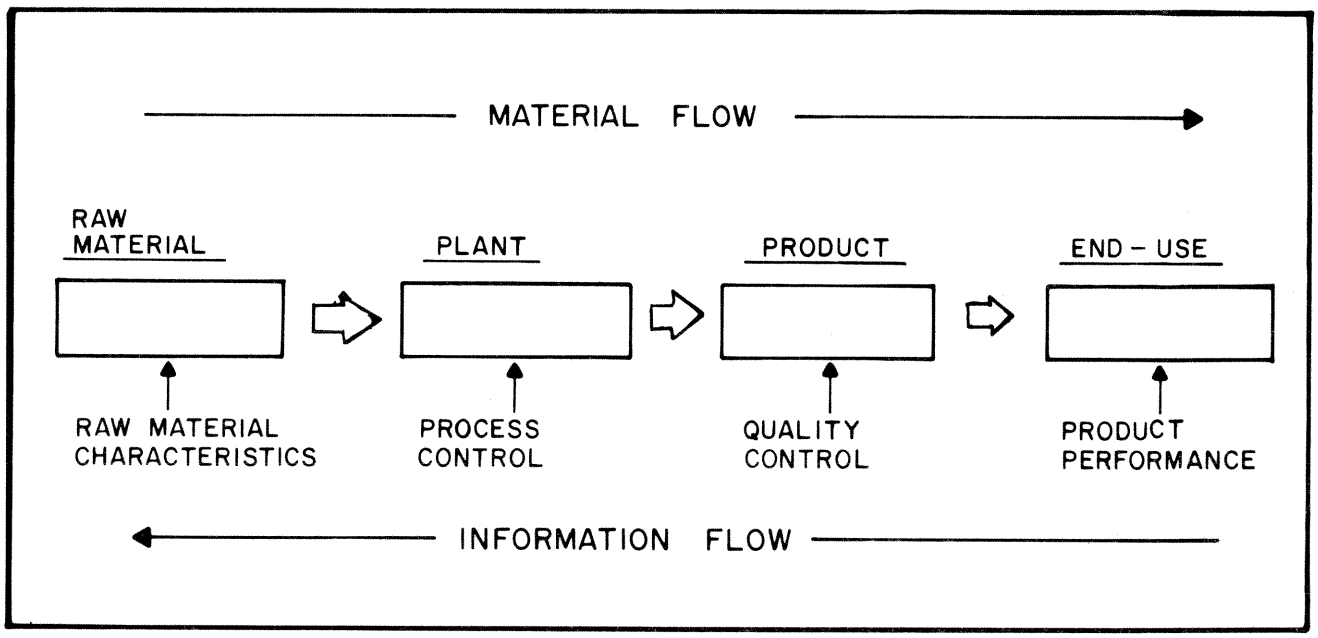

Figure 1.--Schematic representation of an INFORMATION LINKAGE SYSTEM.

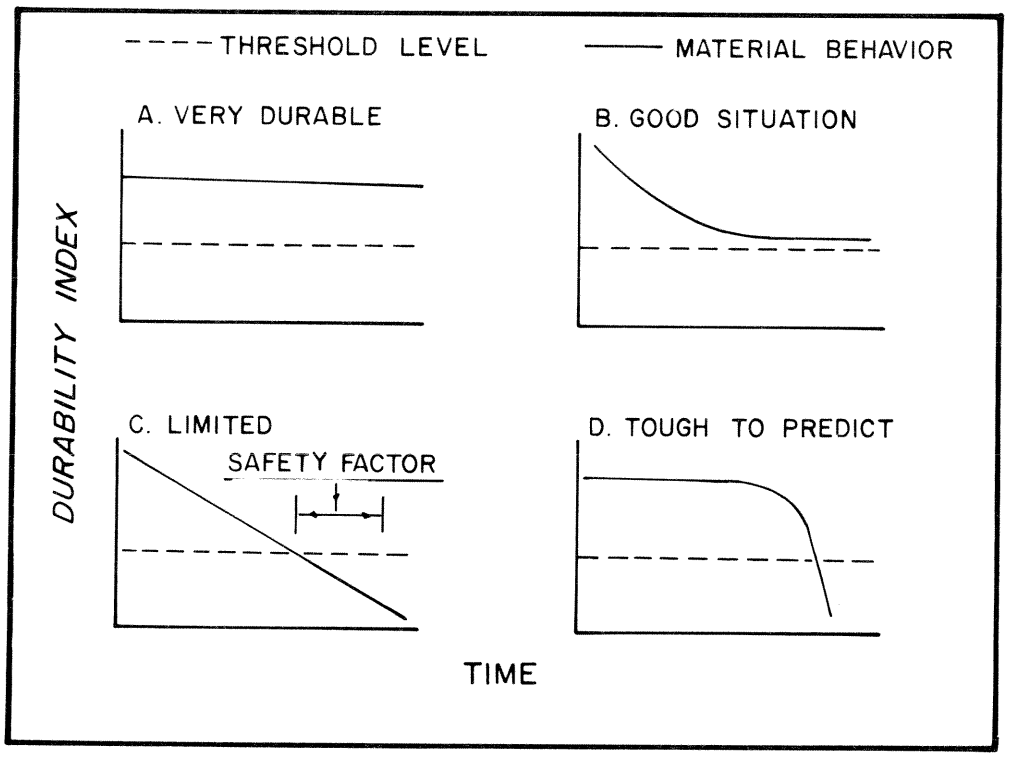

Figure 2.--Types of behavior which could be encountered in durability studies according to Farhi (198).

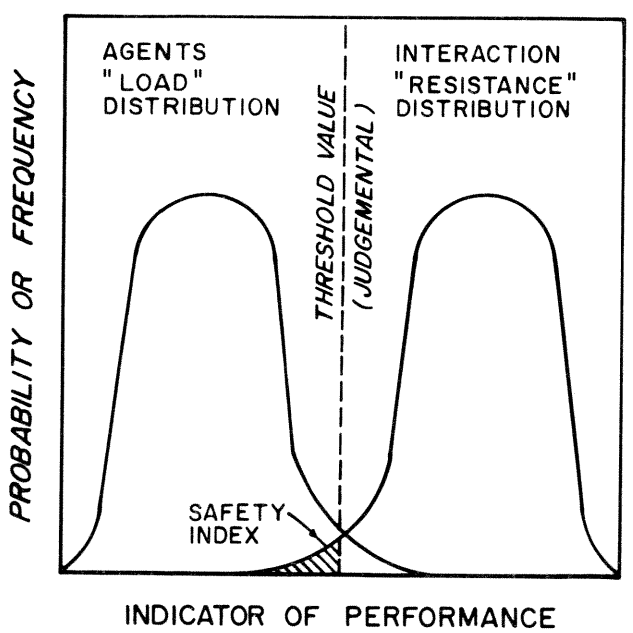

Figure 3.--Concept of safety index based on load and resistance distributions.

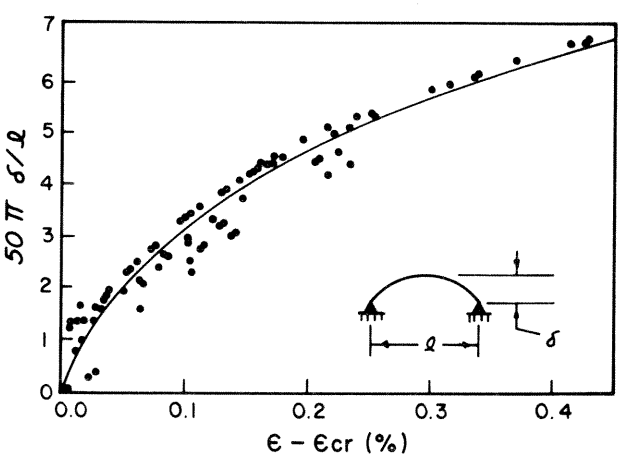

Figure 4.--Buckling of MDS strips (12 manufacturers) as a function of the difference between free swelling strain and the critical buckling strain.

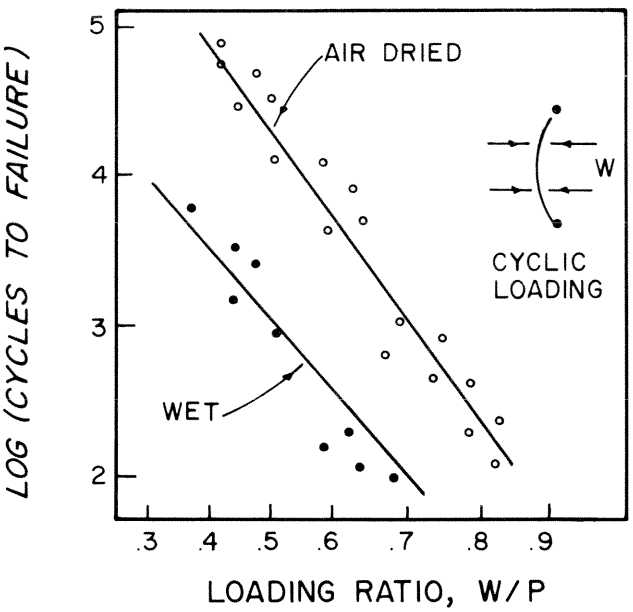

Figure 5.--Results of cyclic bending tests on urea-malamine particleboard (redrawn from: Okuma et al. 1980).

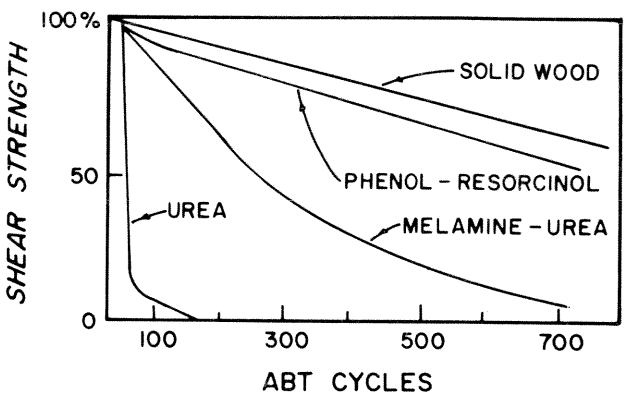

Figure 6.--Reduction in shear as a function of automatic boil test (ABT) cycles (redrawn from: Caster 1980).

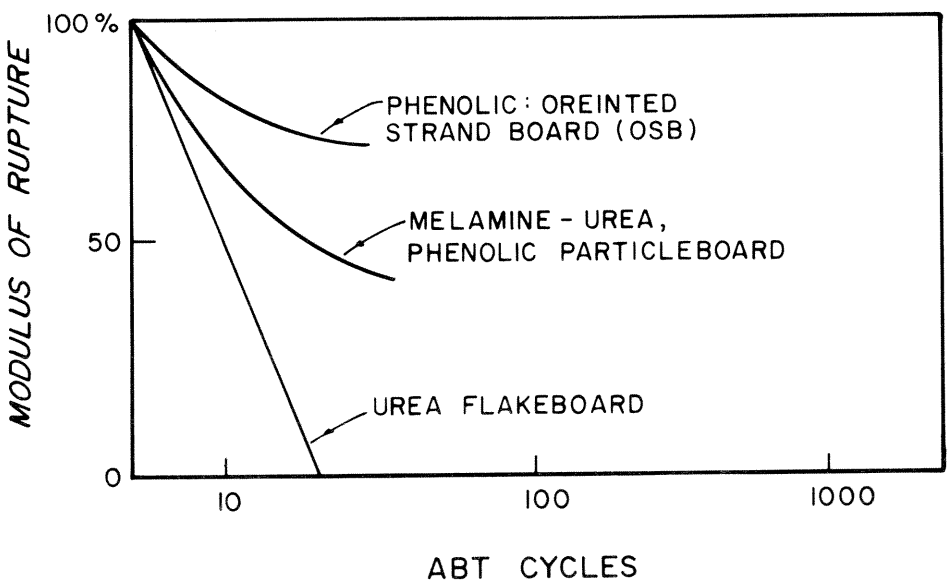

Figure 7.--Strength reduction of wood composite materials as a function of ABT cycles (schematic representation from Caster, private communication).

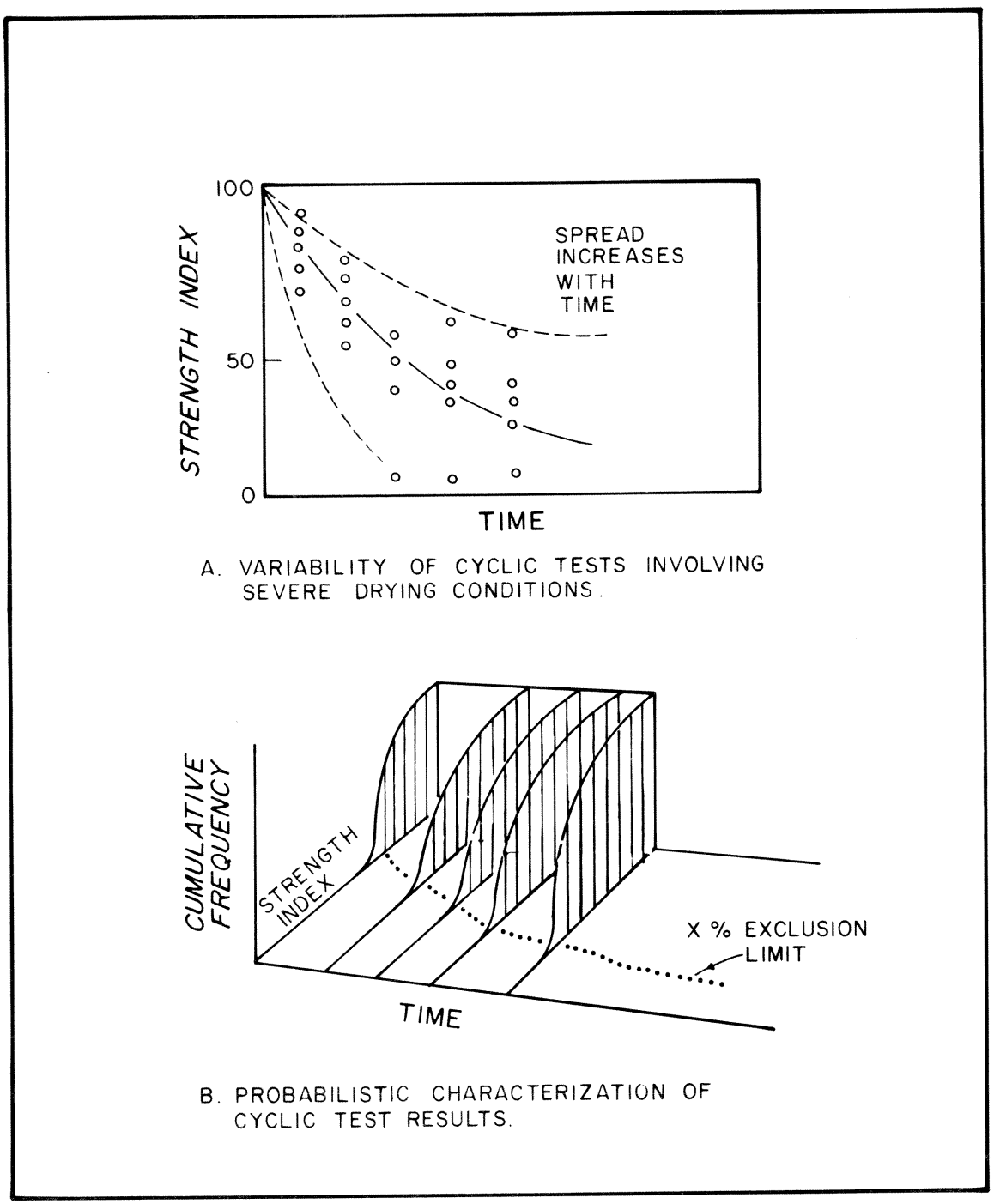

Figure 8.--Difficulty of analyzing durability results and a possible solution.

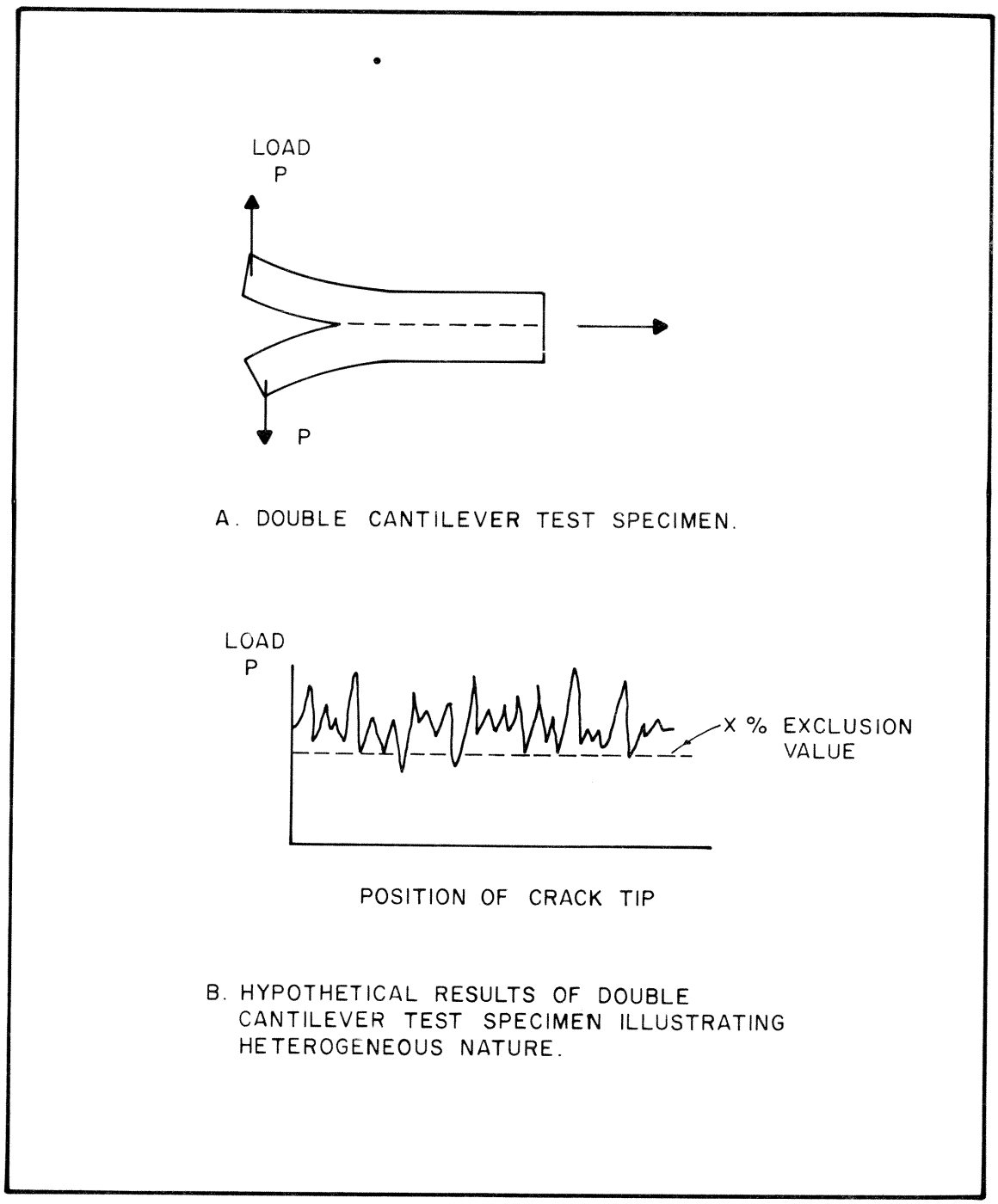

Figure 9.--The use of fracture mechanics to characterize delamination resistance.

ANALYSIS OF THE DIMENSIONAL STABILITY OF WOOD BASED COMPOSITES[1/]

R. C. Tang, E. W. Price and C. C. Chen[2/]

Abstract. A three-dimensional mathematical model capable of predicting the hygroscopic expansions, which occur in layered wood composite materials under changing environments, has been developed. The model is based on the theory of elasticity and the theory of laminated plates. Theoretical results are compared to experimentally measured dimensional changes in a veneer-faced composite board under elevated relative humidity conditions. The comparison shows that experimental results can be accurately predicted by the model. Furthermore, the analysis demonstrates that the distributions of hygroscopically induced swelling stresses which cause the development of warp and delamination in layered wood can be evaluated.

INTRODUCTION

Wood-based composites such as plywood, flakeboard, and veneer-faced composite board, like solid wood, are hygroscopic and dimensionally unstable when exposed to humid environments. In some instances, severe effects such as warp and delamination can be developed which seriously reduce the strength and durability. Therefore, the understanding of the physical nature of wood-based composites under changing environments is very important to the wood products industries for improving the panel dimensional stability. Furthermore, it will provide useful information to structural engineers for building design.

The effects of density, particle configuration particle alignment, resin contents, pressing conditions, and environmental conditions on the dimensional stability of wood coposite boards were extensively investigated by many wood scientists Beech (1975), Chen and Tang (1982), Heebink and Hefty (1969), Heebink et. al. (1964), Lehmann and Hefty (1973), and Price and Lehmann (1978). Due to the anisotropic and heterogenuous nature of wood materials, the interrelationship between the dimensional stability of wood-based composites and the physical nature of their major components is still not conclusively defined.

The theory of dimensional stability of wood-based composite boards was proposed by Heebink et al. (1964). A mathematical model based on this theory was used to predict the linear expansion of plywood from oven-dry to water-soaked. The predicted values of linear expansion were approximately 20 percent higher than observed data. Recently, an improved model was developed by Tabbott et al. (1979). Although this model yields better agreement with experimental results for plywood, the prediction on veneer-faced composite board are approximately 50 percent higher than those of observed data. Furthermore, all of their analyses were limited to one-dimensional models. Therefore, the combined effects of dimensional changes in three orthogonal directions on the distribution of swelling stress, induced by the moisture changes, and the total deformation in the wood composite board were not fully understood.

In this study, a three-dimensional mathematical model capable of predicting the hygroscopic changes as well as the swelling stresses, which occur in layered wood composite board under changing environments, was developed. This model is based on the theory of elasticity (Lekhnitskii, 1963), the theory of laminated plates (Ashton and Whitney, 1970), and the approaches used in the analysis of elastic behavior of cell wall (Tang and Hsu, 1973) and the drying stresses in wood (Hsu and Tang, 1975). The predicted values are compared to experimentally measured dimensional changes in veneer-faced composite board under elevated relative humidity conditions. In addition, the method for calculating the hygroscopically induced swelling stresses was discussed.

[1/] Paper presented at Workshop on Durability of Panel Products, Pensacola, FL, October 5-7, 1982.

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MATHEMATICAL ANALYSIS

Consider a laminated three-layer wood composite element referenced in a rectangular Cartesin coordinate system as shown in figure 1. This element consists of two face layers of equal thickness and physical properties, and the core layer of a different thickness and different physical properties. It is assumed that no residual stresses were left in each layer due to the processes of drying and pressing, and the moisture is uniformly distributed within each layer when the element was equilibrated with the surrounding environments. However, all layers, being bonded together, can not swell or shrink freely during the moisture changing period. Thus, shear stresses were developed at the contact surfaces of each layer. Schematical diagrams of such dimensional changes as well as the distribution of shear stresses occurring at the contact surface in each layer are presented in figures 2 and 3, respectively.

Physically, the shear stresses, $\sigma_{t\ell}$ and σ_{wt}, are mainly concentrated near the edge of the layer and must vanish at the edge because $\sigma_{\ell t}$ and σ_{wt} are equal to zero at the edge of the element. Hence, the shear stress $\sigma_{t\ell}$ can be approximately replaced by a concentrated shear force,

$$\int_0^{L/2} \sigma_{t\ell} d\ell = P/2 \qquad (1)$$

which is acting on the edge of core layer as a compressive force (fig. 4b) and on the face layer as a tensile force (fig. 4a) in the length direction. Similarly, in the width direction, we have

$$\int_0^{W/2} \sigma_{tw} dt = Q/2 \qquad (2)$$

Then, the correspondent stress components in each layer can be expressed in terms of these forces as

$$\begin{aligned}
\sigma_{\ell c} &= -P/(1+\hat{E}_{tc})(1+\hat{E}_{wc})(1-2S)WT, \\
\sigma_{wc} &= -Q/(1+\hat{E}_{\ell c})(1+\hat{E}_{tc})(1-2S)LT, \\
\sigma_{\ell f} &= P/2(1+\hat{E}_{tf})(1+\hat{E}_{wf})SWT, \\
\sigma_{wf} &= Q/2(1+\hat{E}_{\ell f})(1+\hat{E}_{tf})SLT,
\end{aligned} \qquad (3)$$

where σ_{ij} are the swelling stresses; E_{ij} are the measured unrestrained linear expansion of the layer, and subscript i denotes the direction (ℓ, w,t) whereas j is the index for the layer (f:face, c:core); L, W, and T are the length, width, and thickness of the laminated composite element, respectively; S is the fraction referred to the face thickness to the total thickness of the element.

According to the theory of anisotropic elasticity (Lekhniskii, 1963), the strain in the core layer, due to the moisture changes, can be expressed in a tensor form as

$$\begin{bmatrix} \varepsilon_{\ell c} \\ \varepsilon_{wc} \\ \varepsilon_{tc} \end{bmatrix} = \begin{bmatrix} 1/E_{\ell c} & -\mu_{w\ell c}/E_{wc} & -\mu_{t\ell c}/E_{tc} \\ -\mu_{\ell wc}/E_{\ell c} & 1/E_{wc} & -\mu_{twc}/E_{tc} \\ -\mu_{\ell tc}/E_{\ell c} & -\mu_{wtc}/E_{wc} & 1/E_{tc} \end{bmatrix} \begin{bmatrix} \sigma_{\ell c} \\ \sigma_{wc} \\ 0 \end{bmatrix} \qquad (4)$$

and for the face layer, we have

$$\begin{bmatrix} \varepsilon_{\ell f} \\ \varepsilon_{wf} \\ \varepsilon_{tf} \end{bmatrix} = \begin{bmatrix} 1/E_{\ell f} & -\mu_{w\ell f}/E_{wf} & -\mu_{t\ell f}/E_{tf} \\ -\mu_{\ell wf}/E_{\ell f} & 1/E_{wf} & -\mu_{twf}/E_{tf} \\ -\mu_{\ell tf}/E_{\ell f} & -\mu_{wtf}/E_{wf} & 1/E_{tf} \end{bmatrix} \begin{bmatrix} \sigma_{\ell f} \\ \sigma_{wf} \\ 0 \end{bmatrix} \qquad (5)$$

where E_{ij} are the measured modulus of elasticity of the layer and i designates the direction ℓ,w, and t, and j denotes the layer, face and core, and μ_{ikj} (i,k = ℓ,w,t) are the measured Poisson's ratio and $i \neq k$.

By applying the theory of laminated plates (Ashton and Whitney, 1970), the unit linear expansion in ℓ,w, and t directions can be written in the form as

$$\tilde{E}_\ell = \hat{E}_{\ell c} + \varepsilon_{\ell c}(1+\hat{E}_{\ell c}) = \hat{E}_{\ell f} + \varepsilon_{\ell f}(1+\hat{E}_{\ell f}), \qquad (6)$$

$$\tilde{E}_w = \hat{E}_{wc} + \varepsilon_{wc}(1+\hat{E}_{wc}) = \hat{E}_{wf} + \varepsilon_{wf}(1+\hat{E}_{wf}), \qquad (7)$$

$$\tilde{E}_t = \hat{E}_{tc}(1-2S) + 2\hat{E}_{tf}S + \varepsilon_{tc}(1+\hat{E}_{tc})(1-2S) + 2\varepsilon_{tf}(1+\hat{E}_{tf})S, \qquad (8)$$

respectively. Substitution of equations 3-5 into these equations yields

$$\tilde{E}_\ell = \hat{E}_{\ell c} - K_1\{(\hat{E}_{\ell f} - \hat{E}_{\ell c})(M_1G_4 - N_1G_3) + (\hat{E}_{wf} - \hat{E}_{wc})(M_1G_2 - N_1G_1)\}/G, \qquad (9)$$

$$\tilde{E}_w = \hat{E}_{wc} + K_3\{(\hat{E}_{\ell f} - \hat{E}_{\ell c})(M_3G_4 - N_3G_3) + (\hat{E}_{wf} - \hat{E}_{wc})(M_3G_2 - N_3G_1)\}/G, \qquad (10)$$

$$\tilde{E}_t = \hat{E}_{tc}(1 - 2S) + 2S\hat{E}_{tf} + (P/WT)\{\mu_{\ell tc}/\hat{E}_{\ell c}(1+\hat{E}_{wc}) - \mu_{\ell tf}/\hat{E}_{\ell f}(1+\hat{E}_{wf})\} + (Q/LT)\{\mu_{wtc}/\hat{E}_{wc}(1+\hat{E}_{\ell c}) - \mu_{wtf}/\hat{E}_{wf}(1+\hat{E}_{\ell f})\}, \qquad (11)$$

where

$$\begin{aligned}
K_1 &= (1 + \hat{E}_{\ell c})/(1 + \hat{E}_{tc})(1-2S)T, \\
K_2 &= (1 + \hat{E}_{\ell f})/2ST(1 + \hat{E}_{tf}) \\
K_3 &= (1 + \hat{E}_{wc})/(1 + \hat{E}_{tc})(1-2S)T, \\
K_4 &= (1 + \hat{E}_{wf})/2ST(1 + \hat{E}_{tf}), \\
M_1 &= 1/(1+\hat{E}_{wc})\, E_{\ell c}\, W, \\
M_2 &= 1/(1+\hat{E}_{wf})\, E_{\ell f}\, W, \\
M_3 &= \mu_{\ell wc}/(1+\hat{E}_{wc})\, E_{\ell c}\, W,
\end{aligned}$$

$$M_4 = \mu_{\ell wf}/(1+\hat{E}_{wf})\ E_{\ell f}\ W,$$

$$N_1 = \mu_{w\ell c}/(1+\hat{E}_{\ell c})\ E_{wc}\ L,$$

$$N_2 = \mu_{w\ell f}/(1+E_{\ell f})\ E_{wf}\ L,$$

$$N_3 = 1/(1+E_{\ell c})\ E_{wc}\ L,$$

$$N_4 = 1/(1+E_{\ell f})\ E_{wf}\ L,$$

$$G_1 = M_1\ K_1 + M_2\ K_2,$$

$$G_2 = N_1\ K_1 + N_2\ K_2,$$

$$G_3 = M_3\ K_3 + M_4\ K_4,$$

$$G_4 = N_3\ K_3 + N_4\ K_4,$$

$$G = G_2\ G_3 - G_1\ G_4,$$

$$Q = \{(\hat{E}_{\ell f} - \hat{E}_{\ell c})\ G_3 + (\hat{E}_{wf} - \hat{E}_{wc})\ G_1\}/G.$$

$$P = \{(\hat{E}_{\ell f} - \hat{E}_{\ell c})\ G_4 + (\hat{E}_{wf} - \hat{E}_{wc})\ G_2\}/G. \quad (12)$$

From these equations, the hygroscopic linear expansion of layered wood composites can be calculated provided that the engineering constants of its components as aforementioned are available. To demonstrate the validity of the developed mathematical model, experiments on the determination of the linear expansion and the thickness swelling of a 1/2-inch-thick veneer-faced composite board, consisting of two equal thickness (1/8 inches) southern pine veneer as face layer and a 1/4-inch-thick randomly oriented sweetgum flakeboard as core layer, were performed. Two groups of board were involved, one was pre-conditioned constantly under 65% relative humidity (RH) while the other group was treated with a cycling RH (35%-95%-35%). Thereafter, both groups were conditioned and equilibrated at 75°F and RH levels of 35%, 55%, 75% and 95% consecutively and measurements were made at each RH level. The collected data are tabulated in table 1 (Chen and Tang, 1982). Based on these analysis, the theoretically calculated linear expansions and thickness swellings as compared with the experimentally measured data are illustrated in figures 5 and 6.

DISCUSSIONS AND REMARKS

It can be seen from figure 5 that the theoretically predicted values of linear expansion for a veneer-faced composite board are in fair agreement with the experimental results (app. 20 percent off). Such a small discrepany is probably due to the lacking of reliable experimental data of certain elastic constants of the components as indicated in table 1, especially, the modulus of elasticity of veneer in the cross-grain direction. However, these estimated constants are less important in the theoretical determination of hygroscopic expansion in the thickness direction. Therefore, the prediction in thickness swelling, as shown in figure 6, is very accurate as compared with observed values. It is believed that the availability of more reliable elastic constants of components will improve the accuracy of the developed mathematical model for predicting the dimensional stability of layered wood composite boards. Furthermore, once the components of hygroscopic changes are determined, then by applying the theory of orthotropic elasticity, the distribution of swelling stresses can be calculated provided that the engineering constants of the board are known. The analysis in this regard is being conducted and details will be presented in a separate report.

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Table 1. Experimental data of Elastic Constants and Free Linear Expansion of the Components of Veneer-faced Composite Board*

Components	RH%	E x 10^6 psi: Parallel to grain	E x 10^6 psi: Perpendicular to grain	$\mu_{\ell w}$	$\mu_{w\ell}$	$\mu_{\ell t}$	μ_{wt}	$\hat{E}_\ell$ (%)	$\hat{E}_w$ (%)	$\hat{E}_t$ (%)
		*** Pre-treated with one cyclic humidity (35-95-35%) ***								
Flakeboard (core)	55	.5281	.5281	.1894	.1894	.2310	.2310	.0494	.0494	1.9149
	75	.4749	.4749	.1898	.1898	.2315	.2315	.1055	.1055	3.6306
	95	.2883	.2883	.1693	.1693	.2065	.2065	.1612	.1612	13.4003
	48-hr. soaked	.2065	.2065	.1683	.1683	.2053	.2053	.1929	.1929	25.1534
Veneer (face)	55	2.0861	.0648	.3552	.0110	.4560	.3720	.0679	.9469	1.4852
	75	2.0276	.0609	.5017	.0127	.5157	.4207	.1001	2.4507	2.3646
	95	1.8504	.0478	.0656	.0017	.0842	.0687	.1363	5.0512	7.1870
	48-hr. soaked	1.7567	.0403	.0452	.0010	.0580	.0473	.2517	8.0063	14.1254
		*** Pre-treated with Constant 65% RH ***								
Flakeboard (core)	55	.6777	.6777	.3198	.3198	.2310	.2310	.0406	.0406	1.0217
	75	.6273	.6273	.3111	.3111	.2247	.2247	.0866	.0866	3.5132
	95	.3643	.3643	.2685	.2685	.1939	.1939	.1903	.1903	24.5403
	48-hr. soaked	.3121	.3121	.2471	.2471	.1785	.1785	.2527	.2527	38.9288
Veneer (face)	55	2.1551	.0681	.3510	.0111	.4560	.3720	.0350	.7447	1.4362
	75	2.0939	.0642	.4007	.0123	.5206	.4247	.0577	1.7976	2.3308
	95	1.7997	.0502	.1223	.0034	.1589	.1296	.0947	4.0243	8.2503
	48-hr. soaked	1.5528	.0403	.1185	.0031	.1539	.1256	.2118	4.7676	14.1924

* Reference 3; $\mu_{\ell t}$ and μ_{wt}, data of flakeboard are estimated from the sweetgum wood; the E's perpendicular-to-grain, of veneer were adjusted from the measurement of unidirectionally laminated plywood; and linear expansion data were calculated based on 35% RH initial condition.

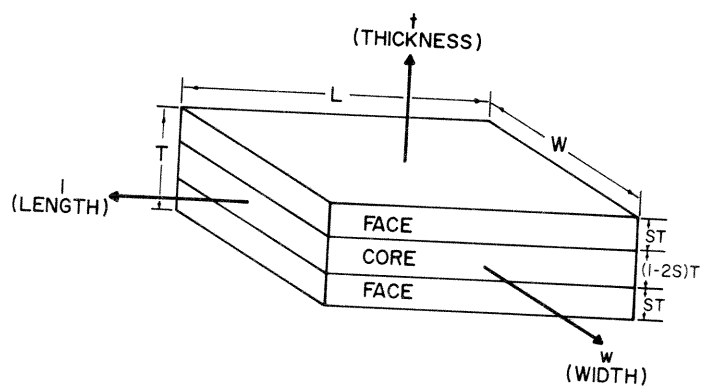

Figure 1.--A three-layer laminated element.

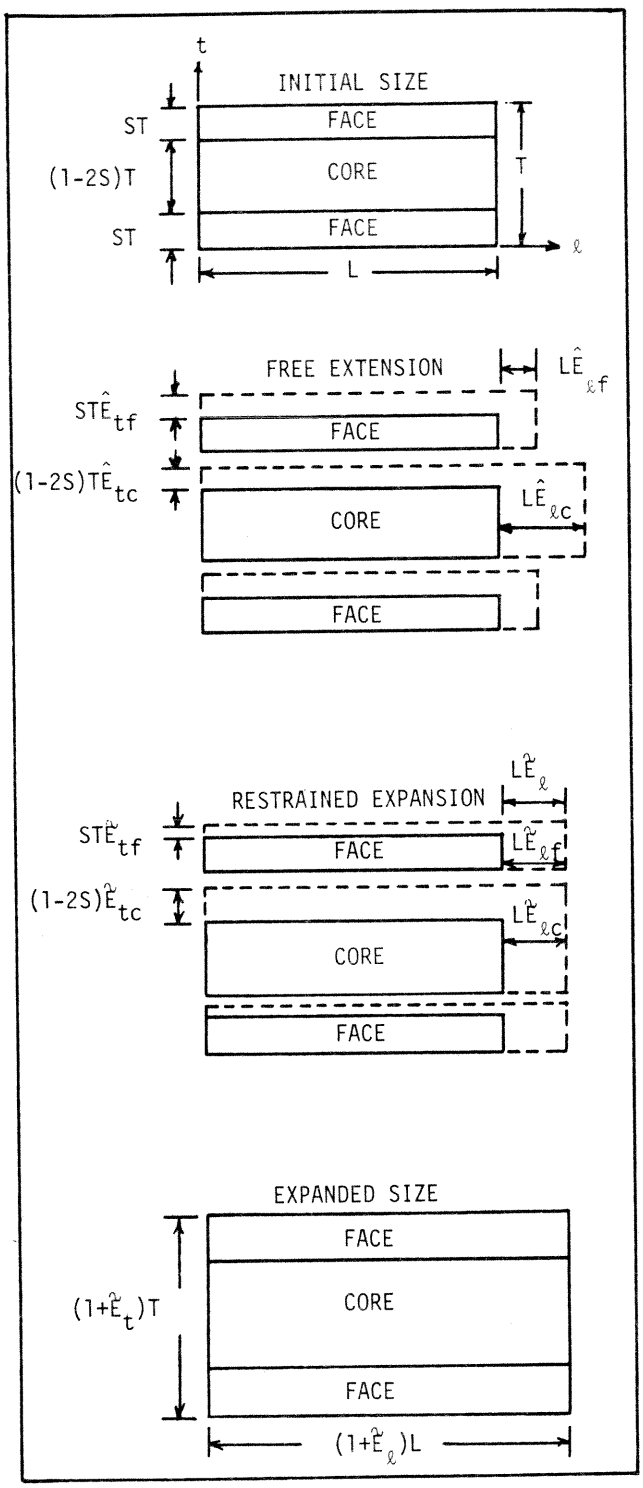

Figure 2.--Schematic diagram of the dimensional changes in ℓ and t-direction of a three-layered wood composite eelment due to moisture changes.

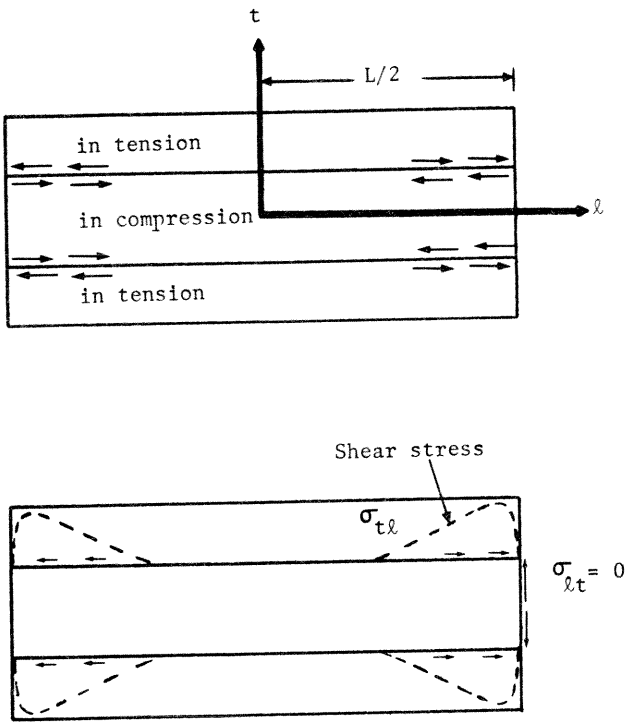

Figure 3.--Schematic diagram of the distribution of the shear stresses occurred at the contact surfaces in the ℓ direction.

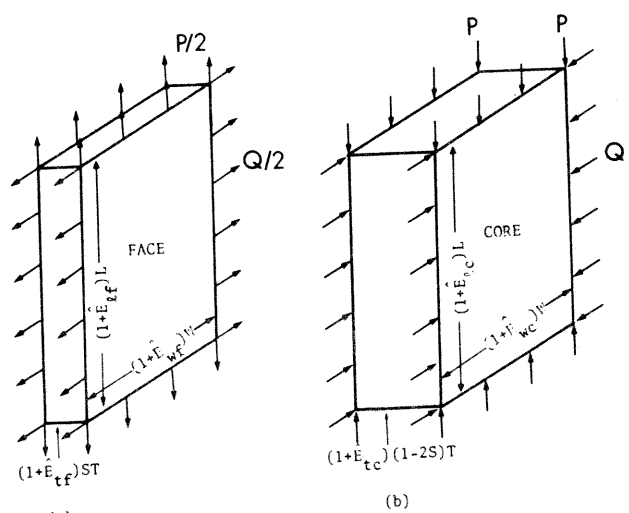

Figure 4.--Schematic diagram of forces developed in the layers due to the moisture changes.

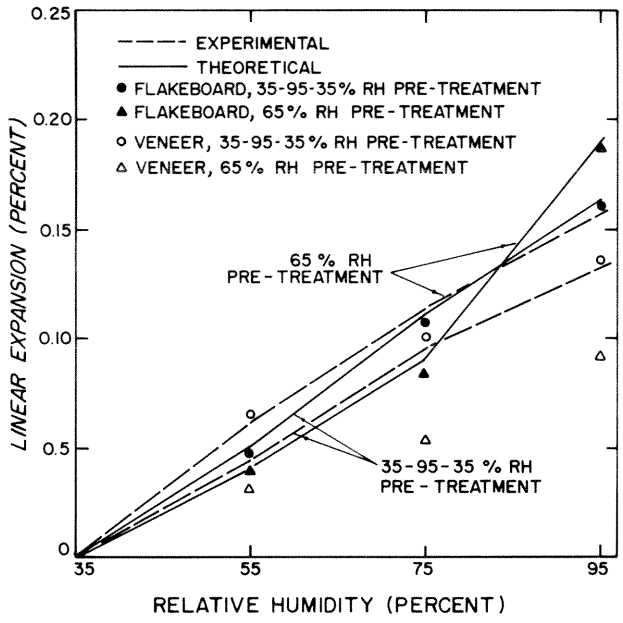

Figure 5.--Predicted and measured linear expansion of veneer-faced composite board.

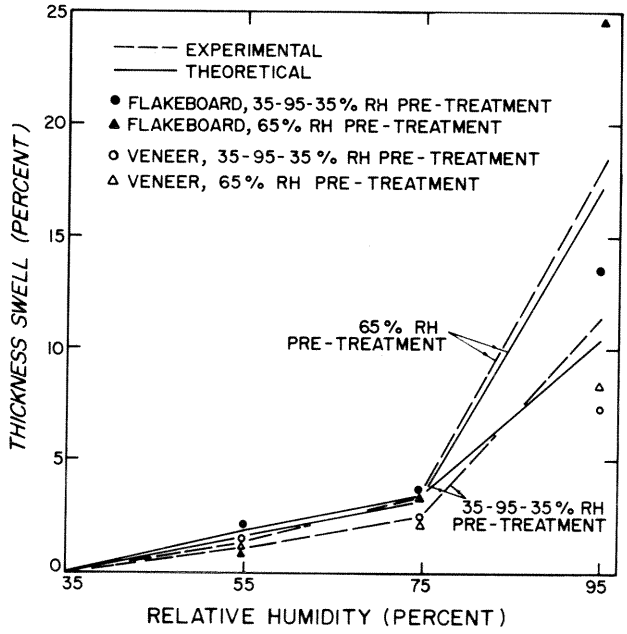

Figure 6.--Predicted and measured thickness swelling of veneer-faced composite board.

EFFECT OF FLAKE-CUTTING PATTERNS AND RESIN CONTENTS ON DIMENSIONAL CHANGES OF FLAKEBOARD UNDER CYCLIC HYGROSCOPIC TREATMENT[1]/

R. C. Tang, C. Y. Hse, and Z. J. Zhou[2]/

Abstract.--Dimensional stability and internal bond strength of flakeboards made with the combination of three factors were evaluated under the cyclic ovendry (OD) and vacuum-pressure-soaking (VPS) treatment. The factors considered were species (sweetgum, white oak, and red oak), flake types based on anatomical flake characteristics (LT, LR, TL, TR, RL, and RT for longitudinal, tangential, and radial directions), and resin contents (3, 5, and 7%). Linear expansion (LE) and thickness swelling (TS) values were significantly affected by the six flake cutting modes. The lowest LE was observed in the boards composed of flakes with flake-length direction parallel to the longitudinal direction of wood (RL and TL flakes). The low TS was observed in boards with RT and TR flakes. The resin content had a substantial effect on the TS boards made with LT, LR, TL, and RL flakes. The resin content, also effected the internal bond strength in all board types.

INTRODUCTION

In recent years, the consumption of wood composite panels, such as waferboard, flakeboard and oriented strandboard has been substantially increased due to the increasing demand of structural panels in building construction. Although some material properties of the composite boards are comparable with the leading structural plywood products, the dimensional stability of composite boards is not equivalent to that of plywood. The difference is especially noticeable in the thickness direction.

In the South, many of the structural exterior flakeboards are manufactured from mixed hardwood species. These species, oaks in particular, are difficult to glue and yield less stable panels (Hse 1975). Since the hardwood volume consists of a large percentage of the oaks, the durability and dimensional stability of panels made with a large percentage of oak species must be improved if a significant volume of hardwood species is to be used for fabricating structural panels. One method of accomplishing this hardwood utilization is to analyze process variables that have a potential of upgrading the panel performance. Two important variables are flake-cutting patterns (anisotropic characteristic of wood) and resin contents. Therefore, the effects of flake-cutting patterns and resin contents on the dimensional stability and internal bond strength were studied and reported in this manuscript.

EXPERIMENTAL PROCEDURE

To evaluate the anisotropic effect and resin content on dimensional stability of flakeboards, panels were fabricated with species, resin content, and flake cutting pattern combinations. Variables considered were:

1. Species: Sweetgum, red oak, and white oak

2. Resin content: 3, 5, and 7 percent liquid, phenol-formaldehyde based on oven-dry weight of flakes

3. Flake cutting patterns: 6 patterns (fig. 1) cut from blocks 3/8" by 3"

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7, 1982.

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Cutting direction	Flake Pattern Width-length (Thickness)
Tangential (T)	LT (R)
Radial (R)	LR (T)
Longitudinal (L)	TL (R)
Radial	TR (L)
Tangential	RT (L)
Longitudinal	RL (T)

Each combination of these variables were replicated 8 times requiring a total of 324 panels to be fabricated (i.e., 3 species x 3 resin contents x 6 flake cutting patterns x 6 panel replications). The flakes, cut on a laboratory disk flaker, were approximately 3 inches long, 0.02-inch thick, and 3/8-inch wide and dried to 3 percent moisture content before adhesive was applied.

Panel fabrication conditions were:

Panel size: 1/2" x 18" x 22"
Panel density: Sweetgum panels - 40 pcf, and oak panels - 46 pcf
Hot press temperature: 340°F
Press time: 6 minutes (1-1/2 min. to stop plus 4-1/2 min. closed.)

Although the panels were replicated 8 times, only six boards were used to obtain the results reported in the manuscript. The six boards, randomly selected, were trimmed to approximately 16 x 20 inches, then into 2 pieces 2 by 16 inches, and 1 piece 16 x 16 inches. Each 2- by 16-inch specimen was then further cut to yield two 2- by 2-inch samples for testing of tensile strength perpendicular to the face (internal bond (IB)) and one 2- by 12-inch sample for the measurement of dimensional stability. This procedure resulted in 24 IB and 12 dimensional stability samples per variable combination.

The IB values were obtained from specimens at approximately 6% moisture content while dimensional stability values were obtained after one cycle of an ovendry-vacuum-pressure-soaking treatment (OD-VPS). The OD-VPS treatment involved (1) drying at 212°F for 72 hours, (2) soaking in water for 16 hours, (3) vacuum in 25-inches of mercury for one hour and then placed under 75 psi pressure (submerged under water at room temperature) for 2 hours, and (4) continuous watersoaking for 12 hours without pressure. Linear expansion (LE) and thickness swelling (TS), measured with a specially designed device (fig. 2), were calculated based on the change of dimensions from OD condition to the end of the OD-VPS cycle.

RESULTS AND DISCUSSIONS

Average of LE, TS, and IB of the tested specimens are summarized in table 1.

Linear expansion (LE): The average LE ranges per three species are:

Sweetgum: 0.09 to 7.57 percent
Red oak: 0.18 to 4.51 percent
White oak: 0.12 to 5.83 percent

The effect of flake cutting patterns on the LE is plotted in figure 3. As expected, the boards composed of RT flakes consistently resulted in the highest LE and followed in a decreasing order of TR, LT-LR, and TL-RL flakes with the exception of TR flakes of sweetgum. The LT-LR and TL-RL flakes were grouped together because there was no signficant difference in LE between these two flake cutting patterns, respectively. The LE changes for these flakeboards closely parallel the uneven dimensional changes for wood along the three orthogonal structural directions (FPL 1960, 1972). As evident in figure 3, the low LE is associated with flakes having flake length direction parallel to the longitudinal direction of wood, the medium LE is associated with flakes having their flake width direction parallel to the longitudinal direction.

In general, as the resin content increased the LE decreased (fig. 4). This relationship was true for panels fabricated with RT, TR, LT, and LR flakes for all species. The exceptions were at the higher resin content, 5 to 7 percent, for RT flakes of red oak and LT flakes of sweetgum. For TL and RL flakes, LE was not affected by the resin content.

Thickness swell (TS): The average TS ranged from 6% to 76%. For individual species, the TS averages are:

Sweetgum: 9.1 to 47.8 percent
Red oak: 6.0 to 49.1 percent
White oak: 9.7 to 75.5 percent

In figure 5, the effects of flake type on TS are presented. The substantially lower TS shown in panels made of RT and TR flakes were due to the fact that the flake thickness is parallel to the longitudinal direction of wood. However, when the flake thickness direction was in the radial wood direction (LT and TL), a large TS difference was obtained between the two flake types. The possible explanation for the result may be that the LT flakes have a tendency to warp more than TL flakes due to the anatomical structure.

As was experienced with LE, as the resin content increased the TS decreased (fig. 6). However a much larger TS decrease occurred as resin content increased from 3 to 5 percent as compared to resin content increased from 5 to 7 percent.

Comparing species, white oak flakes consistently resulted in the greatest TS followed by sweetgum and then red oak at the 3 and 5% resin content (fig. 7). For the 7% resin content, sweetgum often had the highest TS and red oak the least. Therefore, for this study a red oak panel always yielded the smallest amount of TS.

Internal bond strength (IB): Ranges of average IB for the three species are:

Sweetgum: 46 to 288 psi
Red oak: 37 to 217 psi
White oak: 13 to 68 psi

The effects of resin content on IB are shown in figure 8. As expected, the IB increased as the resin content increased. However, the IB for white oak at 7 percent resin content was less than the IB of red oak or sweetgum at 3 percent resin content. The extremely low IB for most white oak flakeboards was partly due to their low panel density. As given in table 1, the panel density of white oak flakeboards ranged from 38.7 to 49.6 pcf. The average panel density, 44.9 pcf, is much less than 48.1 pcf minimum white oak panel density for 70 psi in IB as determined in a previous study (Hse 1975).

In figure 9, the effects of flake type on IB are presented. Surprisingly, the boards made of RT and TR flakes of sweetgum and red oak showed very high IB in comparison with other type flakes. The results indicate that the boards with a high LE or low TS may have a high IB and further examinations using Scanning Electron Microscopy to identify this phenomenon are underway.

SUMMARY

1. The low LE occurred in the flakeboards having flake length parallel to the longitudinal direction of wood, the medium LE developed in these with flakes having flake width aligned with the longitudinal direction of wood and the high LE recorded in these with flakes having flake thickness coincided with the longitudinal direction of wood.

2. LE decreased as resin content increased but the effectiveness of high resin content was not pronounced in the boards with TL and RL flakes.

3. High TS was observed for boards with flakes having their thickness direction in either radial or tangential direction of wood while the low TS occurred only on these with flakes having thickness direction parallel to the longitudinal direction of wood.

4. Increasing the resin content substantially decreased the TS in all types of specimens.

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Hse, C.-Y.
1975. Properties of flakeboards from hardwoods growing on southern pine sites. For. Prod. J. 25(3):48-53.

Table 1.--Average values of linear expansion, thickness swelling, and internal bonding strength of hardwood flakeboards

Flake type	Resin content	White oak					Red oak					Sweetgum				
			ODVPS[1]/					OD-VPS					OD-VPS			
		Weight density[3]/	MC	LE	TS	Internal bond	Weight density[3]/	MC	LE	TS	Internal bond	Weight density[3]/	MC	LE	TS	Internal bond
	%	pcf	--------%--------			psi	pcf	--------%--------			psi	pcf	--------%--------			psi
LT	3	43.7	115	2.80	75.5	18	41.8	118	1.17	49.1	37	41.2	105	.60	30.8	58
	5	46.9	97	1.41	34.4	50	43.8	92	.77	21.0	90	43.0	112	.58	21.2	117
	7	46.1	92	1.16	23.5	61	43.7	81	.77	16.2	104	43.0	102	.77	18.1	127
LR	3	44.0	113	1.39	55.0	20	44.1	104	.84	34.6	43	42.7	136	.80	43.2	46
	5	46.3	96	1.19	32.1	35	44.9	98	.69	23.5	90	44.4	119	.73	31.6	75
	7	45.9	90	1.22	25.4	50	45.0	85	.64	19.6	97	45.2	103	.52	24.8	94
TL	3	45.7	97	.18	43.9	39	47.9	76	.19	30.9	74	44.8	113	.15	39.9	70
	5	46.7	80	.29	26.3	68	47.5	81	.21	17.2	136	45.2	101	.18	28.3	93
	7	47.1	76	.28	20.3	49	47.8	72	.25	14.7	149	47.1	100	.17	25.9	131
TR	3	44.0	111	4.74	11.5	29	43.4	99	3.16	12.3	104	39.6	120	7.57	17.5	50
	5	44.2	87	3.77	11.4	50	44.7	96	3.36	9.8	145	43.7	104	6.43	14.4	193
	7	44.4	81	3.66	9.7	57	43.6	80	3.30	9.2	199	43.4	100	5.63	9.1	254
RL	3	46.5	105	.22	43.5	25	47.1	89	.24	35.4	83	44.5	114	.09	47.8	55
	5	48.9	71	.25	32.4	34	48.0	78	.26	25.5	147	45.5	103	.26	33.8	81
	7	49.6	77	.12	24.0	36	49.1	71	.18	20.1	149	47.3	98	.24	28.8	116
RT	3	40.3	121	5.83	12.0	13	41.4	101	4.51	12.2	104	39.3	107	4.07	13.7	181
	5	39.4	116	5.66	11.5	27	41.2	101	3.48	7.0	94	39.4	93	3.75	12.5	288
	7	38.7	93	5.11	10.8	44	41.0	101	4.30	6.1	217	39.5	102	3.56	10.0	243

1/MC = moisture content, LE = linear expansion, and TS = thickness swell.
2/L, T, and R denote the longitudinal, tangential, and radial direction, respectively. The 1st character designates the width direction of flake whereas the 2nd one is for the length direction.
3/Measured from the samples conditioned at 65% RH and 75°F.

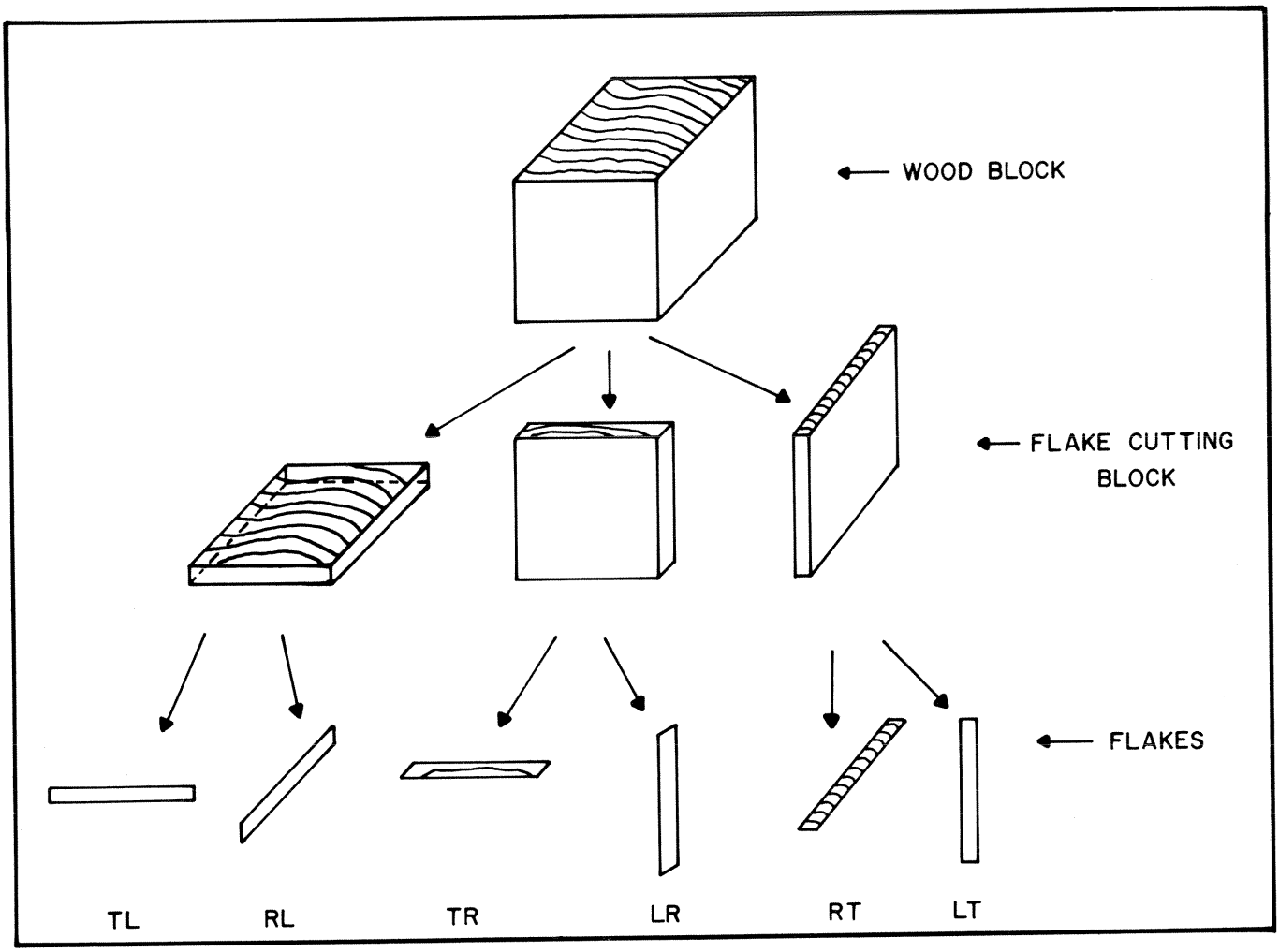

Figure 1.--Methods of flake preparation. L, T, and R denote the longitudinal, tangential, and radial direction, respectively. The first character designates the width direction of flake whereas the second character is for the length direction.

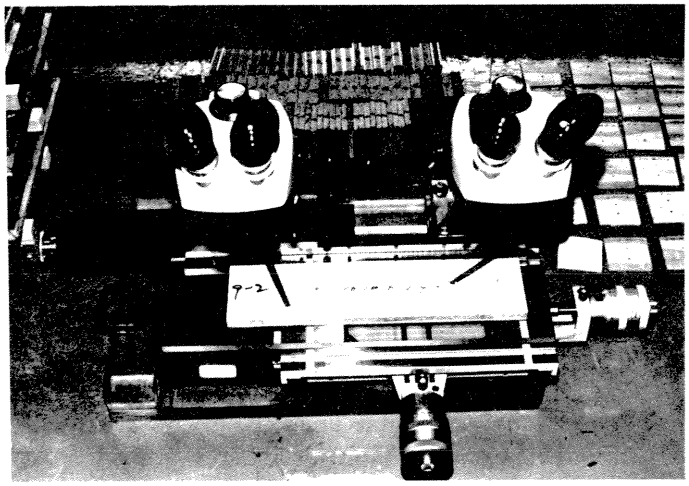

Figure 2.--Optical linear micrometer showing two microscopes, dial gage, and specimen on stage with knobs for lateral x-y stage movement.

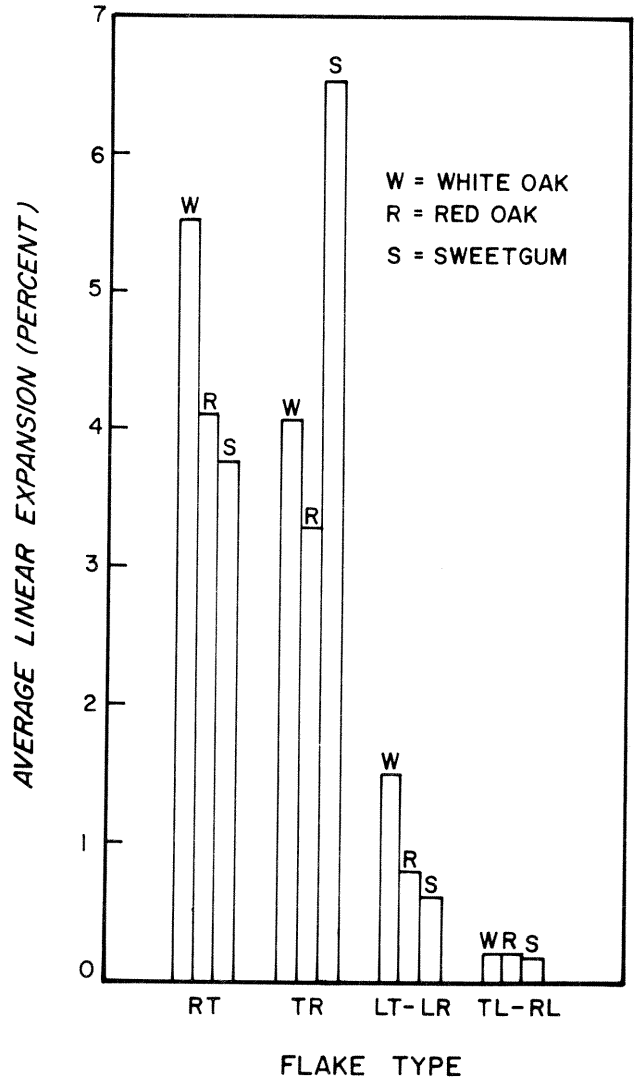

Figure 3.--Effect of flake type on linear expansion of flakeboard.

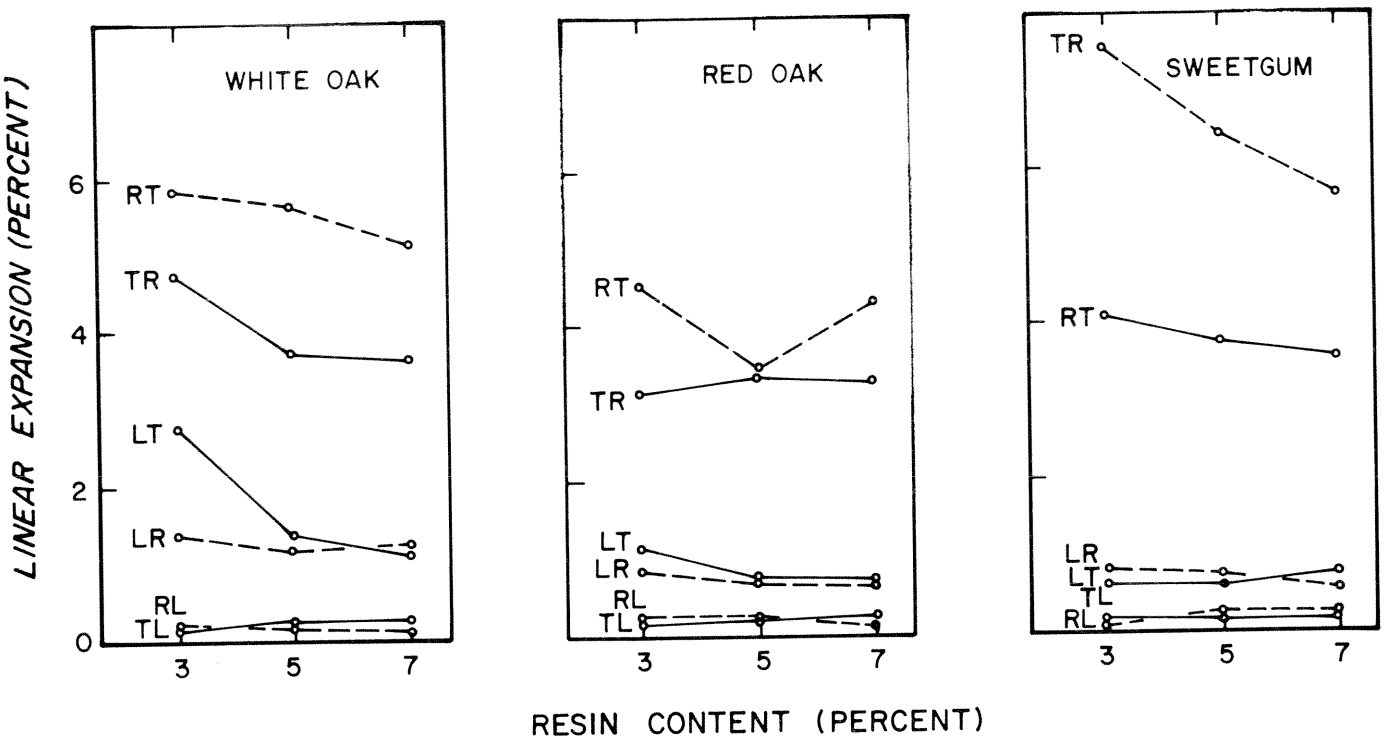

Figure 4.--Variation of linear expansion of different flake types as affected by resin content.

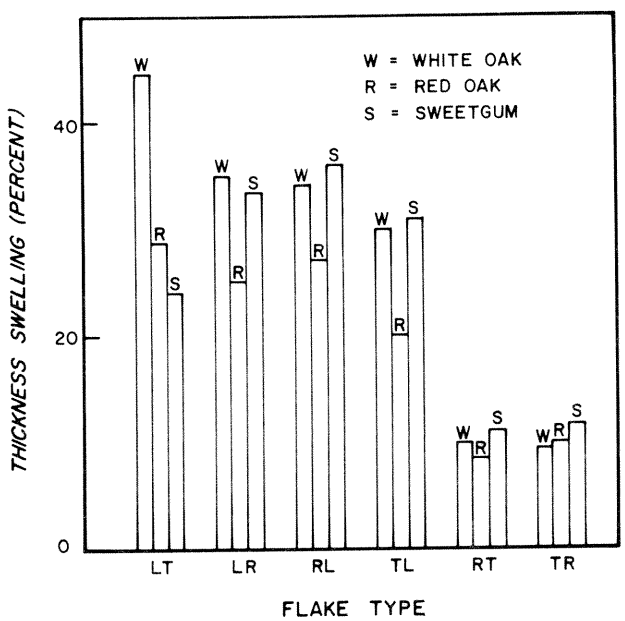

Figure 5.--Effect of flake type on thickness swelling of flakeboard.

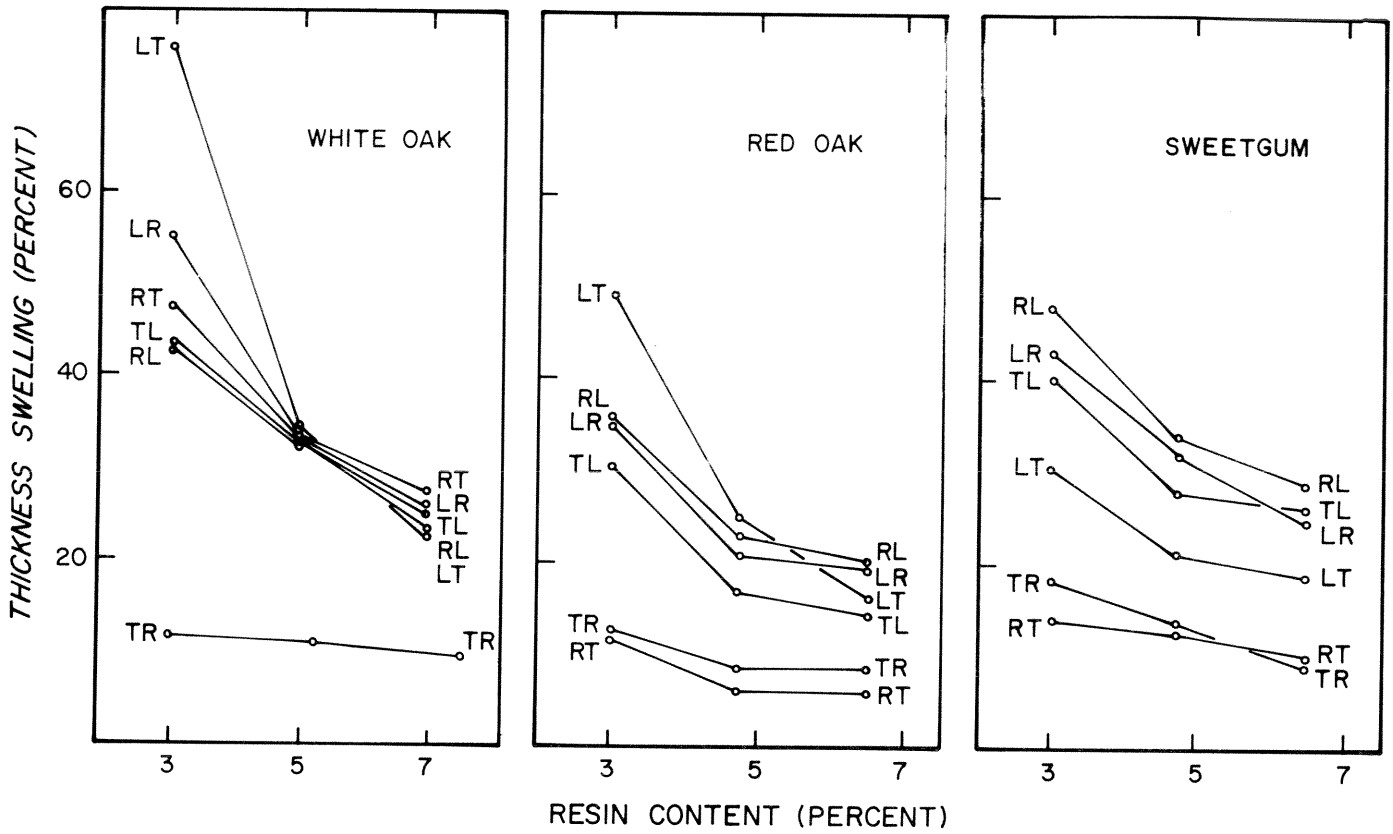

Figure 6.--Variations of thickness swelling of different flake types as affected by resin content.

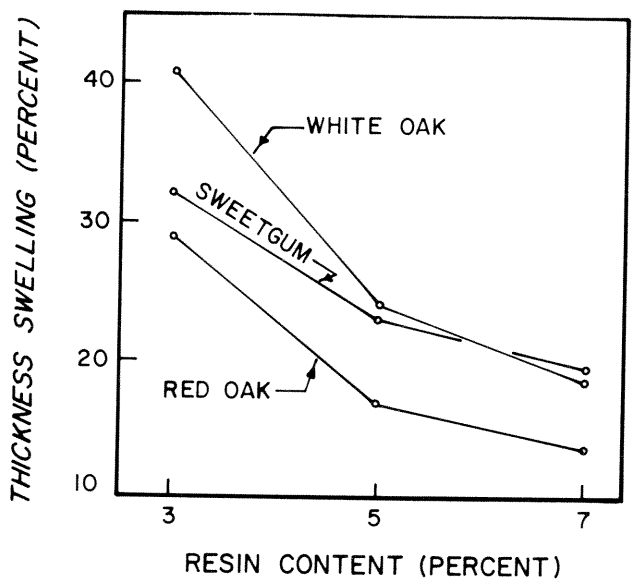

Figure 7.--Effect of resin content on the thickness swelling of flakeboard.

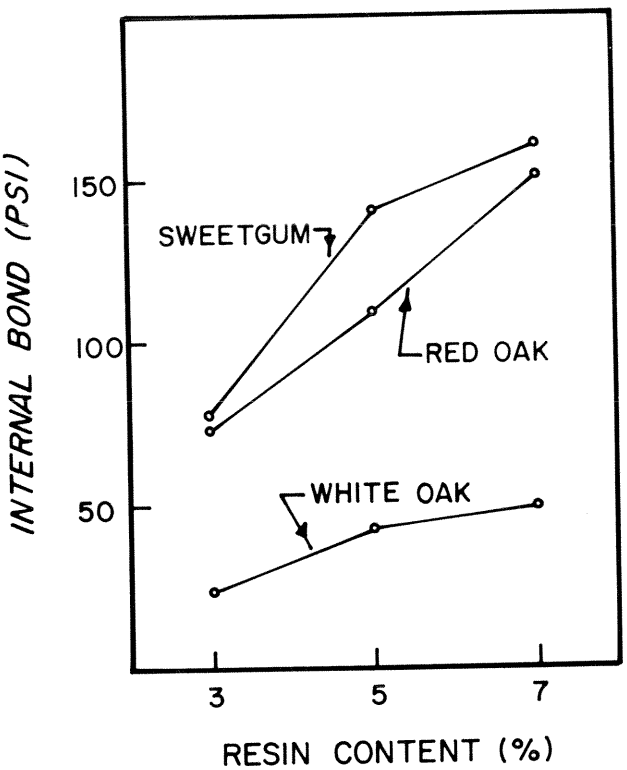

Figure 8.--Effect of resin content on internal bond strength of flakeboard.

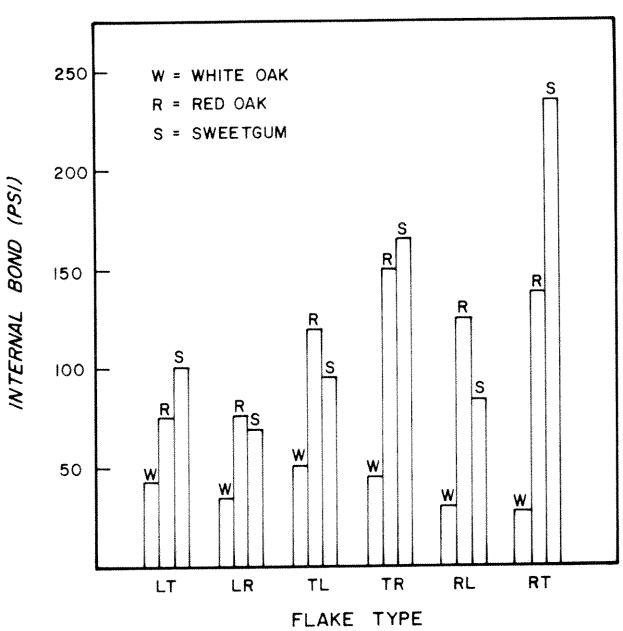

Figure 9.--Effect of flake type on internal bond strength of flakeboard.

DURABILITY AS AFFECTED BY RESIN TYPE[1/]

James B. Wilson[2/3/]

Abstract.--The durability of particleboard and waferboard was examined to determine the effect of resin type. The types of resin examined were urea-formaldehyde, phenol-formaldehyde, emulsifiable polymeric isocyanate, and polymeric isocyanate. To measure durability the boards were subjected to three different tests which reportedly relate to durability; these are the 2-hour boil, 30 to 90 percent relative humidity change, and long-term loading. These tests allowed us to examine strength retention, dimensional stability and creep.

INTRODUCTION

The use of wood composition board for exterior applications has increased tremendously in recent years, and its continued expansion into these markets appears even more likely. Composition boards such as waferboard, oriented strand board, medium density fiberboard, hardboard and particleboard have found increasing acceptance in home construction for use as wall and roof sheathing, siding, decking, and roofing. Exterior applications range from fully exposed uses such as medium density fiberboard roof shingles and waferboard siding to protected uses such as particleboard underlayment and decking and waferboard wall sheathing. Thus, these products are subject to a wide range of environmental regimes. A demand has been placed upon these materials to perform for a long time without significant deterioration. As a result, we are interested in durability, in particular the durability of the wood-adhesive bond.

Durability for materials in general are considered in regards to their ability to resist weathering, abrasion, creep, stress rupture, and fatigue. For most of the exterior uses of composition board these products are most likely to fail in weathering (due to internal stress caused by dimensional changes), creep, or stress rupture.

The durability of the wood-adhesive bond, which is integral to the overall performance of the product, can be assessed in terms of its mechanical and chemical stability, hygroscopicity, and creep. The objective of this study is to assess the durability performance of particleboard and waferboard as a function of the type and amount of resin. The types of resin examined were urea-formaldehyde (UF), phenol-formaldehyde (PF), emulsifiable polymeric isocyanate (EMDI), and polymeric isocyanate (PMDI).

MATERIALS AND METHODS

The study variables selected to evaluate the type and amount of resin were as follows:

• board type	particleboard and waferboard
• resin type	UF, PF, EMDI, and PMDI
• resin level	2, 4, 6, and 8% solids basis for particleboard 1 and 2-1/2% solids basis of liquid resin for waferboard.

Boards, 0.5 by 18 by 18 inches, were fabricated at a density of 40 pcf in the laboratory using commercial resins and Douglas-fir wood furnish. Two furnish types, particles and wafers, yielded two panel types. The particles for the particleboard were obtained from a local particleboard manufacturer, whereas, the wafers (0.025 by 2 by 2 inches) were generated on a laboratory disk flaker. The moisture content of the furnish was suitably adjusted prior to resin and wax application so that the moisture content of the mat into the press was 10 percent. Wax in an emulsion was applied at 0.25 percent to the particles and 1.0 percent to the wafers. All resins and wax were applied in a rotary drum blender using an air spray gun. The mats were pressed at sufficient temperature and duration to cure the individual adhesives.

To examine durability of the various resin/board types the following tests and measurements were made. These tests allow us to examine strength retention, dimensional stability, creep, and possibly stress rupture.

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7,1982.

2/Associate Professor, Forest Products Department, Oregon State University, Corvallis, OR.

3/Appreciation is extended to Fred Kamke and Mike Milota of Oregon State University for assistance in board fabrication and testing.

Test	Measurements
• 2-hour boil	MOR, MOR retention, TS, WG (four repetitions)
• 30-90% RH	LE, TS, WG (four repetitions)
• Creep	Deflection (two repetitions)

where MOR is modulus of rupture (psi)
TS is thickness swelling (%)
WG is weight gain (%)
LE is linear expansion (%)
RH is relative humidity (%)

The 2-hour boil test was done on specimens 3 by 16 inches according to CSA 0.188.0M (1978) for accelerated aging, which consists of a 2-hour boil followed by a 1-hour cold soak at 70°F, and tested wet. The control and 30-90% RH designated specimens, also 3 by 16 inches were (1) conditioned at 30 percent RH and 90°F for three weeks, (2) measured and weighed, (3) conditioned at 90 percent RH and 90°F for three weeks, then (4) remeasured. The LE, TS, and WG were calculated based on the 30% RH values.

The creep test specimens, 1 by 16 inch, were center point loaded at 40 percent of the MOR, obtained from matched samples. The specimens were conditioned and tested at 65% RH and 70°F over a 13-inch span for four months. Relative creep for each specimen was determined by dividing the increase in beam deflection by the initial deflection.

RESULTS AND DISCUSSION

Results of 2-hour boil, 30-90 percent RH change, and creep tests are discussed individually below. Values of internal bond, modulus of rupture, and modulus of elasticity for all boards are found in table 1. Since boards bonded with either EMDI or PMDI behaved similarly, only EMDI results are discussed.

Two-Hour Boil

The MOR of particleboard is significantly greater for isocyanate bonded boards than phenolic. The two resin systems yielded comparable board properties when subjected to a 2-hour boil and tested wet (fig. 1). The phenolic bonded boards, however, had a higher MOR retention than the isocyanate bonded boards (fig. 2). This is important where product specifications require that a product maintain a given percentage of MOR retention to meet commercial standards. Whereas, had the specimens been dried after the 2-hour boil, the isocyanate bonded boards would have appeared to be better than the phenolic bonded boards. This is the case where a test can prejudice a specific resin, whereas, this may not be the case in field performance. None of the urea-formaldehyde bonded boards survived intact the 2-hour boil test.

Thickness swelling is much less for the isocyanate bonded boards than for the phenolic bonded boards (fig. 3). This phenomenon possibly results from the isocyanate chemically bonding to the hydroxyl sites in the wood making them unavailable to absorb water molecules. This, a lesser amount of water absorbed results in less thickness swelling. This was shown to be the case for this study.

Trends that occurred with these resins as binders for particleboard, also occurred when these binders were used for waferboard (fig. 4). The resin levels of 1 and 2-1/2% liquid phenolic used in this study for waferboard are lower than the 5% normally required to meet commercial standards.

30 to 90% RH Change

The isocyanate bonded boards absorbed less water in the 2-hour boil test and also absorbed less for an increase in RH (table 2). Thus, as shown in figure 5, thickness swelling was least for isocyanate resin. The urea and phenolic bonded boards were similar and had the highest thickness swelling. Linear expansion was essentially the same for all resins in the commercial application range of 4 to 8 percent (fig. 6). For lower resin contents, however, isocyanate had the least LE.

Creep

Particleboards exhibited similar creep properties at the 6 percent level for isocyanates and urea binders; with phenolic bonded boards exhibiting somewhat greater creep (fig. 7). It is worthwhile to recall that at the same resin levels the isocyanate bonded boards are much stronger than phenolics, therefore, the applied loads (40 percent of MOR in figure 7) are much larger for isocyanates than for phenolics. Thus, on a relative deflection basis the isocyanate resins can be considered even more impressive. Similarly, for waferboard at the 2-1/2 percent resin content. isocyanate had less creep than PF resin (fig. 8).

CONCLUSIONS

The durability of particleboard and waferboard bonded with several resin types was assessed by tests of 2-hour boil, 30 to 90 percent RH change, and creep. Several conclusions can be made as to the durability of particleboard and waferboard bonded with either isocyanates, urea-formaldehyde, or phenol-formaldehyde adhesives.

When subjected to the 2-hour boil test:

- Urea-formaldehyde bonded boards do not survive

- Isocyanate bonded boards have a higher MOR at lower resin contents
- Isocyanate bonded boards have less TS and WG
- Phenolic bonded boards have the highest percentage of retained MOR when tested wet

Where a 30 to 90% RH change:

- Isocyanate bonded boards are dimensionally more stable
- Isocyanate bonded boards absorb less water than either urea or phenolic bonded boards

For a long-term load:

- At the 6 percent resin level, phenolic bonded particleboards have slightly more relative deflection (creep) than isocyanate and urea bonded boards.
- All particleboards made of the 8 percent resin level behaved similarly.
- For waferboard at a low resin level of 2-1/2%, the isocyanate bonded boards have less creep.

LITERATURE CITED

Canadian Standard Association
1978. Standard test methods for mat-formed particleboard and waferboard. CAN 3-0188-0-M78.

Table 1.--Mechanical properties of all particleboard and waferboard for various resin types and levels

Resin Type	Resin %	Property IB	MOR	MOE
		----------psi----------		
		Particleboard		
EMDI	2	115.0	1947	390,215
	4	161.1	2199	426,581
	6	186.9	2408	461,863
	8	249.0	2632	469,391
PMDI	2	106.0	1747	392,541
	4	168.4	2006	413,810
	6	226.4	2490	468,023
	8	245.5	2634	479,363
PF	2	33.7	1034	229,182
	4	95.2	1676	265,927
	6	135.0	2055	318,924
	8	175.3	2262	393,622
UF	2	73.1	1536	293,187
	4	117.9	1950	338,624
	6	154.9	2213	369,915
	8	178.0	2219	375,940
		Waferboard		
EMDI	1	50.8	4464	852,443
	21/2	102.7	5800	925,130
PF	1	8.2	2238	578,368
	21/2	30.3	4141	692,320

Table 2.--Water absorption in terms of weight gain for particleboard subjected to 2-hour boil and to 30 to 90 percent RH change

Resin Type	Resin %	Water absorption 2-hour boil	30-90% RH
		----------%----------	
EMDI	2	115.4	12.5
	4	68.0	12.1
	6	60.5	12.6
	8	49.1	11.2
PF	2	146.4	15.1
	4	110.1	14.4
	6	99.0	15.6
	8	105.1	16.8
UF	2	-----	12.9
	4	-----	12.8
	6	-----	12.8
	8	-----	11.8

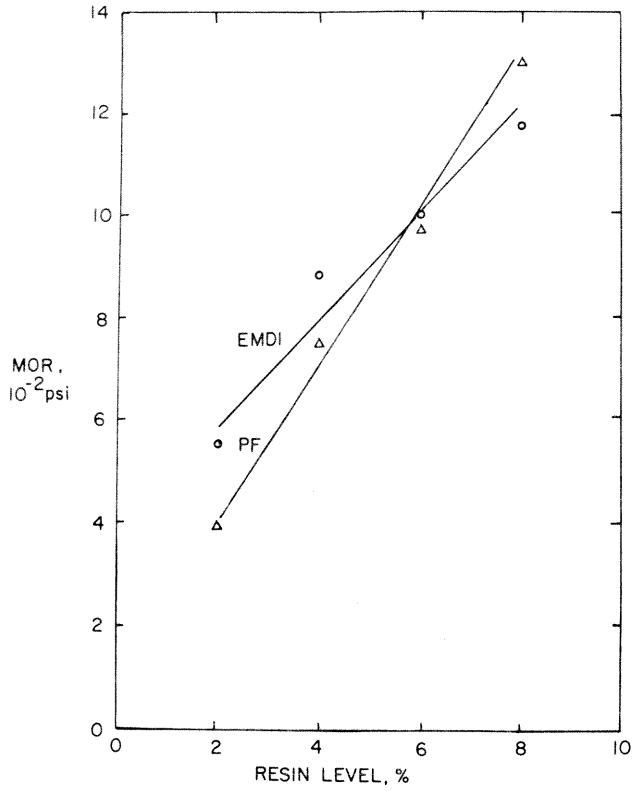

Figure 1.--Effect of resin level and resin type on modulus of rupture for particleboard subjected to a 2-hour boil and tested wet.

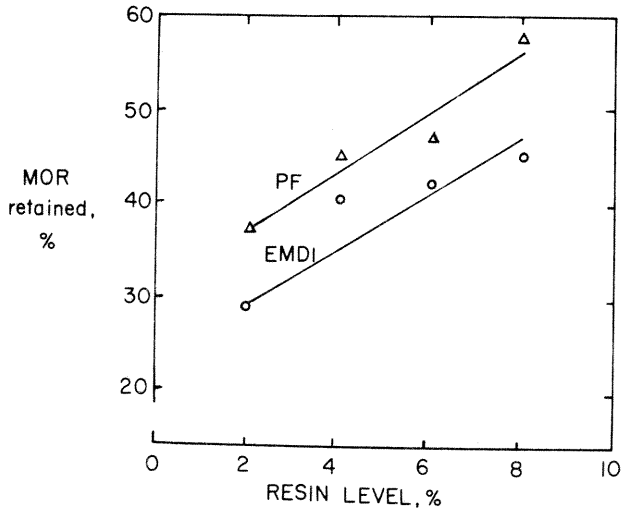

Figure 2.--Modulus of rupture retained after particleboard was tested in 2-hour boil--effect of resin level and type.

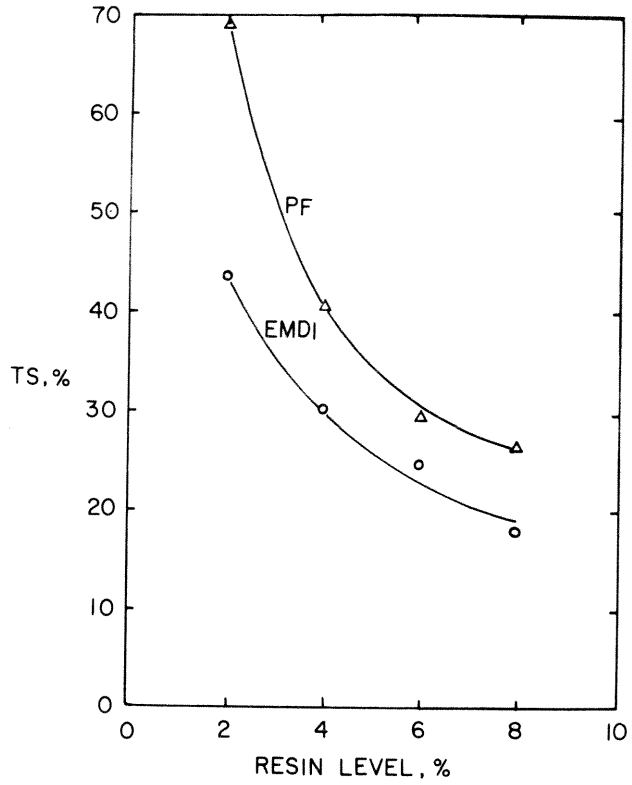

Figure 3.--Thickness swelling of particleboard after a 2-hour boil--effect of resin level and type.

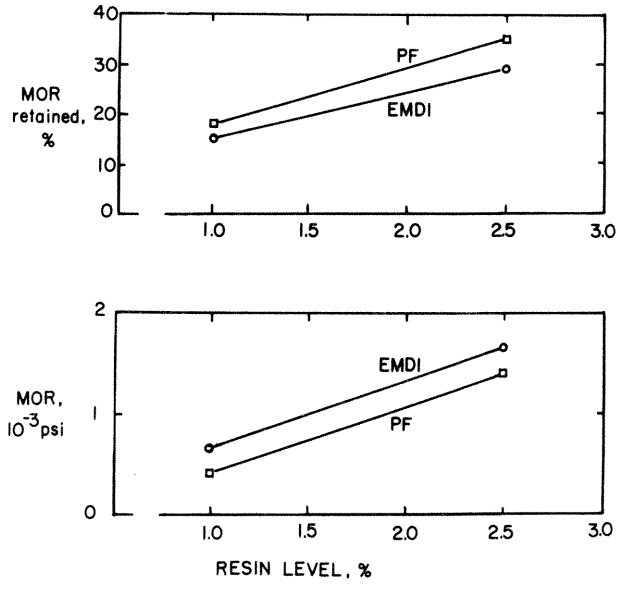

Figure 4.--Modulus of rupture and retention after 2-hour boil for waferboard--effect of resin level and type.

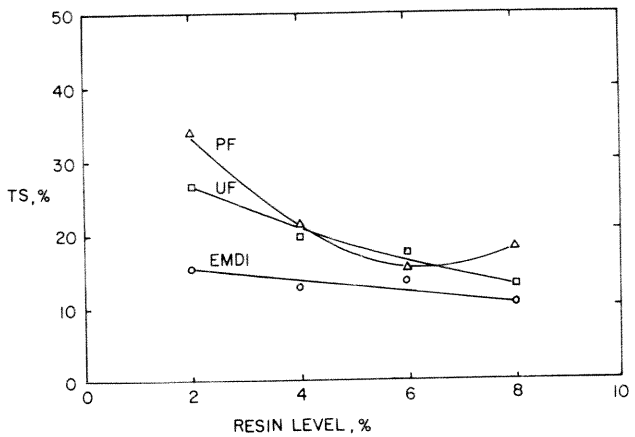

Figure 5.--Thickness swelling of particleboard for a relative humidity change from 30 to 90%--effect of resin level and type.

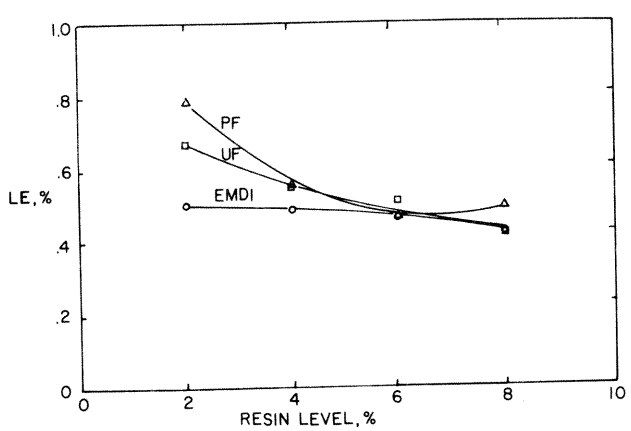

Figure 6.--Creep in terms of relative deflection for particleboard made with 6% resin and loaded at 40%.

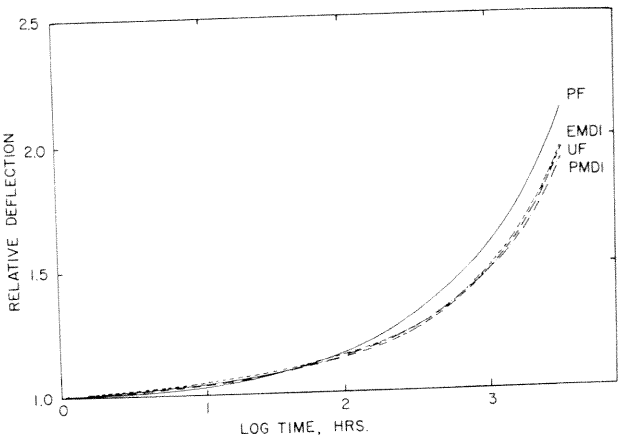

Figure 7.--Creep in terms of relative deflection for particleboard made with 6% resin and loaded at 40%.

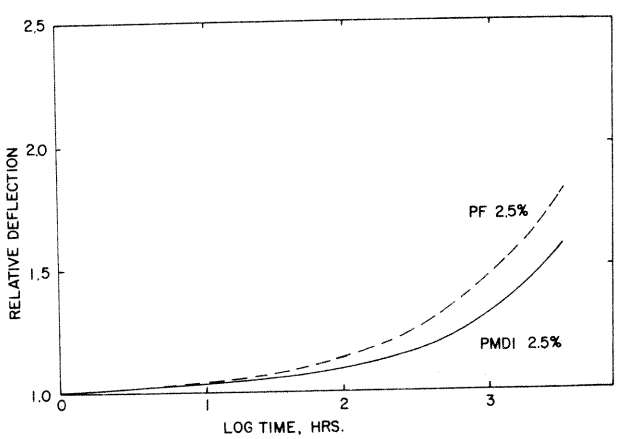

Figure 8.--Creep in terms of relative deflection for waferboard made with 2-1/2% resin and loaded at 40% of MOR.

EFFECT OF RESIN ALKALINITY ON DIMENSIONAL STABILITY OF HARDWOOD FLAKEBOARDS[1]/

C. Y. Hse[2]/

Abstract.--Hardwood flakeboards were prepared from sweetgum, red oak, and white oak with 10 liquid phenolic resins. The phenolic resins were formulated with four molar ratios (0.4, 0.6, 0.8, and 1.0) of sodium hydroxide (NaOH to phenol). The ten resin formulations were obtained by adding the NaOH at two different times, one during resin preparation and one prior to resin application, and by varying the amount of NaOH applied at each addition time. The best dimensional properties were obtained with the resin formulated with 0.2 moles of NaOH applied during resin preparation plus 0.6 moles of NaOH added just prior to resin application. For sweetgum flakeboards, the internal bond increased as total NaOH content of the resin increased. The maximum internal bond for the oak flakeboards occurred with 0.8 mole of NaOH in the resin.

INTRODUCTION

Liquid phenolic resins used in the production of exterior grade hardwood flakeboard are usually catalyzed with an alkaline catalyst (generally NaOH). The alkali base is used to obtain an optimum degree of condensation at as low a viscosity as possible while maintaining a high solid content. By varying the amount of catalyst and the method of alkali addition, a wide variety of phenolic resins can be produced (Redfern 1951, Lambuth 1967, Hse 1972). In liquid resin the alkalinity (pH) usually ranges between 4 and 10 percent.

Several hardwood species are utilized in the development of hardwood flakeboard in the South. The bonding properties and dimensional stability have been found to vary significantly among the hardwood species (Hse 1971). Since dimensional stability appears to be a major concern for panel performance, this study was designed to establish the influence of alkaline catalysts on dimensional stability.

EXPERIMENTAL PROCEDURE

Resin Preparation

All liquid phenol-formaldehyde resins (table 1) were replicated once and prepared with the following formulation variables:

1. Molar ratio of NaOH to phenol - 0.4, 0.6, 0.8, and 1.0.

2. Method of NaOH addition - NaOH was added as a catalyst in two portions as follows:

a. The first portion, 0.2 to 0.8 mole of NaOH per mole of phenol, was added to promote the resin reaction to the Gardner-Holdt viscosity of T-U (≈590 centipoise). To minimize the converting of formaldehyde to formic acid, the NaOH was added to the reaction mixture in three equal parts at 30-minute intervals.

b. The second portion of NaOH, another 0.2 to 0.8 moles of NaOH per mole of phenol, was added to the resin prior to the application of the resin to reduce the resin viscosity to Gardner-Holdt viscosity of H (≈200 centipoise).

To prepare each resin, all of the phenol, formaldehyde, and water was placed in a reaction kettle. The first portion of NaOH was added in three steps at 30-minute intervals. To initiate the reaction, the mixture was quickly heated and maintained at 96° to 100°C (reflux temperature). When the viscosity of the mixture reached a Gardner-Holdt viscosity of R, the temperature in the kettle was reduced to 80°C. When the Gardner-Holdt viscosity reached T-U, the reaction was terminated by rapidly cooling the mixture to 24°C. After cooling, each resin was then treated with the second portion of NaOH. This second addition helped to reduce the viscosity to the range suitable for spraying application (i.e., approximately between Gardner-Holdt viscosity of F and I).

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7, 1982.

2/Author is Principal Wood Scientist, Southern Forest Experiment Station, USDA-Forest Service, 2500 Shreveport Highway, Pineville, LA 71360

Panel Preparation

All panels were prepared in the laboratory with flakes about 3 inches long, 0.02 inches thick, and variable in width. The flakes were cut from a shaping-lathe headrig and dried to an average moisture content of 3 percent before adhesive was added. General conditions for panel preparation were:

Panel size: 1/2 x 22 x 40 inches

Panel density: Sweetgum panel - 42 lbs/ft^3 White and red oak panels - 46 lbs/ft^3

Resin content: Resin solid equaled 6 percent of the oven-dry weight of the wood furnish

Hot press temperature: 350°F

Hot press time: 6 minutes

Press closing time: 45 seconds to stop

Number of replications: 2

Sampling and Testing

Boards were trimmed to 18- by 36-inch panels before cutting into six 2- by 18-inch pieces and seven 3- by 18-inch pieces. Each 2- by 18-inch piece was then cut to yield three 2- by 2-inch samples to test for tensile strength perpendicular to the face (internal bond), and one 2- by 11-inch sample for dimensional stability measurements after vacuum-pressure soak. The 3- by 18-inch pieces were reserved for dimensional stability testing under humidity cycle test conditions.

The vacuum-pressure-soak test consisted of soaking specimens in water under vacuum (25 inches Hg) for 1 hour and then under 85 psi pressure (at room temperature) for 2 hours. Length and thickness were measured before and after soaking with a linear micrometer.

RESULTS

Average linear expansion (LE), thickness swell (TS), and internal bond strength (IB) of the flakeboards are summarized in table 2.

Linear Expansion (LE)

The white oak flakeboards consistently resulted in higher average LE and were followed in decreasing order by red oak flakeboards and sweetgum flakeboards.

Figure 1 shows the general trend that LE decreased slightly as NaOH content increased from 0.4 to 0.8 moles. Thereafter, the LE increased as NaOH content increased to 1.0. For sweetgum flake boards, only a small difference existed in LE as NaOH content level varied.

The effects of method of NaOH addition on LE are shown in figure 2. Averaging across all species, the resins, in decreasing order of linear stability were ranked from 1 to 10. The best resin was prepared with 0.2 moles of NaOH in resin preparation followed by addition of 0.6 moles of NaOH prior to the resin application. The 0.2 moles of NaOH in resin preparation followed by addition of 0.2 moles of NaOH prior to application resulted in the poorest linear stability.

At total NaOH content of 0.6, 0.8, and 1.0, the addition of 0.2 moles of NaOH in resin preparation consistently resulted in more stable panels than when 0.2 moles of NaOH was the concentration added prior to resin application (i.e., 0.2 + 0.4 vs. 0.4 + 0.2; 0.2 + 0.6 vs. 0.6 + 0.2; and 0.2 + 0.8 vs. 0.8 + 0.2).

Thickness Swell (TS)

Figure 3 illustrates the influence of total NaOH content on TS. As in LE, the white oak flakeboards consistently resulted in higher TS regardless of NaOH concentration, followed by red oak and sweetgum flakeboards.

The TS decreased slightly as total NaOH content increased for red and white oak flakeboards. However, for sweetgum panels, the change in TS with variations in NaOH content was not significant (fig. 3).

As shown in figure 4, the TS varied substantially with various methods of NaOH addition. Based on the average TS of the three species, the resins were ranked from 1 to 10 in decreasing order of thickness stability. Resins that yielded the best LE stability (i.e., 0.2 + 0.6) and worst LE stability (i.e., 0.2 + 0.2) also resulted in the best and worst TS stability.

As in LE, within each total NaOH content, the resins prepared with 0.2 moles of NaOH added during resin preparation were superior to the resins that had 0.2 moles of NaOH added just prior to resin application.

Internal Bond (IB)

The influence of resin alkalinity on internal bond strength is shown in figure 5. In sweetgum flakeboards, the average IB increased as total NaOH content increased (fig. 5), while in both red and white oak flakeboards, the 0.8 moles of NaOH consistently resulted in the highest average IB which decreased with 1.0, 0.4, and 0.6 moles of total NaOH content.

Figure 6 illustrates the effects of method of NaOH addition on IB. Based on the average IB of three species, the resins were ranked from 1 to 10 in decreasing order of IB strength. The resin prepared with 0.6 moles of NaOH in resin preparation, followed by addition of 0.4 moles of NaOH prior to the resin application, yielded the highest average IB strength. However, the resin prepared

with 0.4 moles of NaOH in resin preparation and followed by addition of 0.2 moles of NaOH prior to resin application resulted in the lowest IB strength.

DISCUSSION

Although none of the resins formulated in the study yielded both the maximum IB strength and the most stable panels dimensionally, several resins are considered to be good candidates for further improvement. Table 3 summarizes the top three ranking phenolic resins, respectively, in terms of decreasing LE and TS stability and IB strength.

Thus, to obtain the most stable panels with maximum IB strength, it appears that the optimum range for resin formulation may be as follows:

1. Total NaOH content -- 0.8 to 1.0 mole
2. NaOH addition in resin cooking -- 0. 2 to 0.4 moles
3. NaOH addition prior to resin application -- 0.4 to 0.6 moles

Although NaOH addition prior to resin application is not a common practice in manufacturing standard phenolic resin, it does improve bonding quality of hardwood flakeboard. Additional work is in process to determine if other catalyst systems or cooking procedures can further improve the bonding properties of phenolic resins. Among other things, optimization of average molecular weight (at fixed-resin viscosity) and optimization of methylol content - molecular weight ratio are under study to develop a resin with maximum stability and reactivity.

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Table 1.--Variations in concentration of NaOH for 10 resins

Total NaOH content	Method of NaOH addition			
moles	mole NaOH/mole phenol			
0.4	0.2 + 0.2*			
0.6	0.4 + 0.2	0.2 + 0.4		
0.8	0.6 + 0.2	0.4 + 0.4	0.2 + 0.6	
1.0	0.8 + 0.2	0.6 + 0.4	0.4 + 0.6	0.2 + 0.8

*The first number is the portion of NaOH added during resin preparation; the second number is the portion of NaOH added just prior to resin application.

Table 2 -- Dimensional stability and internal bond strength of hardwood flakeboard

Molar ratio NaOH/Phenol	Method of NaOH addition[1]/	Ranking of linear stability	Species: Sweetgum IB[2]/	Sweetgum LE	Sweetgum TS	Red oak IB	Red oak LE	Red oak TS	White oak IB	White oak LE	White oak TS
	(mole)		psi	--percent--		psi	--percent--		psi	--percent--	
0.4	0.2 + 0.2	10	52	0.174	24.8	89	0.342	38.1	59	0.376	43.8
0.6	0.4 + 0.2	8	76	0.186	24.2	67	0.332	32.2	36	0.353	43.4
0.8	0.6 + 0.2	7	64	0.196	26.8	142	0.301	31.0	90	0.352	40.6
1.0	0.8 + 0.2	9	85	0.180	24.6	76	0.341	28.4	69	0.360	42.7
0.6	0.2 + 0.4	6	69	0.172	23.2	93	0.280	27.4	61	0.349	32.6
0.8	0.2 + 0.6	1	89	0.141	22.9	132	0.282	23.2	90	0.322	30.2
1.0	0.2 + 0.8	4	87	0.162	22.0	103	0.277	25.1	77	0.346	30.3
0.8	0.4 + 0.4	3	68	0.146	22.4	92	0.284	28.7	76	0.351	37.3
1.0	0.6 + 0.4	5	81	0.162	24.6	139	0.294	27.9	124	0.340	34.0
1.0	0.4 + 0.6	2	73	0.156	24.4	114	0.289	25.2	80	0.324	32.9

[1]/First number indicates the number of moles of NaOH added to react the resin to viscosity T-U. The second number indicates the number of moles of NaOH added prior to resin application.
[2]/IB = internal bond strength; LE = linear expansion; TS = thickness swelling.

Table 3.--Top three resin formulations for the LE, TS, and IB[1]/

Ranking[2]/	LE	TS	IB
1	0.2 + 0.6	0.2 + 0.6	0.6 + 0.4
2	0.4 + 0.6	0.2 + 0.8	0.2 + 0.6
3	0.4 + 0.4	0.4 + 0.6	0.6 + 0.2

[1]/LE = linear expansion; TS = thickness swell; IB = internal bond
[2]/Performance of the resin is ranked in decreasing order for each property.

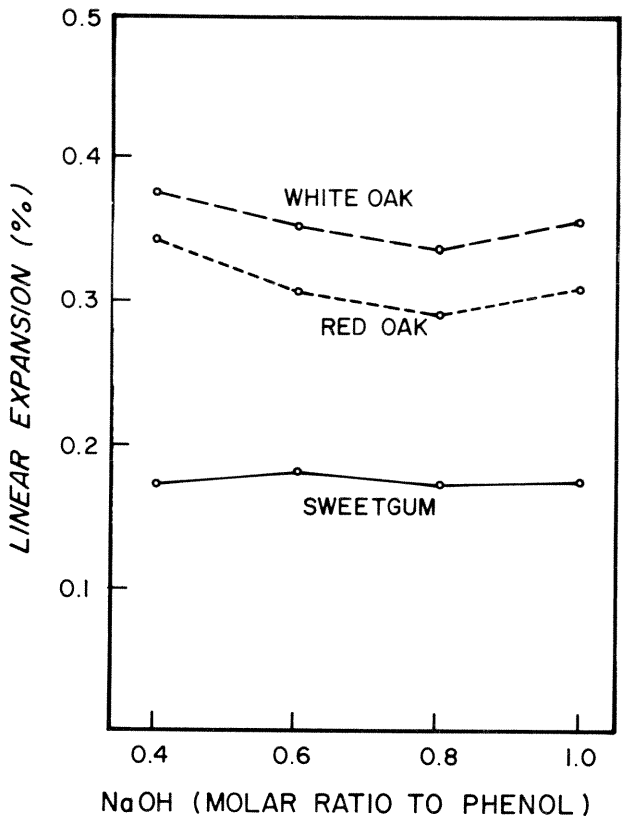

Figure 1.--Effect of total NaOH content on LE.

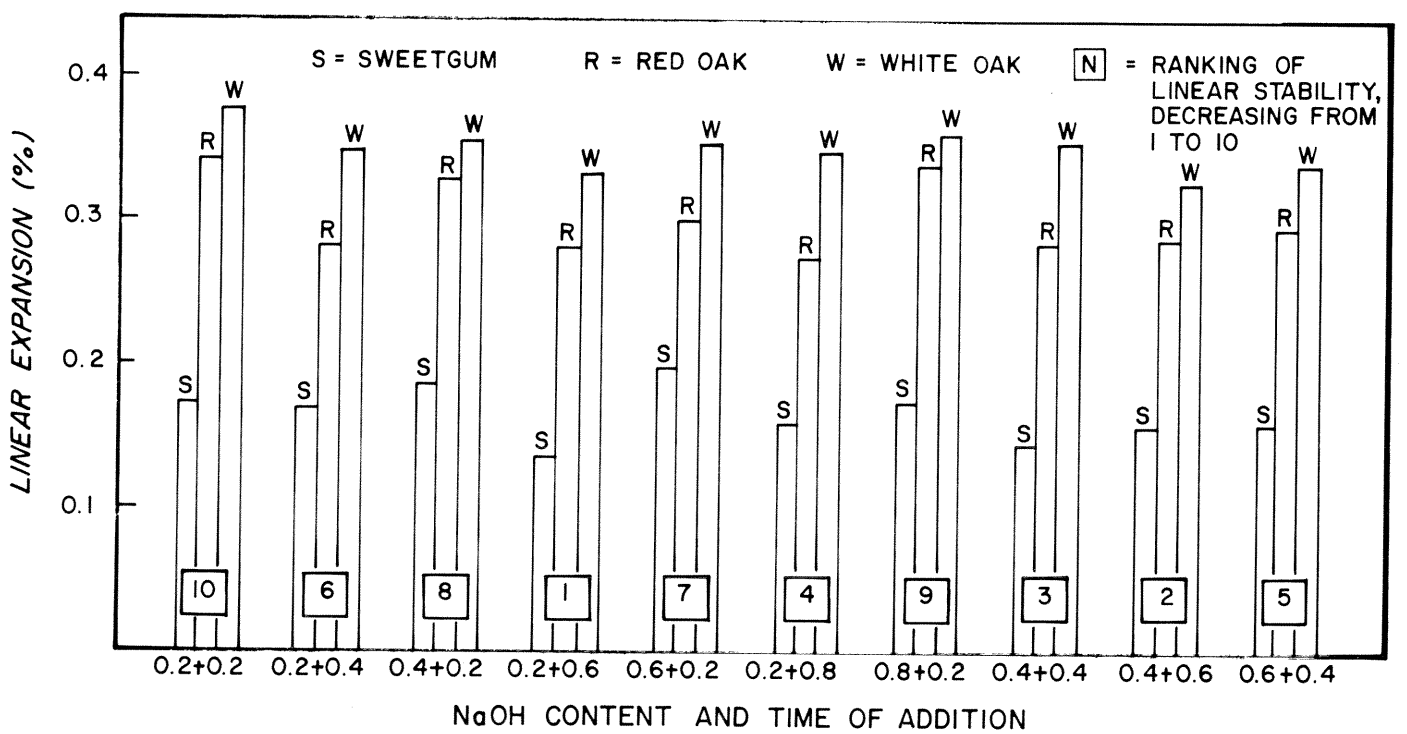

Figure 2.--Effect of method of NaOH addition on linear expansion.

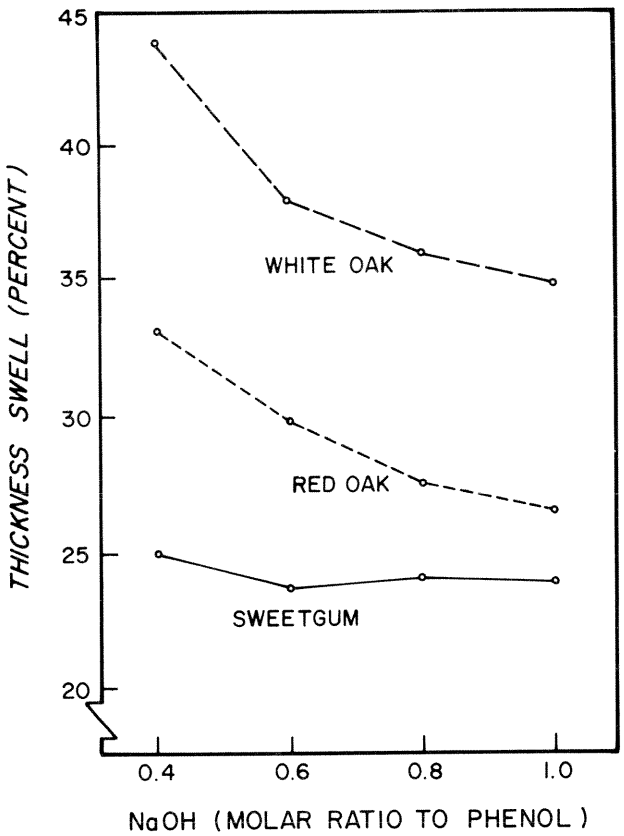

Figure 3.--Effect of total NaOH content on thickness swell.

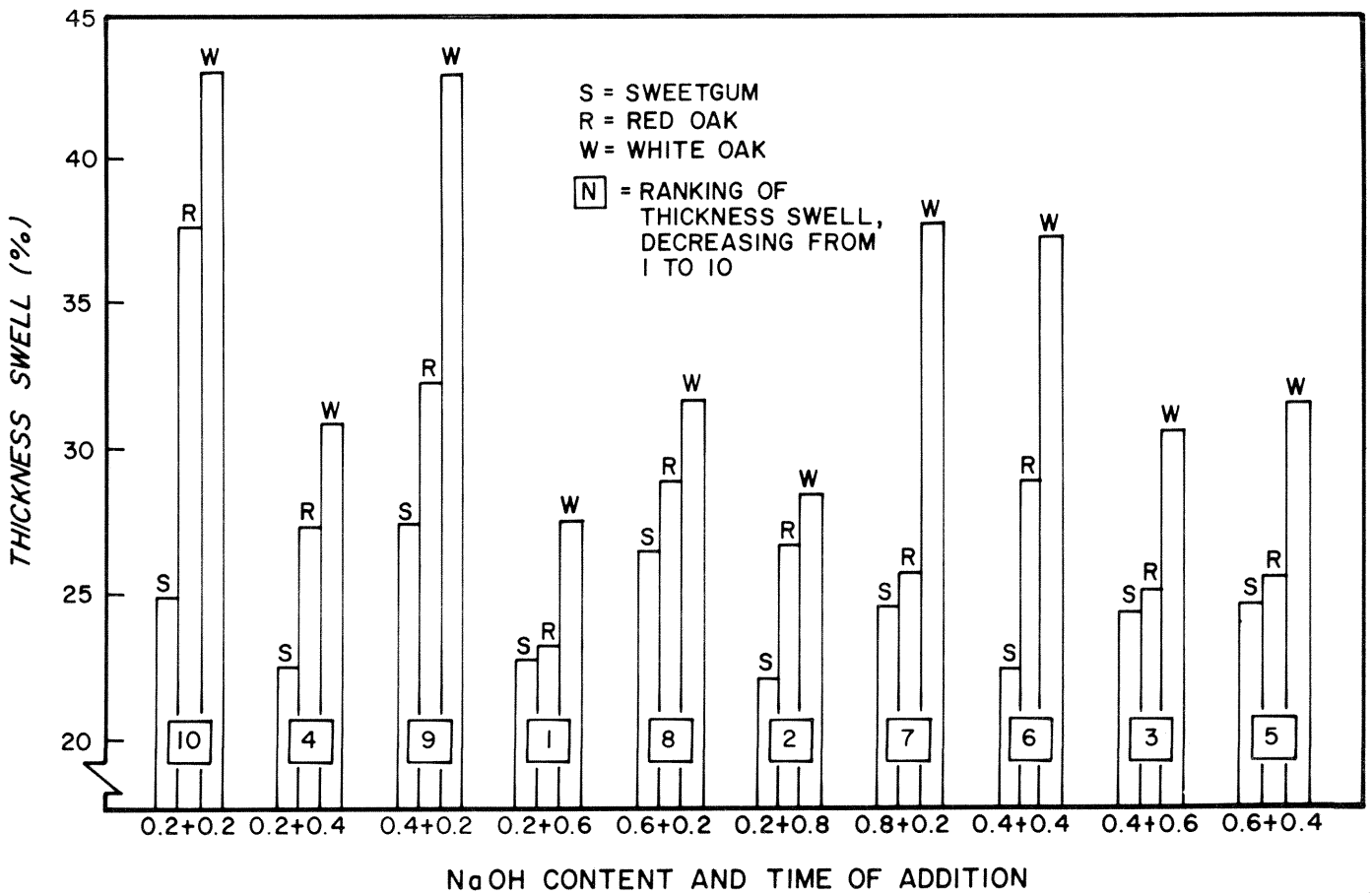

Figure 4.--Effect of method of NaOH addition on thickness swell.

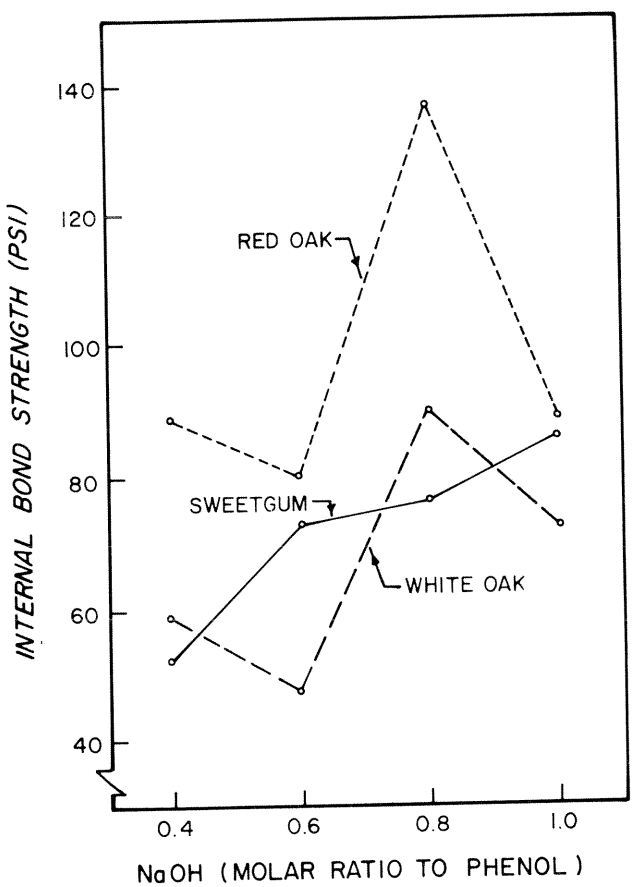

Figure 5.--Effect of total NaOH content on internal bond strength.

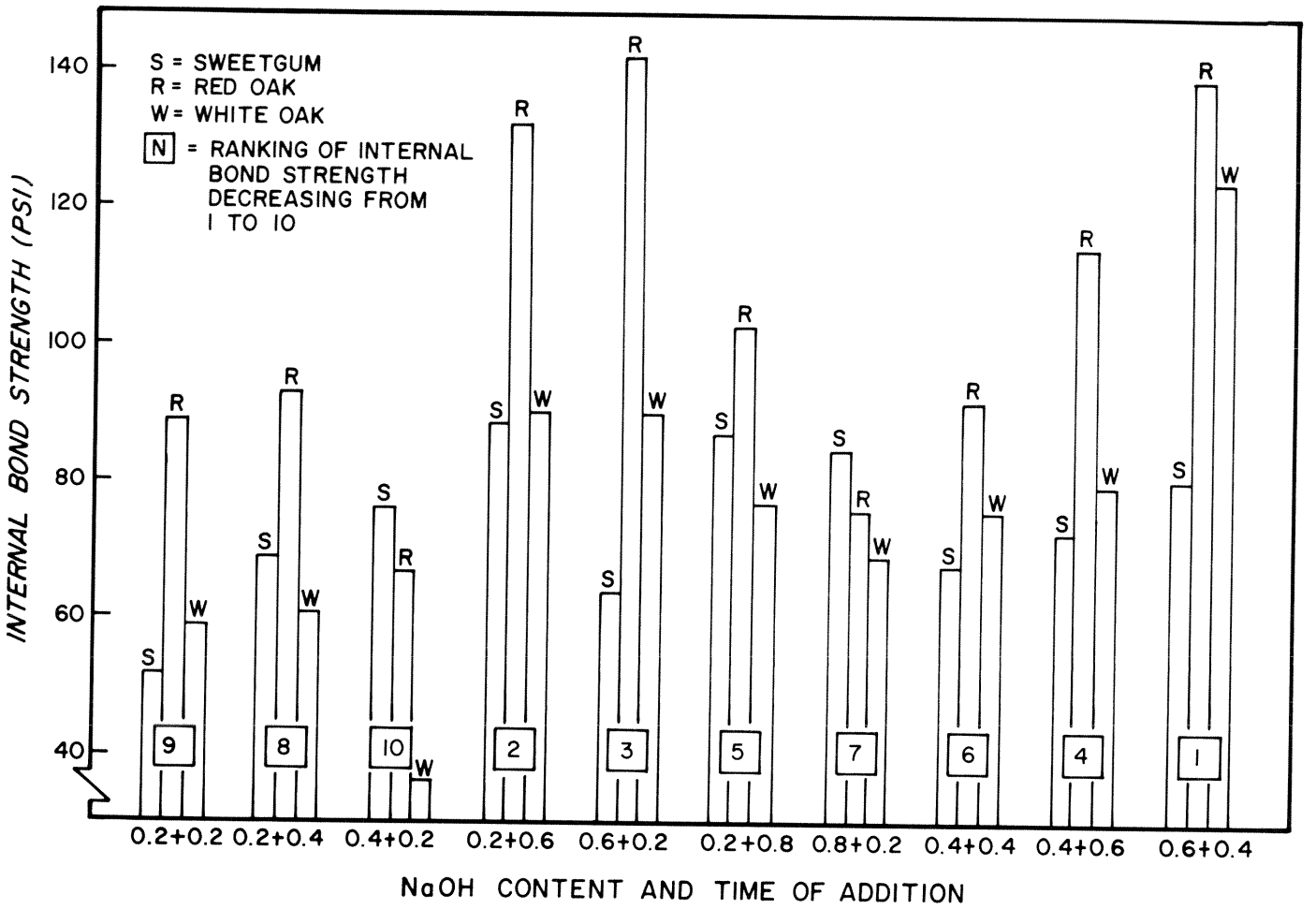

Figure 6.--Effect of method of NaOH addition on internal bond strength.

HOW CYCLIC HUMIDITY AFFECTS STATIC BENDING AND DIMENSIONAL PROPERTIES OF SOME WOOD-BASE PANEL PRODUCTS[1/]

J. Dobbin McNatt[2/]

Abstract.--Selected wood-base panel products were subjected to alternating 30 and 90 percent relative humidity for up to 2 years. The aim was to evaluate the effects of cyclic humidity and length of exposure time during cycling on the dimensional and static bending properties of these products. Materials evaluated were fiberboard sheathing, urea-formaldehyde (UF) and phenol-formaldehyde (PF) particleboard, waferboard, and hardboard. The length of each cycle was either 2 weeks or 2 months. Some specimens were cycled for a total of 2 years. After 12 consecutive 2-week cycles, all panel types retained more than 80 percent of their original load-carrying capacity and stiffness in bending. After 12 consecutive 2-month cycles, the fiberboard sheathing, hardboard, waferboard, and PF particleboard still retained 80 percent. However, the UF particleboard only retained 50 to 60 percent. Deterioration of the urea-resin bond was also reflected in irreversible thickness swelling that was greater than that of other panel types.

INTRODUCTION

Wood-base fiber and particle panel materials used inside for furniture and cabinet parts, floor underlayment, and wall and ceiling covering are seldom subjected to extreme changes in humidity. However, panel products used as mobile home floor decking, exterior siding, and roof, wall, and floor sheathing may be exposed to cycles of high and low humidity owing to daily and seasonal climate variations (Lundgren 1969) or to moisture migration within the structure (Duff 1968, Sherwood and Peters 1977). Such cyclic exposures can result in permanent dimensional changes, particularly in thickness, and in strength and stiffness reductions. For adhesive-bonded wood particle panels, the magnitude of the changes in properties is dictated mainly by the type and quantity of adhesive used. Property changes, in turn, affect the service life of the product. Palmer and Stashevski (1979), for example, give estimates made by Knight (1968) of the service life of formaldehyde-based adhesives. The estimate for urea-formaldehyde (UF) adhesives in semiexterior and damp interior exposures is 5 to 10 years. Under the same conditions, a phenol-formaldehyde (PF) adhesive should perform indefinitely.

The purpose of this study was to evaluate the effects of cyclic humidity and length of exposure time during cycling on the dimensional and static bending properties of various wood-base panel products. Five different wood-base panel types were evaluated for bending strength and stiffness and dimensional changes after exposure to different numbers of cycles (1, 3, 6, or 12) of 30 to 90 percent relative humidity (RH). The length of each cycle was either 2 weeks or 2 months so that some specimens were cycled for only 2 weeks (1 wk, 30% RH + 1 wk, 90% RH) and some for 2 years (12 x (1 mo, 30% RH + 1 mo, 90% RH)). Panel types were selected from those most likely to undergo repeated high-low humidity conditions during service: fiberboard sheathing, hardboard siding, particleboard mobile home floor decking, particleboard factory-built house floor decking, and waferboard.

REVIEW OF LITERATURE

The literature is extensive on the effects of moisture and weathering on physical and mechanical properties of wood-base panel products. Thirty such references were listed by Lehmann (1978). Many publications give physical and mechanical properties of wood-base panel products condidtioned at different RH's from what has been referred to as "mint condition." That is they were not subjected to any prior high-low humidity fluctuations. Some of these publications are listed in literature cited at the end of this paper (Halligan and Schniewind 1974, Lundgren 1969, McNatt 1974a and b, and

1/Paper presented at Workshop on Durability, Pensacola, FL, October 5-7-, 1982.

2/Technologist, Forest Products Laboratory, USDA-Forest Service, Madison, WI.

1975, Stillinger and Goggan 1956, Terentiev 1965). Information from such studies is useful as background for further research; but in "real-life" exposures, some products are constantly subjected to variations in temperature and humidity.

Cyclic Exposure Vs. Moisture Content and Dimensional Changes

In most reports dealing with cyclic exposures of panel products, only changes in specimen moisture content (MC) and dimensions were determined (Beech 1975, Currier 1957, Halligan 1970, Heebink 1967, 1972, Johnson 1964, Ogland 1948, Ranta 1978, Steinmetz and Fahey 1968, Suchsland 1972, 1973). Usually results indicate an increase in equilibrium moisture content (EMC) due to sorption hysteresis and permanent thickness swelling. As reported by Halligan (1970), a number of researchers have pointed out that thickness swelling in particleboard (and other wood-base panels) consists of two parts: swelling of the wood itself--recoverable, and release of compression stresses introduced by compression of the wood particle or fiber mat in the press--not recoverable. Most nonrecoverable dimensional changes occur at humidities above 80 percent (Suchsland 1973). However, Beech (1975) reported an irreversible thickness increase of 1.2 to 1.5 percent for PF particleboards (12% resin) conditioned to equilibrium at 65 percent RH and then held at that condition for more than 20 weeks. This swelling was due to spontaneous relief of compression stresses in the wood and was in many cases essentially the same magnitude as that of specimens cycled between 30 percent and 87 percent RH for 10 cycles (1 week at each condition) and then reconditioned at 65 percent RH. Suchsland (1973) and Lundgren (1969) point out that part of the "permanent" change measured when specimens are reconditioned at the original RH is due to sorption hysteresis and would disappear if the samples were conditioned to their original MC. Fraipont's (1974) data support this. He subjected numerous fiberboards and hardboards to a single cycle of 42 days each at 65-95-40-65 percent RH. The initial EMC averaged 6 percent. Final EMC averaged 7.2 percent.

Results from cyclic studies are affected by the material evaluated, length of exposure for each step in the cycle, number of cycles, and ranges of temperatures and humidities used. For example, Gressel (1980) reported MC increases of 2 to 3 percent and thickness welling of about 0.4 percent during cycling of particleboards between 45 and 80 percent RH every 24 hours at 20°C. For specimens of the same material cycled between 25 and 95 percent RH every 24 hours at 20°C, MC increase was 3-1/2 to 5 percent, and thickness swelling was 1-1/2 to 2 percent. When specimens were cycled between 35°C, 25 percent RH, and 20°C, 95 percent RH, every 48 hours, MC increase averaged 6-1/2 to 12 percent, and thickness swell averaged 2-1/2 to 5 percent.

Different panel products pick up and lose moisture at different rates depending upon raw material and manufacturing variables. It is doubtful that hardboards or particleboards reach EMC in less than 6 or 7 weeks when exposed to high humidity at room temperatures (Fraipont 1974, Heebink 1972, Johnson 1956, Liiri 1961, Lundgren 1969, McNatt 1974b. Shorter exposures would result in intermediate levels of MC and dimensional changes. Lundgren (1969) found that hardboards and particleboards, initially conditioned to EMC at 65 percent RH and then placed at 90 percent RH, took 40 to 50 days to reach EMC but only 3 to 6 days to reach the halfway mark toward EMC. For cyclic humidity studies, he suggested a cycle of 7 days at 30 percent plus 7 days at 90 percent RH.

Cyclic Exposure Vs. Strength Properties[3/]

Liiri (1961) determined loss in modulus of rupture (MOR) and internal bond strength for particleboards subjected to up to 10 cycles of 3 weeks each at 30 and 95 percent RH. The rate of strength loss decreased as the number of cycles increased, suggesting an asymptote somewhere beyond 10 cycles. The MOR and internal bond strength decreased 25 percent for 10 cycles of exposure. Bryan and Schniewind (1965) reported a 16 percent decrease in MOR and modulus of elasticity (MOE) for particleboards subjected to three cycles of 7 days at 20 percent EMC conditions, plus 7 days at 6 percent EMC conditions. In a study by Lehmann (1978), five cycles of 30 days each at 90 and 30 percent RH had very little effect on the load-carrying capacity and stiffness in bending[4/] of several experimental and commercial particleboards. Morze and Synowiec (1979) reported an 88 to 96 percent retention of bending strength and 76 to 93 percent retention of bending MOE for various hardboards after six cycles of the following "stepwise" humidity cycle at 20°C: 48 hours at 80 percent RH plus 120 hours at 95 percent RH followed by 48 hours at 70 percent RH. Dinwoodie (1978), reporting on work done at the Princes Risborough Laboratory, BRE, in England, stated that samples of UF commercial particleboard subjected to 50 cycles of 7 days at 30 percent plus 7 days at 90 percent RH (25°C) retained 58 percent of original MOR and 45 percent of MOE. Panels bonded with phenolic, malamine-urea, or sulfite liquor adhesives retained more than 80 percent of MOR and more than 70 percent of MOE. Lee and Biblis (1976) put UF and PF particleboards through a single cycle of 65-30-65-90-65 RH's at

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3/Reported effects of cyclic humidity exposures on bending properties mentioned here are summarized in Table 4 and discussed later in this paper.

4/The terms "load-carrying capacity" and "stiffness" as used here refer to modulus of rupture and modulus of elasticity, respectively, calculated using original, unswelled specimen dimensions.

72°F (conditioned to EMC at each step). The MOE and MOR were reduced 20 and 16 percent, respectively.

The most severe temperature-humidity cyclic exposure for particleboard was reported by Hann et al. (1963). It consisted of 1 week at 80°F and 90 percent RH, plus 1 week at 150°F and 20 percent RH. This exposure cycle was continued for 2 years on experimental particleboards. Percents of original bending strengths retained ranged from about 70 percent for PF boards to less than 20 percent for UF boards.

MATERIALS

The five different commerical wood-base panel products in this study represented those products that were likely to undergo fluctuating MC in use. The materials were:

1. 1/2-inch-thick regular-density fiberboard sheathing
2. 3/8-inch-thick medium-density hardboard siding
3. 5/8-inch-thick UF mobile home decking particleboard (Note: This material was manufactured under Class D-1 of the 1970 Standard for Particleboard for Mobile Home Decking, NPA 1-70. Class D-1 was deleted in revision of the standard so that now this material would not meet the current minimum property requirements for particleboard mobile home decking in NPA 1-82.)
4. 5/8-inch-thick PF factory-built house decking particleboard.
5. 1/2-inch-thick PF aspen waferboard

The material used for specimens consisted of five 2- by 4-foot sections cut from five different panels of each of the panel types. Properties of these materials were determined from control specimens (Table 1).

METHODS

Two separate series of specimens were evaluated in this study. The first series was subjected to repeated cycling of 1 week at 30 percent plus 1 week at 90 percent RH at 80°F for a 2-week cycle. For the second series a cycle of 30 days at 30 percent plus 30 days at 90 percent RH was used for a 2-month cycle.

Each of the 2- by 4-foot sections of material described in the previous section was cut into two sets of twelve 3-inch-wide bending specimens (fig. 1). Specimen length was 24 times the specimen thickness plus 2 inches as specified in American Society for Testing and Materials (ASTM) Standard D 1037 (1972). All specimens were initially conditioned to EMC[5/] at 80°F and 65 percent RH. Those marked "C" were then tested as controls without any cyclic exposure. One of each of the other specimens in each set was randomly selected and subjected to either 1, 3, 6, or 12 of the appropriate cycle (2 wk or 2 mo). Afterwards these specimens were reconditioned to EMC at 65 percent RH and tested in static bending. Three of the 5 replications subjected to 12 repetitions of the 2-week or 2-month cycle were weighed and measured after each half cycle to determine progressive changes in MC, thickness, and length during the 24 weeks or 24 months of total exposure time.

DISCUSSION AND RESULTS

Moisture Content and Dimensional Stability

Figure 2 shows the progressive changes in moisture content, thickness, and length during the 24 weeks or 24 months of cyclic humidity exposure for the waferboard specimens. Average changes in MC, thickness, and length for the 23 times the waferboard specimens were transferred from 30 to 90 percent RH (or from 90 to 30) over the total exposure time were:

	2-week cycle (%)	2-month cycle (%)
MC change	6.2	8.4
Thickness change	3.5	5.8
Length change	.10	.12

These values and figure 2 are presented simply as an example and do not represent the other materials. The corresponding values for all five panel types are shown in figure 3. As supposed, changes in moisture content as well as thickness and length were greater for the 2-month cycle than for the 2-week cycle because of the longer exposure time at each humidity. The exception to this was the fiberboard sheathing which was able to pick up, or lose, moisture faster because of its lower density and greater porosity (Fraipont 1974). The percent moisture change did not vary greatly among the panel types for either the 2-week cycle (5.2% to 7%) or the 2-month cycle (7.1% to 9.4%); however, the weight of moisture gained, or lost, varied considerably. For example, the MC changes for the fiberboard sheathing and the hardboard siding were both about 7 percent, but the hardboard gained (and lost) double the weight of moisture since it weighed twice as much as the fiberboard. Relative thickness change, and to a lesser degree linear change of the fiberboard and hardboard, were affected by the density difference. The higher-density hardboard changed more in both thickness and length than did the fiberboard sheathing.

5/"Practical equilibrium" as defined in ASTM D 1037 was used to determine when specimens were ready for testing (specimens were neither losing nor gaining weight by more than 0.05% in a 24-hr period).

For both cyclic exposures, thickness change was greater for the waferboard than for either of the two particleboards which were made primarily from planer shavings. On the other hand, linear expansion was much greater for the particleboards than for the waferboard. This is typical of comparative behavior of panels made from large flat flakes (wafers) and those made from finer particles (McNatt 1974a and 1974b, Suchsland 1973). In panels made from wafers, the grain direction of the wood lies essentially in the plane of the panel; whereas in panels made from planer-shaving- or sawdust-type particles, the grain direction can deviate substantially from the plane of the panel. Bonding of the randomly distributed overlapping wafers restricts linear movement in much the same way as cross alinement of veneers in plywood. At the same time, thickness swelling in flake-type panels is maximized because the grain of the flakes lies in the plane of the panel and wood swells much more across the grain than along the grain.

Residual changes in MC and dimensions of the specimens reconditioned to 65 percent RH following the 12 humidity cycles are given in Table 2. Except for irreversible thickness swelling (springback) of the UF particleboard, little difference exists between results from the 2-week and 2-month cycle exposures. Springback of the UF particleboard specimens after the twelve 2-month cycles (5.6%) was more than twice the springback after the twelve 2-week cycles (2.1%).

The longer exposure time at high humidity appears to have a greater effect on the point-to-point bonds in the UF particleboard than in the PF particleboard. Little difference in the PF particleboard springback exists between the 2-week cycle (1.2%) and the 2-month cycle (1.7%). Scharfetter (1977) stated that chemical degradation was not the cause of deterioration of exterior particleboard; rather the causes are of a mechanical nature. The greater deterioration of the UF panel is likely the result of hydrolytic decomposition of the adhesive bond as discussed by Gillespie (1968) in addition to the repeated internal (mechanical) stressing at the glue bonds as a result of the cycling (Dinwoodie 1977, Gillespie 1965).

As suggested by O. Suchsland (personal correspondence, Michigan State University, 1982), a change in properties of all densified wood-base products associated with permanent thickness swelling exists aside from any deterioration of the glue bonds. Glue bonds will break during swelling, but not because of the effect of moisture on the bonds. This change in properties whould be independent of glueline quality and should be subtracted from the original (control) property before glue bond deterioration is determined.

For long exposure to high humidity in a nonsterile environment, deterioration due to fungus attack is a possibility. Phenolics are more resistant to fungus attack than ureas (Schmidt et al. 1978).

Specimens in this study were reconditioned at 65 percent RH from the 90 percent RH exposure. Due to sorption hysteresis, final EMC values at 65 percent RH were 1.2 to 2.8 percent higher than those after initial conditioning. Residual changes in length were inconsistent and ranged from -0.04 percent to +0.07 percent.

Static Bending Properties

The effects of humidity cycling on static bending properties were determined from values of "load-carrying capacity" and "stiffness," defined here as being MOR and MOE calculated using initial specimen thickness at 65 percent RH. Calculations based on initial thickness remove the influence of irreversible thickness swelling on load-carrying capacity and stiffness. Changes in a wood-base panel's ability to carry the required load or resist deflection due to cyclic exposure after being placed in a structure should be determined independent of changes in dimension.

The average values for the five panel types, expressed as a percent of control values, are given in table 3 and plotted in figures 4 and 5. The effects of cycling were essentially the same for both load-carrying capacity and stiffness. The effects of the 2-month cycling were much more severe for the UF particleboard than for any of the other panel types.

After 12 of the 2-month cycles, the UF particleboard retained only 50 percent of the original strength and 61 percent of the original stiffness; the other four panel types retained 82 to 97 percent of their original strength and stiffness. After 12 of the 2-week cycles, all panel types, including the UF particleboard, retained 83 to 97 percent of their original strength and stiffness (fig. 6).

Except for the UF particleboard, differences between strength and stiffness retained after 12 cycles of the 2-month and 2-week exposures were not significant.

Using information from various literature sources (and this study), I have summarized the effects of cyclic humidity exposures on MOR and MOE in bending of wood-base panel products (table 4). With one exception (Lehmann 1978), previously published data were calculated using specimen dimensions at test. Therefore, Lehmann's 1978 data and the data in this study were converted to the same base so that some comparisons could be made. Because of the diverse exposure conditions used, direct comparisons among studies are difficult; however, certain statements can be made based on table 4:

1. Properties of UF particleboards are affected more by cyclic exposure than those

than those bonded with more durable adhesives such as phenol-formaldehyde (Dinwoodie 1977, Hann, Black, and Blomquist 1963, Morze and Struk 1980, Palmer and Stashevski 1979 and this study).

2. Cyclic exposures affect board properties more severely at higher temperatures (Dinwoodie 1977 compared with Hann, Black, and Blomquist 1963 and Morze and Struk 1980).

3. At given temperature/humidity conditions, and the same total cyclic exposure time, effects on properties of UF particleboard will be comparable regardless of duration of individual cycle. For example, for 50 cycles of 7 days each at 30 and 90 percent RH, an exposure time of about 2 years (Dinwoodie 1977) gave essentially the same property retention (50%) as 12 cycles of 30 days each at 30 and 90 percent RH (current FPL study). This does not appear to be true for PF particleboards. Comparisons among values reported by Dinwoodie (1977), by Lehmann (1978), and in this study show little differences in property retention for 5, 12, or 50 cycles or 2-week or 2-month exposures per cycle.

CONCLUSIONS

The results of cycling selected wood-base panel products between 30 and 90 percent RH--2 weeks or 2 months per cycle--for up to 12 cycles show that:

1. For particleboard, the long cycle exposure affected the UF product properties much more than it affected the PF product. After 12 of the 2-month cycles, the UF panel retained 50 to 60 percent of original load-carrying capacity and stiffness in bending whereas the PF particleboard, as well as the waferboard, hardboard siding, and fiberboard sheathing, retained more than 80 percent. However, after 12 of the 2-week cycles, all panel types, including the UF particleboard, retained more than 80 percent of their original load-carrying capacity and stiffness.

2. Deterioration of the urea-resin bond was also reflected in greater irreversible thickness swelling (springback) as compared to the other panel types.

3. The data in this study indicate that, with the exception of UF particleboard, the 2-week cycle is as effective as the 2-month cycle for evaluating the behavior of wood-base panel products in fluctuating humidity environments.

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Table 1.--Static bending properties of control specimens[1/]

Panel type	Thickness	Specific gravity[2/]	Moisture content[3/]	Modulus of rupture	Modulus of elasticity
	In.		%	Psi	1,000 psi
Regular-density fiberboard sheathing	1/2	0.42	6.1	870	147
Hardboard siding	3/8	.89	7.1	3,910	495
Urea-formaldehyde particleboard[4/]	5/8	.67	9.1	1,930	389
Phenol-formaldehyde particleboard	5/8	.78	8.8	3,190	522
Waferboard	1/2	.60	6.7	2,590	495

1/ Each value is the average of 20 specimens.
2/ Based on dimensions at test and ovendry weight.
3/ At equilibrium at 80° F and 65% RH.
4/ See NOTE under MATERIALS section.

Table 2.--Residual changes in moisture content and dimensions of wood-base panel products subjected to 12 cycles of 30 to 90 percent relative humidity and reconditioned at 65 percent relative humidity

Panel type	Moisture content increase		Permanent thickness swelling (springback)		Length change	
	2-week cycle	2-month cycle	2-week cycle	2-month cycle	2-week cycle	2-month cycle
	%	%	%	%	%	%
Fiberboard sheathing	1.4	1.2	1.1	0.6	-0.04	-0.01
Hardboard siding	2.2	2.2	3.2	3.1	-.02	.02
Urea-formaldehyde particleboard	1.9	2.8	2.1	5.6	.00	.07
Phenol-formaldehyde particleboard	1.6	2.3	1.2	1.7	.00	.00
Waferboard	2.4	2.5	2.0	2.5	.01	.02

Table 3.--Percent retention of bending properties by wood-base panel products after cyclic 30 to 90 percent relative humidity exposure. Each value is the average from five specimens

Panel type	One cycle			Three cycles			Six cycles			Twelve cycles		
	Moisture content	Load-carrying capacity	Stiffness	Moisture content	Load-carrying capacity	Stiffness	Moisture content	Load-carrying capacity	Stiffness	Moisture content	Load-carrying capacity	Stiffness
	%	% of control	% of control	%	% of control	% of control	%	% of control	% of control	%	% of control	% of control
						2-WEEK CYCLE						
Fiberboard sheathing	7.3	89	91	7.8	90	93	7.5	86	92	7.5	85	86
Hardboard siding	7.7	95	100	8.2	96	99	8.9	97	97	9.3	97	96
Urea-formaldehyde particleboard	10.0	93	95	10.2	92	95	10.7	78	81	11.0	83	87
Phenol-formaldehyde particleboard	9.4	92	95	9.6	95	95	9.9	94	99	10.4	88	92
Waferboard	8.3	94	96	8.3	88	94	8.2	98	97	9.2	91	90
						2-MONTH CYCLE						
Fiberboard sheathing	6.7	95	93	7.3	95	90	6.9	88	88	6.2	86	87
Hardboard siding	8.1	98	101	9.3	94	93	9.3	90	89	9.1	94	97
Urea-formaldehyde particleboard	10.7	83	90	11.6	88	83	11.9	69	75	11.3	50	61
Phenol-formaldehyde particleboard	10.2	95	104	10.8	99	95	11.1	88	99	10.7	86	90
Waferboard	8.6	88	97	9.5	91	90	9.6	92	99	9.0	82	97

Table 4.--Summary of effects of cyclic humidity exposure on bending properties of wood-base panel products. Data from the literature and this study

Researcher	Test material	Conditions of cycle	Number of cycles	Modulus of rupture retained[1/]	Modulus of elasticity retained[1/]
				%	%
Dinwoodie	Urea-formaldehyde particleboard	7 days at 30% + 7 days at 90% relative humidity (at 25° C)	50	58	45
	Phenol-formaldehyde board and MUF board	do.	50	80+	70+
Hann et al.	Phenol-formaldehyde particleboard	7 days at 80° F--90% relative humidity + 7 days at 158° F--20% relative humidity	52	70-77	68-73
	Melamine-urea-formaldehyde board	do.	52	34	50
	Urea-formaldehyde board	do.	52	4-26	<10
Lee and Biblis	Urea- and Phenol-formaldehyde particleboard	65% → 30% → 65% → 90% → 65% relative humidity (at 72° F--to equilibrium moisture content at each humidity)	1	84	80
Lehmann	Phenol-formaldehyde flakeboard	30 days at 30% + 30 days at 90% relative humidity (at 75° F)	5	86	80
Liiri	Urea-formaldehyde particleboard	3 weeks at 95% + 3 weeks at 30% relative humidity (at 20° C)	10	75	--
Morze and Struk	Phenol-formaldehyde particleboard	Stepwise: 840 h at 50° C-95% relative humidity → dried 24 h at 50° C + 24 h at 100° C	5	96	88
	Urea-formaldehyde particleboard	do.	5	76	69
Morze and Synowiec	Hardboard	Stepwise: 48 h at 80% → 120 h at 95% → 48 h at 70% → 120 h at 37% relative humidity (at 20° C)	6	88-96	76-93
	do.	Same humidity, 60° C	6	82-91	72-89
Palmer and Stashevski	Phenol-formaldehyde and Tannin-F particleboard	7 days at 25% + 7 days at 85% relative humidity (at 38° C)	65	100	--
	Urea-formaldehyde	do.	65	14-35	--
McNatt (current FPLstudy)	Fiberboard sheathing	7 days at 30% + 7 days at 90% relative humidity (at 80° F)	12	82	82
	Hardboard	do.	12	93	88
	Urea-formaldehyde particleboard	do.	12	80	82
	Phenol-formaldehyde particleboard	do.	12	85	88
	Phenol-formaldehyde waferboard	do.	12	86	83
	Fiberboard sheathing	30 days at 30% + 30 days at 90% relative humidity (at 80° F)	12	86	87
	Hardboard	do.	12	88	88
	Urea-formaldehyde particleboard	do.	12	45	51
	Phenol-formaldehyde particleboard	do.	12	82	85
	Phenol-formaldehyde waferboard	do.	12	78	90

1/ Modulus of elasticity and modulus of rupture values calculated using dimensions at time of test.

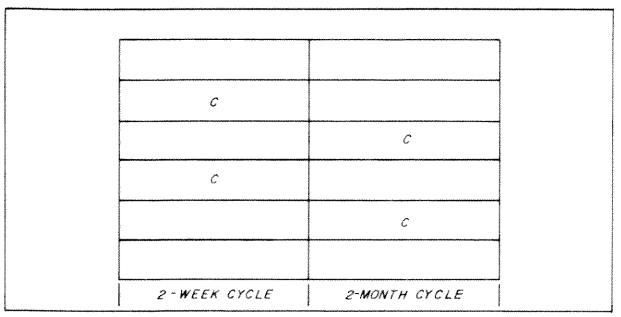


Figure 1.--Layout of 3-inch-wide bending specimens on 2- by 4-foot sample of wood-base panel product. Specimens marked "C" were tested as controls without cyclic humidity exposure. (M 151 709)

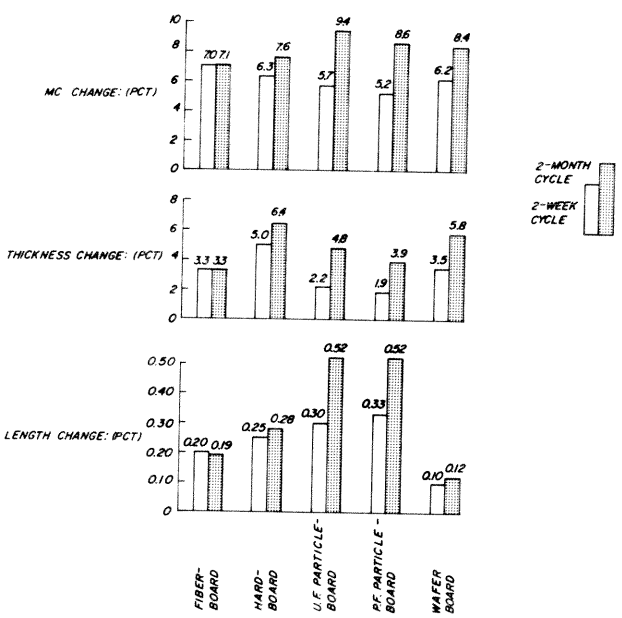


Figure 3.--Changes in moisture content, thickness, and length of wood-base panel products between 30 and 90 percent RH. Average of 12 cycles and and 5 specimens of each product type. (M 151 708)

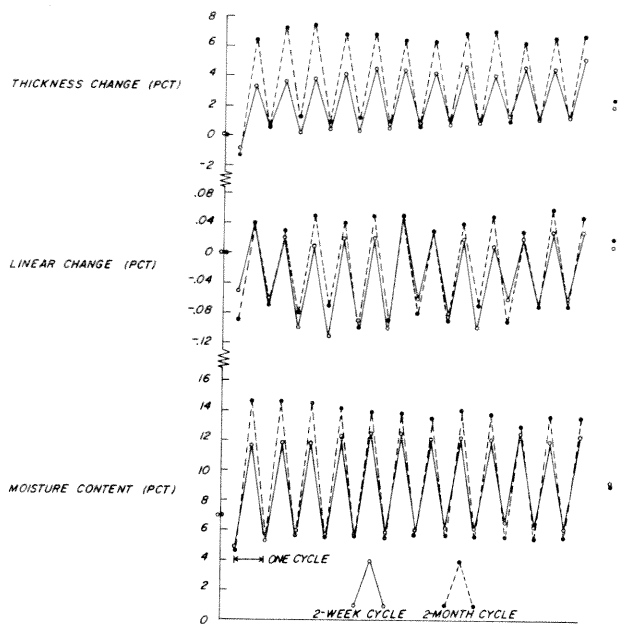


Figure 2.--Progressive changes in thickness, length, and moisture content of waferboard cycled between 30 and 90 percent RH. Data points at far left and far right represent initial conditioning and reconditioning to EMC at 80°F, 65 percent RH.

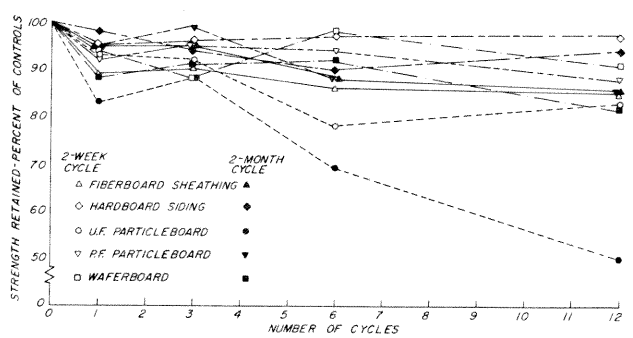
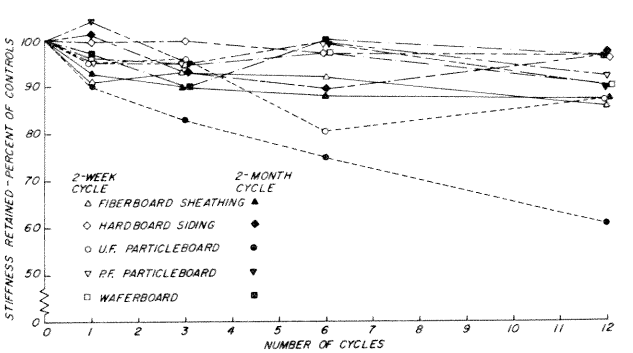


Figure 4.--Percent retention of bending strength after 30 to 90 percent RH cyclic exposures. Each point is the average of five values. (M 151 706)

Figure 5.--Percent retention of bending stiffness after 30 to 90 percent RH cyclic exposures. Each point is the average of five values. (M 151 705)



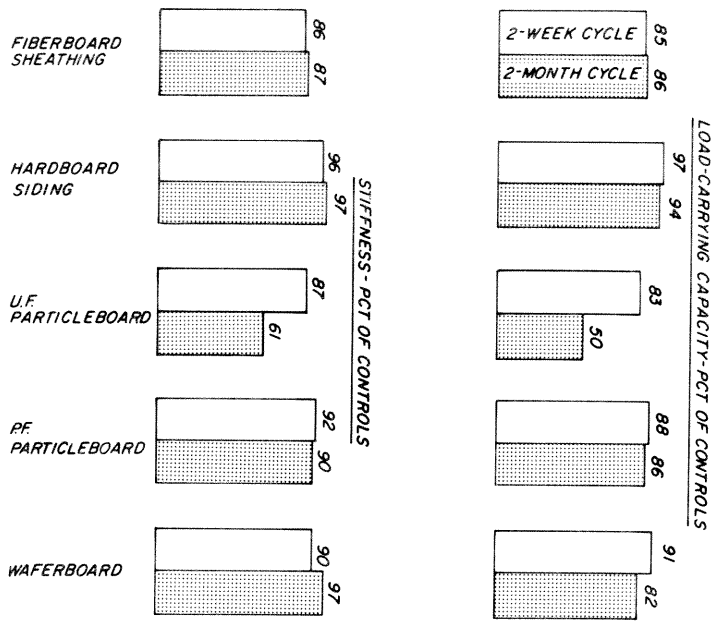


Figure 6.--Percent bending strength and stiffness retained after 12 cycles of 30 to 90 percent RH. (M 151 707)

PREDICTING ASTM D1037 6-CYCLE ACCELERATED AGING OF WAFERBOARD IN 27 HOURS[1/]

R. M. Knudson and G. N. Rosenberg[2/]

Abstract.--An excellent correlation, which allows prediction of aged MOE in 27 hours compared to three weeks for the ASTM test, was established in the laboratory between CSA 0188.0 two-hour boil test followed by a 24-hour drying cycle and six-cycle ASTM D1037 test. ASTM MOE predicted by this method, after adjustment for specific gravity showed that the majority of panels fell within ±15% of the actual MOE value (r^2 = 0.67). For an in-plant evaluation, MacMillan Bloedel Research personnel established and monitored the rapid aged MOE test at MacMillan Bloedel's Thunder Bay Division for about one year. Findings confirmed the suitability of the test method as a quality control procedure, which would enable immediate corrective action if there is evidence that the process is out of control. The rapid aged MOE test has been adopted as part of the regular mill test procedure to evaluate significant process changes at MacMillan Bloedel mills.

INTRODUCTION

Considerable research has been carried out to develop accelerated weathering tests and to correlate these tests with long term natural weathering of wood based panel products (Deppe 1981; Deppe, Stolzenburg, and Schmidt 1976; Deppe and Schmidt 1979; Endicott and Frost 1967; Lehmann 1977; Shen 1977). Purpose of this work, however, was to develop a rapid method of simulating ASTM D1037 accelerated aging (American Society for Testing and Materials 1982) as a quality control procedure for waferboard manufacture.

Six-cycle ASTM D1037 accelerated aging test is required by U.S. regulatory agencies for marketing waferboard in the United States. Minimum time to complete six-cycle ASTM accelerated aging is 14 days. However, as most laboratories do not have automated aging facilities, the normal time to complete six cycle ASTM accelerated aging is three weeks. Because of the long time to complete the aging cycle, the test method is not a suitable quality control procedure to enable corrective action in a production situation.

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PROCEDURE

Work to develop a rapid method for predicting six-cycle ASTM D1037 accelerated aging as a quality control procedure for waferboard manfacture was carried out in three successive stages.

Preliminary Screening Tests

A mill-produced 7/16-inch (11.1 mm) thick 4 x 8 foot (1220 x 2440 mm) panel with known areas of good and poor bonding was cut into ASTM D1037 static bending test specimens (American Society for Testing and Materials 1982). Specimens were assigned for testing after accelerated aging by the following methods:

A. ASTM D1037 six-cycle accelerated aging (29 samples; designated ASTM in remainder of text). Each cycle consists of the following:

1. Immerse in water at 120 ± 3°F (49 ± 2°C for 1 hour.

2. Spray with steam and water vapor at 200 ± 5°F (93 ± 3°C) for 3 hours.

3. Store at 10 ± 5°F (-12 ± 3°C) for 20 hours.

4. Heat at 210 ± 3°F (99 ± 2°C) in dry air for 3 hours.

5. Spray again with steam and water vapor at 200 ± 5°F (93 ± 3°C) for 3 hours.

6. Heat in dry air at 210 ± 3°F (99 ± 2°C) for 18 hours.

After completion of the six cycles of exposure, samples are conditioned at a temperature of 68 ± 6°F (20 ± 3°C) and a relative humidity of 65% ± 1% for at least 48 hours before testing.

B. CSA 0188 accelerated aging consisting of 2 hours boil followed by 1 hour cold water soak (Canadian Standards Association 1978); test wet at room temperature (21 samples; designated CSAW).

C. CSA 0188 accelerated aging with drying cycle (20 samples; designated CSAD). One cycle consisting of the following:

1. Boil for 2 hours.
2. Soak in cold water for 1 hour.
3. Dry at 221°F (105°C) for 24 hours.

Test after specimens are at room temperature.

D. Vacuum-pressure-soak cycle where specimens are submerged in cold water and subjected to 30 minutes under a vacuum of 25 inches of mercury (85 kPa) followed immediately by 30 minutes under pressure of 65 to 70 psi (450-480 kPA) and 2 hours water soak at 150°F (66°C); test wet at room temperature (21 samples; designated VPSW).

E. Vacuum-pressure-soak cycle followed by 18 hours drying at 210°F (99°C); test after conditioning at 68 ± 6°F (20 ± 3°C) and relative humidity of 65% ± 1% for 48 hours (20 samples; designated VPSD).

Prior to accelerated aging, all specimens were proof loaded to determine modulus of elasticity (MOE). After accelerated aging all specimens were tested by ASTM D1037 procedures to determine modulus of rupture (MOR), MOE and retention of pre-aged MOE after accelerated aging.

Laboratory Development of Test

Preliminary screening tests had shown a relationship between CSAD and ASTM accelerated aging test results. Preliminary tests also indicated a strong relationship between properties and density. Thus, specific gravity had to be taken into account in order to make a valid comparison between CSAD and ASTM results.

Further development was carried out in the laboratory to improve the relationship between CSAD and ASTM by including the contribution of specific gravity. This work was carried out in two parts.

The first portion of the work was carried out to determine the relationships between CSAD MOE and ASTM MOE including the contribution of specific gravity. Six 11.1 mm panels from each of two different mills were cut, parallel and perpendicular to machine direction, and tested by CSAD and ASTM methods. These samples were selected to cover a wide range of specific gravity. The following samples were tested by each of the two methods (CSAD and ASTM).

Mill 1	14 parallel	29 perpendicular
Mill 2	18 parallel	47 perpendicular

After testing by the CSAD method, sample MOE values were plotted against specific gravity, and regression parameters were calculated. Mean CSAD MOE for each panel was adjusted to the same specific gravity at which ASTM MOE was measured for that panel. A plot, CSAD MOE vs ASTM MOE, was then made based on the results for each of the 12 panels tested.

The second portion of the work was carried out to confirm the validity of the relationship determined between CSAD MOE and ASTM MOE. Twenty 11.1 mm panels from a single mill manufactured over a two-month period were tested. A portion of each panel was tested by the CSAD method, while the remainder of the panel was tested according to ASTM D1037. Three samples parallel and three samples perpendicular to machine direction from each panel were tested by each method. The effect of specific gravity on CSAD was determined for these panels. Predicted ASTM MOE was determined from an equation developed in the first section of the work after adjustment for specific gravity and compared to measured ASTM MOE values for these 20 panels.

Mill Verification Tests

After laboratory development of the CSAD rapid accelerated aging procedure, the test was monitored at MacMillan Bloedel's Thunder Bay Division for a 10-month period. Seventy-six 11.1 mm panels were sampled and a portion of each panel was tested in the mill by the CSAD method. The remainder of the panel was tested according to ASTM D1037 by the testing agency which certifies our product quality in the United States. Four static bending samples parallel and four samples perpendicular to machine direction from each panel were tested by each method.

MOE results after ASTM aging were analyzed using the method of multiple regression on predictors of sample specific gravity in each test and CSAD MOE. Regression equations were calculated for parallel and perpendicular directions as well as for the combined data.

RESULTS AND DISCUSSION

Preliminary Screening Tests

Results of preliminary screening tests by the different accelerated aging test methods are

given in table 1. CSAD aging values for MOR, MOE, and percent retention of MOE all closely followed the corresponding values obtained after ASTM accelerated aging. Values obtained after CSAD aging generally ranged between 0% and 10% higher than corresponding values obtained after ASTM aging. The CSAD test was also able to differentiate between good and bad areas of the panel. CSAD aging showed an MOE difference of 174 Mpsi and ASTM aging showed an MOE difference of 192 Mpsi between good and bad areas of the panel. CSAD aging test gave the combined characteristics of correlation with ASTM test results and ability to differentiate between good and bad areas of the panel. Thus, the CSAD accelerated aging test method was chosen for further evaluation as a rapid test procedure to predict ASTM accelerated aging.

CSAW and VPSW tests gave MOR, MOE, and percent retention of MOE values which were generally between 50% and 70% of those obtained by ASTM aging. CSAW and VPSW tests did not adequately differentiate between good and bad areas of the panels. Comparing MOE values, CSAW aging showed a difference of 85 Mpsi, VPSW aging showed a difference of 58 Mpsi, and ASTM aging showed a difference of 192 Mpsi between good and bad areas of the panel. CSAW aging gave 54% and 49% MOE retention, VPSW againg gave 45% and 44% MOE retention, and ASTM aging gave 86% and 71% retention for good and bad areas of the panel. Because of their inability to adequately differentiate between good and bad panel areas, CSAW and VPSW test methods were not chosen for further evaluation.

VPSD aging showed very little effect on panel properties. Aged MOR and MOE values were considerably higher than those obtained by ASTM aging. There was virtually no loss in MOE from VPSD aging as shown by the 99% retention of preaged MOE. This test was judged to be unsatisfactory for predicting ASTM accelerated aging.

Initial screening tests also indicated that sample specific gravity had a large influence on results regardless of the test method. Thus specific gravity was included as a variable in all subsequent test method development.

Laboratory Development of Test

The first portion of laboratory development work was carried out to determine the relationships between CSAD and ASTM aged MOE including the effect of specific gravity. Table 2 shows regression equations describing the relationship between CSAD MOE and specific gravity. CSAD MOE for each panel was then adjusted to the same specific gravity at which ASTM MOE was measured for that panel. Figure 1 shows the plot of ASTM MOE against specific gravity corrected CSAD MOE. The relationship derived between ASTM MOE and CSAD MOE was as follows:

$$\text{MOE ASTM (Mpsi)} = 0.698 \text{ MOE CSAD} + 86.1 \qquad \ldots 1$$

$$r^2 = 0.40$$

Results of the second portion of laboratory development work testing 20 panels are given in Table 3. CSAD MOE values corrected to the specific gravity of ASTM MOE samples for the corresponding panel are also shown. Corrected CSAD MOE values were determined from regression equations relating CSAD MOE and specific gravity for the 20 panels.

Predicted ASTM MOE was determined from equation 1 after adjustment for specific gravity, and compared to measured ASTM MOE values for these panels (Table 4). ASTM MOE values predicted from CSAD MOE for the 20 panels are in very good agreement with the actual ASTM MOE results. Maximum difference between predicted and measured MOE values for an individual panel was 30%, with the majority of panels falling within the range of +5% to +15% of the actual value. When MOE values were averaged for the 20 panels in either the parallel or perpendicular directions the percentage difference between predicted and measured ASTM MOE was reduced to approximately 5%.

CSAD MOE and measured ASTM MOE from the 20 panel sample (Table 3) can be combined with data from figure 1 to give an improved prediction equation (see fig. 2).

$$\text{MOE ASTM (Mpsi)} = 0.681 \text{ MOE CSAD} + 92.4 \qquad \ldots 2$$

$$r^2 = 0.58$$

Laboratory development work established a relationship between CSAD and ASTM accelerated aging tests. Based on the laboratory development work CSAD accelerated aging test was implemented as a mill quality control procedure to predict ASTM accelerated aging MOE.

Mill Verification Tests

Results of correlating CSAD MOE measured in the mill with ASTM MOE measured by an outside testing agency are shown in table 5. The predictive equations in table 5 are very similar, regardless of the direction of sample orientation. This was confirmed by substituting a range of CSAD values into the equations at a common specific gravity. At low values of CSAD MOE, i.e, 450 Mpsi, there was a 5% maximum difference in predicted ASTM MOE between the three predictive equations. This difference increased to about 11% at a CSAD MOE of 700 Mpsi and to about 15% when CSAD MOE was 900 Mpsi (table 6).

Since the purpose of the predictive equations is to inform production staff when the mill process is out of control (i.e., ASTM MOE is falling below 400 Mpsi which is the minimum allowable value for 11.1 mm thick panels), all three equations in table 5 would appear equally valid in this range of ASTM MOE. Since the equation calculated from parallel and perpendicular values has the largest sample size (n = 143) and the best index of determination (r^2 =

0.67) it would be best suited as a predictive equation. This equation from table 5 can be simplified for use as a quality control tool by reducing to a common specific gravity.

$$\text{MOE ASTM} = 0.351 \text{ MOE CSAD} + 396 \text{ SG} - 106 \quad \ldots 3$$

$$r^2 = 0.67$$

Based on 10 months of in-mill monitoring, the CSAD rapid accelerated aging test was adopted as part of the regular mill test procedure for measuring panel quality when significant process changes had occurred. Equation 3 would be recommended for use as a quality control tool to predict ASTM MOE. As additional results from in-mill CSAD MOE and ASTM MOE from the outside agency become available, that data can be combined with previous data to improve the relationship between CSAD MOE and ASTM MOE.

SUMMARY AND CONCLUSIONS

Four different accelerated aging procedures were evaluated as potential methods of rapidly simulating six-cycle ASTM D1037 accelerated aging for waferboard. One accelerated aging procedure (CSAD), consisting of CSA 0188 accelerated aging (2 hours boil and 1 hour cold water soak) followed by 24 hours drying showed a close relationship with ASTM accelerated aging. Three other accelerated aging methods, CSA 0188 accelerated aging with no drying cycle and two vacuum-pressure-soak methods, did not show sufficiently close relationship with ASTM accelerated aging.

Subsequent laboratory development work established an excellent correlation between CSAD and ASTM accelerated aging tests. ASTM MOE predicted by CSAD method, after adjustment for specific gravity, showed that the majority of panels fell within ±15% of the actual ASTM MOE value. CSAD accelerated aging test allows prediction of aged properties in 27 hours compared to 3 weeks for six-cycle ASTM accelerated aging test.

MacMillan Bloedel Research established and monitored the CSAD rapid aged MOE test at MacMillan Bloedel's Thunder Bay Division for approximately one year. Findings confirmed the suitability of the CSAD test method as a quality control procedure which would enable immediate corrective action if there is evidence that the process is out of control. CSAD rapid aged MOE test has been adopted as part of the regular mill test procedure to evaluate significant process changes at MacMillan Bloedel mills.

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Table 1.--Bending property results after various accelerated aging cycles

Test methods	Entire panel MOR psi	Entire panel MOE Mpsi	Entire panel MOE % retention	Good areas MOR psi	Good areas MOE Mpsi	Good areas MOE % retention	Bad areas MOR psi	Bad areas MOE Mpsi	Bad areas MOE % retention
ASTM D1037									
$\bar{x}$	1999	470	82	2225	523	86	1408	331	71
SD	551	124	10.4	454	101	8.6	272	49	6.7
n	29	29	29	21	21	21	8	8	8
range	870-3404	248-824	66-101	1322-3404	386-824	74-101	870-1758	248-392	66-83
CSA-0188 (wet)									
$\bar{x}$	1279	290	52	1387	318	54	1063	233	49
SD	295	83	8.8	295	84	8.9	140	44	8.8
n	21	21	21	14	14	14	7	7	7
range	856-2054	167-398	33-64	942-2054	187-398	35-64	856-1243	167-280	33-59
CSA-0188 (dry)									
$\bar{x}$	2031	496	89	2263	548	91	1488	376	84
SD	587	118	7.4	534	98	7.1	254	52	6.6
n	20	20	20	14	14	14	6	6	6
range	1236-3654	320-761	72-103	1677-3654	439-761	78-103	1236-1896	320-451	72-90
VPS (wet)									
$\bar{x}$	1243	253	45	1304	272	45	1120	214	44
SD	251	72	8.0	282	79	9.0	108	35	5.9
n	21	21	21	14	14	14	7	7	7
range	887-2121	151-428	29-59	877-2121	151-428	29-59	968-1251	170-262	36-52
VPS (dry)									
$\bar{x}$	2332	555	99	2483	581	99	1880	475	97
SD	556	109	7.7	533	106	8.0	365	79	7.0
n	20	20	20	15	15	15	5	5	5
range	1458-3674	393-919	84-115	1794-3674	448-919	84-115	1458-2403	393-576	89-107

1/ $\bar{x}$ = mean, SD = standard deviation, n = number of samples

Table 2.--Relationship between specific gravity and CSAD MOE

		r^2	n*
Mill 1			
Parallel	CSAD MOE (Mpsi) = 982SG - 242	0.43	14
Perpendicular	CSAD MOE (Mpsi) = 1404SG - 535	0.59	29
Mill 2			
Parallel	CSAD MOE (Mpsi) = 1004SG - 227	0.38	18
Perpendicular	CSAD MOE (Mpsi) = 1592SG - 644	0.69	47

*Number of samples

Table 3.--The specific gravity CSAD MOE based on measured CSAD MOE and measured ASTM MOE

Panel No.	Measured CSAD[1/] MOE Parallel	Measured CSAD[1/] MOE Perpendicular	Measured CSAD[1/] SG Parallel	Measured CSAD[1/] SG Perpendicular	Measured ASTM[1/] MOE Parallel	Measured ASTM[1/] MOE Perpendicular	Measured ASTM[1/] SG Parallel	Measured ASTM[1/] SG Perpendicular	Corrected CSAD[1/] MOE Parallel	Corrected CSAD[1/] MOE Perpendicular
	------Mpsi-----				------Mpsi-----				------Mpsi-----	
1	442	469	.669	.676	394	357	.668	.681	437	476
2	502	540	.678	.675	407	397	.665	.660	480	512
3	467	481	.650	.655	473	407	.679	.677	512	518
4	508	474	.696	.668	378	425	.675	.685	474	502
5	585	591	.696	.702	454	393	.690	.690	574	568
6	511	524	.685	.678	460	386	.697	.675	528	517
7	511	464	.684	.681	492	468	.681	.683	505	466
8	477	522	.650	.663	438	431	.690	.670	538	531
9	554	508	.694	.681	482	451	.684	.667	537	482
10	562	551	.676	.678	486	395	.675	.647	559	495
11	488	606	.639	.703	586	461	.708	.683	596	564
12	597	494	.712	.680	450	502	.695	.702	567	531
13	477	560	.664	.678	411	474	.657	.688	464	576
14	437	483	.665	.675	526	486	.690	.687	475	502
15	506	464	.662	.663	416	376	.662	.631	504	405
16	449	536	.628	.722	528	424	.698	.686	557	472
17	451	537	.680	.719	471	332	.692	.662	468	434
18	440	452	.687	.702	468	426	.711	.717	476	475
19	583	500	.719	.696	446	327	.706	.689	561	486
20	578	479	.705	.670	520	355	.717	.664	595	469

1/Average of 3 specimens

Table 4.--Predicted and measured ASTM MOE

Panel No.	Corrected CSAD MOE Parallel	Corrected CSAD MOE Perpendicular	Predicted ASTM MOE Parallel	Predicted ASTM MOE Perpendicular	Measured ASTM MOE Parallel	Measured ASTM MOE Perpendicular	Difference Parallel	Difference Perpendicular
	-------Mpsi----------		-------Mpsi---------		-------Mpsi---------		-------Percent------	
1	437	476	392	419	394	357	-1	+17
2	480	512	422	444	407	397	+4	+12
3	512	518	444	449	473	407	-6	+10
4	474	502	418	437	378	425	+11	+3
5	574	568	488	484	454	393	+7	+23
6	528	517	456	448	460	386	-1	+16
7	505	466	440	412	492	468	-11	-12
8	538	531	463	458	438	431	+6	+6
9	537	482	462	423	482	451	-4	-6
10	559	495	477	433	486	395	-2	+10
11	596	564	502	481	586	461	-14	+4
12	567	531	483	458	450	502	+7	+9
13	464	576	411	489	411	474	0	+3
14	475	502	419	437	526	486	-20	-10
15	504	405	439	370	416	376	+6	-2
16	557	472	476	416	528	424	-10	-2
17	468	434	414	390	471	332	-12	+17
18	476	475	419	419	468	426	-10	-2
19	561	486	479	426	446	327	+7	+30
20	595	469	503	414	520	355	-3	+17
Average			450	435	464	414	-3	+5
Range							-20 to +11	-12 to +30

Table 5.-- Multiple regression equations correlating ASTM MOE with CSAD MOE and specific gravity (SG)

Orientation	r^2	N
1. Parallel ASTM MOE (Mpsi) = 0.297 CSAD MOE - 1132 SG_{CSAD} + 1649 SG_{ASTM} - 172	.35	72
2. Perpendicular ASTM MOE (Mpsi) = 0.395 CSAD MOE - 262 SG_{CSAD} + 1116 SG_{ASTM} - 419	.43	72
3. Combined ASTM MOE (Mpsi) = 0.351 CSAD MOE - 905 SG_{CSAD} + 1301 SG_{ASTM} - 106	.67	143

Table 6.--Predicted ASTM MOE values for selected values of CSAD MOE at a specific gravity of 0.65

CSAD MOE (Mpsi)	450	700	950
Orientation	Predicted ASTM MOE (Mpsi)		
Parallel	298	372	446
Perpendicular	314	413	513
Combined	309	397	485
Maximum difference (%)*	5.4	11.0	15.0

*Maximum difference in predicted ASTM MOE between parallel, perpendicular, and combined parallel-perpendicular values.

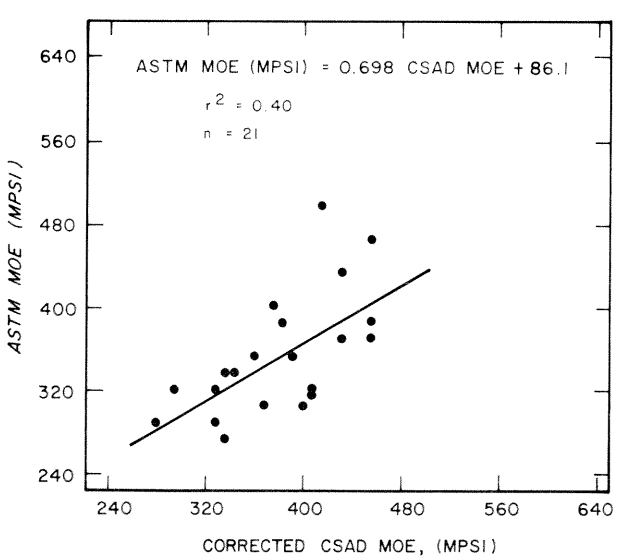

Figure 1.--Plot of ASTM MOE against specific gravity corrected CSAD MOE.

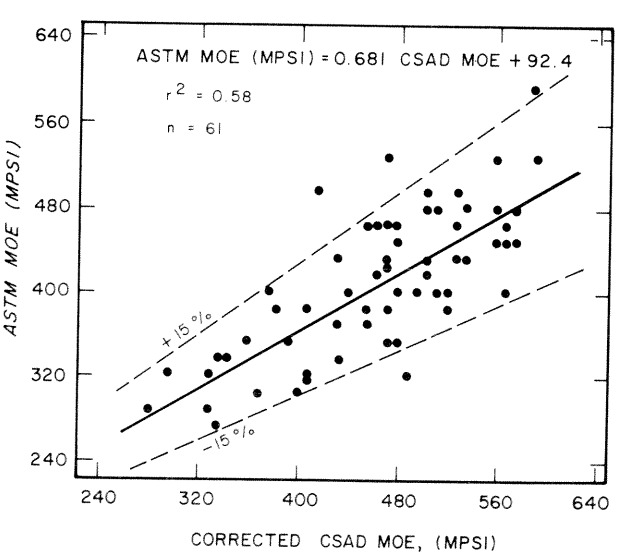

Figure 2.--Plot of ASTM MOE against corrected CSAD MOE.

DURABILITY OF STRUCTURAL FLAKEBOARD FROM SOUTHERN HARDWOODS SPECIES[1/]

M. W. Kelly and E. W. Price[2/]

Abstract.--Flakeboard panels made with individual species (sweetgum, hickory, red oak, white oak, and pine) and with a 20 percent mixture of each species were subjected to a series of exposure conditions. Mechanical and physical properties were determined and compared to commercial waferboard. At 50 percent RH condition, sweetgum, red oak, and hickory panels had properties similar to the commercial waferboard at a similar density (42 pcf). However, after the APA 6-cycle exposure and the ovendry-vacuum-pressure soak exposure, only sweetgum retained physical properties equal to waferboard.

INTRODUCTION

The quantity of low-grade hardwoods growing in the South continues to increase. These hardwoods are on sites more suitable to pines and on hardwood sites that are not properly managed. Until the forest sites are stocked with quality trees and properly managed, the quantity of low-grade hardwoods will continue. However, the fiber presently occupying these sites must first be economically removed. Structural particleboard or flakeboard may provide a solution or incentive to remove this undesired fiber material.

Our objective was to determine if a structural panel could be produced from this material with properties comparable to that of commercially-available waferboard. We were particularly interested in property retentions after several exposure evaluation conditions.

Many laboratory exposure conditions are used to evaluate the property retention or durability of structural panels. Some widely used conditions are the ASTM D 1037 (ASTM 1977), variations of the vacuum-pressure soak test (Heebink 1967) including ovendrying prior to soak, multiple vacuum-pressure and soaking times and temperatures (Gertjejansen et al. 1973; Hall and Gertjejansen 1974; Hall and Gertjejansen 1979; Hse 1976; Lehmann 1974; and River et al. 1981) and the APA test methods S-6 after D-5 exposure (American Plywood Association 1981). With the possible exception of the vacuum-pressure soak and its variations, these conditions are all too long for assistance in process control. Also, all of these tests do not accurately simulate the type of exposure encountered by most structural panels in service.

MATERIALS AND METHODS

Five species, sweetgum, hickory, red oak, white oak, and pine, were used to make flakeboard panels at three different densities per species. A sixth panel type, consisting of equal portions of the previous five species, also was made at three different panel densities. Table 1 contains the species, species density, nominal panel target densities, and the calculated compaction ratios for each panel density. Four replicate panels were produced from each species-panel density combination for a total of 72 panels. Also, for comparative purposes, commercial waferboard (assumed to be fabricated with aspen) was purchased and evaluated.

The laboratory panels (table 1) were produced with the following manufacturing parameters.

1.	Panel size (trimmed)	-	36 by 32 inches
2.	Nominal thickness	-	0.5 inch
3.	Press temperature	-	350°F
4.	Press time	-	8 minutes
5.	Liquid phenolic resin	-	5.5 percent resin solids based on OD wood weight
6.	Flakes	-	Produced on shaping lathe; approximately 3-inch long, random width, thicknesses of 0.025 inch for core and 0.015 inch for face

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7. Panel construction - random flake orientation with 50% of panel weight in core and 25% of panel weight in each face

8. Time to stops - 5 seconds to 1 minute dependent on species and panel density

9. Maximum press pressure - 340 to 600 psi dependent on species and panel density

The properties and exposure conditions evaluated for each panel type were:

1. Static bending and internal bond (ASTM D 1037 test procedures).

   a) Control conditioned at 50% RH, 70°F (2 specimens per panel). Internal bond determined from non-failed portion of sample.

   b) Tested wet after ovendry-vacuum-pressure soak (2 specimens per panel). Unable to determine internal bond because of rough surfaces.

   c) Tested after APA 6-cycle D-5 exposure (2 specimens per panel). Unable to determine internal bond because of rough surfaces.

2. Linear expansion and thickness swelling

   a) Equilibrium at 50% RH to equilibrium at 90% RH (ASTM D 1037) (2 specimens per panel).

   b) From ovendry to vacuum-pressure soak (2 specimens per panel).

3. Static bending of 1- by 5-inch specimen on edge, APA S-6 test procedure (American Plywood Association 1981).

   a) Control conditioned at 50% RH and 70°F (4 specimens per panel).

   b) Tested after APA 6-cycle D-5 exposure (4 specimens per panel)

   c) Tested after equalization at 50% RH and 70°F following D-5 exposure (4 specimens per panel).

In addition, two specimens per panel were exposed in a weatherometer to continuous irradiation with a Xenon arc lamp at a wavelength of 340 nm to a total irradiation of 500 kj/m^2. For 18 minutes of each two-hour cycle specimens were subjected to a water spray on the irradiated surface. Qualitative evaluation of appearance and percent thickness swelling were determined after exposure.

RESULTS AND DISCUSSION

Static Bending (ASTM)

The average density, compaction ratio, and modulus of rupture (MOR) of specimens from all density-species combinations after conditioning, after the ovendry-vacuum-pressure soak (OD-VPS), and after the APA D-5 exposures were obtained (table 2). MOR values are based on dimensions of test specimen at time of testing.

Comparing the results for the conditioned specimens, most species-density combinations have MOR values higher than the commercial waferboard. The lowest density pine, 37.5 lbs. per cu. ft. (pcf), and white oak (42.5 pcf) panels are the only exceptions. Pine, at 42.5 pcf, red oak at 42.4 pcf, hickory at 42 pcf, and the sweetgum at 42.9 and 35.9 pcf are the species-density combinations with average MOR values higher than waferboard values at similar or lower panel densities. All other species-density combinations have both MOR values and panel densities greater than the waferboard. These results illustrate the increase in MOR with increasing panel density or compaction ratio.

The two exposure conditions had a catastrophic effect on the MOR for all panels. The OD-VPS exposure resulted in only a 25% retention of the conditioned MOR values for the waferboard. The sweetgum, red oak, and pine panels at densities similar to waferboard also retained only 25% of the conditioned MOR. Other species-density combinations, with densities and MOR values similar to waferboard values, did not retain 25% of the conditioned MOR after the OD-VPS exposure.

The waferboard samples retained 44% of the unexposed MOR after the D-5 exposure. None of the experimental panels with densities similar to the waferboard before exposure retained this level of MOR after D-5 exposure; the lowest density sweetgum had the highest retention of 39%. Even though none of the experimental panels equaled the waferboard in percent MOR retention after the D-5 exposure, the two lower density sweetgum classes had higher MOR values than the waferboard after exposure.

The extremely poor results for all densities of white oak panels after exposure indicates a lack of durable bonding with this species. The original MOR values for the unexposed samples were lower than would be expected for the panel density but after both the OD-VPS and D-5 exposures the samples practically fell apart; the MOR retention for all density-exposure white oak combinations was less than 10%.

Table 3 contains the apparent modulus of elasticity (MOE) determined on the same specimens reported in table 2. MOE values are based on

dimensions of test specimen at time of test. Internal bond strength of specimens obtained from a non-failed portion of the conditioned static bending samples are also reported in table 3.

The MOE results for the conditioned specimens closely follow MOR trends. Only the lowest density panels of hickory, pine, and white oak had average MOE values below and the waferboard average in the unexposed state and these were only marginally lower. The experimental panels with density comparable to the waferboard all had MOE values which compared favorably with the waferboard.

The waferboard samples after OD-VPS exposure retained 27% of the MOE of the unexposed samples. Only the lowest density of the sweetgum panels retained a higher percentage after exposure (30%) but the lowest density of red oak as well as the middle density of sweetgum and pine all retained above 20%. For experimental panels of initial density similar to that of the waferbord only the red oak, sweetgum, and pine had MOE values similar to the waferboard after OD-VPS exposure.

The MOE retention for the waferboard after the APA D-5 exposure was also 27% but the two lower density classes of the sweetgum panels retained more than 30%. All other experimental panels retained less than 20% of the MOE value after this exposure condition. Also, only the sweetgum and pine had MOE values comparable to the waferboard at similar density levels.

The internal bond averages for all experimental panels with densities similar to that of the commercial waferboard were all substantially below the 82 psi average of waferboard. Only experimental panels with densities higher than the waferboard produced internal bonds equal to waferboard. The increase in internal bonds within the three density classes of each species reflects the increase in the compaction ratio and the subsequent improvement in bonding. The lower internal bonds for the sweetgum and pine panels as compared to the hickory and red oak, even when the compaction ratios are higher for the pine and sweetgum, probably is a reflection of the higher adhesive level per unit of particle surface with the higher density species--hickory and red oak. The low internal bonds for the white oak panels as compared to the hickory panels at similar compaction ratios is a further indication of the poor bonding normally obtained with white oak and phenol-formaldehyde adhesive.

The combined results of tables 2 and 3, MOR and MOE after exposure versus the control, indicate only the sweetgum species is capable of producing a phenolic bonded panel with bending properties comparable to commercial waferboard on equivalent panel density basis. Even though panels from other species were produced with conditioned density and bending strength properties similar to waferboard, the similarity of properties is not retained, except for sweetgum, after both exposures.

Linear Expansion and Thickness Swelling

Fifty to Ninety Percent Relative Humidity

The linear expansion and thickness swelling of one specimen per panel were determined between equilibrium at 50% and equilibrium at 90% relative humidity, both at 70°F (table 4). The equilibrium moisture content (EMC) and density at 50 and 90% relative humidity were also determined.

The waferboard attained a substantially lower EMC at 50 and 90% RH than any of the experimental panels. The reduced hygroscopicity of the waferboard material is probably due to differences in the drying or pressing conditions between the commercially produced waferboard and the experimental panels. The wax in the waferboard is not believed to be effective in reducing the hygroscopicity of the waferboard.

The higher EMC's in the experimental panels did not result in higher linear expansion; the white oak was the only species with linear expansion values comparable to the waferboard. Most of the experimental panels, except white oak, had only ten percent of the linear expansion of the waferboard. However, the percent thickness swelling trend in the same relative humidity increment was reversed; i.e., thickness swelling of experimental panels was at least equal or 10% higher than that of the waferboard. The white oak panel thickness swelling was approximately 70% higher than the waferboard.

The higher compaction ratio of the aspen in the waferboard should produce a higher resin utilization efficiency as compared to the experimental panels. However, improved resin efficiency would be expected to produce lower linear expansion and thickness swelling. If the aspen in the waferboard had tension wood, a higher longitudinal change would occur. Another possible explanation for the difference in linear expansion could be particle orientation. A severe inclination angle of the wafers during the forming process resulting in the wafers not being in the plane of the panel could contribute to a higher linear expansion. Also, if the flakes were accidentally oriented with the long axis parallel to the length of the linear expansion specimen, the linear expansion would be less. Unfortunately, no linear expansion measurements were made in the across-the-panel direction. Other possible differences could be related to the resin. The resin content of the expermental boards was higher and was a liquid. This may have resulted in a heavier and possibly a more uniform resin application in the experimental boards.

Ovendry to Vacuum-Pressure Soak

Table 5 contains the average moisture content, thickness swelling, and linear expansion values for each species-density combination of samples subjected to vacuum-pressure soaking after oven drying. Also included in table 5 are the averages

for waferboard specimens subjected to the same exposure.

The average moisture content at the end of the soaking cycle decreased with increasing panel density, consistent with the decrease in the panel void volume. With this exposure the thickness swelling for the waferboard was again less than that of most of the experimental panels and only the white oak panels had higher linear expansion than the waferboard. The trend of these results duplicates those for the 50 to 90% relative humidity exposure. Also, no consistent relationship within species was evident between either thickness swelling or linear expansion and panel density. The higher compaction ratio of the commercial waferboard probably resulted in better resin efficiency which also produced lower thickness swelling for this exposure. However, the anomalous results for the linear expansion of the waferboard do not indicate better resin efficiency.

The linear expansion and the thickness swelling for all panels were both higher for the ovendry to vacuum-pressure soak exposure than for the 50 to 90% relative humidity exposure. The results for both exposures indicate that, except for white oak, panels produced from the species used in this study will behave similarly to the commercial waferboard. Red oak and sweetgum resulted in panels with dimensional properties most comparable to the waferboard.

Static Bending (APA S-6)

Control

The average breaking loads for edge-loaded specimens, 1 by 5 inches, for all density classes of all species, and for the waferboard, are presented in table 6. The test specimens were conditioned to moisutre equilibrium at 50% relative humidity and 70°F prior to testing.

The average breaking load increased with increasing panel density (compaction ratio) for every species studied. With the exception of the lowest density classes of hickory, pine, and white oak, all experimental panels had average breaking loads higher than the commercial waferboard. However, except for the low density mixture and the middle density pine panel classes, the experimental panels also had densities higher than the waferboard. The higher density panels and the higher resin content both contributed to the higher breaking load for the experimental panels.

After APA D-5 Exposure

Table 7 contains the average breaking load for edge-loaded samples, 1 by 5 inches, after exposure to the APA 6-cycle D-5 accelerated aging test. The average breaking load of the lowest density panels within each species was always significantly lower than the two higher densities and only the highest density panels of hickory, pine, and the mixture were significantly better than the middle density. The white oak panels did not have much bond integrity after exposure; the thickness swelling was extremely large reducing the specimen density to less than 20 pcf. All of the sweetgum density classes, the two higher red oak density classes, and the highest density of hickory, pine, and the mixture all had breaking loads at least as high as the waferboard after the D-5 accelerated aging exposure.

Re-conditioned after D-5 Exposure

Table 8 contains the average breaking load, density, and moisture content for samples exposed to the 6-cycle D-5 aging and then re-conditioned to moisture equilibrium at 70°F and 50% relative humidity. The final step in the D-5 exposure is a 15-hour drying period in an oven set at 180°F. Consequently, the moisture content of the test specimens tested after the D-5 exposure (table 7) is lower than for the re-conditioned specimens in table 8. All density classes of the sweetgum panels had breaking loads significantly above those of the waferboard, as did the two higher densities of the red oak and the highest density of the hickory, pine, and mixture.

The comparison between the experimental panels and the waferboard after exposure to the D-5 tests should not only consider panel density and the breaking load but percent retention. The percent retention can be calculated from the information in tables 6, 7, and 8.

Most of the species used in the study retained only 30% of the original breaking load but the sweetgum and waferboard both retained approximately 60%. The white oak continued as the worst performer, retaining less than 10% of the original breaking load.

Weatherometer

Table 9 contains the average moisture content and thickness swelling for all panel types after weatherometer exposure. This exposure consisted of 500 kj/m^2 irradiation with a Xenon arc lamp at 340 nm wavelength, and an 18-minute water spray on one surface of the sample every two hours. Thus, the samples were subjected to a cyclic wetting and drying exposure. Four separate weatherometer runs with one specimen per panel type per run were performed and the average given in table 9. The target irradiation level, 500 kj/m^2, occurred shortly after the completion of the water spray cycle in one run resulting in a 66% M.C. average. The others averaged 49, 43, and 44%. Since the thickness swell of the samples was similar in the four runs, moisture content and thickness swelling are averaged over all four runs (Table 9).

None of the experimental panels came close to equaling the commercial waferboard in either thickness swelling or moisture content. The average moisture content of the waferboard samples was only 9% with only a 4% increase in

thickness. The lowest density sweetgum panel had the next lowest moisture content and thickness swelling, 45.9% and 32.8%, respectively. There was very little difference in either the moisture content or thickness swelling between species or between densities within species except for the white oak panels. With similar density values the white oak panels had substantially higher moisture content and more thickness swelling than panels of other species. In fact, white oak panels essentially doubled in thickness (100% thickness swell) and had moisture contents above 65% at the end of the exposure cycle.

The appearance of the irradiated surfaces of all experimental samples compared to the commercial waferboard was a more bleached look. The experimental samples also had surface flakes lifting from the panel which were not evident with the waferboard. In addition, the white oak panels had a dark, viscous material which exuded from the back face of the sample. This occurred while the sample was in the weatherometer and is believed to be a water soluble extractive unique to the white oak. It did not appear on other samples.

The exceptionally low water absorption and thickness swelling of the commercial waferboard is somewhat surprising. Much of this excellent water resistance can undoubtedly be attributed to the wax content in the waferboard preventing the water spray from penetrating the surface.

The weatherometer results with the waferboard are substantially different from the results obtained in the ovendry to vacuum-pressure soak test. In the soaking test the wax did not prevent water from penetrating and swelling the panel. Usually wax is thought to be ineffective in limiting water vapor adsorption and quite effective in reducing small amounts of liquid water penetration. The results of this study indicate that the wax may have been very effective against liquid water sprayed on the surface but much less effective when the material was submerged in water and the included air evacuated. The experimental panels contained no wax and did not offer any resistance to the penetration of the water spray into the surface of the weatherometer specimens.

CONCLUSIONS

The results of this study are not overly encouraging with regard to using the southern hardwoods as a furnish for exterior-quality flakeboard at a density comparable to commercial waferboard. Many of the experimental panels had properties as good as waferboard on unexposed samples but, upon subjecting the panels to the various exposures, the majority of the experimental panels did not have percent retentions equal to waferboard. Sweetgum was the only species examined which produced panels with properties comparable to commercial waferboard at a comparable density. But sweetgum, the lowest density species used in the study, had a higher compaction ratio compared to the other species. This higher compaction ratio enhances all of the physical properties relative to other species with the same panel density but lower compaction ratio. To obtain panel properties after exposure equal to or greater than waferboard with all the other species studies, the panel densities must be increased above that of the waferboard.

The waferboard used in this study as a control for the experimental panels was not exceptionally durable or resistant to all exposures. The MOE and MOR values determined by the ASTM static bending test, after ovendry to vacuum-pressure soak exposure, and APA D-5 exposure, were only about 25% of the unexposed values. The other measured properties were also similarly reduced by the various exposures which leads one to question the product's suitability in continuous exterior exposures.

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Table 1.--Species, density, nominal target density, and calculated target compaction ratio for experimental panels

Species	Species density[1]/	Target panel density[2]/ and compaction ratio[3]/		
Hickory	43.0	43/1.00	46/1.07	54/1.26
Pine	30.7	38/1.24	43/1.40	46/1.50
Red oak	36.7	43/1.17	46/1.26	49/1.34
Sweetgum	29.0	36/1.24	43/1.48	46/1.59
White oak	40.1	43/1.07	46/1.15	50/1.25
Mixture	35.9	43/1.20	46/1.28	49/1.36

[1]/Ovendry weight, green volume in pcf
[2]/Ovendry weight, test volume in pcf
[3]/Compaction ratio = $\frac{\text{panel density}}{\text{wood density}}$

Table 2.--Average test density and modulus of rupture for ASTM D 1037 static bending after conditioning and after two exposure treatments for all species density combinations[1]/

	Conditioned			OD-VPS exposure		D-5 exposure	
Species	CR[2]/	Density	MOR[3]/	Density	MOR[3]/	Density	MOR[3]/
		pcf	psi	pcf	psi	pcf	psi
Hickory	0.98	42.0	2677 A	29.1	483 A	26.6	405 A
	1.07	46.0	3636 B	30.8	585 A	29.0	550 A
	1.18	50.7	4450 C	36.7	1151 B	33.9	1268 B
Pine	1.21	37.5	2167 A	27.5	471 A	26.2	515 A
	1.38	42.4	3506 B	31.6	810 B	29.7	818 B
	1.47	45.2	4213 C	32.2	795 B	31.1	957 B
Red oak	1.15	42.2	3473 A	30.5	844 A	28.0	739 A
	1.26	46.1	4857 B	32.8	1149 B	30.6	1264 B
	1.34	49.3	5492 B	34.8	1200 B	31.2	1128 B
Sweetgum	1.24	35.9	3387 A	28.4	928 A	27.3	1334 A
	1.48	42.9	5193 B	31.4	1250 B	30.2	1590 A
	1.52	44.1	4950 B	33.0	1356 B	31.5	1600 A
White oak	1.06	42.5	2524 A	23.1	165 A	17.9	70 A
	1.12	45.0	2843 AB	25.1	228 B	19.8	113 B
	1.18	47.3	3217 B	26.5	299 C	20.9	137 C
Mixture	1.16	41.7	3404 A	29.2	656 A	28.3	757 A
	1.28	46.0	4013 AB	31.5	789 A	27.8	709 A
	1.33	47.6	4676 B	34.5	1091 B	30.7	1092 B
Waferboard[4]/	--	42.0	2618	30.4	654	31.3	1154

[1]/Averages based on 2 specimens from each of 4 replicate panels. All MOR and density values are based on specimen dimension at time of test.
[2]/Compaction ratio = $\frac{\text{specimen density at test (OD weight, test volume)}}{\text{wood density (OD weight, green volume)}}$
[3]/Averages within species per test condition followed by common letter are not significantly different at 0.0005 level.
[4]/Average of 4 specimens

Table 3.--Internal bond, density, and modulus of elasticity for ASTM D 1037 test specimens of all species-density combinations[1]/

Species	Conditioned				OD-VPS exposure		D-5 exposure	
	CR[2]/	IB	Density	MOE[3]/	Density	MOE[3]/	Density	MOE[3]/
		psi	pcf	1000 psi	pcf	1000 psi	pcf	1000 psi
Hickory	0.98	43 A	42.0	434 A	29.1	73.6 A	26.6	49.3 A
	1.07	50 A	46.0	509 B	30.8	76.6 A	29.0	57.8 A
	1.18	115 B	50.7	590 C	36.7	147.7 B	33.9	124.5 B
Pine	1.21	23 A	37.5	568 A	27.5	83.8 A	26.2	77.6 A
	1.38	38 B	42.4	630 B	31.6	132.8 B	29.7	119.8 B
	1.47	53 C	45.2	731 C	32.2	121.6 B	31.1	129.0 B
Red oak	1.15	64 A	42.2	540 A	30.5	123.4 A	28.0	94.0 A
	1.26	101 B	46.1	668 B	32.8	161.6 B	30.6	140.2 B
	1.34	92 AB	49.3	727 B	34.8	171.3 B	31.2	125.5 B
Sweetgum	1.24	49 A	35.9	502 A	28.4	149.1 A	27.3	178.2 A
	1.48	68 B	42.9	677 B	31.4	167.9 A	30.2	207.2 A
	1.52	88 C	44.1	658 B	33.0	181.4 A	31.5	189.6 A
White oak	1.06	30 A	42.5	477 A	23.1	26.3 A	17.9	6.2 A
	1.12	38 A	45.0	521 AB	25.1	32.8 A	19.8	9.6 B
	1.18	59 B	47.3	548 B	26.5	42.5 B	20.9	11.5 C
Mixture	1.16	40 A	41.7	542 A	29.2	102.5 A	28.3	90.1 A
	1.28	64 B	46.0	615 AB	31.5	113.5 A	27.8	73.1 B
	1.33	80 B	47.6	678 B	34.5	153.5 B	30.7	118.6 C
Waferboard[4]/	--	82	42.0	486	30.4	129.6	31.3	132.5

1/Averages based on 2 specimens from each of 4 replicate panels. All MOE and density values are based on specimen dimensions at time of test.

2/Compaction ratio = $\frac{\text{specimen density at test (OD weight, test volume)}}{\text{wood density (OD weight, green volume)}}$

3/Averages within species per test conditions followed by common letter are not significantly different at 0.0005 level.

4/Average of 4 specimens

Table 4.--Panel density and moisture content in equilibrium with 50 and 90 percent relative humidity and linear expansion from equilibrium at 50 to equilibrium at 90 percent relative humidity[1]/

Species	Density[2]/		Moisture content		Linear expansion[3]/	Thickness swelling
	50% RH	50% RH	50% RH	90% RH	50-90% RH	50-90% RH
	pcf				Percent	
Hickory	40.3	31.3	8.15	23.49	0.021 AB	28.7 A
	43.4	34.5	7.92	22.58	0.002 A	25.7 A
	49.5	39.8	8.16	22.63	0.044 B	24.4 A
Pine	37.9	31.0	7.85	21.10	0.017 A	22.1 A
	43.4	34.9	7.85	21.45	0.005 A	24.0 A
	46.0	36.7	7.89	21.48	0.012 A	25.4 A
Red oak	42.9	35.8	7.56	20.31	0.015 A	19.5 A
	45.0	37.1	7.62	21.20	0.011 A	21.1 AB
	47.9	38.3	7.76	21.37	0.029 B	24.9 B
Sweetgum	35.3	30.3	7.75	21.55	0.002 A	16.4 A
	41.7	34.2	7.85	22.76	---	22.1 B
	44.0	35.9	7.61	22.41	---	22.5 B
White oak	40.3	30.1	7.87	20.91	0.171 A	33.0 A
	42.8	31.8	7.77	21.29	0.186 A	34.0 A
	47.1	34.8	8.25	21.67	0.194 A	34.9 A
Mixture	42.9	34.9	7.65	21.06	0.036 A	22.5 A
	44.4	36.2	8.03	21.01	0.044 A	22.4 A
	47.3	38.2	7.82	21.58	0.030 A	23.7 A
Waferboard[4]/	42.5	35.2	5.84	17.37	0.197	20.1

1/Average of 1 sample from each of 4 replicate panels
2/Ovendry weight, test volume
3/Averages within species followed by common letter are not significantly different at 0.0005 level
4/Average of 2 samples

Table 5.--Average of moisture content, thickness swelling, and linear expansion for specimens subjected to ovendry to vacuum-pressure soak exposure[1]/

Species	Moisture content		Thickness swelling		Linear expansion	
	Average[2]/	Standard deviation	Average[2]/	Standard deviation	Average[2]/	Standard deviation
	Percent					
Hickory	126.4 A	7.11	45.1 A	2.30	0.29 AB	0.027
	113.9 B	4.16	45.8 A	6.72	0.28 A	0.036
	87.6 C	3.67	39.0 B	3.20	0.31 B	0.030
Pine	144.8 A	5.92	42.3 A	3.90	0.19 A	0.018
	123.6 B	2.95	45.2 AB	4.76	0.17 A	0.032
	115.7 C	3.99	47.9 B	4.47	0.19 A	0.018
Red oak	122.8 A	4.88	38.0 A	2.47	0.18 A	0.019
	106.8 B	3.05	36.6 A	4.41	0.19 A	0.011
	102.1 C	7.41	38.6 A	5.23	0.22 B	0.006
Sweetgum	153.0 A	10.90	33.2 B	4.57	0.13 A	0.016
	123.5 B	13.70	38.6 A	4.54	0.14 A	0.016
	114.9 B	4.49	41.5 A	2.40	0.17 A	0.102
White oak	143.2 A	8.82	74.2 A	10.48	0.46 A	0.037
	134.7 AB	7.43	68.8 B	1.59	0.47 A	0.025
	126.9 B	6.09	68.0 B	5.65	0.47 A	0.009
Mixture	131.3 A	7.14	42.6 A	3.06	0.24 AB	0.019
	116.2 B	3.86	45.3 B	2.07	0.25 A	0.028
	105.5 C	4.95	40.7 A	2.35	0.22 B	0.021
Waferboard[3]/	112.0	4.65	37.2	1.84	0.39	0.007

1/Average based on 2 specimens from each of 4 replicate panels
2/Within species averages with common letter are not significantly different at the 0.0005 level
3/Average of 4 specimens

Table 6.--Average breaking load for each density class of all species for 1-inch by 5-inch control specimens tested in static bending on edge[1]/

Species	Density[2]/	Compaction ratio[3]/	Breaking load[4]/
	pcf		lbs
Hickory	40.3	0.93	203 A
	44.2	1.03	318 B
	50.4	1.17	511 C
Pine	36.9	1.20	214 A
	42.0	1.37	331 B
	45.8	1.49	398 C
Red oak	41.0	1.12	325 A
	45.5	1.24	443 B
	47.0	1.28	490 B
Sweetgum	35.4	1.22	299 A
	42.0	1.45	420 B
	44.8	1.54	499 C
White oak	40.9	1.04	196 A
	43.7	1.09	248 B
	47.2	1.18	323 C
Mixture	40.8	1.14	267 A
	45.1	1.26	402 B
	47.1	1.31	468 C
Waferboard[5]/	41.8	--	237

[1]/Averages based on 4 specimens from each of 4 replicate panels

[2]/Ovendry weight, test volume

[3]/Compaction ratio = $\frac{\text{panel density (OD wt, test volume)}}{\text{wood density (OD wt., green volume)}}$

[4]/Within species averages with common letters are not significantly different at the 0.0005 level

[5]/Average of 8 specimens

Table 7.--Average breaking load after D-5 cyclic exposure for each density class of all species for 1-inch by 5-inch specimens tested by edge static bending[1]/

Species	Density[2]/	Moisture content	Breaking load[3]/	Standard deviation
	pcf	%	lbs	
Hickory	25.4	3.13	62 A	26.5
	27.7	3.19	103 B	37.9
	32.1	2.96	199 C	45.0
Pine	26.5	1.88	61 A	18.8
	29.7	1.65	121 B	32.3
	31.7	1.68	153 C	22.8
Red oak	26.7	3.79	112 A	37.0
	29.7	3.65	168 B	48.9
	28.8	3.30	160 B	49.7
Sweetgum	27.6	2.56	190 A	51.2
	28.6	2.82	247 B	79.1
	29.7	2.83	279 B	75.4
White oak	18.9	3.04	18 A	8.1
	19.3	2.71	25 B	8.2
	19.6	2.39	28 B	10.1
Mixture	24.0	3.74	95 A	28.2
	26.9	4.04	117 B	18.6
	29.1	3.54	155 C	29.8
Waferboard[4]/	29.5	1.94	145	51.1

[1]/Average of 4 specimens from each of 4 replicate panels

[2]/Ovendry weight, test volume

[3]/Within species averages with common letter are not significantly different at the 0.0005 level

[4]/Average of 8 specimens

Table 8.--Average breaking load after equalization[1]/ following D-5 cyclic exposure for each density class of all species for 1-inch by 5 inch specimens tested by edge static bending[2]/

Species	Density[3]/	Moisture content	Breaking load		Standard deviation
	pcf	%	lbs		
Hickory	25.9	9.42	85	A	26.4
	27.6	9.44	120	B	45.3
	31.6	9.19	224	C	49.3
Pine	25.1	9.14	87	A	16.6
	28.5	9.04	143	B	25.3
	29.7	9.16	165	C	27.6
Red oak	26.2	8.44	128	A	46.1
	29.2	8.41	190	B	54.4
	28.6	8.43	193	B	57.7
Sweetgum	27.5	8.72	229	A	57.6
	28.0	8.75	263	A	69.2
	30.0	8.74	318	B	37.3
White oak	18.6	9.36	23	A	9.3
	19.5	9.70	32	B	12.0
	20.3	9.67	35	B	9.5
Mixture	25.9	9.04	113	A	31.4
	27.9	9.11	145	B	25.0
	30.3	8.92	201	C	28.2
Waferboard[5]/	28.1	7.72	138		28.2

[1]/Equalized to 70°F and 50% RH
[2]/Average of 4 specimens from each of 4 replicate panels
[3]/Ovendry weight, test volume
[4]/Within species averages with common letter are not significantly different at the 0.0005 level.
[5]/Average of 8 specimens

Table 9.--Average moisture content and thickness swelling after weatherometer exposure for all density classes of all species studied

Species	Moisture content[1]/		Thickness swell[1]/	
	Average	Standard deviation	Average	Standard deviation
	Percent			
Hickory	52.5	14.7	56.4	6.5
	50.2	10.6	60.0	5.3
	49.1	8.4	53.0	4.2
Pine	49.4	11.6	45.6	6.7
	46.5	12.6	45.6	7.0
	47.6	11.9	49.1	6.2
Red oak	55.0	12.4	51.1	7.5
	55.3	12.7	50.3	6.9
	56.7	9.6	57.6	7.2
Sweetgum	46.9	14.9	32.8	3.8
	49.9	12.6	48.7	8.1
	47.6	10.9	48.3	6.0
White oak	65.6	22.1	98.2	7.9
	68.3	20.4	98.9	4.5
	68.9	15.0	101.9	3.5
Mixture	50.6	14.0	55.6	9.0
	51.0	10.5	58.8	5.9
	50.8	11.4	54.5	5.1
Waferboard[2]/	9.0	0.5	4.0	2.0

[1]/Averages based on 2 specimens from each of 4 replicate panels
[2]/Average of 4 specimens

STRUCTURAL DURABILITY OF 3-LAYER ORIENTED FLAKEBOARD FROM SOUTHERN HARDWOODS[1]/

E. J. Biblis[2]/

Abstract.--This paper presents partial experimental results of an ongoing study that concerns properties of oriented flakeboard from southern hardwood species. Specifically, the paper contains experimental tests results of physical and certain important mechanical properties of 3 layered oriented flakeboard fabricated from a mixture of southern hardwoods (35% red oak, 15% white oak, 35% sweetgum, and 15% yellow poplar) blended with a commercial liquid phenol formaldehyde resin (6% solids). Boards were 1/2-inch thick (1/8-inch face and back, 1/4-inch core) with an average board density of 44.6 pounds per cubic foot. The preliminary experimental results indicate that appropriate mixtures of high and low density southern hardwoods can be used to fabricate commercially acceptable oriented boards 1/2-inch thick for sheathing in housing.

INTRODUCTION

Southern forests consist primarily of southern yellow pine and several hardwoods of commercial importance such as southern red and white oak, sweetgum, yellow poplar, tupelo, and hickories. Southern yellow pine is the main raw material for pulp and paper, for lumber, plywood, for poles and for particleboard and fiberboard.

Demand for hardwoods by the pulp, paper, and particleboard industries is small, amounting to only 15 to 25% of their needs. The greatest demand for hardwoods is for pallets and railroad ties, with a smaller demand for flooring, furniture, veneers, plywoods, and tools.

In recent years, the growth from the southern yellow pine forests has been increasing. However, the diameter of harvested pine trees has been decreasing with time (American Plywood Association 1981). At the same time, utilization of hardwood forests yields is decreasing (Koch 1982). Thus, new suitable uses, products and technologies for hardwoods may be feasible (Hunt et al. 1978).

Approximately 50% of the United States' softwood plywood for sheathing in housing is manufactured from southern yellow pine. When the current economic conditions improve and house construction reaches levels to satisfy needs, demand for plywood sheathing will surpass current production levels by 3 to 4 billion sq. ft. (3/8-inch basis) per year (American Plywood Association 1981). Part of this additional sheathing may be manufactured in the form of oriented flakeboard either entirely from individual southern species of low density hardwoods (sweetgum, yellow poplar), or from a mixture of the above species with a large percentage of southern oaks.

According to the U.S. Forest Service statistics (1977), the growing stock (9 inches above in diameter) of all hardwoods in the South (104.3 billion cubic ft.) represents 52% of the total southern forests (Forest Service-USDA 1978). Sweetgum and yellow poplar represent 12% and 7%, respectively, of all hardwood growing stock in the South.

From sweetgum and yellow poplar, thin, long and smooth flakes desirable for structural flakeboard can be produced (Geimer and Price 1978, Price and Lehmann 1978). Both species have excellent gluability and could be used to produce a flakeboard panel equal to or better than the existing commercial Canadian waferboards from Aspen.

Southern oaks (non-select) represent approximately 29% of all hardwood growing stock in the South (Forest Service-USDA 1978). Red and white oaks are dense and difficult species to machine into high quality flakes and difficult to glue for exterior use. Thus, mixing southern oaks with lower density hardwood species, such as sweetgum, and yellow poplar, might produce structural boards with acceptable properties and board densities.

This paper presents the current experimental results from an ongoing study concerning oriented flakeboard from southern hardwood species. Speci-

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fically, experimental data are presented on certain properties of 3-layer oriented boards fabricated from a mixture of red oak (35%), white oak (15%), sweetgum (35%), and yellow poplar (15%).

PANEL FABRICATION

Twenty panels, 4 ft. by 8 ft, 1/2-inch thick, with three layers cross-oriented, were fabricated in a pilot plant at Lewiston, Idaho. Following are the variables used for fabrication of these panels:

Raw material: Debarked logs, 8 ft. long, less than 9-inch diameter

Flaker: (PRZ-28 Hombak) drum-type machine

Particle size: 0.025-inch thick, 70 mm long, variable length

Removal of fines: Passing screen 1/16-inch

Particle of moisture (MC): 4-5% dry; 9% out of blender

Resin: Liquid phenol-formaldehyde, 6% solids (Reichhold No. 22-743)

Wax: Emulsion, 1% solids

Mat formation: 1/8-inch each face and back layers, oriented parallel to panel length

1/4-inch thick core oriented perpendicular to faces

Hot pressed: At 420°F for 6 mintues

Desired density: 42 to 48 pcf

Board size: 53 inches by 102 inches trimmed to 48 inches by 96 inches

PANEL TESTING

Six panels were selected for this testing from the 20 fabricated panels. Panels were selected to represent the density variation among all fabricated panels, and were used to obtain specimens for evaluation of the following properties at three moisture (MC) conditions.

1) Flexure parallel to face particle orientation. Four specimens with orientation of face particles parallel to span from each of the six panels were tested to destruction under each MC condition. A total of 72 specimens (4 replications for each of 6 panels under 3 moisture conditions) were tested. The three test conditions were the following: original (65 RH, 72°F), soaked (48 hours), and cycled (soaked and reconditioned at 65% RH and 72°F). Specimen dimensions were 6 inches by 26 inches (24-inch span). Matching of specimens in three conditions was obtained by consecutively assigning each cut specimen to one of the three MC test conditions in sequence and repeating. Specimens were tested to failure with central loading at speeds according to ASTM D1037 (American Society for Testing and Materials 1981).

2) Plate shear modulus. Two specimens 16 inches by 16 inches, from each panel (12 specimens) were tested under each moisture MC condition. Testing was performed according to ASTM D3044 (American Society for Testing and Materials 1981).

3) Edgewise shear strength (rail shear). Four specimens 3.5 inches by 10 inches from each panel were tested under each MC condition. A total of 72 specimens (4 replications for each of 6 panels under 3 moisture conditions) were tested according to ASTM D1037 (American Society for Testing and Materials 1981).

4) Internal bond (IB). Twenty-four specimens from each panel (144 specimens altogether) were tested. One half of the specimens were tested at the original condition, the other half tested after 48-hour soaking and reconditioned to original condition, according to ASTM D1037 (Society for Testing and Materials 1981).

5) Dimensional changes with changes in MC. Twelve specimens, 16 inches by 16 inches (two specimens from each panel) were measured for dimensional change and water absorption. Changes in length (parallel to face particle orientation and in width (perpendicular to face particle orientation) were measured from the original moisture condition (65% RH, 72°F) to the 48-hour soaked condition. Changes in thickness and the percent of water absorption were measured from the original condition to the soaked condition and again when the specimens reached equilibrium back at the original condition.

RESULTS AND DISCUSSION

Strength properties of 3-layered oriented flakeboard from one mixture of southern hardwoods are presented in table 1. Presented for comparison, in the same table, are published properties of other wood panels tested at the same moisture conditions (Biblis and Lee 1982, Biblis and Mangalousis 1982).

In flexure parallel to particle orientation, the modulus of elasticity (MOE) after cycling is 53% and 59% of MOE values of composite plywood and 3-ply CDX southern pine plywood, respectively. It is more than 2 times stiffer than Aspen waferboard. After cycling, the MOE of the 3-layer OSB was reduced by 28%, the composite plywood reduced by 16.5%, the southern plywood by 7.7% and the Canadian flakeboard reduced by 26.8%. The MOR value of the oriented board after cycling was 60% and 8)% of the MOR values of composite plywood and of CDX southern pine plywood, respectively. It is more than 2 times stronger than the Aspen waferboard.

Table 1.--Strength properties of 3-layered OSB and other wood panels

Panel type	Moisture condition	Density	Flexural parallel[1]/ MOE	MOR	Plate shear modulus	Rail shear strength	I.B.
		pcf	psi				
1/2", 3-layer OSB, 50% southern oaks, 35% sweetgum 15% yellow poplar	Original[2]/	44.9	1,091,650	6,057	172,066	1,525	101
	Cycled		785,570	4,430	121,758	1,046	54
	Reduction (%)		28.0	24.3	29.2	31.4	32.8
1/2" composite plywood southern pine veneer faces 1/4" oriented board core	Original	44.6	1,781,785	9,230	232,850	1,200	111
	Cycled		1,488,450	7,360	161,555	813	67
	Reduction (%)		16.5	20.0	30.6	32.2	39.6
1/2", 3-ply plywood southern pine	Original	37.0	1,450,000	7,170	81,600	970	----
	Cycled		1,339,000	5,504	65,300	780	----
	Reduction (%)		77	23.2	19.9	19.6	----
1/2" Aspen waferboard	Original	41.6	477,553	2,558	226,120	1,155	39
	Cycled		349,495	2,033	177,030	895	----
	Reduction (%)		26.8	20.5	21.7	22.5	

1/Specimens were 6" wide, tested over 24" span with face orientation along the span.
2/Original = conditioned to 65% RH; Cycled = 48-hour soak and reconditioned to original.

Table 2.--Dimensional changes of 3-layered OSB and other wood panels.

Type of panel	Density	Swelling from 65 RH to 48-hour soaked		Thickness swelling from 65 RH		Water absorption from 65 RH	
		Length	Width	Soaked	Cycled[1] /	Soaked	Cycled
	pcf	Percent					
1/2", 3-layer OSB	44.9	0.09[2] /	0.09	16.09	7.55	55.05	2.92
50% southern oak		0.03	0.03	2.72	2.34	16.57	0.29
35% sweetgum							
15% yellow poplar							
1/2" composite plywood	44.6	0.15	0.30	12.66	5.82	35.19	3.87
southern pine veneer faces		0.04	0.03	0.74	0.50	3.32	0.05
1/4", oriented board core							
1/2", 3-ply plywood	37.0	0.13	0.27	9.20	5.01	45.90	2.9
southern pine		0.11	0.08	2.44	2.44	2.3	0.1
1/2", Aspen waferboard	41.6	0.03	0.02	13.86	4.38	25.40	1.48
		0.03	0.02	1.39		2.38	

1/ Specimens were first soaked for 48 hours, then reconditioned to 65% RH, 72°F, and measured.
2/ Each upper value represents the average of six specimens; lower values represent one standard deviation.

The plate shear modulus of the oriented board after cycling, was 75% and 69% of shear values for composite plywood and Canadian waferboard, respectively. The value of oriented board was 85% larger than that of southern pine plywood. The rail shear strength of the oriented board after cycling was 29%, 34%, and 17% higher than values of composite plywood, CDX southern pine plywood and Canadian waferboard, respectively. The internal bond strength of the oriented board after cycling was slightly higher than the value of the composite plywood and higher than the Aspen waferboard.

Results in table 1 indicate that properties of 3-layer oriented board from a mixture of southern hardwoods are lower than commercial CDX southern pine plywood and experimental composite plywood; however, they are considerably higher than properties of the Canadian waferboard. It should be pointed out that while the 3-layer oriented board is approximately 8% higher in density than the Canadian waferboard, the flexural properties of the oriented board are more than double those of the Aspen waferboard.

Dimensional changes of the oriented board and of other wood panels are presented in table 2. Linear swelling of the oriented board along the panel's length and width (parallel and perpendicular to face particle orientation, respectively) is equal to that of the Aspen waferboard and considerably lower than that of composite plywood and commerical southern pine plywood. Water absorption from 65% RH to 48-hour soaking is higher for the oriented board than for any of the other boards.

SUMMARY

This paper presents partial experimental results of an ongoing large study that concerns properties of oriented flakeboard from southern hardwood species. Specifically, the paper contains experimental tests results of physical and certain important mechanical properties of 3 layered oriented flakeboard fabricated from a mixture of southern hardwoods (35% red oak, 15% white oak, 35% sweetgum, and 15% yellow poplar) blended with a commercial phenol formaldehyde resin (6% solids). Boards were 1/2-inch thick (1/8-inch face and back, 1/4-inch core) with an average board density of 44.6 pounds per cubic foot.

Experimental results indicate that properties of the oriented boards are lower than commerical CDX southern pine plywood and of experimental composite southern pine plywood, however, they are considerably higher than properties of commercial Aspen waferboard. It should be pointed out that although the 3-layer oriented board is approximately 8% denser than the Aspen waferboard, the flexural properties in the direction of face particle orientation of the oriented board are more than twice that of the randomly oriented Aspenite waferboard. Linear dimensional changes of the oriented board with changes of moisture from 65% RH to 48-hour soaked condition are equal to those of the Canadian waferboard and much better than those of the southern pine plywood and composite plywood. Thickness swelling of the oriented board is approximately 2% higher than that of the Aspen waferboard.

In summary, the preliminary experimental results indicate that appropriate mixtures of high and low density southern hardwoods can be used to fabricate commercially acceptable oriented boards 1/2-inch thick for sheathing in housing. Such boards, although 5-10% denser than Aspen waferboards, would also be substantially stronger and stiffer.

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COMPACTION RATIO AND RESIN COVERAGE EFFECTS ON PROPERTIES OF THICK, PHENOLIC-BONDED FLAKEBOARD[1/]

James T. Rice[2/]

Abstract.--Flakeboards 1.5-inch thick were made with various wood densities (species), board densities, flake thicknesses, and weight percent resin contents. Property data were analyzed for dependence on compaction ratio (C/R) and resin coverage (R/C). Linear regression analyses showed that some 72% of the variation in MOR, MOE, and IB data was explainable through dependence upon C/R and R/C, thus suggesting that these parameters may be useful in preliminary analysis of untested board compositions. For a 24-hour watersoak thickness swelling, a dependence on R/C was significant but accounted for only 35% of the variation in the swelling data. However, C/R did not significantly affect the swelling.

INTRODUCTION

The concept of COM-PLY panel and lumber products has been fully described by Koenigshof and others (1977-1982) in the U.S. Forest Service's COM-PLY report series. COM-PLY basically utilizes a particleboard (most often a flakeboard) center or core with adhesively bonded solid wood (usually veneer) faces or edge-bands to add strength and stiffness. The thrust of the COM-PLY idea is to utilize small, and perhaps low grade, trees to generate the construction lumber and panels which currently have to be produced from larger, higher quality and increasingly scarcer timber. The practical and economic feasibility of the COM-PLY concept will thus hinge on being able to use a wide range of wood species, and the economic success will certainly depend on keeping binder content and costs as low as possible.

The present study was undertaken to evaluate the usefulness of the compaction ratio (C/R) and resin coverage rate (R/C) parameters as predictors of particleboard properties (and related COM-PLY performance) when using a range of species. From the earliest days of particleboard research the topic of species effects and related interactions with other material and process variables has been of interest. Early work tended more toward empirical studies of common species and related variables (Klauditz 1952, Rice 1960). However, recent studies have been more analytical as to which characteristics have contributed most to the differences between species, and considerable attention has been given to the interaction between wood density and board density, variously called compression ratio or compaction ratio (Geimer and Price 1978, Hse 1975, Rice and Carey 1978, Vital, Lehmann, and Boone 1974). These latter studies have all indicated a definite effect of the compaction ratio, especially on the strength properties of particleboard. It is generally assumed that the compaction ratio is indicative of the degree of consolidation and inter-particle contact established within a board as it is pressed. It could also be thought of as a measure of the bonding pressure available to form the inter-particle adhesive joints needed to hold the board together.

One of the most widely recognized and researched factors in particleboard composition has been the adhesive binder amount and its distribution. Numerous studies have examined variation of the weight percentage of resin binder solids included in particleboard (Klauditz 1952, 1954, Rice and Carey 1978, Turner 1954). It has further been recognized that the normal wood gluing concept of adhesive spread rate (lbs/MSGL, g/m^2 might be a better parameter to measure and report than weight percentage, if it could be accurately determined (Meinecke and Klauditz 1962). The problem of determining resin coverage rate with precision is evident when one considers the difficulty of accurately determining the total surface area for a given quantity of particles. The problem is somewhat solvable in the case of flake-like particles with a known average thickness. Fairly simple formulas have been put forth to compute the surface area of flakes and the resultant resin coverage rates when given weight percentages of resin are added (Meinecke and Klauditz 1962).

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In the present study, this computational approach to the determination of flake surface area was taken and a modified formula is given later. It will be seen that the key factors affecting resin coverage rate are (a) weight percent resin added, (b) wood density, and (c) particle geometry (especially flake thickness).

It can thus be seen that the key species characteristic of wood density affects both compaction ratio and resin coverage rate. Species effects on board properties might then be best expressed through consideration of these two factors.

EXPERIMENTAL DESIGN

As indicated, the objective of this study was to determine the effectiveness of compaction ratio and resin coverage rate as predictors of particleboard properties, especially in coreboard for COM-PLY lumber, i.e, in 1½-inch thick flakeboards. The ultimate purpose was to devise an approach for assessing new species and species blends without exhaustive laboratory tests each time.

It was recognized (a) that the key factors affecting compaction ratio are wood density and board density, and (b) that the key factors affecting resin coverage rate are weight percent resin addition, wood density, and flake thickness. Four southeastern hardwood species, covering a fairly broad range of recorded wood densities (FPL 1974) were chosen for study. They are listed in table 1, along with their target (book value) specific gravities, their actual average green volume basis specific gravities and their estimated specific gravities based on volume at 5% moisture content. Loblolly pine was also included in the study as a control reference species, and is also cataloged in table 1.

In addition to the species variable, three levels of board density were chosen, namely 32, 38, and 44 pounds per cubic foot (based on wood and resin dry weight per unit volume of board conditioned to EMC at 70°F and 65% RH). Furthermore, two weight percent levels of phenol-formaldehyde resin solids addition, namely 4% and 7% and two levels of target average dry flake thickness, namely .015" and .030", were chosen. Thus a range of compaction ratios was generated, based on the different wood and board densities chosen. To further enhance this aspect of the study, two species blends were also included, namely (a) yellow-poplar and white oak blended to the specific gravity average of sweetgum, and (b) sweetgum and mockernut hickory blended to the specific gravity average of white oak. Table 2 summarizes the vital information on the experimental combinations studied showing the calculated compaction ratios and resin coverage rates and measured average flake thicknesses obtained. Since experimental variation in the actual vs. target board densities and flake thicknesses were encountered, the actual values were measured and reported and used in computing the compaction ratios and resin coverage rates recorded. The formulas used in computing compaction ratios and resin coverage rates are given as footnotes to table 2. The literature has not been specific as to what exact measure of wood and board density should go into the computation of compaction ratio. However, it is clear that the intent is to estimate the degree of compaction or densification of the wood in the pressing of a board. Thus, in this study an attempt was made to approximate that wood densification and the formula shown as footnote 2 to table 2 was used. In reviewing table 2, it is seen that compaction ratios, in this study, ranged from as low as around 0.6 up to a high of around 1.4. Based on other wood and board density measurements (e.g., green volume wood density and as-is total weight per unit volume of board) the equivalent values would have ranged from approximately 0.8 up to 1.75.

The formula used for computing resin coverage rate is given as footnote 3 to table 2 and the computed values are recorded in the body of table 2. As will be noted, the actual average flake thicknesses varied from the two target levels chosen. This reflected the differing responses the species had to cutting on the laboratory flaker. These differences were not noted until the study had been essentially completed. The resin coverage rates reported ranged from a low of around 3.5 grams of PF solids/m^2 of flake surface up to around 14.5 g/m^2. As a matter of comparison with more traditional glue spreads, a 40 lbs/MSGL spread (20 lbs/M of divided spread) of a 28% PF solids glue mix in pine plywood would correspond to 27.34 grams of PF solids per square meter of surface.

EXPERIMENTAL PROCEDURE

Raw Material

The wood utilized in this study all came from trees from a single, mature, mixed pine-hardwood stand located near the campus of the University of Georgia (Oconee-Denmark forest). An initial survey of that stand showed that all five species to be studied (i.e., yellow-poplar, sweetgum, white oak, mockernut hickory and loblolly pine) were present in good amount. Increment cores were sampled at breast height from several trees of each species. The specific gravities (Sg's) of these cores were determined by the maximum moisture content method and whole tree averages estimated. Trees of estimated proper whole tree average Sg values were taken in sufficient number (generally 2-3 trees of each species) to yield an adequate amount of wood for flaking.

When felled, disks were cut from the base, mid-section and top of the tree, and Sg values for the wood in those disks used to determine the tree-average Sg values reported in table 1.

Logs from the selected trees were sawn into nominal 2" x 4" and 2" x 6" lumber on a small

sawmill. Care was taken to cut as much flat grained lumber as possible. The pieces were then cross-cut to yield blocks 3-3/4" along the grain and were then reduced to approximately 1-1/4" long flake ribbons on a disk flaker described in earlier publications (Rice and Carey 1978). Although the flaker was initially set with care, to cut the prescribed target flake thicknesses of .015" and .030", later measurements on samples of the dried and milled flakes showed that the .030" flakes, in fact, averaged between .017" and .023" for the various species. This was not discovered until well after all boards had been made and tested, and thus became a factor confounded with species in these data. However, since the actual average dry flake thicknesses were known at the time of data analysis, those values were used in calculating R/C rates. Therefore, the R/C values used in the multiple regression analysis should be reasonably accurate.

The green flakes were immediately kiln dried to a moisture content of 3-4% (subsequently averaging around 5%) and then hammermilled to reduce the width to less than 1/4". A range of particle sizes was generated during the milling and fines (material passing through a 16 mesh window screen) were subsequently removed by screening. Samples of the dried and milled particles for each species and thickness category were screen analyzed, and the data are reported in table 3. Both weight percentage and average flake dimensions are included for each particle type and screen size classification. The screening was done on two, approximately 100 gram samples for each species x thickness class of flakes. A Ro-tap shaker was used, with the screens as noted in table 3, and running time of 20 minutes.

The screen fractions were weighed, and the weight percentages caught on each screen size (and pan) have been reported. In addition a random sample of 50 flakes from each fraction (or fewer, where 50 were not available) were measured for length, width, and thickness, and average values for these measurements are also reported.

Since the COM-PLY concept generally calls for as durable an adhesive bond as possible, a phenol-formaldehyde resin, designed for use in particleboard manufacture was chosen. A 55 gallon drum of the Borden Chemical Company's Cascophen PB-65 was obtained and used as the resin binder. This resin is a 45% solids, 300 cps (Brookfield at 25°C) viscosity product, tailored for use in particleboard. Periodic checks on viscosity and gel time showed the resin to be on specification throughout the life of this study.

Material Calculations

In this study, board density is defined as oven dry flake and resin solids weight per unit of target board volume. Since the nominal board size was to be 1-1/2" thick x the full press platen size (26" x 26"), the amount of flakes and liquid resin were calculated to give the target board densities (32, 38, and 44 pcf) for a 1-1/2" x 26" x 26" panel. Table 2 includes average densities for each experimental combination (based on measurements made on the MOR/MOE strips), and it can be seen that measured values were generally a bit on the light side. This was probably due to a small material loss resulting from "squeeze-out" at the edges of the panel when pressed.

Once the flake amounts had been determined, the resin solids weight percentages prescribed in the study plan (4% and 7%) were used to calculate the weight (and, based on resin specific gravity, the volume) of resin needed for each board. As will be described later, this prescribed amount of resin was sprayed, as uniformly as was possible, onto the flakes.

Panel Fabrication

The study plan required 168 panels. Since the laboratory procedures placed no particular constraints on production sequence, the panels were made in a random order (based on blind drawing of numbers). The rate of panel production was such that a total time span of six weeks was involved.

The fabrication sequence consisted of using a round, cascade-type blender, 4 feet in diameter and 2 feet deep, as a blending chamber. The resin spray was accomplished using a semi-externally-atomizing nozzle, spraying from the center toward the blender periphery and into the recirculating cascade of flakes. The air pressure on the nozzle were adjusted to give a fine resin atomization and a moderate rate of spray.

Due to the large quantity of particles needed to make these relatively large test panels, it was necessary to make two blender runs (using half of the flakes each time) and then combine all resin coated flakes just before mat formation. The half-batch flake amounts varied from a low of around 9 pounds to a high of around 13 pounds, depending on board density and resin content. Corresponding spray times ranged from a low of around 5 minutes to a high of around 11 minutes.

Flake samples were taken both before and after blending and moisture contents checked. Moisture content of the flakes going into the blender average around 5% (as previously noted) and coming out of the blender they ranged from a low of 8% to a high of 13%, depending primarily on the resin content and concurrent moisture addition. Since no further adjustment was made in flake moisture content after unloading the blender, any effects of mat moisture content, within the range of 8-13% are confounded, primarily with resin coverage.

The mats were hand formed in a 26" x 26" removable frame which rested on a 1/4" thick aluminum caul sheet. Care was taken to form the mats as uniformly as possible, and, an analysis of the within-board density variation (as measured on the two bending-test strips for each

board) showed no significant within-panel density variation effect. Once each mat was formed, it was lightly pre-pressed around its edges (manually, using a wooden tamper) so as to minimize any mat spalting when the forming frame was removed.

Once each mat was formed and the forming box frame removed, a matching top caul sheet was added and the mat loaded into the single-opening, up-acting, steamheated, hydraulic press. The press (platen) temperature was set at 375-380°F and the closing load variously set to produce 444 psi for the 32 pcf board density, 592 psi for the 38 pcf board density, and 740 psi for the 44 pcf board density. Final panel thickness (1.5" target) was monitored by observation of a dial gage mounted on the press and controlled by manual reduction of the pressure during the press cycle. Closure times were still quite variable, ranging from lows of 20 seconds to highs of around 180 seconds (out of a total press time of 18 mins.), depending primarily on compaction ratio and mat moisture content. Again, whatever effect closure rate has on board properties (and associated density gradient) is confounded in the data. However, this type of confounding is largely unavoidable without complete "a priori" information on each individual board's pressure vs. closure-time relationship and without almost unlimited press pressure capacity. The initial plan had been to use a constant maximum closing pressure of around 500 psi, but preliminary tests revealed the need for higher pressures on the higher densities. At 500 psi, 44 pcf boards of low wood density (high C/R) were taking up to 6 minutes or more to close to 1.5", and this would have undoubtedly led to precure problems. Thus what seemed to be the best compromise was selected.

Although these panels were not large enough for a true hot stacking effect, they were, upon removal from the hot press, dead stacked with the accumulated production. Left in contact with one another this way, they may have experienced some slight hot stack cure.

Once all the panels were made (168 total), they were trimmed to 22" x 22" (trimming approximately 2" from each edge) and then divided into approximately equal halves. Approximately half of each board was labeled and transferred to the U.S. Forest Service cooperators to be cut into 2.83" wide strips for use in actual fabrication and testing in COM-PLY lumber construction. The remaining half was ripped into two 2" wide and two 3" wide strips which were then conditioned at 70°F and 65% RH, eventually coming to an average EMC of 9.8%.

Test Procedure

After conditioning, the two 3" wide strips from each board were used as bending test specimens and, insofar as possible, were tested according to ASTM D1037 (American Society for Testing Materials 1978). The laboratory press size and the needs for edge trimming of panels placed constraints on maximum trimmed panel size and thus on bending specimen length. D1037 calls for a specimen length of (24 x thickness) + 2" and a support span (centerpoint loading) of 24 x thickness. For 1-1/2" thick boards, this would mean 38" long specimens and a support span of 36". With the specimens limited to 22" in length and a support span of only 20" the test was somewhat non-standard. The problem with short spans is that failure in horizontal shear (as opposed to the normal surface compression or tension failure) is much more likely to occur and did occur in some of the specimens in this study.

Prior to testing, all bending specimens were weighed and measured (length, width, and thickness). These data were used to generate the density and thickness variation data reported. A dozen specimens, selected to be representative of most board types made, were used to determine moisture content in the conditioned bending specimens. Their oven dry weights had been calculated earlier from moisture contents measured on an adjoining coupon. These conditioned bending specimens showed a range of 9.5-10.0% with an average of 9.8% MC.

The two, 2" wide strips were cut into 10 each, 2" x 2" specimens. Five of the 2" x 2" specimens from each strip (essentially every other specimen) were allocated to internal bond testing and another three allocated to thickness swelling in 24-hour watersoak. The remaining two specimens from each strip were held in reserve. The internal bond and 24-hour watersoak tests were done according to ASTM D1037 (American Society for Testing and Materials 1978) procedures.

RESULTS AND DISCUSSION

The effect of the experimental variables on the physical and mechanical properties were analyzed by analyses of variance (AOV). A factor was designated significant at the 5% level. For condensation purposes, analysis of variance tables that contain the sum of squares, F value, and the calculated probability are not reported in this manuscript. (Tables and other figures, however, may be obtained directly from the author.)

BENDING TEST

The standard centerpoint loading formulas and loading data, along with measured widths and thicknesses for individual specimens, were used to calculate moduli of rupture (MOR) and elasticity (MOE). Based on the AOV, all of the major factors (species, board density, resin content, and flake thickness) significantly affect MOR and MOE. While no three-way or four-way interactions were significant, several two-way interactions are significant. In fact, for MOR, the only two-way interaction that is not significant is species x density. While for MOE, the species x density, species x thickness, and density x thickness interactions are not significant.

Species averages for MOR ranged from a low of 3,330 psi for pine to a high of 4,238 psi for sweetgum (table 4). Sweetgum also had the highest MOE at 515,000 psi but white oak had the lowest MOE, 404,000 psi. The AOV for MOR indicated that the only statistically significant species interactions are species x resin content (fig. 1) and species x chip thickness (fig. 2). However, only the species x resin content (fig. 6) interaction is significant for MOE. Regarding the significance for MOR of the species x chip (flake) thickness interaction (fig. 2), it should be remembered that there are some noticeable deviations from target flake thicknesses (tables 2 and 3). Since some of the species accidentally had flake thickness discrepancies, the species x flake thickness may be biased.

Since the board density is a highly significant factor and the effect of density is about the same for all species, the species x board density interaction is nonsignificant for both MOR and MOE. An increase in board density, as expected, yielded an increase in both MOR and MOE (table 4).

There are some interactions involving board density that are significant. For instance, the interaction of board density with resin content is significant for both MOR and MOE (figs. 3 and 7). As illustrated in the figures, an increase in resin content had a greater effect on the MOR or MOE of the 38 pcf boards than for either the 32 or 44 pcf boards. Another interaction, board density with flake thickness, is only significant for MOR. Figure 4 shows a slightly greater increase in MOR with board density for the thinner (.015" target thickness) flakes than for the thicker ones (.030" target thickness).

Resin content and flake thickness, both significant factors for MOR and MOE, had a directly proportional effect on these mechanical properties.. That is an increase in resin content or an increase in flake thickness resulted in increased MOR and MOE properties (table 4). The interaction of resin content with flake thickness is also significant for both MOR and MOE. Surprisingly, the increase in MOR or MOE with increasing flake thickness is more pronounced at the 7% resin content level than at 4% (figs. 5 and 8).

Linear model regression analysis results, for both MOR and MOE, on compaction ratio (C/R) and resin coverage rate (R/C) were calculated and plotted (tables 5 and 6 and figs. 12 and 13, respectively). Both MOR and MOE showed a statistically significant regression on C/R and R/C with some 73% of the overall variation in either MOR or MOE explainable by dependency on C/R and R/C. This, along with the analysis of variance results, indicates that, for both MOR and MOE examination of the related C/R and R/C values for various species, species blends, flake thicknesses and resin addition levels, should be a good place to begin in predicting the properties of untested combinations.

INTERNAL BOND

The analysis of variance for internal bond data indicates that, as with MOR and MOE, all main effects (species, board density, resin content, and flake thickness) and several interactions have a statistically signfiicant effect on internal bond (IB). Internal bond increases with increasing board density, resin content, and flake thickness (table 4). However, the statistical significance of 56 psi for the thinner flakes vs. 68 psi for the thicker flakes may be of doubtful practical significance. The species effect on IB, with a low of 39 psi for white oak and a high of 84 psi for yellow-poplar, is of practical importance.

The significant interactions are species x board density (fig. 9), species x resin content (fig. 10), board density x resin content (fig. 11) and species x resin content x chip. The pattern of these interactions is much the same as with MOR and MOE.

Table 7 and figure 14 summarize the linear model regression analysis results for IB on C/R and R/C. Again the impact of C/R and R/C on IB are clearly significant, and some 72% of the overall variation in IB is explainable by dependence on C/R and R/C. For IB as with MOR and MOE, indications are that C/R and R/C assessment is a good place to begin in evaluating the effect of new species or species blends, resin contents, particle geometries, etc. on internal bond.

THICKNESS SWELLING

Based on the analysis of variance results, thickness swelling of the panels, as measured by 24-hour water soaking is, statistically speaking, significantly affected by the main factors (species, board density, resin content, and flake thickness) and several interactions. However, the practical significance is rather doubtful. For example, the species averages range from a low of 17.5% for pine to a high of only 22.9% for sweetgum. Likewise, the interactions of species with board density, resin content, flake thickness, etc. often yielded only a 2 or 3% swelling range among values which average around 20%. The most noteworthy main effect is for resin content. Boards with 4% resin content averaged 27.7% swelling and those with 7% resin averaged only 12.7% swelling.

Table 8 summarizes the linear regression analysis for 24-hour thickness swelling on C/R and R/C. In contrast to MOR, MOE, and IB, the effect of C/R on swelling was not significant, and only some 36% of the variation in the thickness swelling data was explainable by differences in C/R and R/C. The effect of R/C was clearly significant and accounts for the vast majority of the 36%. This finding indicates that some factor(s) other than C/R and R/C are involved in controlling the amount of thickness swelling produced by the boards.

The basic nature of the thickness swelling of particleboard seems to follow the mechanism which has been put forth to explain thickness swelling and shrinking in paper (Stamm and Cohen 1956). This involves components from (a) the normal reversible swelling of wood due to cell walls expanding and contracting as adsorbed water is taken into or given off from them, (b) the irreversible recovery of any crushing of fibers (crushed fibers tend to balloon back when wetted), and (c) a reversible relaxation with fibers which have taken on a "set" or "bend" and which then "lever" or "pry" open the board structure when wetted and then close back when redried. In particleboard (including flakeboard, especially) the component (a) for normal wood swelling should increase with wood density in most cases. The component (b) for irreversible crushing recovery should be primarily controlled by C/R and logically increase with it, unless conditions for a permanent "set" occur. The component (c) for reversible relaxation could be influenced by several factors, including C/R and particle geometry, especially length to thickness ratio. Further study of thickness swelling as affected by C/R and R/C and possibly by wood permeability, should be undertaken and measurements made to relate these results, as much as possible, to normal wood swelling, irreversible recovery and reversible relaxation.

CONCLUSIONS

For these data, compaction ratio (C/R) and resin coverage rate (R/C) can be seen as significant basic factors affecting the mechanical properties of thick flakeboards. The linear model regression equations obtained for modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) approximations are:

$$MOR \text{ (in psi)} = (3258)(C/R)+(363)(R/C)-2083$$

$$MOE \text{ (in psi)} = (339246)(C/R)+(37025)(R/C)-126721$$

$$IB \text{ (in psi)} = (154.0)(C/R)+(9.2)(R/C)-152.5$$

The analyses of variance for the various main effects and interactions for these three mechanical properties can generally be seen to verify the regression analysis findings when one takes into account (a) the effects of wood density (of the species and blends) and board density on compaction ratio, and (b) the effects of wood density, resin content, and flake thickness on resin coverage rate.

With regard to the property of 24-hour watersoak thickness swelling percent, further study or analysis is needed. The analysis for linear regression on C/R and R/C indicated that (a) the dependence on C/R is not statistically significant, and (b) that the overall coefficient of determination was only 0.36.

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Table 1.--Summary of wood densities (specific gravities).

Species	Target[1/]	Measured Sg[1/]	Estimated Sg[2/]
Yellow-poplar	0.40	0.41	0.45
Sweetgum	0.46	0.50	0.56
White oak	0.57	0.59	0.68
Mockernut hickory	0.64	0.69	0.82
Loblolly pine	0.48	0.49	0.54

1/Specific gravity on oven-dry weight and green volume basis.
2/Specific gravity on oven-dry weight and volume at 5% moisture content basis; estimated from specific gravity.

Table 2.--Tabulation of experimental combinations and resulting compaction ratios and resin coverage rates in study.

		Target board densities											
		32 pcf				38 pcf				44 pcf			
		Resin contents											
		4%		7%		4%		7%		4%		7%	
		Target particle thickness[1/]											
Species	Property	.015"	.030"	.015"	.030"	.015"	.030"	.015"	.030"	.015"	.030"	.015"	.030"
Yellow-poplar (YP) Sg = 0.41	C/R[2/]	1.04	1.08	1.02	1.06	1.20	1.25	1.22	1.24	1.42	1.43	1.41	1.43
	R/C (g/m^2)[3/]	3.54	5.29	6.04	9.26	3.45	5.29	6.04	9.26	3.45	5.29	6.04	9.26
	Den. (pcf)[4/]	30.5	31.8	30.7	32.1	35.4	36.8	36.8	37.3	41.7	42.0	42.5	43.8
Sweetgum (SG) Sg = 0.50	C/R	0.89	0.86	0.86	0.85	1.03	1.02	1.03	1.01	1.17	1.19	1.19	1.17
	R/C (g/m^2)	3.69	5.95	6.45	10.42	3.69	5.95	6.45	10.42	3.69	5.95	6.45	10.42
	Den. (pcf)	32.2	31.3	31.9	31.8	37.2	36.9	38.4	37.6	42.3	43.0	44.2	43.7
Blend YP and WO Sg = 0.50	C/R	0.84	0.86	0.85	0.84	1.00	1.02	0.99	1.01	1.16	1.15	1.14	1.14
	R/C (g/m^2)	3.88	6.18	6.79	10.82	3.88	6.18	6.79	10.82	3.88	6.18	6.79	10.82
	Den (pcf)	30.9	31.4	31.7	31.5	36.4	37.0	37.1	37.7	42.2	41.7	42.6	42.7
White oak (WO) Sg = 0.59	C/R	0.70	0.72	0.70	0.69	0.83	0.83	0.83	0.84	0.96	0.95	0.97	0.95
	R/C (g/m^2)	4.51	7.63	7.89	13.36	4.51	7.63	7.89	13.36	4.51	7.63	7.89	13.36
	Den. (pcf)	31.2	31.7	32.0	31.5	36.7	36.8	38.0	38.1	42.5	42.3	44.2	43.3
Blend SG and MH Sg = 0.59	C/R	0.73	0.70	0.71	0.70	0.85	0.84	0.84	0.82	0.98	0.99	0.98	0.96
	R/C (g/m^2)	4.50	6.92	7.88	12.11	4.50	6.92	7.88	12.11	4.50	6.92	7.88	12.11
	Den. (pcf)	32.5	31.0	32.3	31.9	37.7	37.2	38.4	37.7	43.4	43.9	44.7	44.2
Mockernut hickory (MH) Sg = 0.69	C/R	0.60	0.60	0.60	0.60	0.71	0.72	0.71	0.71	0.83	0.81	0.82	0.82
	R/C (g/m^2)	5.80	8.28	10.14	14.49	5.80	8.28	10.14	14.49	5.80	8.28	10.14	14.49
	Den. (pcf)	31.9	31.7	32.5	32.6	37.6	38.3	38.5	38.8	43.8	42.9	44.5	44.7
Loblolly pine (SP) Sg = 0.49	C/R	0.90	0.89	0.88	0.88	1.05	1.03	1.04	1.03	1.20	1.20	1.21	1.21
	R/C (g/m^2)	3.87	4.70	6.77	8.22	3.87	4.70	6.77	8.22	3.87	4.70	6.77	8.22
	Den. (pcf)	31.7	31.4	31.9	32.0	37.2	36.4	37.7	37.5	42.5	42.4	43.8	43.8

1/The actual particle thicknesses were less than the target values. The actual values were YP (0.015 and 0.023), SG (0.013 and 0.021), WO (0.013 and 0.022), MH (0.014 and 0.020), and SP (0.014 and 0.017).

2/C/R = Compaction Ratio = $\frac{\text{board density}}{\text{wood density}}$; where: board density = oven dry flake-only weight/unit vol. of board conditioned to an EMC of 9.8% (70°F and 65% RH); wood density = estimated density based on oven dry weight and estimated volume at 5% MC.

3/R/C = binder coverage rate (g/m^2) = (D)(R)(T)(1.27 x 10^4); where: D = wood density (g/cm^3), R = resin content as dec. fract. (i.e., 7% = .07), and T = flake thickness (inches).

4/Den. = actual average measured board density (pcf) from the bending (MOR/MOE) test strips; based on oven dry weight (flakes and resin) and volume conditioned to an avg. of 9.8% (70°F and 65% RH).

Table 3.--Screen analysis and average dimensions for flakes

Species	Factor	Target flake thickness .015" Screen size 1/2"[1]	1/4"	No. 7[2]	No. 12	No. 100	PAN[3]	.030" Screen size 1/2"[1]	1/4"	No. 7[2]	No. 12	No. 100	PAN[3]
Yellow-Poplar (YP)	Weight (%)	0.04	14.07	45.02	26.76	13.69	0.28	0.22	18.48	48.07	25.12	8.02	0.16
	Thick. (in.)	.015	.016	.016	.015	.013	----	.025	.024	.023	.021	.020	----
	Length (in.)	1.12	1.25	1.07	1.01	0.68	----	1.46	1.26	1.18	1.00	0.64	----
	Width (in.)	0.67	0.24	0.14	0.09	0.06	----	0.56	0.25	0.16	0.09	0.06	----
Sweetgum (SG)	Weight (%)	0.03	12.87	45.74	29.68	11.48	0.09	0.06	17.78	47.67	25.82	8.69	0.07
	Thick. (in.)	.015	.014	.013	.012	.012	----	.026	.020	.022	.020	.016	----
	Length (in.)	1.29	1.27	1.19	1.05	0.71	----	1.50	1.22	1.18	1.03	0.74	----
	Width (in.)	0.37	0.29	0.14	0.09	0.06	----	0.50	0.29	0.16	0.09	0.06	----
White oak (WO)	Weight (%)	0.00	3.52	35.74	41.08	19.57	0.07	0.00	3.96	47.08	33.86	15.03	0.08
	Thick. (in.)	----	.015	.014	.012	.012	----	----	.024	.025	.019	.018	----
	Length (in.)	----	1.30	1.27	1.14	0.85	----	----	1.31	1.22	1.05	0.73	----
	Width (in.)	----	0.25	0.14	0.08	0.05	----	----	0.26	0.14	0.09	0.06	----
Mockernut Hickory (MH)	Weight (%)	0.00	4.09	34.18	33.78	27.56	0.33	0.00	4.67	41.18	29.99	24.02	0.16
	Thick (in.)	----	.014	.015	.014	.011	----	----	.024	.019	.019	.016	----
	Length (in.)	----	1.30	1.24	1.15	0.85	----	----	1.34	1.26	1.18	0.84	----
	Width (in.)	----	0.29	0.15	0.08	0.06	----	----	0.25	0.13	0.09	0.06	----
Loblolly Pine (SP)	Weight (%)	0.00	5.04	34.18	31.31	28.84	0.64	0.16	4.44	43.25	31.07	20.81	0.28
	Thick. (in.)	----	.015	.014	.014	.012	----	.015	.018	.018	.017	.018	----
	Length (in.)	----	1.24	1.15	1.06	0.72	----	1.31	1.24	1.16	0.95	0.70	----
	Width (in.)	----	0.26	0.15	0.09	0.06	----	0.63	0.29	0.17	0.09	0.06	----

1/Where flakes were caught on the 1/2" opening screen, the number was much fewer than the present sample size of 50, usually less than 10.

2/Tyler screen size numbers.

3/Dust caught on pan. Too small to measure dimensions.

Table 4.--Averages for board densities and panel properties

Factors	Measured panel[1/] density	Modulus of rupture	Modulus of elasticity	Internal bond	Thickness[2/] swelling	Water[2/] absorption
	pcf	psi	1,000 psi	psi	Percent	
Overall	37.4	3698	468.4	62	20.2	87.1
Species[3/]						
YP	36.7	3547	460.1	84	21.0	82.0
SG	37.5	4238	515.2	79	22.9	89.8
YPWO	36.9	3833	467.6	61	20.0	85.1
WO	37.3	3498	433.9	39	21.8	88.6
SGMH	37.9	3599	460.1	65	19.2	88.3
MH	38.1	3843	486.8	44	19.2	89.8
SP	37.3	3330	454.8	63	17.5	86.4
Target Panel[4/] Densities						
32 pcf	31.7	3018	398.0	37	18.3	107.6
38 pcf	37.4	3718	472.3	61	20.3	85.7
44 pcf	43.2	4358	534.8	88	22.1	68.0
Resin Contents						
4%	37.0	2810	373.3	35	27.7	98.3
7%	37.8	4586	563.5	89	12.7	75.9
Target Flake Thicknesses						
.015"	37.4	3292	433.2	56	19.7	87.9
.030"	37.4	4104	503.5	68	20.8	86.3

1/ Measured panel densities based on oven dry weight and conditioned volume (70°F and 65% RH, EMC average = 9.8%) of the bending specimens.

2/Values based on 24-hour, room temperature, water soak test.

3/The species code is: YP = yellow poplar; SG = sweetgum; WO = white oak; MH = mockernut hickory; SP = loblolly pine; YPWO = yellow poplar and white oak blended to the specific gravity average of sweetgum; SGMH = sweetgum and mockernut hickory blended to the specific gravity average of white oak.

4/Target panel densities based on oven dry weight and target volume of manufactured board (26" x 26" x 1½").

Table 5.-- Analysis for linear regression of modulus of rupture on compaction ratio and resin coverage

Parameter	Estimate	Prob > |T|	Standard error of estimates
Intercept	-2082.94	0.0001	459.53
Resin coverage (R/C)	363.08	0.0001	25.77
Compaction ratio (C/R)	3258.36	0.0001	371.58

Table 6.--Analysis for linear regression of modulus of elasticity on compaction ratio and resin coverage

Parameter	Estimate	Prob > |T|	Standard error of estimates
Intercept	-126720.77	0.0089	47296.89
Resin coverage	37025.23	0.0001	2652.54
Compaction ratio	339246.38	0.0001	38245.04

Table 7.--Analysis for linear regression of internal bond on compaction ratio and resin coverage

Parameter	Estimate	Prob > |T|	Standard error of estimates
Intercept	-152.53	0.0001	15.18
Resin coverage	9.24	0.0001	0.85
Compaction ratio	153.99	0.0001	12.27

Table 8.--Analysis for linear regression of thickness swelling in 24-hour watersoak on compaction ratio and resin coverage

Parameter	Estimate	Prob > |T|	Standard error of estimates
Intercept	34.59	0.0001	4.82
Resin coverage	-1.74	0.0001	0.27
Compaction ratio	-1.71	0.6608	3.89

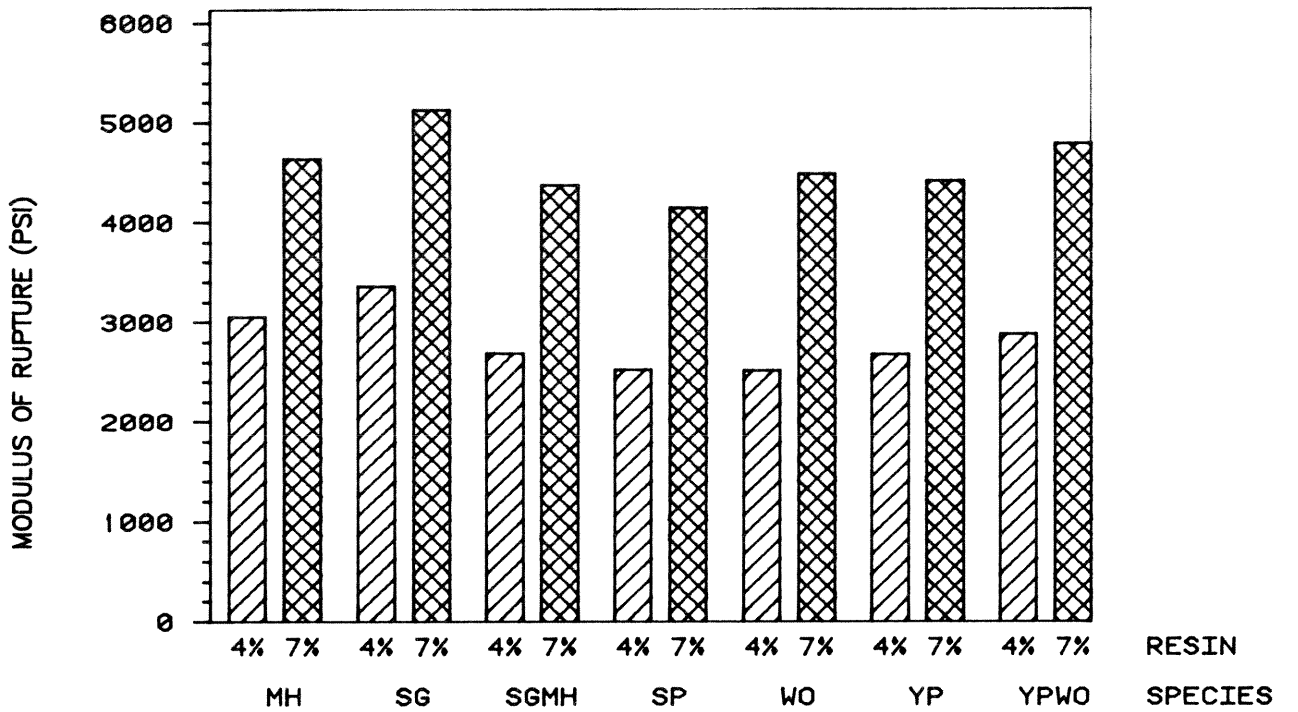

Figure 1.--Average modulus of rupture values for the several species and species blends (see Table 2 for codes) and target board resin content weight percents tested.

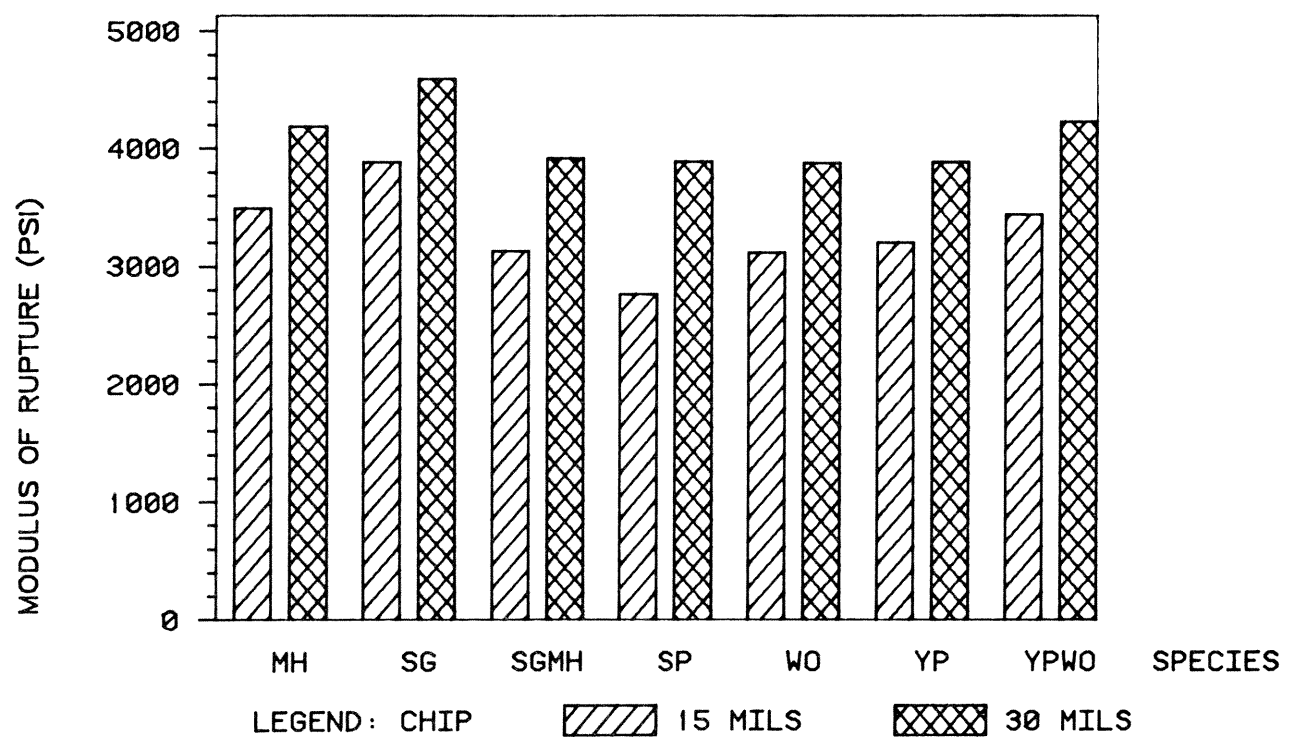

Figure 2.--Average modulus of rupture values for the several species and species blends (see Table 2 for codes) and target chip (flake) thicknesses tested.

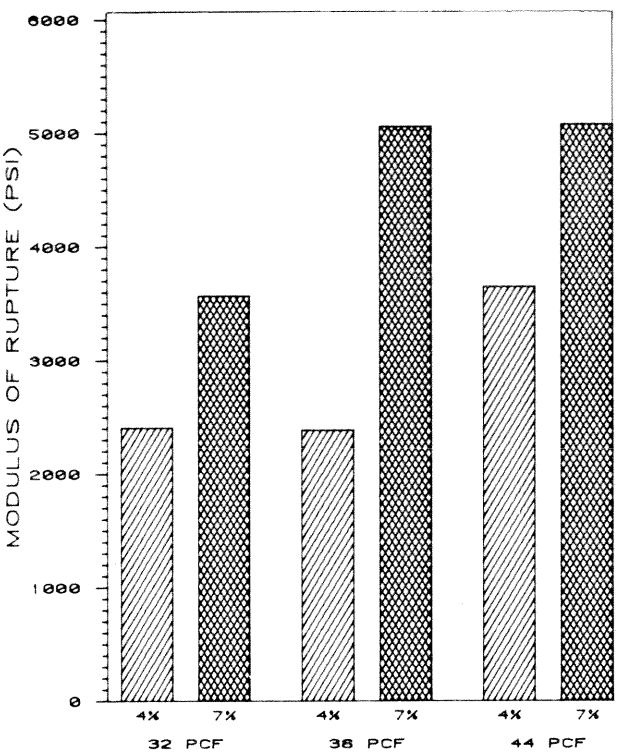

Figure 3.--Average modulus of rupture values for the target board densities and resin content weight percents tested.

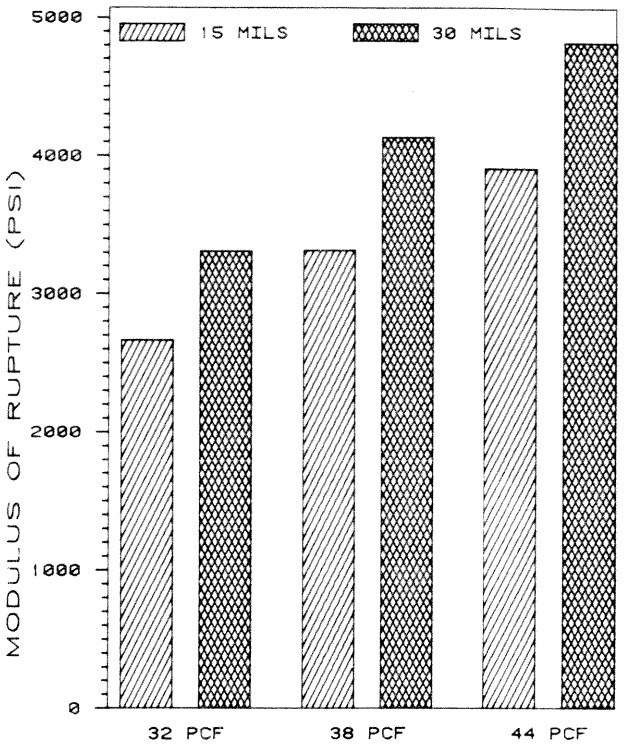

Figure 4.--Average modulus of rupture values for the target board densities and flake thicknesses tested.

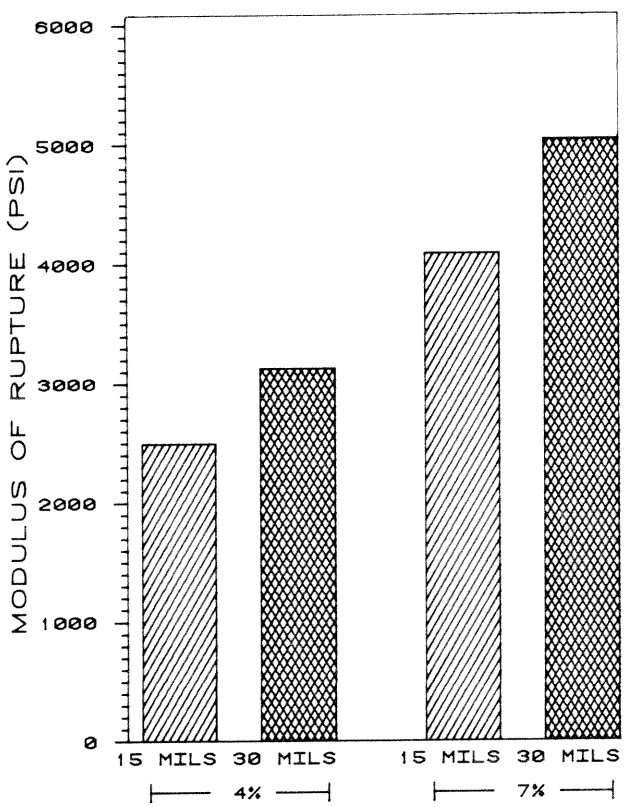

Figure 5.--Average modulus of rupture values for the target board resin content weight percents and flake thicknesses tested.

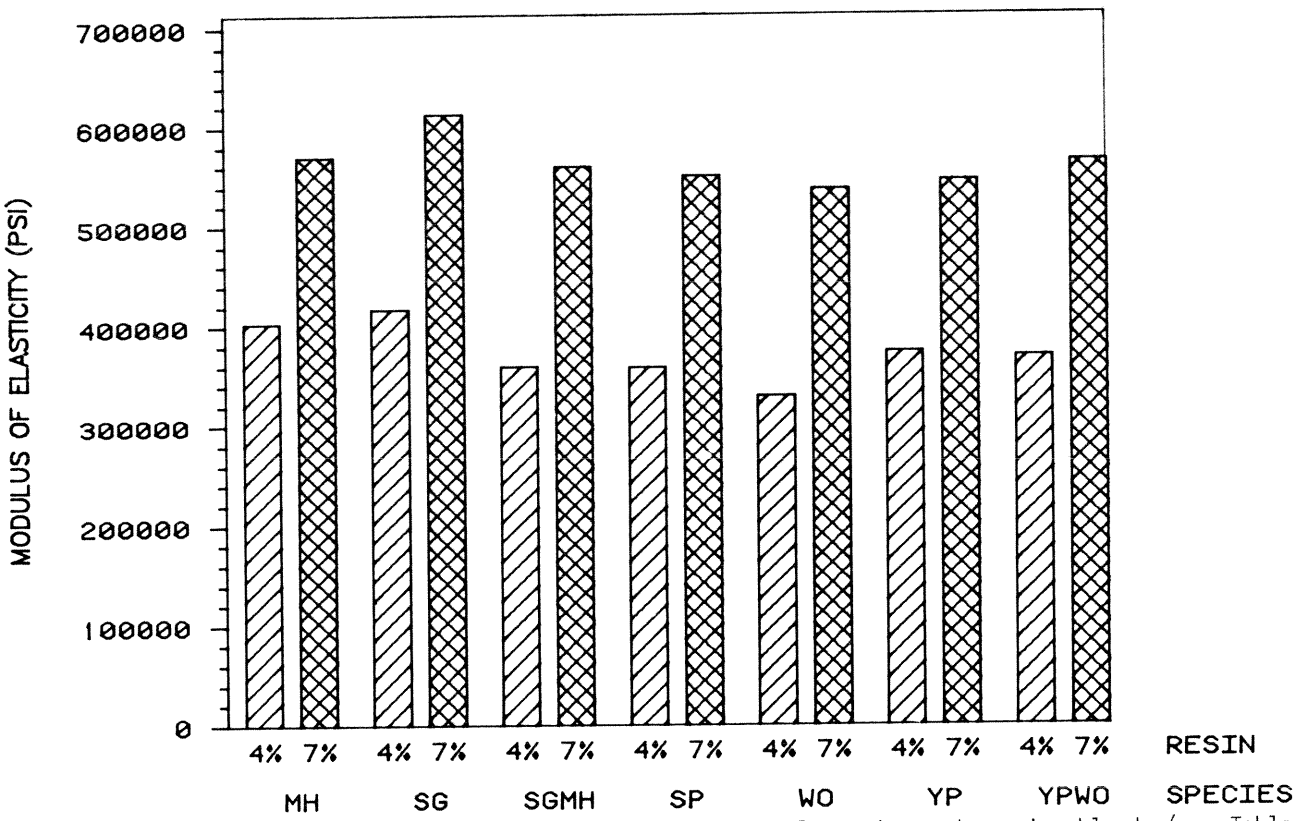

Figure 6.--Average modulus of elasticity values for the several species and species blends (see Table 2 for codes) and target board resin content weight percents tested.

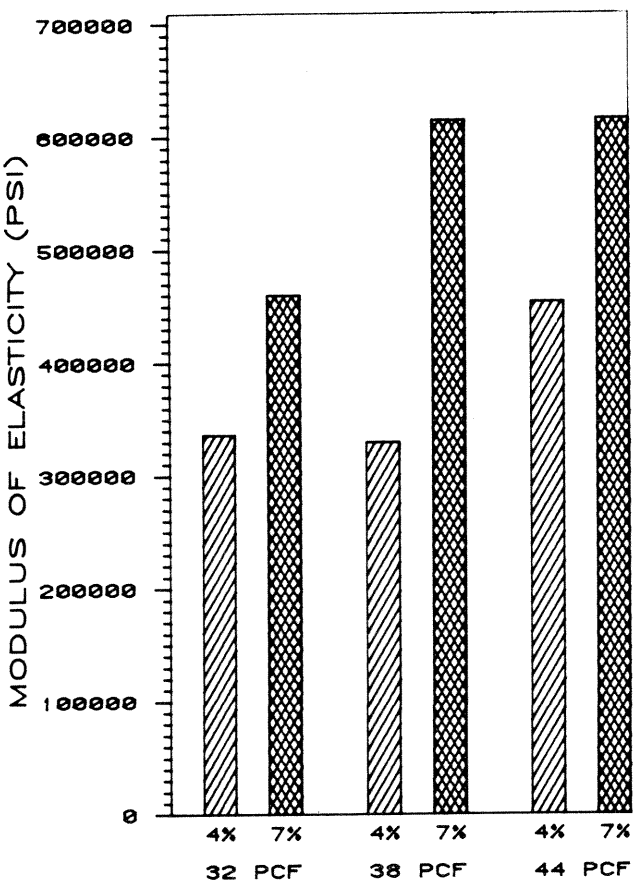

Figure 7.--Average modulus of elasticity values for the target board densities and resin content weight percents tested.

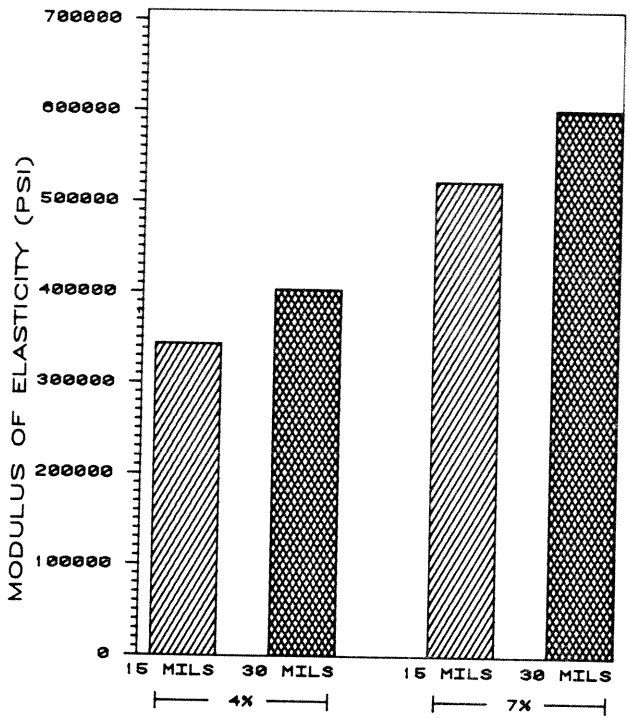

Figure 8.--Average modulus of elasticity values for the target board resin content weight percents and flake thicknesses tested.

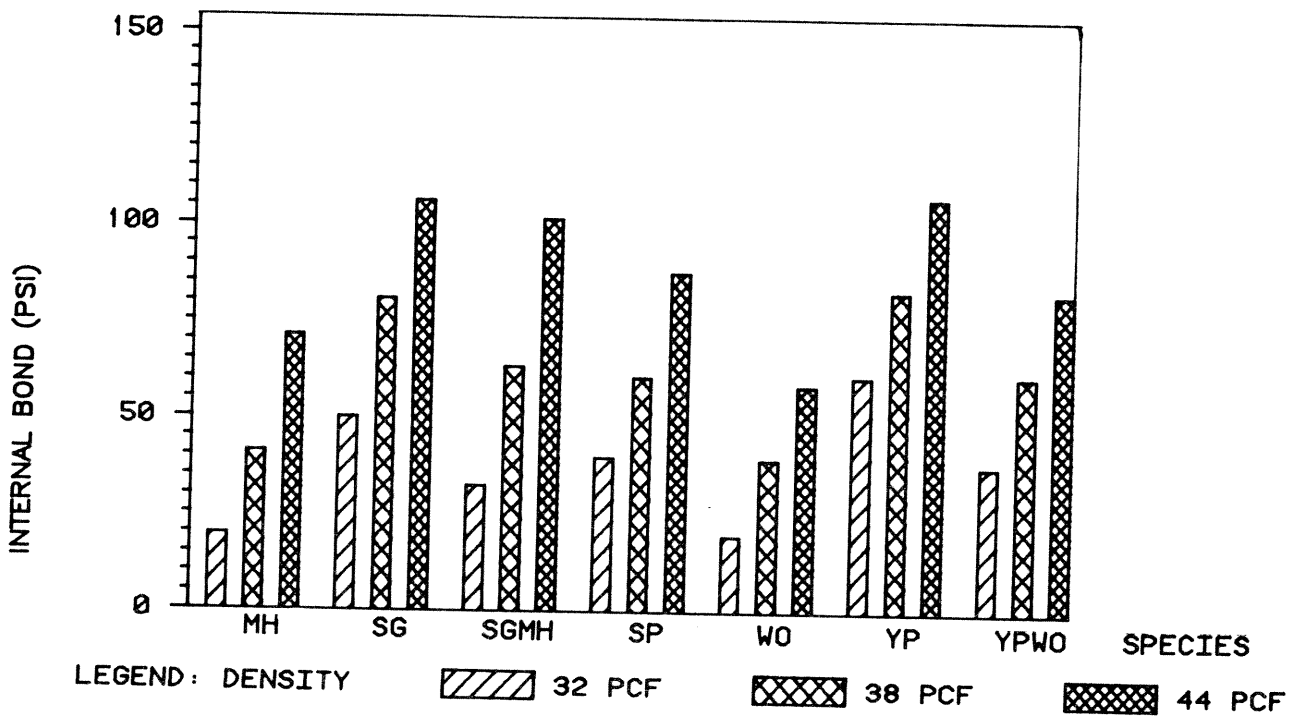

Figure 9.--Average internal bond values for the several species and species blends (see Table 2 for codes) and target board densities tested.

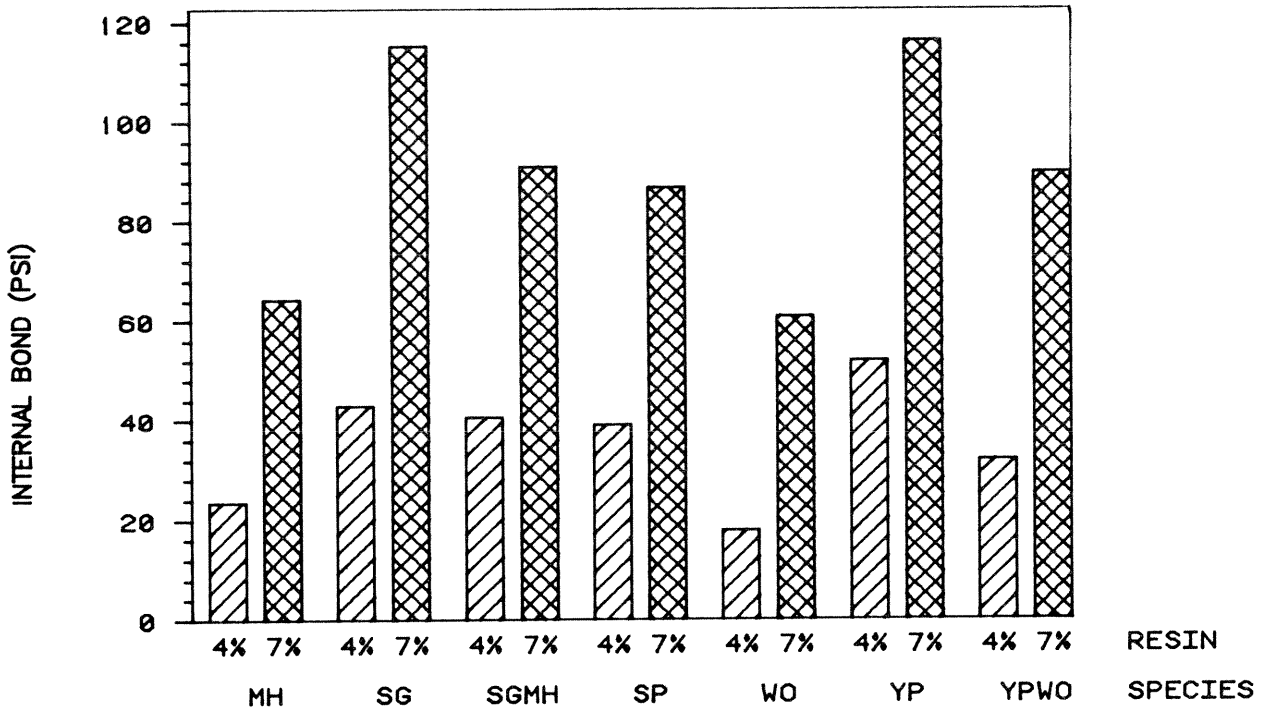

Figure 10.--Average internal bond values for the several species and species blends (see Table 2 for codes) and target board resin content weight percents tested.

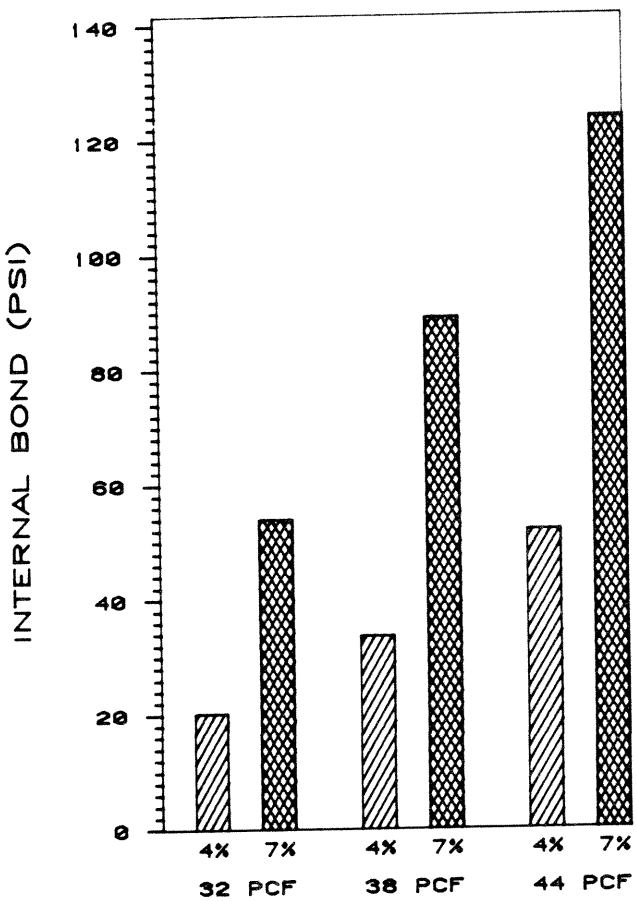

Figure 11.--Average internal bond values for the target board densities and resin content weight percents tested.

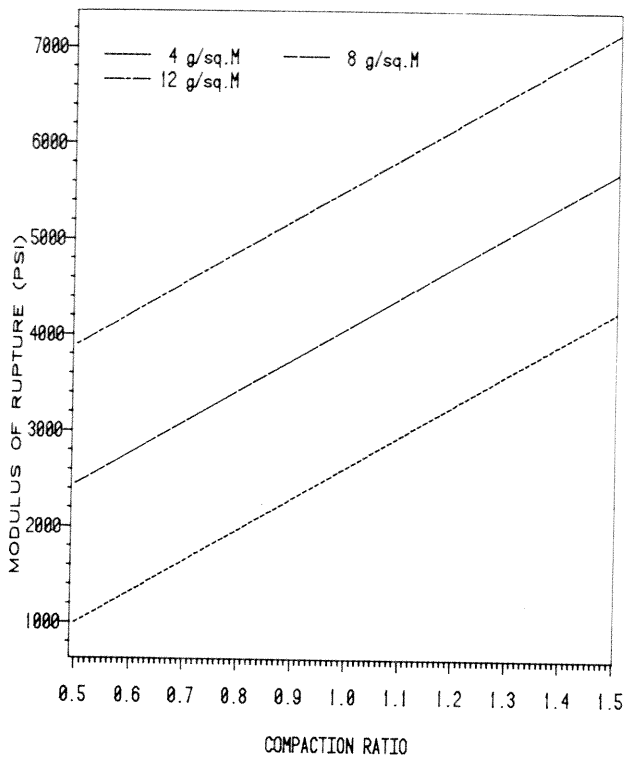

Figure 12.--Plots of linear regression equation predicted values for modulus of rupture as a function of compaction ratio (see explanation in footnote 1 of Table 2) for three selected levels of resin coverage (in g/sq.M).

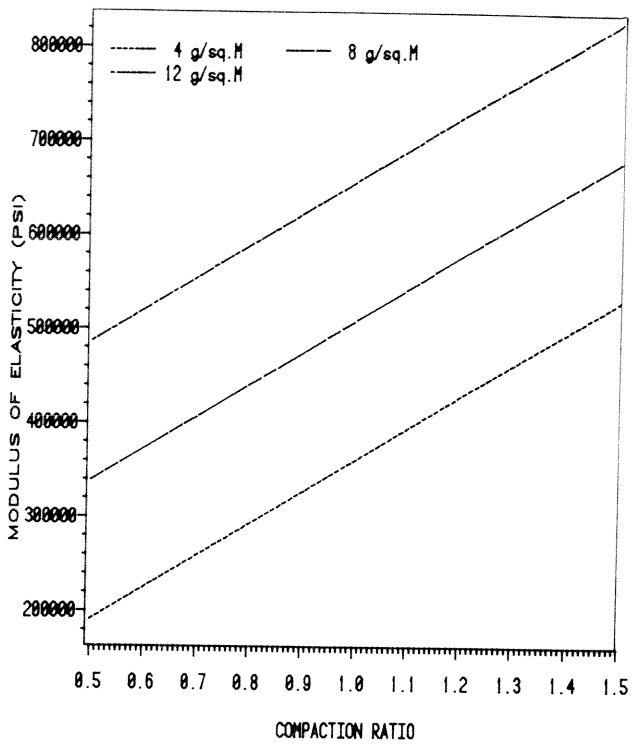

Figure 13.--Plots of linear regression equation predicted values for modulus of elasticity as a function of compaction ratio (see explanation in footnote 1 of Table 2) for three selected levels of resin coverage (in g/sq.M).

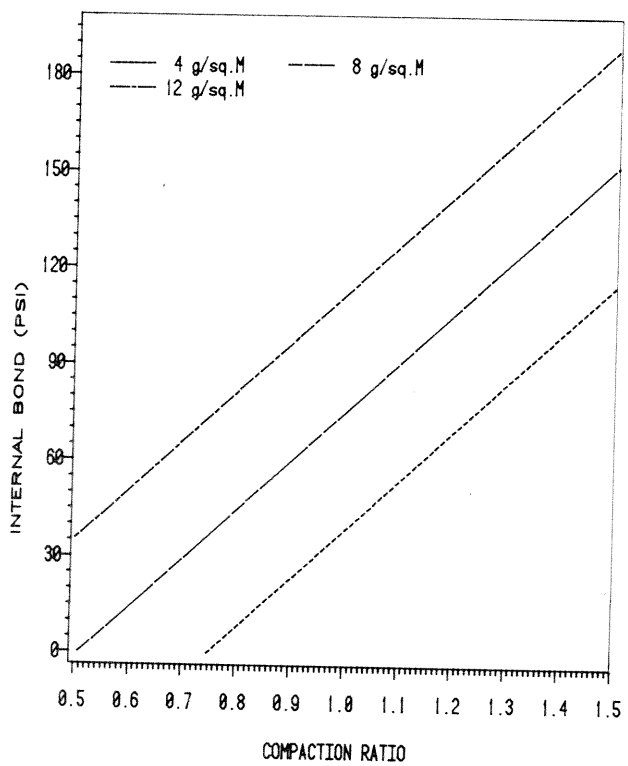

Figure 14.--Plots of linear regression equation predicted values for internal bond as a function of compaction ratio (see explanation in footnote 1 of Table 2) for three selected levels of resin coverage (in g/sq.M).

DURABILITY EVALUATION OF HARDWOOD VENEERED FLAKEBOARD COMPOSITES[1,2]

P. Chow and J. J. Janowiak[3]

Abstract.--The ranking of the effects of various exposure tests on strength values of the hardwood reconstitued structural composite panels in a decreasing order of severity was (1) 24-hour soak, (2) 1-hour boil, (3) 2-hour boil, (4) ASTM-6 cycles, and (5) WCAA-6 cycles. Both ASTM and WCAA tests had similar influences on all properties. Also, 4-cycles of either of these tests resulted in about the same degree of strength reduction as 6-cycles. The dry phenolic resin film and wet melamine formaldehyde resin, used to laminate the veneer over the core material yeilded similar strength values. The 1/2-inch thick panels appeared to be more stable with more strength retention than panels 3/4-inch thick. Also, panels with an exterior particle-board core had higher IB values than wafer type flakeboard core panels.

INTRODUCTION

The American Plywood Association has forecasted that the total demand for softwood plywood will increase from approximately 15.5 billion square feet (3/8-inch) basis in 1975 to about 22 billion square feet in 1985 (fig. 1) (Mahoney 1975). In order to relieve any anticipated shortage of softwood plywood and extend future supplies, wood products of other species may be required. The U.S. Forest Service reported that the nation has a substantial volume of hardwood growing stock, but more than one third of the hardwood inventory in 1970 consisted of oaks, hard maple, and poplar (U.S. For. Serv. 1973). Many studies related to the feasibility of making construction plywood and veneered composite panels from hardwoods have been reported (Chow 1972, Chow and Janowiak 1983, Chow and Redmon 1981, Jokerst, Lutz, and Kurel 1976, Lutz and Jokerst 1974). One reason for not commercializing the panel has been inadequate data related to the internal bond and shear strength performance of hardwood veneered composite panels under severe weather exposure.

The objective of this study was to determine the effect of several variables on the internal bond and shear strength of a hardwood veneer composite panel. The construction variables consisted of (1) veneer species (red oak and hard maple), (2) core material (exterior particleboard and wafer type of flakeboard, (3) glueline (dry and wet), and (4) total panel thickness (1/2-inch and 3/4-inch). The properties were evaluated using (1) 24-hour water soak, (2) 1-hour boil, (3) 2-hour boil, (4) the American Society for Testing and Materials (ASTM-6 cycles test), and (5) the West Coast Adhesive Manufacturers Association (WCAMA or WCAA-6 cycles test) accelerated aging test.

MATERIALS AND PROCEDURE

In order to achieve two panel thicknesses, 3/8- and 1/2-inch thick exterior particleboard and wafer type aspen flakeboard core material were purchased from commercial manufacturers. Also, two thicknesses (1/6- and 1/8-inch) of No. 2 face grade red oak and hard maple veneers were obtained from a manufacturer in the Midwest. The 1/16-inch thick veneer was used with the 3/8-inch core material to obtain a 1/2-inch composite. Likewise, the thicker 1/8-inch veneer and 1/2-inch core panels were combined to obtain the 3/4-inch thick composite. Because of the

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planten size of the hot press, the veneers, particleboards, and flakeboards were cut into 20- by 24-inch pieces for lamination.

The lamination process consisted of gluing face veneers to particleboard and flakeboard cores with one of the two different types of adhesives selected for evaluation. The two adhesives were a melamine formaldehyde resin (wet form) and a thin dry film of phenolic resin. The adhesive suppliers claimed that both of these resins meet the requirements of U.S. Products Standard P51-74 for exterior glue bond (National Bureau of Standards 1974).

Prior to lamination, all core panels were sanded slightly with 60 grit sandpaper to elimi nate uneven surfaces and to improve the glue-bond property. Panels laminated with the dry - film glue were hot pressed at a pressure of 225 psi and 300°F temperature. The press times were 6 minutes and 7-1/2 minutes for 1/2-inch and 3/4-inch thick panels, respectively. Core panels laminated with the melamine liquid resin had a glue spread rate of about 80 pounds per square foot (double glueline), pressed with a platen temperature of 270°F and 200 psi pressure. Press times were 5-1/2 minutes and 7-1/2 minutes for 1/2- and 3/4-inch thick composite panels, respectively. For all of the panels, the grain direction of the veneer overlays was parallel to the length of the core material.

After being pressed, all panels were trimmed to specimen dimensions as specified in ASTM D 1037-72a (American Society for Testing and Materials 1981). All specimens were coded, and conditioned at a relative humidity of 65 1 percent and a temperature of 68 6°F. For comparison purposes, matched specimens were also cut from commercial 1/2-inch sheathing grade Douglas-fir plywood, 1/2-inch exterior particleboard, and 1/2-inch exterior wafer type aspen flakeboard. The control samples were also cut from the test materials.

Accelerated Aging Tests

Six accelerated aging regimes were selected for evaluation. The test procedures were:

1. ASTM D1037-72a, 6 cycles, 12 days to complete (American Society for Testing and Materials 1981, National Particleboard Association 1980)
   a. Soaked in water at 120°F for 1 hour
   b. Steamed at 200°F for 3 hours
   c. Frozen at 10°F for 20 hours
   d. Dried at 210°F for 3 hours
   e. Steamed at 200°F for 18 hours
   f. Dried at 210°F for 18 hours
2. WCAA-6 cycles, 6 days to complete (West Coast Adhesive Manufacturers Association 1966)
   a. Submerged in water at 70°F with 27-inch vacuum for 30 minutes
   b. Boiled in water at 210-212°F for 3 hours
   c. Dried at 220°F for 20 hours
3. 24-hour soak test (American Society for Testing and Materials 1981)
   a. Specimens were submerged in water at room temperature, approximately 75°F
   b. Specimens were removed after 24 hours
4. 1-hour boil test
   a. Specimens were submerged in boiling water 210-212°F
   b. Specimens were removed after 1 hour
5. 2-hour boil test (Shen and Wrangham 1971)
   a. Specimens were submerged in boiling water 210-212°F
   b. Specimens were removed after 2 hours

For the ASTM test, a set of specimens was removed at the end of each cycle. Similarly, specimens were removed from the WCAA test at the end of cycles 2, 4, and 6. This permitted comparisons of strength reductions due to the number of exposure cycles for the two test procedures.

Strength Properties Tests

After completing the accelerated aging regimes, specimens were conditioned with the control group specimens in a climate chamber maintained at a relative humidity of 65 1 percent and a temperature of 68 6°F.

The IB and shear tests were performed on conditioned core material, composite panel type exposed to the aging tests, and the conditioned control specimens using a Tinus Olson testing machine and a plywood shear tester. The IB tests were performed according to method described in ASTM D 1037-72a (American Society for Testing and Materials 1981), while the shear test specimens were tested according to methods described in ASTM D805-63 (American Society for Testing and Materials 1970).

EXPERIMENTAL DESIGN

In this experiment, analysis of variances (AOV) was conducted through the use of a completely randomized design. Components of the composite panels were considered as seperate factors: factor A--veneer species, 2 levels, red oak and hard maple; factor B--core material, 2 levels, particleboard and flakeboard; factor C--glueline, 2 levels, dry and wet; factor D--composite panel thickness, 2 levels, 1/2-inch and 3/4-inch; and factor E--accelerated aging method, 5 levels, 24-hour soak, 1-hour boil, 2-hour boil, ASTM-6 cycles, and WCAA-6 cycles. Thus the experiment was a 2x2x2x2x5 factorial design (Steel and Torrie 1980). The number of replications per variable was four for both IB and shear tests. However, due to the occurrence of the delamination of some wafer type flakeboard cores, the number of replicates tested for some ASTM and WCAA type specimens was less.

RESULTS AND DISCUSSION

Control Condition

Tables 1 and 2 give the average IB and shear strength values for the control specimens. No glueline failures were found between the face veneer and core board in these controlled veneered composite specimens. The average particleboard IB value was higher than that of the flakeboard. This IB property difference also occurred for the composite panels. Most likely the difference is due to variation in the gluing properties of smaller particles relative to large flakes or wafers.

Plywood specimens were found to have higher IB and shear strengths than specimens made from particleboard or flakeboard core.

Accelerated Aging Test

The percent of IB and shear reductions based on values obtained at control conditions were tabulated for replication that had no delaminated specimens (Tables 1 and 2).

Except for the ASTM-6 cycle compared with the WCAA-6 cycle test, the IB means obtained by any two test methods were significantly different at the 1 percent level (Table 3). For the shear values, the two 6-cycle test methods were statistically equivalent as well as the 24-hour versus the control.

Factorial Analysis

Both IB and shear values were statistically analyzed using an analysis of variance (AOV). The results of the AOV (Table 4) show that (1) factor A (veneer species) significantly affected the IB values; (2) factor B (core material) significantly influenced the IB values; (3) factor C (glueline) did not have any effect on either strength value (4) factor D (thickness), and (5) factor E (accelerated aging tests) had a significant effect on all strength values. Average strength values and ratios of strength retention for all exposed composites are listed in Table 5.

Based on this analysis, several conclusions can be stated. First, composite panels made with the particleboard cores had a superior IB property, and resisted the degrading effects of the exposure conditions better than panels made with flakeboard cores. Secondly, 1/2-inch thick panels would be recommended over 3/4-inch thickness. This recommendation can be given because a large portion of the 3/4-inch specimens had delaminated flakeboard core, and greater thickness swelling. Thirdly, the 2-hour boil test created the greatest average thickness swelling of all hardwood veneered composite panel specimens (Table 6). Finally, the exposure condition greatly affected the amount of strength reduction based on the unexposed specimens:

Specimen condition	Percent strength reduction	
	IB	Shear
24-hour soak	9	1
1-hour boil	42	14
2-hour boil	46	34
ASTM 6-cycle	69	44
WCAA 6-cycle	74	54

ASTM-6 Cycles Versus WCAA-6 Cycles Test

Two of the most widely used accelerated aging tests are ASTM and WCAA cyclic tests. Both of these test methods resulted in a large percentage of strength reduction for all materials evaluated (Table 7). For this reason, special attention was given to a comparison between these two tests and effect on the number of cycles.

To determine the effects of the number of cycles of both ASTM and WCAA accelerated aging procedures on the strength properties of composite panel, specimens were evaluated for 2, 4, and 6 cycles and compared statistically using the Duncan's Multiple Range Test. For both accelerated test methods IB and shear properties both showed no significant difference between 2 and 4 exposure cycles or 4 and 6 cycles except the shear values for ASTM cyclic test (Table 8). The result of this analysis suggests that hardwood composite panel specimens subjected to four cycles of either ASTM or WCAA aging test could achieve the same degree of strength reduction as specimens subjected to six cycles.

It was found that the most drastic reduction of IB and shear was observed from the first to second cycle of exposure for the

ASTM procedure. A gradual decline of IB and shear was also shown for both ASTM and WCAA test methods.

CONCLUSIONS

Based on this experimental design and results, several conclusions can be stated.

1. Internal bond and shear for plywood were superior to any of the hardwood composites or core materials tested. Because of core delamination, adhesive bond of red oak face veneer to core material is stronger than the coherence of chips or flakes in the core material. Significant shear property differences are observed between core material and hardwood composites while the IB of the two panel types are similar.

2. The 24-hour soaking test had the least amount of strength reduction and caused the least amount of thickness swelling. The WCAA accelerated aging method resulted in the greatest observed average reduction for the two strength properties examined. However, statistical analysis showed there is no real difference between WCAA and ASTM, in reducing both values. Significant differences are noted between 1-hour boil and 2-hour boil; between 2-hour boil and ASTM 6-cycles; and between 2-hour boil and WCAA 6-cycles test in reducing both internal bond and shear by tension loading properties.

3. Significant differences were observed between control condition and 24-hour soak for IB property while both IB and shear values were significantly different for 1-hour boil and 2-hour boil.

4. A gradual reduction occurred in both IB and shear strength with an increase in the number of exposure cycles for either the ASTM or WCAA test method. However, no significant differences in most of the strength values were found between 4-cycle and 6-cycle tests.

5. Internal bond was significantly influenced by the core material and overall panel thickness. The maximum IB value for a composite panel was obtained using a particleboard core and 1/2-inch composite thickness.

6. Shear strength is significantly influenced by the overall thickness of the composite.

7. Red oak veneered composite panels demonstrated better gluability characteristics than hard maple veneered panels.

8. Part of the decreased strength properties due to accelerated aging test in hardwood composite panels may be attributed to a lower density as a result of thickness swelling and the deterioration of the glue bond.

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Table 1.--Internal bond of control specimens and percent reduction of value after several aging tests

Panel		Composite	Panel		24-hour	1-hour	2-hour	ASTM	WCAA
Face	Core	glueline	thickness	Control	soak	boil	boil	6-cycles	6-cycles
			in.	psi	----------% reduction from control----------				
Flakeboard(Waferboard)			1/2	72	+13.0	-41.8	-62.7	-93.3	-93.0
Particleboard			1/2	84	-3.0	-22.8	-35.0	-49.6	-63.9
Plywood			1/2	180	-2.2	-20.7	-16.1	-52.4	-54.4
Red oak	Particleboard	Dry	1/2	86	-7.3	-26.1	-35.7	-35.5	-59.0
			3/4	85	--	--	--	-73.0	-80.3
		Wet	1/2	81	--	-20.7	-28.8	-57.6	-48.7
			3/4	89	-13.4	--	--	--	-79.6
	Flakeboard	Dry	1/2	73	-3.0	-66.7	-73.1	--	--
			3/4	88	-30.8	--	--	-96.4	-96.9
		Wet	1/2	82	-6.0	-56.4	-67.7	--	-80.8
			3/4	68	-3.0	--	-39.7	-96.9	-97.1
Hard maple	Particleboard	Dry	1/2	91	-18.7	-28.7	-64.0	-65.1	-63.4
			3/4	57	--	--	--	--	--
		Wet	1/2	82	-27.0	-39.0	-51.0	-63.0	-67.0
			3/4	80	--	--	-30.0	--	--
	Flakeboard	Dry	1/2	48	+8.3	-74.0	-80.7	--	--
			3/4	76	--	--	--	--	--
		Wet	1/2	85	-35.6	-62.2	-70.9	--	--
			3/4	75	--	--	+6.2	--	--

Table 2.--Shear strength of control specimens and percent reduction of values after several aging tests

Panel		Composite	Panel		24-hour	1-hour	2-hour	ASTM	WCAA
Face	Core	glueline	thickness	Control	soak	boil	boil	6-cycles	6-cycles
			in.	psi	----------% reduction from control----------				
Flakeboard(Waferboard)			1/2	145	-7.9	-50.8	-60.5	-79.9	-94.8
Particleboard			1/2	163	-14.9	-13.6	-46.4	-37.2	-74.4
Plywood			1/2	332	+6.6	+6.9	-53.7	-15.1	-10.5
Red oak	Particleboard	Dry	1/2	155	-4.4	-18.0	-14.8	-42.9	-36.8
			3/4	88	--	+;8.5	--	-6.6	-48.6
		Wet	1/2	146	-1.6	-12.3	-5.0	-24.3	-38.0
			3/4	93	+11.1	+20.0	--	-40.0	-54.6
	Flakeboard	Dry	1/2	139	+46.1	-13.5	-39.2	--	--
			3/4	106	+1.4	-17.5	--	-73.5	-64.0
		Wet	1/2	147	-7.3	-29.6	-38.5	--	-61.5
			3/4	110	-7.1	-33.8	--	-71.8	-65.4
Hard maple	Particleboard	Dry	1/2	166	--	-8.0	--	-8.0	--
			3/4	102	--	--	--	--	-48.0
		Wet	1/2	155	-13.0	-16.0	-19.0	-58.0	--
			3/4	120	--	-2.8	--	--	-52.1
	Flakeboard	Dry	1/2	148	-14.2	--	--	--	--
			3/4	103	--	-30.5	--	--	--
		Wet	1/2	141	-11.7	-21.2	-12.3	--	--
			3/4	81	--	--	--	--	--

Table 3.--Contrast Analysis of Average IB and Shear Values Between Two Different Accelerated Aging Tests.

Difference between two test models	Properties	
	IB	SHEAR
Control vs. 24-hour soak	**	NS
1-hour boil vs. 2-hour boil	**	**
2-hour boil vs. ASTM 6-cycles	**	**
2-hour boil vs. WCAA 6-cycles	**	**
WCAA 6-cycles vs. ASTM 6-cycles	NS	NS

** - difference significant at 1 percent level
NS - difference not significant at 5 percent level.

Table 4.--Factorial Analysis for Two Strength Properties of Veneered Composite Panels.

Source	F-Ratio	
	IB	SHEAR
A (veneer species)	**	NS
B (core)	**	NS
C (glue line)	NS	NS
D (thickness)	**	**
E (aging test)	**	**
AB	NS	**
AD	**	NS
AE	**	NS
DE	NS	NS
BD	NS	**
BC	NS	NS
CD	**	*
CE	NS	NS
CA	NS	NS
ACD	NS	NS
BCD	**	NS

** - difference significant at 1 percent level.
NS - different not significant at 5 percent level.
* - difference significant at 5 percent level.

Table 5.--Average IB and shear Properties of of Hardwood Composite Panels at controlled and Accelerated Aging Exposed Conditions.

Strength Properties(Psi)		Veneer, A		Core, B		Glueline, C		Thickness, D	
		Red Oak	Hard Maple	Pt. Bd.	Fl. Bd.	Dry	Wet	1/2 inch	3/4 inch
IB	Control	82	73	81	74	76	79	78	77
	Exposed[1]	38 (0.46)[2]	45 (0.62)	45 (0.56)	36 (0.49)	38 (0.50)	43 (0.54)	44 (0.56)	35 (0.46)
Shear	Control	103	123	124	122	126	120	149	100
	Exposed	88 (0.85)	101 (0.82)	94 (0.76)	88 (0.72)	89 (0.71)	93 (0.78)	113 (0.76)	57 (0.57)

[1]Average of all accelerated.
[2]Ratio of strength retention based on value at control condition.

Table 6.--Average Percent Thickness Swell of Composite Panel for Various Exposure Conditions (4)

Panel Materials	Accelerated Aging Test				
	24-hour soak	1-hour boil	2-hour boil	ASTM-6 cycles	WCAA-6 cycles
	- - - - - - -	- - - - - -	- percent -	- - - - - - -	- - - - - -
1/2" Plywood	2	3	2	2	2
1/2" Ext. Particleboard	2	7	22	13	17
1/2" Ext. Flakeboard	4	7	25	28	24
Red Oak/Pt. Bd. Core (1/2" and 3/4")	4	10	17	12	14
Red Oak/Fl. Bd. Core (1/2" and 3/4")	4	15	29	28	28
Hard Maple/Pt. Bd. Core (1/2" and 3/4")	4	12	17	13	15
Hard Maple/Fl. Bd. Core (1/2" and 3/4")	5	25	31	--	15

Table 7.--Percent Reduction of Strength Properties - Average of ASTM-6 cycles, and WCAA-6 cycles Exposure Conditions.

Material[1]	Strength Property Reduction (%)	
	IB	Shear
1/2" RO (PP)	43	32
3/4" RO (PP)	77	48
1/2" RO (PC)	45	23
3/4" RO (PC)	80	47
1/2" RO (FP)	73	39
3/4" RO (FP)	97	69
1/2" RO (FC)	74	50
3/4" RO (FC)	78	69
3/4" HM (PP)	68	8
3/4" HM (PP)	DL[2]	48
3/4" HM (PC)	30	52
1/2" HM (FP)	DL	DL
3/4" HM (FP)	DL	12
1/2" HM (FC)	DL	DL
3/4" HM (FC)	DL	DL
1/2" Pt. Bd.	50	53
1/2" Fl. Bd.	83	78
1/2" plywood	41	26

[1]The first letter in parenthensis refer to the core material (P = particleboard, F = flakeboard), the second letter refers to the glueline (P = phenolic film, c = liquid melamine resin)

Table 8.--Comparison of strength properties for different number of cyclic exposures for ASTM and WCAA accelerated aging test method.

Strength property	No. of cycles	ASTM Mean[1]	WCAA Mean
		------psi------	
IB	2	40A	37A
	4	35AB	34AB
	6	32B	37B
Shear	2	123A	102A
	4	100B	97AB
	6	105B	89B

[1]The same capital letters within a strength property test method group indicate no real difference between two strength values based on Duncan's Multiple Range test and 0.05% level.

DURABILITY OF FIBROUS-FELTED BOARDS[1/]

George E. Woodson[2/]

Abstract.--A segment of the composition board industry consisting of panel materials known as structural insulating board, medium density fiberboard (MDF), and hardboard can be classified as fibrous-felted boards. This paper reviews some of the characteristics that make fibrous-felted boards "durable." A distinction is made between "durability" and "permanence" as follows:

Durability - Resistance to degradation under the influence of stress and environmental conditions.

Permanence - Resistance to degradation due to age only, i.e., where stress is absent or negligible.

It is shown that materials are durable or nondurable according to the interaction of elements of environment with the material. Elements such as weathering, biological, stress, incompatibility, and use are important degradation factors to fibrous-felted substrates and coatings. Materials are more durable, therefore, when these factors are controlled to minimize their influence.

INTRODUCTION

A fibrous-felted board has been defined by Maloney (1977) as: "A felted wood-based panel material manufactured of refined or partly refined lignocellulosic fibers characterized by an integral bond produced by an interfelting of fibers and, in the case of certain densities and control of conditions of manufacture, by ligneous bond, and, to which other materials may have been added during manufacture to improve certain of its properties." The following discussion will be limited to a segment of the composition board industry consisting of panel materials known as structural insulating board, medium density fiberboard (MDF), and hardboard.

The basic difference in these types of fibrous felted boards are summarized below:

Board type	Density ---pcf---	Forming Process
Insulating board	10-31	wet
MDF	31-50	wet or dry
Hardboard	50-	wet or dry

Typically, MDF-wet is called hardboard and MDF-dry is called medium density fiberboard. Although significant differences exist between wet and dry formed hardboard they compete in the same market. It is widely accepted that lignocellulosic bonds hold the boards together in wet formed panels and synthetic resins or other suitable binders form the interfiber bond in dry formed panels. Other materials may be added to improve certain properties, such as stiffness, hardness, finishing properties, resistance to abrasion, resistance to moisture, strength, utility, and durability.

The subject of this paper is to review some of the characteristics that make the fibrous-felted boards "durable." It is useful to make a distinction between the terms "durability" and "permanence" as follows:

Durability: Resistance to degradation under the influence of stress and environmental conditions

Permanence: Resistance to degradation due to age only, i.e., where stress is absent or negligible.

These definitions were proposed by a workshop group at a conference on adhesion in cellulosic and wood-based composites and appeared in a Proceedings of that conference edited by Oliver (1981).

According to the above definitions, permanence is not applicable to fibrous-felted boards because these composites, even if not subjected to external stress, are in a state of self-stress near the bonded regions. Specifications for

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durability of these products must recognize the wide range of density and quality that exists and evaluations must be made in relation to end-use requirements.

The durability classes of "exterior" and "interior" are in many cases too restrictive for the intended use. It is highly desirable to have additional classes of durability for more economical use of materials. The commercial standard specifications for hardboard were apparently developed with the idea that each piece of hardboard was a Jack-of-all trades and could be used for any and all end uses. Maximum economy and efficiency of operation can be achieved when the hardboard can be made to specific end uses and when specifications are made to adequately do the end use job required. For example, almost all the interior uses of hardboard in building and furniture are used as companion pieces to, or in competition with interior plywood and gypsumboard, both of which have very poor water resistance. Why spend a lot of money to make a water resistant product to compete with a product which has no water resistance in the glue line or with a product such as gypsumboard which will simply fall to pieces under any amount of liquid water? According Eustis (1979), hardboard siding is one of the few hardboard products where liquid water absorption is an important specification. Liquid water absorption is also important in hardboard to be used in manufacturing tileboard, for use in bathroom shower stalls, kitchens, and laundries. A great many uses of hardboard, however, do not encounter liquid water and the money spent on additives for these end uses is an unnecesary expense in the manufacturing process. Other specifications may require expensive waterproof adhesives for materials that may be subjected to moderately hazardous conditions for short periods of time, e.g., rain at a building site. These specifications are designed to protect against extreme conditions and not only increase costs but inhibit the development and use of alternative adhesives.

In an effort to remove restrictions on the wider use of cellulosic or wood-based composites, four durability classes have been suggested (Oliver 1981). These durability classes were suggested with good durability against the hazards outlined for the respective classes. They are as follows:

Suggested Durability Classes

Class 1 - Exterior: wetting and drying cycles, exposure to UV radiation, large temperature variations, attack by micro-organisms.

Class 2 - Protected exterior: cycles of wide range of relative humidity and temperature changes.

Class 3 - Interior, humid conditions: cycles of high and low humidity.

Class 4 - Interior, dry conditions: cycles of moderate changes in relative humidity.

Additional requirements were suggested to provide adequate mechanical properties and limited creep under the respective environmental conditions.

In order to get a clear understanding of the various types and physical properties of fibrous-felted boards, the reader is encouraged to consult the appropriate product standard. A review of the quality requirement for each product is beyond the scope of this paper but the reader may find the following tabulation useful in seeking information about different products:

Product	Product Standard	Citation
Insulating board	PS-57-73	U.S. Dep. Commerce (1973a)
Basic hardboard	PS-58-73	U.S. Dep. Commerce (1973b)
Prefinished hardboard paneling	PS-59-73	U.S. Dep. Commerce (1973c)
Hardboard siding	PS-60-73	U.S. Dep. Commerce (1973d)
Medium density fiberboard	NPA-4-73	National Particleboard Association (1973)

MOISTURE-RELATIONS

Fibrous-felted boards like any other wood-based material, exhibit an expansion in all directions when its moisture content increases. This hygroscopic expansion is particularly important when boards are used as structural elements and the results can be disastrous if the materials are installed without regard for changes due to environment. Numerous studies have been made to investigate dimensional changes in composition boards as a result of moisture absorption. Lehmann (1972) used four types of particleboard, five types of hardboard, and five types of insulation board in a study of the relationships of physical properties to dimensional stability characteristics of the panels. He concluded that mechanisms which reduced the rate of moisture movement had only slight value as stabilizing agents and the best possibilities for panel stability appeared to be the use of coatings and bulking agents which prevent the passage and/or subsequent absorption of liquid or vapor forms of water.

Insulation Board Additives

Materials commonly used in the insulation board industry to retard moisture absorption are:

1. Molten wax
2. Wax emulsion

3. Paraffin wax
4. Rosin
5. Asphalt

Each additive has its advantages and disadvantages. For example, asphalt strengthens the insulation board while the waxes and rosin reduce the strength of the board. Occasionally, starch is added to strengthen the board, but as the amount of starch increases the boards become more and more attractive to rodents and insects. Thus, an additive that is beneficial for one property can be detrimental for another.

Hardboard Additives

Common additives to improve water resistance in hardboard are:

1. Wax emulsion
2. Petrolatum
3. Linseed oil)
4. Tung oil) drying oils
5. Tall oil)
6. Soybean oil)

The drying oils are used in conjunction with heat treatment to produce tempered boards. Oil tempering provides improved paint hold-out, high abrasive resistance, scratch and scar resistance, surface water resistance and generally improves wear quality of the board. All these features are of great importance in the manufacture of premium quality factory finished wall panels.

Important markets for hardboard products have developed because hardboard is a good substrate for industrial application of finishes. It presents a smooth hard surface. It can be manufactured to close dimensional tolerances, and its properties can be controlled and modified to suit special applications. The commercial success of hardboard siding is due to a reputation of durability based on the quality of industrially applied finishing systems.

Basic Finishing Materials

All finishes have three basic components:

1. Resin or binder - component which develops the necessary adhesive and cohesive forces to form the film and to bond it to the substrate. It also controls many of the important properties of the finish such as water resistance, weatherability, and strength.

2. Pigments - component to provide color in coatings.

3. Solvents - component that maintains the coating in the liquid state and conrols the working properties

There is a common belief in the industry that development of water base coatings of high molecular weight has been the key to durability. In the developing years of hardboard siding, molecular weights of 10,000 were common for coatings. Current systems can have molecular weights as high as 500,000. One thing must always be kept in mind regarding durability. Even with the advanced technology of finishing systems today, good coatings on poor substrates will result in undesirable finished products. Thus, it is imperative for the industry to meet the standards for each particular product and produce an acceptable substrate in combination with a compatible coating.

Probably one-third of all hardboard siding is completely prefinished and the remaining two-thirds coated with a prime coat. Primed siding provides greater flexibility for color selection of the final coat or coats and removes the burden of providing a performance guarantee for the finished product. Coatings applied in the field, however, cannot be expected to give the performance of coatings applied at the plant and cured at high temperatures.

Performance Guarantees

Typical performance guarantees for hardboard sidings will place a cash limited 5-year warranty on factory applied primer, a 5-year warranty on factory finish and a 25-year warranty on the substrate. All performance guarantees require that the manufacturer's published application instructions must be followed to make the warranty meaningful. Other special coatings are warranted for 15 years not to require refinishing due to peeling, blistering, cracking, or erosion of the factory applied finish except for reasonable color fade from normal weathering. One manufacturer will provide a 25-year warranty on the performance of the finished surface against blistering, peeling, or checking if their innovative installation method is used, but only a 5-year warranty with standard face nailing applications. Another manufacturer provides a 30-year warranty for a siding product that contains a polyvinyl fluoride film.

The important thing to remember about predictable performance is that it is dependent on successful control of nature's forces. Materials are durable or nondurable according to the interaction of elements of environment with the material. For any mechanism or process to promote deterioration one or more elements of environment must be acting upon the material (Garden 1980). If any one of the essential factors can be eliminated or controlled, the process will be controlled. For example, fungal decay of an organic material occurs when spores, oxygen, suitable temperature, and suitable moisture conditions are present. If any one of these conditions is controlled, rot will not occur. Intentionally altering the balance of heat, air, and moisture inside a building creates environmental differences across walls, windows, floors, and roofs. One of the major hardboard manufacturers has

noted (personal communication with the author) that claims for decay or other biological activity in hardboard siding has shown a significant increase since the new government standards were issued for energy savings in homes. Prior to 1975, reports of decay in siding were nonexistent. The obvious solution to biological activity would be to incorporate a preservative into the hardboard siding. Adding a preservative to a product made primarily by the wet process, however, presents a major problem in control of water pollution and the costs appear to be prohibitive.

DEGRADATION FACTORS AFFECTING DURABILITY

As an aid to understanding the degradation factors that may affect the performance of building materials and components, Frohnsdorff and Masters (1980) proposed a list of degradation factors one should consider. With modifications, a list appropriate for consideration for fibrous substrates and coatings can be proposed as:

I. Weathering
- Radiation
  - Solar
  - Nuclear
  - Thermal
- Temperature
  - Elevated
  - Depressed
  - Cycles
- Water
  - Solid (snow, ice)
  - Liquid (rain, condensation, standing water)
  - Vapor (high relative humidity)
- Normal Air Constituents
  - Oxygen and ozone
  - Carbon dioxide
- Air Contaminants
  - Gases (oxides of nitrogen and sulfur)
  - Mists (salt, acids, alkalies in water)
  - Particulates (sand, dust, dirt)
- Freeze-Thaw
- Wind

II. Biological
- Microorganisms
- Fungi
- Bacteria

III. Stress
- Sustained
- Periodic
  - Physical action of water
  - Physical action of wind
  - Combination of water and wind
  - Movement due to other factors (settlement)

IV. Incompatibility
- Chemical
- Physical

V. Use
- Design of system
- Installation procedures
- Maintenance procedures
- Normal wear and tear
- Abuse by user

Many of the factors have minimal effect on fibrous substrates but thermal shock is a serious matter in coatings and it can be disastrous in vinyl overlays. Temperature changes from daylight to dark can be substantial. Another item of current interest is the effect of air contaminants such as acid rain. Sulfide staining in exterior coatings is a discoloration phenomena which has the potential for widespread occurrence. A factor contributing to this problem is the recognition of acid rain as an atmospheric pollutant. Metallic compounds susceptible to sulfide staining are commonly present in most exterior paints and the problem is common in industrialized areas.

The list of factors is included as a means of identifying some of the key factors that affect durability. No attempt has been made to identify the factors that influence durability most. Although some are more important than others, each has an influence and under the right conditions can become significant.

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PERFORMANCE OF WAFERBOARD: LOAD DURATION, DIMENSIONAL STABILITY AND BIODETERIORATION[1/]

J. Alexopoulos and T. Szabo[2/]

Abstract.--The behavior of two commercial types of waferboard bonded with phenol-formaldehyde (PF) and one type of experimental waferboard bonded with methylolated kraft lignin phenol-formaldehyde (MKL/PF) was studied in terms of load duration, dimensional stability and biodeterioration. In the case of load duration, a 4-element model was used to describe the creep behavior of the waferboard specimens. The highest creep resistance at all three load levels was exhibited by the long-wafer PF specimens tested parallel to panel length followed closely by the MKL/PF specimens at the low load level, then by the long-wafer PF specimens tested perpendicular to panel length. At the high load levels, however, the MKL/PF specimens showed much higher creep deflection and approached the creep resistance of the long-wafer PF perpendicular specimens. In linear expansion (LE), thickness swelling (TS) and water absorption (WA) comparisons, the MKL/PF specimens performed as well or better than both commercial PF board types. Differences in dimensional stability means (significant at the 0.05 level of confidence) among the three board types occurred in linear expansion tested perpendicular to panel length, thickness swelling, and water absorption. All board types displayed more or less equal resistance to fungal decay. However, relative to the aspen poplar control specimens, significantly higher decay resistance (0.01 level) was shown by all board types with the decay fungus *Lenzites trabea*. With *Poria placenta*, the short-wafer PF and MKL/PF specimens were more decay resistant than the control. Mold was found not to have a significant effect on the bending strength of specimens tested on edge.

INTRODUCTION

Wood and wood-based products, in their various applications, are expected to safely withstand the conditions imposed by the particular service environments. Structural wooden members and panels are designed to carry loads continuously for long periods of time in adverse environmental conditions and under the influence of possible biodegradation. Information is available on the mechanical behavior of traditional wood products with respect to load duration, moisture and micro-organisms. However, the same cannot be said for commercial or experimental waferboards. Thus, a study was initiated to assess the effects of 1) load on the time-dependent behavior of waferboard in bending, 2) moisture on the dimensional stability of waferboard, and 3) mold and fungi on the durability of waferboard.

MATERIALS

For this study, two types of commonly used waferboard for roof sheathing in residential wood construction and one experimental waferboard were selected (fig. 1). The commercial boards, produced to meet the requirements of CAN3-0188.2-M78 and ANSI A208.1-79 standards, had randomly oriented wafers bonded with a phenolic powder resin (PF). The two panels, designated PF_1 and PF_2 differed by wafer length. The PF_1 had long wafers (89 mm) while the PF_2 panels had shorter wafers (38 mm). The commercial panels were randomly selected from shipments of two manufacturers.

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The experimental waferboard was bonded with methylolated kraft lignin/phenol formaldehyde (MKL/PF) resin. These boards were made with randomly oriented wafers (38 mm in length) in the laboratory. The fabrication technique involved spraying the wafers with 2 percent slack wax, then blending 2.5 percent powdered phenol-formaldehyde resin in a drum-type blender for 2 minutes. The mats with 5 ± 0.5 percent moisture content were pressed for 5 minutes at 210°C press temperature. Press closing time was approximately 60 seconds. For more detailed information on this resin system and its application in waferboard production see Dolenko and Clarke (1978).

EFFECT OF LOAD ON THE TIME-DEPENDENT BEHAVIOR OF WAFERBOARD IN BENDING

When a structural panel like waferboard is used in roof sheathing applications, its mechanical behavior exhibits time dependency. Depending on the circumstances, the panels may deviate from their plane exhibiting what is commonly referred to as sagging, buckling or creep. The amount of creep depends upon a number of factors including the magnitude of the load, the duration of the load, the environmental temperature, and moisture content fluctuations.

Using the deformation curve in figure 2, the time-dependent behavior can be discussed as illustrated. On the application of a load at time (t_0), there is an instantaneous elastic deformation (OA). On maintaining the load to t_1, the deformation increases at a decreasing rate; thus increment (AB) is known as "creep". On removal of the load at t_1, an instantaneous creep recovery (BC) occurs which is approximately equal in magnitude to the initial elastic deformation (OA). With time, there is a partial recovery (CD) of the creep deformation at a decreasing rate until time t_2. The amount of creep that has occurred during loading can be divided into a "recoverable" component, which displays delayed elastic behavior, and an "irrecoverable" component which is due to plastic or viscous flow (Pierce and Dinwoodie, 1977).

In this study, only the creep portion (AB) of the time-dependent behavior of waferboard is addressed. The creep evaluation consisted of subjecting one commercial waferboard (PF_1) and the MKL/PF experimental waferboard to three load levels (table 1). After equilibration to room conditions (21°C and 65 percent relative humidity), the specimens, 11.1 x 153 x 660 mm, were center-point loaded over a span of 610 mm. For the commercial waferboard, approximately 15 specimens were evaluated from both panel directions. Since the MKL/PF specimens do not show directional properties, only one test direction with respect to panel length was considered.

A creep loading frame and deflection measurement apparatus was constructed (fig. 3). The measurement apparatus contained a dial gauge with an accuracy of 0.01 mm and mounted as shown in figure 4. The apparatus was a tripod design of aluminum for stability and handling ease. The dial gauge arm rested on the actual specimens by means of holes drilled in the loading frame and 22-mm diameter steel pipes. This method of measuring deflections enabled the load to be removed or applied with the reference point maintained; thus the elastic response of the specimens, the deflection of the specimens immediately following load application and load removal, could be recorded.

Deflection measurements were taken at appropriate times for two months with the load applied and two months with the load removed. Deflection at 1/2 minute following load application and load removal was defined as the elastic response of the specimens. At the end of the creep tests, all specimens including adjacent controls were tested in static bending over a 610-mm span. The test procedures followed the recommendations of CAN3-0188.0-M78 (1978).

The results of the creep experiments are summarized graphically in figures 5 and 6. To better apprehend the creep resistance, relative deflection values obtained at two selected times were compared (table 2). The two times chosen were the instantaneous response (1/2 minute after loading) and at 900 hours. For analysis, the data can be compared by 1) effect of board type--within load levels, 2) effect of load level--among load levels, and 3) combination of load level and board type--within and among load levels. For all these cases, the instantaneous deflection of specimens with the highest creep resistance were chosen as the control and the other measurements were rated based on the control measurement.

In the "within load level" comparisons, the highest creep resistance was displayed by the PF_1 parallel specimens followed by MKL/PF, then PF_1 perpendicular specimens. However, the gap between the MKL/PF specimens and the controls widened and approached the creep resistance exhibited by the PF_1 perpendicular specimens for the high load level.

In "among load level" comparisons, when going from the low to the medium load level, all specimens showed an approximate increase of three times the control deflection at both time instances. However, at the high load level, the commercial specimens in the two test directions had close values (i.e., approximately 400 and 600 percent for t=1/2 minute and t=900 hours, respectively) whereas those for MKL/PF were somewhat greater (i.e., 600 and 800 percent for the two times).

When load levels and materials are compared, it can be seen that at the high load level the MKL/PF and PF_1 perpendicular specimens exhibited approximately 800 and 900 percent increase in creep deflection at the instanteous time and 1200 and 1300 percent at 900 hours, respectively, relative to the PF_1 parallel control specimens.

The creep response was analyzed in terms of a 4-parameter viscoelastic model (fig. 7). The viscoelastic behavior has been represented by various spring and dashpot anologues in which the spring simulates the elastic component and the dashpot the plastic or viscous component. The four governing parameters are the spring constants E_o and E_1, and the dashpot constants μ_o and μ_1.

The governing differential equation for a 4-parameter or Burger's model according to Szabo and Ifju (1970) is:

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\varepsilon} + q_2\ddot{\varepsilon} \qquad \{1\}$$

Where: $\dot{\sigma}$ and $\ddot{\sigma}$ = first and second derivatives of stress with respect to time

$\dot{\varepsilon}$ and $\ddot{\varepsilon}$ = first and second derivatives of strain with respect to time

$$p_1 = \frac{\mu_o\,(1 + E_1/E_o) + \mu_1}{E_1}$$

$$p_2 = \frac{\mu_o\,\mu_1}{E_o\,E_1}$$

$$q_1 = \mu_o$$

$$q_2 = \frac{\mu_o\,\mu_1}{E_1}$$

E_o = modulus of elasticity of the free spring

μ_o = viscosity of the liquid in the free dashpot

E_1 = modulus of elasticity of the spring in the retarded element

μ_1 = viscosity of the liquid in the dashpot of the retarded element

The solution of the differential equation for creep is:

$$\varepsilon(t) = \sigma_o\{1/E_o + 1/E_1(1 - e^{-t/\tau}) + t/\mu_o\} \qquad \{2\}$$

Here: σ_o/E_o = elastic deformation

$\sigma_o/E_1(1 - e^{-t/\tau})$ = delayed elastic deformation

$\sigma_o t/\mu_o$ = viscous flow

$$\tau = \frac{q_2}{q_1} = \frac{\mu_1}{E_1} = \text{retardation time} \qquad \{3\}$$

The constants in Equation {2} could be obtained from the experimental data:

σ_o (L,M,H) = experimental stress levels (1.88, 4.79, and 7.69 GPa)

E_o (PF_1, MKL/PF) = initial moduli of elasticity of the two waferboards (PF_1 parallel - 5.5 GPa, PF_1 perpendicular-2.7 GPa, MKL/PF - 4.4 GPa)

The approximately constant slope attained by the creep curves in figures 5 and 6 allowed calculation of μ_o from the relationship:

$$\text{slope} = \frac{\sigma_o}{\mu_o}$$

For the end of the creep curves in figures 5 and 6 where constant slope is reached (fig. 8), the solution of the differential equation may be rewritten as follows:

$$\varepsilon(t) = \sigma_o\{1/E_o + 1/E_1 + t/\mu_o\}$$

Since the first two terms $1/E_o$ and $1/E_1$, are constants, it is easy to see that the slope of the curve is σ_o/μ_o for large values of t. The intercept of the tangent from the above solution is therefore:

$$\varepsilon(t) = \left(\frac{1}{E_o} + \frac{1}{E_1}\right)\sigma_o$$

From this, E_1 can be calculated.

There remains only μ_1 to be calculated to describe strain behavior in terms of the equation. This may be found from Equation {3}.

In this study, τ, a material constant, was not determined experimentally. Arbitrary values could be assigned to τ and the one that satisfied Equation {2} was considered to be the true value. This procedure was followed in the analysis of the experimental data using digital computer techniques to find τ, the retardation time. Then, from Equation {3}, μ_1 was obtained.

The results concerning the model parameters and coefficients of the governing differential equation are given in table 3 for PF_1 board in parallel direction at the low load level. For the other cases (load level and board type), relative values are given as the percentage of PF_1 parallel specimen data at the low load level. These results (table 3) substantiate the discussion presented earlier with the creep curves. Thus, the highest creep resistance was demonstrated by PF_1 parallel specimens at all three load levels. The high elasticity in the system was confirmed by the high magnitude of elastic constants. At the same time, the magnitude of μ_1 suggests that the viscous flow resistance of the system was also high.

The PF_1 perpendicular specimens demonstrated substantially lower elasticity and less resistance to viscous flow relative to the controls. The MKL/PF specimens indicated slightly less elasticity as compared to the PF parallel specimens and their resistance to viscous flow was only slightly better than that of the PF perpendicular specimens.

The MKL/PF specimens were tested three weeks following manufacture and some post-curing may still have been in progress. This may explain the high viscous behavior of the board, especially at high load levels.

Bending tests following the creep tests showed that creep had no significant effect on the bending properties of the test specimens relative to the control specimens at the low load level. Testing is not completed at the other load levels.

EFFECT OF MOISTURE ON THE DIMENSIONAL STABILITY OF WAFERBOARD

Waferboard, a hygroscopic material, will shrink and swell when exposed to conditions causing desorption or adsorption of water. The phenomenon can be attributed to the basic wood nature. The dimensional response of waferboard to moisture change is very important in its major applications. Two examples are joint quality due to edge swelling and buckling as a result of expansion.

In this work, the dimensional stability of 11.1-mm waferboard was studied in terms of linear expansion (LE), thickness swelling (TS), and water absorption (WA). Ten specimens per panel direction were used for both PF commercial waferboards. The MKL/PF specimens totaled 20 with no consideration given to direction of testing. All specimens were cut to the same dimensions as the creep specimens.

Linear expansion tests were carried out according to APA Test Method P-1: Linear Expansion Measured from Oven Dry to Vacuum-Pressure Soak (American Plywood Association, 1980). As the title suggests linear expansion was determined from length measurements taken following oven-drying and after the specimens were exposed to water, vacuum and pressure. Thickness swelling and water absorption were determined using the same LE specimens going from oven-dry to the saturated condition.

Linear expansion was measured to the nearest 0.01 mm using a bar-type trammel equipped with a dial gauge (fig. 9). A 610-mm gauge length was defined on the longitudinal axis of each specimen by driving a common aluminum nail through the thickness at 25.4 mm from each end. A 1.1-mm hole was drilled in the geometric center of each nail to accommodate the needles of the trammel. A brass bar having identical holes drilled 610 mm apart served as the reference measurement. For accuracy, each specimen was placed in a flattening jig which removed any out-of-plane distortions.

The results of the dimensional stability tests are shown in table 4. The linear expansion for specimens in the perpendicular test direction was higher than the corresponding linear expansion in the parallel direction for both commercial board types. The differences, however, were not significant at the 0.05 level of confidence. The MKL/PF specimens had a LE of 0.26% which equaled the average of both commercial boards tested parallel to panel length.

From the point of view of thickness swelling, PF_2 specimens performed the best, followed by PF_1 then by the MKL/PF specimens, but the difference between PF_1 and MKL/PF is non-significant. Water absorption tests showed that the MKL/PF specimens displayed the best performance by having approximately 11 percent less water absorption than the average of the commercial specimens.

Analysis of variance for a one-way classification showed that the difference in means among the three board types within each category were found to be significant at the 0.05 level of confidence in all cases except in linear expansion comparisons with specimens tested parallel to panel length.

EFFECT OF MOLD AND FUNGI ON THE DURABILITY OF WAFERBOARD

Waferboard, in its various applications, could be exposed to ambient conditions that make it prone to mold and/or fungal attack. It has been shown that wood species, particle geometry, board structure density, and adhesive factors are all involved in susceptibility of particleboard to fungi (Smith, 1974; Willeitner, 1965).

Waferboard is normally made from poplars which are susceptible to mold and decay. The PF resin has been known to provide some protection against micro-organisms (Bosshard and Futo, 1963), but the combination effects with poplar and PF resin or MKL/PF resin in waferboard are not known.

Since the biodeterioration process usually commences with mold followed by decay, the effects of both on the behavior of waferboard were examined.

EXPOSURE TO MOLD

Resistance to mold was evaluated using a modified APA Test Method D-2: Mold Test. The modification was not subjecting the control specimens to APA Test Method D-4: Moisture Cycle for Quality Assurance. It was believed that variables beyond our control would be introduced and allowing the controls to attain equilibrium moisture content at 21°C and 65 percent relative humdity was better.

The test specimens were placed in a cabinet under mold-producing conditions (fig. 10). Each specimen measured 11.1 x 25.4 x 127 mm and was tested on edge across a 102-mm span with the load applied at midspan. The effect of mold was based on bending strength (MOR) differences between test and adjacent control specimens. One series of specimens was tested every two weeks starting at the four-week exposure time.

Table 5 presents the bending strength retention results of the mold specimens. Whether mold had a definite effect on MOR cannot be clearly stated. In some cases, the bending strength increased with increased exposure time as indicated by higher retention values. From a

visual standpoint (fig. 11), there was no noticeable difference in mold growth among the three board types.

EXPOSURE TO DECAY FUNGI

The method applied for this investigation was a slightly modified version of the Standard Method of Accelerated Laboratory Tests of Natural Decay Resistance of Woods ASTM D 2017-71. *Polyporus versicolor* L. ex Fr. (S-634 in Forintek's Eastern Laboratory Culture Collection), *Lenzites trabea* Pers. ex Fr. (A-188), and *Poria placenta* (Fr.) Cooke (A-189), which are all wood-rotting Basidiomycetes recommended for tests on hardwoods, were used as test fungi. *Chaetomium globosum* Kunze ex Fr. (C-367), an Ascomycete, was also included. The Ascomycete causes soft rot, grows well in soil-block jars and usually is included in testing the resistance of materials against fungal attack.

The test consisted of exposing six 11.1 x 25.4 x 25.4-mm blocks of each waferboard types to each of the four test fungi. Aspen poplar sapwood blocks of the same dimensions were used as control specimens. The resistance of the specimens to the attack of fungi was based on percent weight loss following exposure to the decay fungi.

The weight losses obtained with the four fungi are shown in table 6. *Polyporus versicolor* caused losses ranging between 4 and 9 percent, *Lenzites trabea* between 44 and 65 percent, *Poria placenta* between 38 and 67 percent and *Chaetomium globosum* between 5 and 6 percent. Table 7 compares the percent weight loss results between the different materials within each test fungus category. The student's "t" test was employed for statistical comparison. Relative to the aspen poplar control samples, all board types were found to have a significantly higher decay resistance when exposed to *Lenzites trabea*. When exposed to *Poria placenta*, PF_2 and MKL/PF specimens showed higher resistance than the controls. Since the MKL/PF specimens lost statistically the same weight as either or both of the commercial specimens, it may be concluded that all three board types were equally resistant to the attack of decay fungi.

CONCLUSIONS

Creep Resistance

1. The highest resistance to creep at all three load levels was exhibited by the long-wafer PF_1 specimens tested parallel to panel length. At the low load level they were followed closely by the MKL/PF specimens then at a distance by the long-wafer PF_1 perpendicular specimens. At the high load level, however, the MKL/PF specimens showed much higher creep deflection and approached the creep resistance of the long-wafer PF_1 perpendicular specimens.

2. A 4-element model could adequately describe creep phenomenon of waferboard in bending for better understanding of its time-dependent behavior.

Dimensional Stability

In LE, TS, and WA comparisons, the MKL/PF specimens performed as well or better relative to the two commercial board types in both directions. The difference in means among the three board types within each category were found to be significant at the 0.05 level of confidence in all cases except in linear expansion comparisons with specimens tested parallel to panel length.

Biodeterioration Resistance

1. Mold did not have a significant effect on the bending strength of specimens tested on edge.

2. With *Lenzites trabea*, all board types showed significantly higher decay resistance relative to the control aspen poplar samples.

3. With *Poria placenta*, short-wafer PF and MKL/PF specimens showed significantly higher decay resistance relative to the control aspen poplar samples.

4. All board types were more or less equal in decay resistance.

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Table 1.--Load levels used in creep experiments[1/]

Level	Load[2/]		Stress[3/]	
	kg	lbs	MPa	psi
Low (L)	3.95	8.7	1.88	273
Medium (M)	10.05	22.2	4.79	696
High (H)	16.15	35.6	7.69	1116

1/Load of 16.15 kg simulates the average snow load in Canada of 2.7 kN/m^2 (57 lbs/ft^2)

2/1 kg = 2.20462 lbs

3/1 MPa = 145.038 psi

Table 2.--Comparison of creep deflection curves of the various waferboards

Load level	Board type	Relative deflection (%) Instantaneous	900 hours
	Within Load Levels		
Low	PF$_1$ parallel	100	175
	PF$_1$ perpendicular	238	393
	MKL/PF	144	244
Medium	PF$_1$ parallel	100	155
	PF$_1$ perpendicular	191	296
	MKL/PF	135	204
High	PF$_1$ parallel	100	144
	PF$_1$ perpendicular	199	301
	MKL/PF	181	270
	Among Load Levels		
Low	PF$_1$ parallel	100	174
Medium		303	469
High		438	632
Low	PF$_1$ perpendicular	100	165
Medium		242	376
High		367	554
Low	MKL/PF	100	170
Medium		284	417
High		552	823
	Within and Among Loads		
Low	PF$_1$ parallel	100	175
	PF$_1$ perpendicular	238	393
	MKL/PF	144	244
Medium	PF$_1$ parallel	303	469
	PF$_1$ perpendicular	577	896
	MKL/PF	408	618
High	PF$_1$ parallel	438	632
	PF$_1$ perpendicular	874	1321
	MKL/PF	792	1182

Table 3.--Model parameters and coefficients of governing differential equation of waferboards at 21°C and 65% RH

Parameters and coefficients	PF$_1$ parallel low load values	Relative values (%)[1/] PF$_1$ Parallel L	M	H	Perpendicular L	M	H	MKL/PF L	M	H
σ_0	1.88 (MPa)	100	255	409	100	255	409	100	255	409
E_0	5.50 (GPa)	100	100	100	49	49	49	80	80	80
E_1	9.32 (GPa)	100	137	165	69	66	72	89	132	134
μ_0	32.45 (GPa-hr)[2/]	100	129	180	33	67	69	76	78	88
μ_1	1.40 (GPa-hr)[2/]	100	127	166	62	71	61	78	96	105
ρ_1	9.53[2/]	100	115	152	61	124	123	92	83	93
ρ_2	886.27[2/]	100	120	181	62	147	120	84	71	86
q_1	32.45[2/]	100	129	180	33	67	69	76	78	88
q_2	4,874.46[2/]	100	120	181	30	72	59	67	56	69

1/Relative values are expressed as the percentage of the PF$_1$ parallel specimen values obtained at the low load level.
2/Values should be multiplied by 10^3.

Table 4.--Dimensional properties of waferboard specimens

Board type	Linear expansion		Thickness Swelling	Water Absorption
	Parallel	Perpendicular		
	----------	%	----------	
PF_1	0.25	0.38	39.3	128.9
PF_2	0.27	0.31	35.6	126.3
MKL/PF	0.26		40.1	113.1

Table 5.--Retention of bending strength of mold specimens

Board type	Exposure period	Retention of bending strength	
		Parallel	Perpendicular
	Weeks	---------- % ----------	
PF_1	4	53.6	48.4
	6	66.8	53.0
	8	50.5	50.0
	10	46.5	55.2
PF_2	4	60.1	55.7
	6	65.6	51.6
	8	62.8	53.7
	10	60.8	63.1
MKL/PF	4	65.8	
	6	58.3	
	8	57.7	
	10	59.5	

Table 6.--Weight losses obtained for six specimens per material type with *Polyporus versicolor*, *Lenzites trabea*, *Poria placenta*, and *Chaetomium globosum*[1/]

Material	*Polyporus versicolor*	*Lenzites trabea*	*Poria placenta*	*Chaetomium globosum*
	---------- % ----------			
PF_1 waferboard	3.50 (53.8)	49.46 (15.1)	38.04 (64.2)	5.60 (11.5)
PF_2	5.40 (15.2)	43.45 (11.0)	51.76 (6.5)	6.22 (10.4)
MKL/PF waferboard	5.71 (23.7)	48.55 (20.1)	51.78 (8.1)	6.19 (15.2)
Aspen wood	8.64 (45.4)	65.00 (7.2)	66.98 (3.0)	5.90 (68.7)

1/The first value per fungi is the mean and value in parentheses is the coefficient of variation.

Table 7.--Comparison of weight loss results at 99 percent level of confidence using Student's "t" test

Material comparisons	Test fungus[1/]			
	Polyporus versicolor	*Lenzites trabea*	*Poria placenta*	*Chaetomium globosum*
Aspen wood vs PF_1	8.64 vs 3.50 NS	65.00 vs 49.46 **	66.98 vs 38.04 NS	5.90 vs 5.60 NS
Aspen wood vs PF_2	8.64 vs 5.40 NS	65.00 vs 43.45 **	66.98 vs 51.76 **	5.90 vs 6.22 NS
Aspen wood vs MKL/PF	8.64 vs 5.71 NS	65.00 vs 48.55 **	66.98 vs 51.78 **	5.90 vs 6.19 NS
PF_1 vs PF_2	3.50 vs 5.40 NS	49.46 vs 43.45 NS	38.04 vs 51.76 NS	5.60 vs 6.22 NS
PF_1 vs MKL/PF	3.50 vs 5.71 NS	49.46 vs 48.55 NS	38.04 vs 51.78 NS	5.60 vs 6.19 NS
PF_2 vs MKL/PF	5.40 vs 5.71 NS	43.45 vs 48.55 NS	51.76 vs 51.78 NS	6.22 vs 6.19 NS

1/** = significant difference, NS = nonsignificant difference.

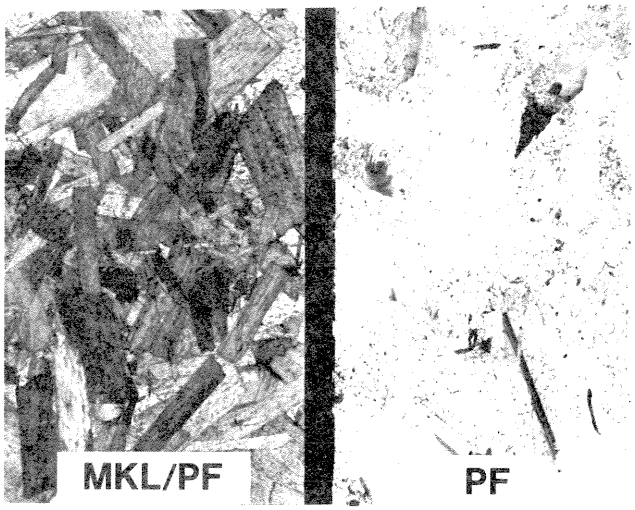

Figure 1.--General appearance of commercial and experimental waferboards

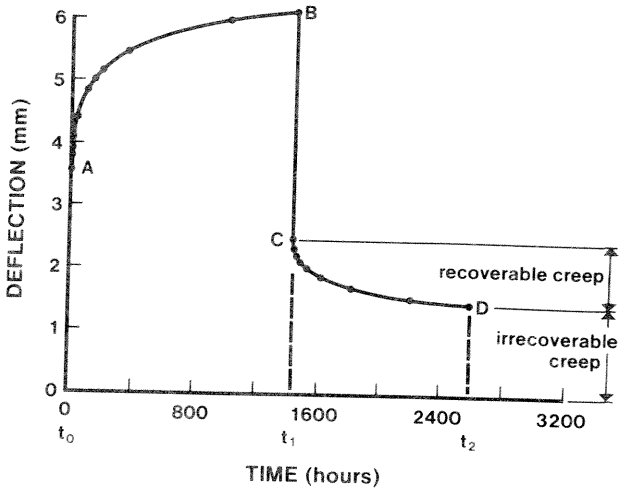

Figure 2.--Time-dependent behavior of wood under sustained load

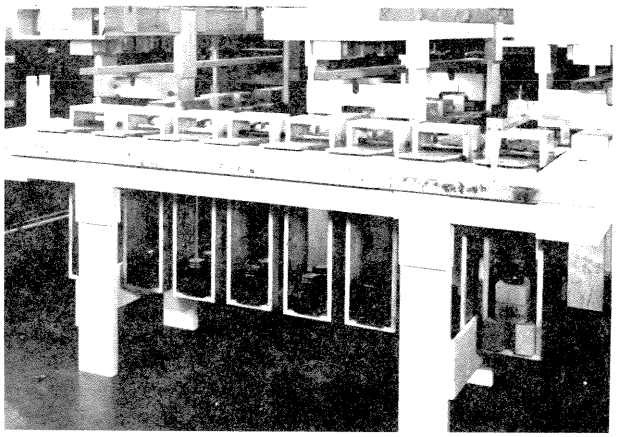

Figure 3.--Creep loading frame and deflection measurement apparatus

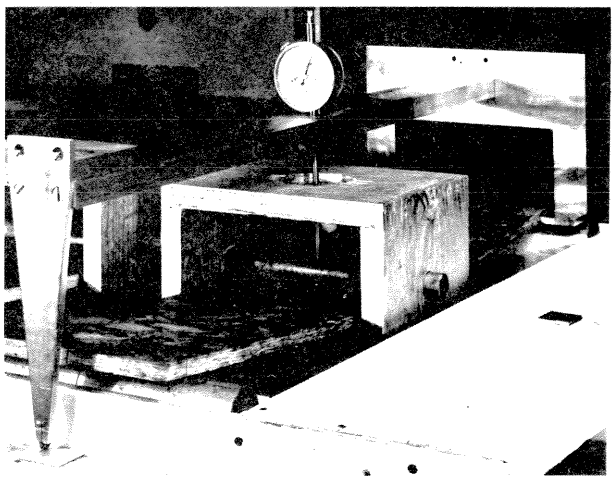

Figure 4.--Deflection measurement apparatus

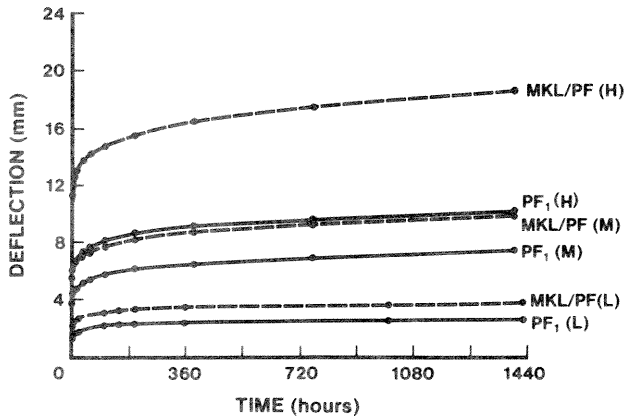

Figure 5.--Effect of load on creep deflection of waferboard specimens tested parallel to panel length

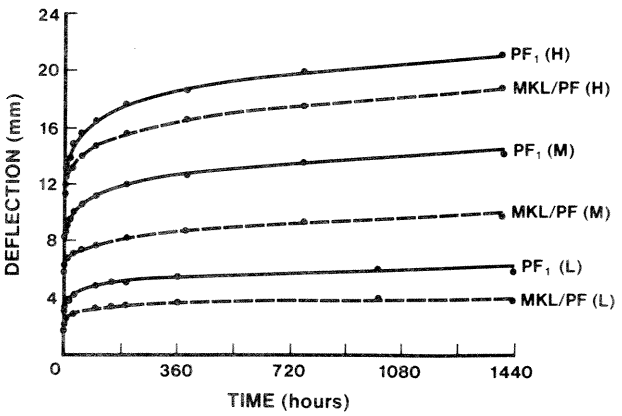

Figure 6.--Effect of load on creep deflection of waferboard specimens tested perpendicular to panel length

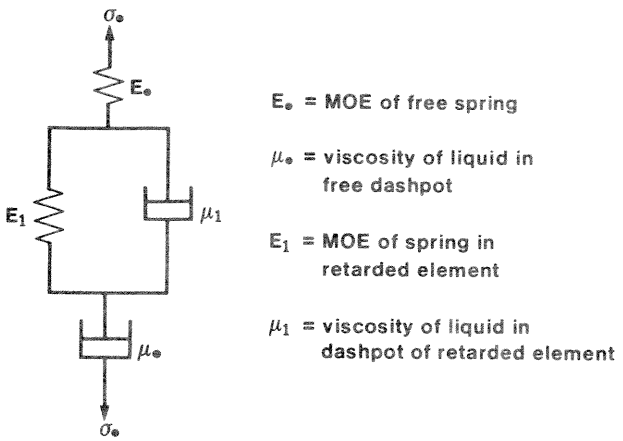

Figure 7.--4-parameter rheological model to represent the viscoelastic behavior of wood

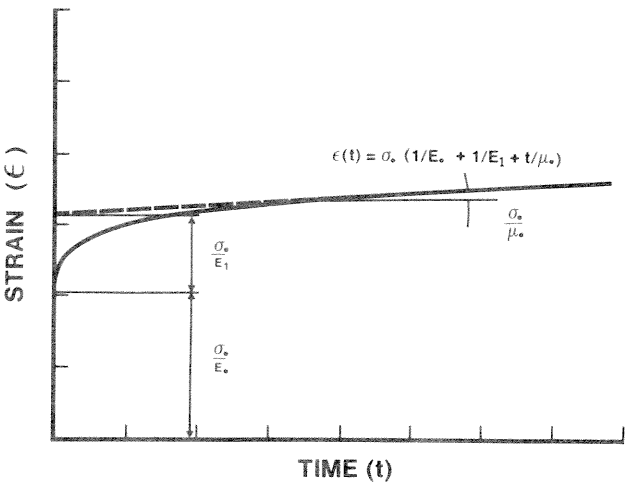

Figure 8.--Graphical analysis of the creep response of the 4-parameter model

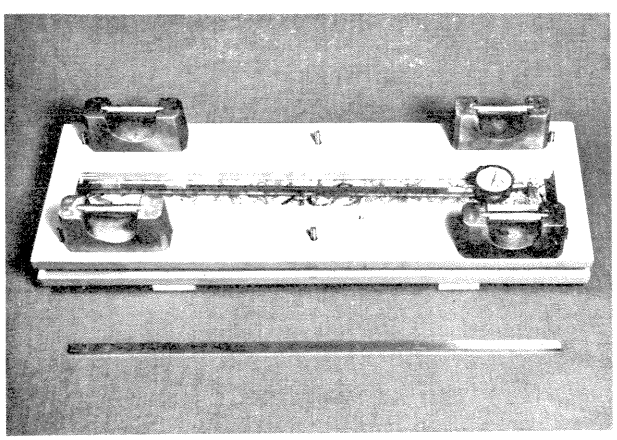

Figure 9.--Linear expansion measurement equipment

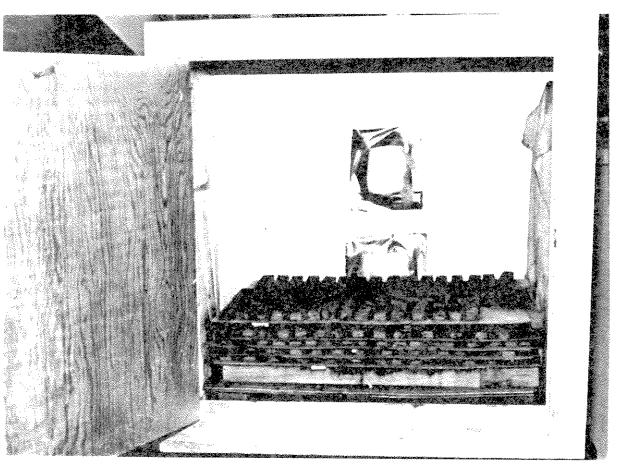

Figure 10.--Mold cabinet

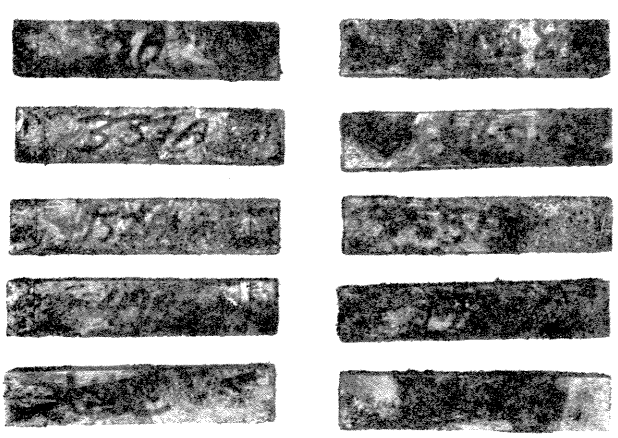

Figure 11.--Typical mold development on specimens

PRESERVATIVE TREATMENT EFFECTS ON MECHANICAL AND THICKNESS SWELLING PROPERTIES OF ASPEN WAFERBOARD[1/2/3/]

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Abstract.--Eighteen liquid or powdered phenolic resol resin-bonded types of aspen (*Populus tremuloides* Michx.) waferboard were manufactured incorporating eight commercially manufactured and one experimental preservative. Preservatives were applied by pretreating wafers, incorporating them with wax or resin at the time of furnish preparation, or by dipping or pressure treating finished panels.

Testing was conducted before and after accelerated aging, as outlined by the American Society for Testing and Materials standard method D 1037. The minimum property requirements of 450,000 psi (3,103 MPa) for modulus of elasticity and 2,500 (17.2 MPa) for modulus of rupture of the American National Standard (ANSI A208.1 - 1979) for mat-formed grade 2-MW wood particleboard were attained by all panel types. However the 50 psi (345 kPa) internal bond specification was not attained in the panel type containing wafers pretreated with formaldehyde and sulfur dioxide or the panel type pressure treated with ammoniacal copper arsenite. Also, the formaldehyde and sulfur dioxide treated panel type did not retain a modulus of at least 1,250 psi (8.6 MPa) after accelerated aging as required by the American National Standard. All panel types but the formaldehyde and sulfur dioxide treated and those treated with a chromated copper arsentate wax emulsion prior to the addition of resin retained at least 50 percent of their control modulus after accelerated again.

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3/Mention of company trade names is solely to identify the material used and should not be interpreted as an endorsement by the University of Minnesota or the U.S. Department of Agriculture.

4/The authors are Scientist and Professor, Department of Forest Products, and Research Associate, Department of Plant Pathology, University of Minnesota, St. Paul, MN, and Technologist, Structural Composite Products and Project Leader, Protection of Wood in Use, Forest Products Laboratory, Madison, WI, respectively. They would like to acknowledge the technical assistance of the following individuals: D. Fahey, S. Okoro, R. Samayoapineda, M. Setzer, and S. Zylkowski, former students of Department of Forest Products, University of Minnesota, St. Paul, MN. The authors also express gratitude to Penta Wood Products, Inc.,Siren, WI, and The MacGillis and Gibbs Company, New Brighton, MN, for pressure treating panels.

INTRODUCTION

Waferboard is being used increasingly in applications where the deleterious effects of moisture and fungi may be encountered, such as structural panels for residential roof and wall sheathing, tongue and groove decking for recreational vehicles, panels for geodesic homes, packaging, crating, sheds, ice fishing shelters and other small structures.

Theoretically, phenol formaldehyde resin offers resistance to fungal degradation because of its customarily high pH and the presence of non-condensed phenol (Schmidt, et al. 1978). However, in practice, leaching of non-condensed phenol can reduce decay resistance thereby necessitating protection (Neusser and Schedl 1970). Furthermore, paints or sizings used to minimize these problems cannot be relied upon as permanent protection (Hedley 1976). Therefore, it is desirable to have a means for imparting some degree of protection to waferboard, preferably at the time of panel manufacture. The type and quantity of preservative or water repellent employed would depend on whether occasional-risk or high risk uses are envisioned.

Wood preservation methods in the United States rely heavily on creosote, chlorinated phenols and copper and arsenic compounds; while the European community has developed alternative compounds specifically formulated for mixing with liquid phenolic particleboard resins (Becker 1972, Becker and Gersonde 1976, Deppe 1970).

The intent of this study was to provide preservative protection for a full spectrum of end uses by incorporating 9 selected preservative treatments (table 1) in one or more of the following ways:

1. Dip treating finished panels
2. Pressure treating finished panels
3. Incorporating with resin or wax during furnish preparation
4. Pretreating the wafers

In this paper we present the first phase of a three phase ongoing study. We report the influence of preservative inclusion on the modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB) and irreversible thickness swelling properties of powdered and liquid phenolic resol resin-bonded aspen (*Populus tremuloides* Michx.) before and after acclerated aging (AA) as outlined by American Society for Testing and Materials (ASTM) Standard D 1037 (1981).

MATERIALS AND METHODS

Five panels of each of eighteen different types (table 2) were made for a total of 90 individual panels. Due to difficulties associated with equipment cleanup and chemical waste disposal, the manufacturing sequence was such that all replicates of one panel type were made consecutively. Ideally, from a statistical point of view, one panel of each type should have been made consecutively, and this process replicated five times. Thus, the manufacturing sequence used provided the opportunity for unrecognized factors to affect some types and not others. Even though the utmost care was exercised during board manufacture to minimize these opportunities, it was felt that an additional safeguard was desirable. Because of this, all statistical analyses were performed at the 1 percent level of significance with Hartley's sequential variant of Newman-Keuls' Q Method (Snedecor and Cochran 1967). This made it increasingly difficult for significant differences to be detected, but at the same time reduced the likelihood of experimental error causing treatments to be declared significantly different when in fact they were not. The net effect of this was a conservative estimation of significant differences. Analyses of variance were conducted for irreversible thickness swelling and IB with a TxR randomized complete block factorial design, where T = 7 or 11 treatments for liquid or powdered resin bonded panels, respectively, and R = 3 replicates. The moduli of rupture and elasticity were analyzed with a TxRxE randomized complete block factorial design, where T and R are as previously stated and E = 2 environments (control and AA).

Preservative Selection

Although pentachlorophenol (PCP) is a common wood preservative in the United States and has been used successfully as a particleboard preservative (Chow 1979, Huber 1976), it was not selected for this study because of reports of excessive loss during hot pressing (Deppe 1970, Hedley 1976) and increasing reservations for its use in human habitats (Anonymous 1980).

Pressure treatments of finished panels using ammoniacal copper arsenate (ACA) and chromated copper arsenate (CCA), respectively, (A and B, table 1), were included as they are known to be effective wood preservatives. Previous studies (Boggio and Gertjejansen 1982, Hall and Gertjejansen 1979) using wood particles pretreated with these preservatives indicated diminished mechanical properties due to their inclusion. Nevertheless, panels from wafers pretreated with (A) to an equivalent of 0.4 pcf retention, and bonded with powdered resin (BD 019, Reichhold Limited) were included to provide a known reference material. Since both preservatives are commercially important in the United States, optional ways of incorporating them also were considered. It was decided to incorporate them with the wax emulsion. The wax used in this study (Paracol 810 NP wax emulsion, Hercules Incorporated) was found to be compatible with (A), but not with (B). Therefore, it was necessary to use a special waxy water repellent additive (WeatherShield, Osmose) with (B) that was not specifically formulated for particleboard manufacture. Our personal experience indicated that typical liquid phenolic resol resins used in the United States (PB 65, Borden Chemical) and (Plenco 650, Plastics Engineering Company) were incompatible when mixed with (A) or (B), so this method was not employed.

Two liquid preservatives specifically formulated for mixing with liquid phenolic particleboard resins that contained either chloronaphthalene and tributyltinoxide (C, table 1), or a mixture of water soluble fluorine and copper compounds (D, table 1) were screened for suitability. Both mixed with the liquid resin used in this study (PB 65, Borden Chemical) and therefore were incorporated and applied during furnish preparation. Unlike (C), (D) also was found to be semi-compatible (some wax coagulated) with the Paracol 810 NP wax emulsion and therefore was incorporated with it during furnish preparation in another panel type that was bonded with the powdered resin. Additional searching for liquid preservatives compatible with liquid phenolic resin or the wax emulsion indicated that 2-(thiocyanomethylthio) benzothiazole (E, table 1) mixed with the liquid resin and therefore was included during furnish preparation in another panel type.

The powdered resin was mixed with CIS-N-{(1,1,2,2-tetrachloroethyl) thio}-4-cyclohexene-1,2-dicarboximide (F, table 1), also a powder, and

applied simultaneously during furnish preparation. This chemical is a widely used agricultural fungicide and a known skin sensitizer to certain people. However, it was estimated that in use the risk would be minimal since it would not be concentrated on the panel faces as would be the case if applied in the usual manner by dipping or spraying.

A novel technique, (G, table 1) that is under study in Europe is to sequentially treat wood with formaldehyde and sulfur dioxide gases. In our study this technique was used to pretreat wafers. Studies (Dewispelacre, Van Raemdonck, and Stevens 1977, Stamm 1959, Stevens, Schalck, and Van Raemdonck 1979) with paper or small wood blocks indicated that this treatment imparts dimensional stability by cross linking wood substance with formaldehyde (acetal formation). A secondary benefit from this cross-linked formaldehyde is that fungal attack is substantially reduced. This treatment was included both for its fungicidal effect and the added dimensional stability that could reduce the reversible component of thickness swelling.

Two proprietary formulations of water repellent preservatives were applied as dip treatments to previously untreated finished panels. One formulation was a petroleum-borne preservative that contained copper-8-quinolinolate (H, table 1). The second preservative was water-borne and contained 3-iodo-2-propynyl butyl carbamate (I, table 1).

Treating Procedures

Preservatives mixed with liquid resin were applied to wafers with a handheld spray gun, subsequent to the application of wax. Preservative application rates were at 0.71 times the preservative manufacturers' recommended rates (No. 13, table 2), at the manufacturers' recommended rates (Nos. 14, 15, 17, table 2) and at 1.4 times these rates (Nos. 16, 18, table 2). Atomizing pressures of 30 to 40 psi (207 to 276 kPa) were used to apply the resin-preservative mixtures. When spraying some of these resin-preservative mixtures (Nos. 13, 14, 17, 18, table 2), it was necessary to warm them to approximately 100°F (38°C) for proper atomization.

Preservatives mixed with wax emulsions (Nos. 6, 7, 10, table 2) were sprayed at approximately 75°F (24°C) at atomizing pressures of 20 to 30 psi (138 to 207 kPa). In the case of No. 6, table 2, water that normally was added in a separate spraying process to raise the mat MC of powder resin-bonded panels was used to dilute the preservative-wax mixture to make it more sprayable. Also, it was necessary to use 30 psi (207 kPa) air pressure to expel some coagulated wax globules when spraying this preservative-wax mixture. In another panel type (No. 10, table 2) the amount that was incorporated with the wax was limited since the desired retention level of 0.98 percent active solids likely would have caused internal delaminations upon press opening due to the low solids content (12 percent) of the stock solution.

Pretreatment of wafers with ACA (No. 11, table 2) was performed in the following manner. The wafers first were saturated with water and subsequently air dried to 98% moisture content (MC); the approximate MC of fresh green wafers. A slightly pressurized nonatomized stream of preservative (2% concentration) then was applied to each batch in a blender. A solids retention of 0.98% (ovendry (OD) wafer basis) was obtained for each batch. Treated batches were sealed in plastic bags and placed in a constant temperature room (72°F, 22°C) for 3 days to allow for chemical diffusion. They then were air dried and finally kiln dried to 5.9% MC (total OD solids basis) prior to panel manufacture.

Wafers selected for treatment with formaldehyde and sulfur dioxide (No. 5, table 2), received a 4-hour fumigation with gaseous formaldehyde at 212-230°F (100-110°C) under a 100 Torr vacuum, followed by a 30-minute fumigation with 16 percent (by volume) sulfur dioxide flowing at about 1L/minute. Subsequent heating in a forced air oven for 24 hours at 221°F (105°C) to drive off free formaldehyde resulted in an approximate 1 percent net weight gain.

Application of powdered preservative to wafers (No. 4, table 2) was accomplished by mixing the preservative with the powdered resin, and tumbling the mixture with the wafers.

All panels, including those to be subsequently treated via pressure (Nos. 8, 9, table 2) or dip treatment (Nos. 2, 3, table 2), were scuff sanded with a drum sander equipped with 80 grit aluminum oxide abrasive. This was done to remove any traces of silicone release agent from the panels bonded with liquid resin. Powdered resin-bonded panels which did not require a release agent also were sanded so that MOR and MOE would be affected equally in all panel types.

Panels designated to be pressure or dip treated were trimmed to 19 X 21 inches (48.3 cm X 53.3 cm) and edge-sealed with an elastomeric contact cement. With panels to be pressure treated, aluminum foil also was used to seal the edges. Pressure treating was done commercially. Panels receiving CCA and ACA pressure treatments (Nos. 8, 9, table 2, respectively) were included with charges of posts or plywood, respectively. Preservative loadings of CCA and ACA were determined by assay [Mercury displacement was used to determine density and samples were digested per AWPA A7-75 and analyzed per AWPA A2-78 specifications (American Wood Preservers Association 1981)] to be 0.62 and 0.57 pcf (9.9 and 9.1 kg/m^3), respectively. Panels to be dip treated (Nos. 2, 3, table 2) were removed from a drying oven and immediately weighed and then immersed horizontally in the treating solution for 3 minutes. They then were removed and allowed to drip for 3 minutes before reweighing and air-drying.

Panel Manufacturing Parameters

Untrimmed panels were 23 X 24 X 5/8 inches (58.4 cm X 70 cm X 1.6 cm) thick and had a nominal density of 42 pcf (673 kg/m^3). This density was based on ovendry mass of wood, resin solids, and wax solids, and volume at moisture equilibrium in a control environment of 50% relative humidity at 72°F (22°C). All panels contained the same OD weight of commercially produced, dried, and screened aspen (*Populus tremuloides* Michx.) wafers and wax solids (1 percent wax solids, based on the OD weight of wafers). All boards, aside from those which received pressure-treating, contained 3 percent resin solids (based on OD weight of wafers); panels which received subsequent pressure-treating contained 4 percent resin solids. A wax emulsion (Paracol 810 NP wax emulsion, Hercules Incorporated) was sprayed onto the wafer prior to resin application. One panel type (No. 7, table 2) contained a different wax emulsion (WeatherShield, Osmose). The two resol type phenol formaldehyde resins already mentioned were used. Initially a series of trial waferboards were manufactured to determine the manufacturing parameters needed to give a similar MOR, IB, and thickness swelling properties for panels bonded with powdered or liquid phenolic resins. Results indicated that comparable properties were obtained when 3% solids of either powdered or liquid resin were employed, provided the wafer mats had equivalent moisture contents just prior to pressing, and that panels containing powdered resin were exposed to a slightly higher closing pressure, 515 psi (3.6 MPa) instead of 494 psi (3.4 MPa) and were pressed for a slightly longer time, 8-1/2 minutes instead of 7-1/2 minutes. Panels to be pressure treated contained 4 percent resin to minimize the effects of irreversible thickness swelling during treatment. The press temperature and mat MCs for all panel types were 410°F (210°C) and approximately 8.0 percent (total OD solids basis). After manufacture, all panel types received a simulated hot stacking by sandwiching panels between layers of fiberglass insulation.

Specimen Testing

Approximately 3 inches (7.6 cm) on all edges were trimmed from the original dimensions of all panels to remove potential low density areas. Then six, 3-inch by 17-inch (7.6 cm by 43.2 cm) strips were cut from each panel replicate and were labeled as outer, middle, or inner strips to indicate their former position within the panel. Thus, there were 2 outer, middle, and inner strips from each panel. Static bending test specimens then were allocated as follows. Three of the 5 replicates of each panel type were selected to provide 1 static bending specimens per panel so that an outer, middle, and inner strip was allocated for testing in an unaged (control) condition. This process was repeated again for allocating specimens to an aged, AA (1), condition. Thus, 3 specimens, each from different panel replicates and from different locations within a panel replicate were allocated to each condition. However, the control and AA specimens did not necessarily come from the same 3-panel replicates. This allocation scheme was used to insure that the estimate of experimental error was based on independent samples.

Static bending and IB properties were determined at the control condition of 50 percent RH at 72°F (22°C) in accordance with ASTM standard D 1037-78 (American Society for Testing and Materials 1981). Three IB specimens were cut from intact portions of each failed control bending strip. Irreversible thickness swelling, which is the difference between re-equilibrated thickness and initial thickness at the control condition expressed as a percentage of initial thickness at the control condition, was determined after AA.

RESULTS AND DISCUSSION

Table 3 and figures 1 through 8 give the basic properties of the 18 panel types. Odd numbered figures pertain to powdered resin-bonded panels and even numbered figures to liquid resin-bonded panels.

MODULUS OF ELASTICITY

The requirement of 450,000 psi (3,103 MPa), MOE for grade 2-MW particleboard specified by ANSI A208.1 - 1979 (National Particleoard Association) was met by all panel types (control, MOE, table 3). These moduli were computed with post-preservative treatment thicknesses. Significantly different MOEs exist for the different powdered resin-bonded panels (fig. 1), but not for the liquid-bonded panels (fig. 2). The coefficient of variation (COV) for untreated panels with powdered resin and liquid resin are 7.1 percent and 11.6 percent, respectively, for the unaged condition, and 3.6 percent and 8.2 percent, respectively, after exposure to AA.

The MOE behavior of some of the treated powdered resin-bonded panel types will be discussed next. Exposure to AA significantly reduced MOE of panels made of formaldehyde and sulfur dioxide treated wafers (No. 5, fig. 1), while panels which received one of the dip treatments (No. 3, fig. 1) showed no MOE loss as a result of AA exposure. This lack of MOE loss is not readily explained. Panels from formaldehyde and sulfur dioxide treated wafers (No. 5, fig. 1) showed MOE values after AA that were significantly lower than MOE values for any other panel type. Also, the control MOE for panel type (No. 6, fig. 1) was found to be statistically higher than the MOE after AA of pressure treated panel types (Nos. 8, 9, fig. 1). Due to thickness swelling during pressure treating and the fact that post preservative-treatment re-equilibrated thickness were used to compute MOE, the pressure treated panels (Nos. 8, 9, fig. 1) had the lowest MOE values.

Modulus of Rupture

Figures 3 and 4 illustrate the MOR properties of the powdered and liquid resin-bonded panels, respectively. The COVs for untreated panels bonded with powdered resin and liquid resin are 15.9 percent and 18.7 percent, respectively, for the unaged condition, and 5.5 percent and 21.7 percent, respectively, after exposure to AA. Moduli of rupture, computed on the basis of thickness after preservative treatment, are presented in table 3. All panel types initially met the ANSI (National Particleboard Association 1979) minimum requirement of 2,500 psi (17.2 MPa) MOR (control MOR, table 3). However, panels made of formaldehyde and sulfur dioxide treated wafers and bonded with powdered resin (No. 5, AA MOR, table 3) did not meet the minimum MOR requirement of 1,250 psi (8.6 MPa) after AA as required by the standard. Loss of MOR resulting from AA exposure was statistically significant in some panel types (Nos. 5, 7, 17, MOR loss, table 3) while the loss for panel no. 18 (MOR loss, table 3) was nearly significant.

The poor performance after AA of panels made from formaldehyde and sulfur dioxide treated wafers (No. 5, fig. 3) may be due to cross-linked formaldehyde occupying a large number of previously available hydroxyl sites for resin bonding, thus reducing the bonding ability of resin to cellulose. The loss of MOR shown by panels made of wafers sprayed with CCA mixed in a wax emulsion (No. 7, MOR loss, table 3) is possibly pH related. The extremely low treating solution pH for this panel type could cause either a retarding or accelerating effect on resin cure (Wake 1976). In either case, limited bonding or pre-curing could occur. To illustrate this point, notice the values for another panel type (No. 6, MOR loss, table 3 and fig. 3). This preservative treatment is the same one used for a similar panel type (No. 18, MOR loss, table 3 and fig. 4), a difference being that the preservative was mixed with wax, and powdered rein was used instead of liquid resin. The fact that different resins were used may be the primary reason for the different MORs. One of the dip treated panel types (No. 3, MOR loss, table 3) showed the least percent loss of MOR from AA.

When unaged MORs of liquid resin-bonded panels are compared, there are no significant diferences among treatments. Likewise, when aged liquid resin-bonded panels are compared in a similar manner, no significant differences in MOR are found.

Internal Bond

Determining the IB of aged material was not feasible because of visible shear failure in the core of some panel types (Nos. 5, 7, 11, 14-18, table 2) during the static bending testing. The results of unaged IB tests are given for the powdered and liquid resin-bonded panels in figures 5 and 6, respectively, and table 3. The COVs for unaged untreated panels bonded with powdered and liquid resins are 16.6 percent and 10.4 percent, respectively. Panels made from formaldehyde and sulfur dioxide treated wafers and ACA pressure-treated panels (Nos. 5, 9, control IB, table 3) did not meet the minimum IB requirement of 50 psi (345 kPa) IB specified by the ANSI standard (National Particleboard Association 1979). The only statistically significant difference for powdered resin-bonded panels (Nos. 1-11, fig. 5) is between the highest and lowest IBs, i.e, panel types Nos. 4 and 9 (fig. 5). However, it is obvious that the panel type made from formaldehyde and sulfur dioxide treated wafers (No. 5, fig. 5) also is suspect. When making these comparisons, it should be remembered that the pressure treated panels (Nos. 8, 9, fig. 5) contained an additional 1 percent resin solids to minimize irreversible thickness swelling and subsequent loss of IB.

Also, it was determined statistically that two of the liquid resin-bonded panels types, each one containing a different preservative, one applied at 0.71 times the manufacturer's recommended rate and the other at 1.4 times the manufacturer's recommended rate, (Nos. 13 and 16, fig. 6, respectively), had significantly higher IBs than another liquid resin-bonded panel type containing a third preservative applied at 1.4 times its manufacturer's recommended rate (No. 18, fig. 6). The preservative applied at 0.71 times its manufacturer's recommended rate (No. 13, fig. 6) also was applied at 1.4 times its recommended rate, but this level caused core delaminations upon hot press opening and therefore was not included in table 2.

Irreversible Thickness Swelling

Because much irreversible thickness swelling occurred during pressure treating, panels which were pressure-treated (Nos. 8 and 9, fig. 7) swelled the least from AA exposure. These panel types were equal statistically, and had significantly less swelling than some other powdered resin-bonded panel types (Nos. 1,2,5,7, fig. 7). It also can be stated that panels made from formaldehyde and sulfur dioxide treated wafers (No. 5, fig. 7) were statistically equivalent to panels from wafers sprayed with CCA mixed in a wax emulsion (No. 7, fig. 7) and those which received no preservative treatment or those which received one of the dip treatments (Nos. 1, 2, fig. 7). The COVs of irreversible thickness swelling after AA for untreated powdered and liquid resin-bonding panels were 10.6 percent and 16.7 percent, respectively. No statistically significant differences in irreversible thickness swelling were found between any of the different board types bonded with liquid resin (Nos. 12-18, fig. 8).

SUMMARY

All panel types met the American National Standard (ANSI A208.1-1979) static bending

requirements of 450,000 psi (3,103 MPa) modulus of elasticity (MOE) and 2,500 psi (17.2 MPa) modulus of rupture (MOR) for mat-formed, grade 2-MW wood particleboard (National Particleboard Association 1979). However, the panel type manufactured from wafers pretreated with formaldehyde and sulfur dioxide (No. 5, table 2) did not meet this standard's minimum requirement of 1,250 psi (8.6 MPa) modulus of rupture after ASTM D 1037-78 accelerated aging (American Society for Testing and Materials 1981). The panel type from wafers pretreated with formaldehyde and sulfur dioxide (No. 5, table 2) and the panel type that was pressure treated after panel manufacture with ammoniacal copper arsenate (No. 9, table 2) failed to meet the minimum requirement of 50 psi (345 kPa) internal bond specified by the standard (National Particleboard Association 1979). Panel types pressure treated with chromated copper arsenate (No. 8, table 2) and ammoniacal copper arsenate (No. 9, table 2) swelled in thickness during treating such that subsequent accelerated aging (American Society for Testing and Materials 1981) caused less than 1 percent irreversible thickness swelling. The panel type from wafers pretreated with formaldehyde and sulfur dioxide (No. 5, table 2) was statistically equivalent to the panel type containing chromated copper arsenate that was applied as a mixture with a wax emulsion during furnish preparation (No. 7, table 2), the untreated panel type (No. 1, table 2) and the panel type whose finished panels were dip treated with a copper-8-quinolinolate solution (No. 2, table 2). There were no statistically significant differences in irreversible thickness swelling between any of the panel types bonded with liquid resin (Nos. 12-18, table 2).

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Table 1.--Selected preservatives for the treatment of aspen waferboard

A.	Ammoniacal copper arsenate (ACA): Chemonite, J. H. Baxter and Co., 1700 South El Camino Real, San Mateo, CA 94402.
B.	Chromated copper arsenate (CCA): K-33-C, Osmose, 980 Ellicott Street, Buffalo, NY 14209.
C.	Chloronaphthalene and tributyltinoxide: Basileum SP 70, Desowag-Bayer Holzschutz GmbH, Ross-Strasse 76, D-4000 Dusseldorf 30, Federal Republic of Germany.
D.	Fluorine and copper compounds: Wolmanit ClO, Dr. Wolman Gmbh, Postfach 1160, 7573 Sinzheim, Federal Republic of Germany.
E.	2-(thiocyanomethylthio) benzothiazole: Busan 30, Buckman Laboratories, Inc., Memphis, TN 38108.
F.	CIS-N-[(1,1,2,2-tetrachloroethyl)thio]-4-cyclohexene-1,2-dicarboximide: Difolatan, Chevron Chemical Co., 575 Market Street, San Francisco, CA 94105.
G.	Sequential treatment with formaldehyde and sulfur dioxide gases.
H.	Copper-8-quinolinolate: PQ-675, Chapman Chemical Co., P. O. Box 9158, Memphis, TN 38109.
I.	3-iodo-2-propynyl butyl carbamate: water base Woodlife, Roberts Consolidated Industries, 600 North Baldwin Park Boulevard, City of Industry, CA 91749.

Table 2.--Aspen waferboard panel types

1.	No treatment, powdered resin, 3 percent resin solids.
2.	Dip treatment of finished panel, copper-8-quinolinolate, 0.03% solids retention, powdered resin, 3% resin solids.
3.	Dip treatment of finished panel, 3-iodo-2-propynyl butyl carbamate, 0.03% solids retention, powdered resin, 3% resin solids.
4.	Preservative mixed with resin and applied during furnish preparation, CIS-N-[(1,1,2,2-tetrachloroethyl) thio]-4-cyclohexane-1, 2-dicarboximide, 0.25% active solids retentions, powdered resin, 3% resin solids.
5.	Pretreatment of wafers with gaseous formaldehyde and sulfur dioxide, approximate 1% net weight gain, powdered resin, 3% resin solids.
6.	Preservative mixed with wax emulsion and applied during furnish preparation, aqueous copper and fluorine mixture, 0.98% active solids retention, powdered resin, 3% resin solids.
7.	Preservative mixed with wax emulsion and applied during furnish preparation, chromated copper arsenate, 0.98% active solids (0.40 pcf equivalent) retention, powdered resin, 3% resin solids.
8.	Pressure treatment of finished panel, chromated copper arsenate, 0.62 pcf active solids retention determined by assay, powdered resin, 4% resin solids.
9.	Pressure treatment of finished panel, ammoniacal copper arsenate, 0.57 pcf active solids retention determined by assay, powdered resin, 4% resin solids.
10.	Preservative mixed with wax emulsion and applied during furnish preparation, ammoniacal copper arsenite, 0.61% active solids (0.25 pcf equivalent) retention, powdered resin, 3% resin solids.
11.	Pretreatment of wafers with ammoniacal copper arsenate, 0.98% active solids (0.40 pcf equivalent) retention, powdered resin, 3% resin solids.
12.	No treatment, liquid resin, 1% resin solids.
13.	Preservative mixed with resin and applied during furnish preparation, 2-(thiocyanomethylthio)benzothiazole, 0.11% active solids retention, liquid resin, 3% resin solids.
14.	Preservative mixed with resin and applied during furnish preparation, 2-(thiocyanomethylthio)benzothiazole, 0.15% active solids retention, liquid resin, 3% resin solids.
15.	Preservative mixed with resin and applied during furnish preparation, monochloronaphthalene and tributyltinoxide, 1.0% stock solution, liquid resin, 3% resin solids.
16.	Preservative mixed with resin and applied during furnish preparation, monochloronaphthalene and tributyltinoxide, 1.4% stock solution, liquid resin, 3% resin solids.

Table 2, continued

17. Preservative mixed with resin and applied during furnish preparation, aqueous copper and fluorine mixture, 0.70% active solids retention, liquid resin, 3% resin solids.

18. Preservative mixed with resin and applied during furnish preparation, aqueous copper and fluorine mixture, 0.98% active solids retention, liquid resin, 3% resin solids.

Table 3.--Physical and mechanical properties at equilibrium with 72°F (22°C) and 50% relative humidity (control environment) of untreated and treated aspen waferboard before and after accelerated aging

Panel Type [1]	Density [2,3] (pcf)	(kg/m³)	Control EMC [2] (%)	Control MOR [2,4] (psi)	(MPa)	AA MOR [2,3] (psi)	(MPa)	MOR [5] loss (%)	Control MOE [2,4] (x10³ psi)	(MPa)	AA MOE [2,3] (x10³ psi)	(MPa)	Control IB [6] (psi)	(kPa)	AA ITS [2,7] (%)
1	42.3	678	6.0	4310	29.7	3550	24.5	18	788.6	5437	711.0	4902	78	538	23.2
2	43.4	696	6.9	4290	29.6	3200	22.1	26	775.9	5350	711.6	4906	65	448	24.0
3	42.3	678	6.2	3740	25.8	3470	23.9	7	710.0	4896	713.5	4920	68	469	13.4
4	42.5	681	5.9	4810	33.2	3420	23.6	29	844.5	5823	662.0	4564	81	558	7.4
5	43.1	691	5.8	2960	20.4	730	5.0	75	775.0	5344	272.0	1875	45	310	38.7
6	43.9	704	5.7	5420	37.4	3990	27.5	26	902.9	6226	727.5	5016	79	545	6.0
7	44.5	713	5.8	4270	29.4	1740	12.0	59	852.2	5876	660.0	4551	62	427	44.8
8	39.3	630	7.6	3270	22.5	2650	18.3	19	587.0	4047	535.9	3695	53	365	0.7
9	37.9	607	8.1	3150	21.7	2310	15.9	27	571.0	3937	504.7	3480	44	303	0.6
10	43.4	696	5.9	4140	28.5	3530	24.3	15	806.9	5564	695.1	4793	65	448	8.0
11	42.3	678	6.0	3900	26.9	2370	16.3	39	801.7	5528	597.3	4118	50	345	11.8
12	43.2	692	6.2	4600	31.7	3500	24.1	24	778.3	5366	736.1	5075	66	455	27.8
13	42.7	684	6.0	4410	30.4	3790	26.1	14	790.3	5449	739.4	5098	70	483	28.2
14	43.2	692	6.1	4350	30.0	3330	23.0	24	745.7	5142	724.4	4995	67	462	31.2
15	43.2	692	6.2	3970	27.4	3540	24.4	11	761.5	5250	759.6	5237	65	448	31.4
16	43.9	704	6.0	3890	26.8	3260	22.5	16	773.1	5330	730.1	5034	72	496	29.7
17	44.1	707	6.2	4330	29.9	2450	16.9	44	830.3	5725	699.4	4822	62	427	36.5
18	42.8	686	6.2	4140	28.5	2350	16.2	43	763.5	5264	686.8	4736	51	352	36.2

[1] The panel types are described in Table 2.

[2] Values are the average of 3 specimens.

[3] Based on equilibrated thickness after preservative treating before accelerated aging.

[4] Based on equilibrated thickness after preservative treating.

[5] Based on test values, not the minimum property requirement of ANSI A208.1 - 1979.

[6] Values are the average of 9 specimens.

[7] Irreversible thickness swelling (ITS) is the difference between equilibrated thickness after accelerated aging and initial equilibrated thickness as a percent of initial equilibrated thickness.

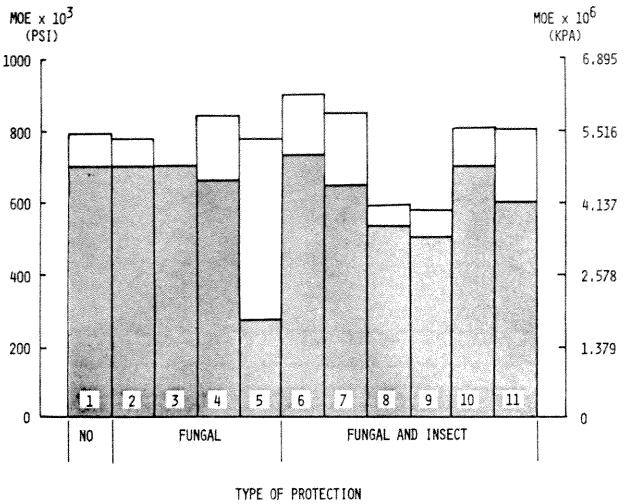

Figure 1.--Modulus of elasticity of powdered phenolic resin bonded waferboard before □ and after ■ ASTM accelerated aging.

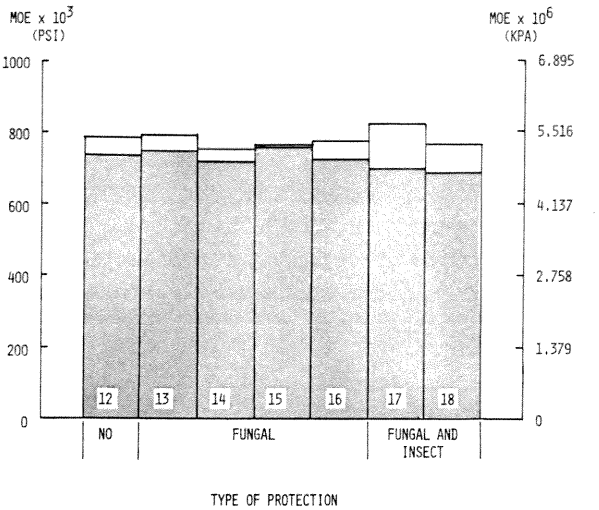

Figure 2.--Modulus of elasticity of liquid phenolic resin bonded waferboard before □ and after ■ ASTM accelerated aging.

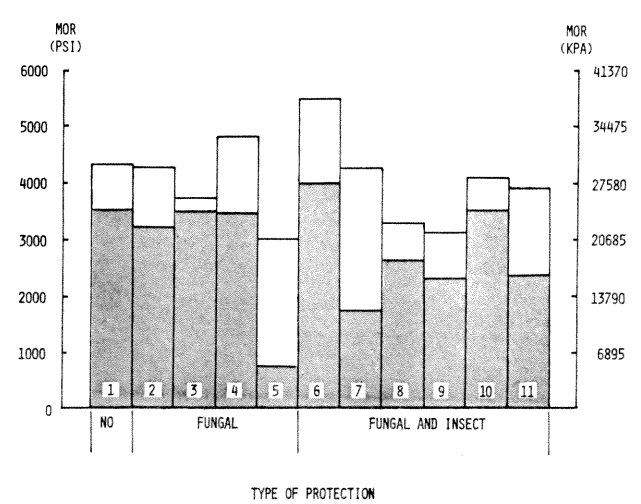

Figure 3.--Modulus of rupture of powdered phenolic resin bonded waferboard before □ and after ■ ASTM accelerated aging.

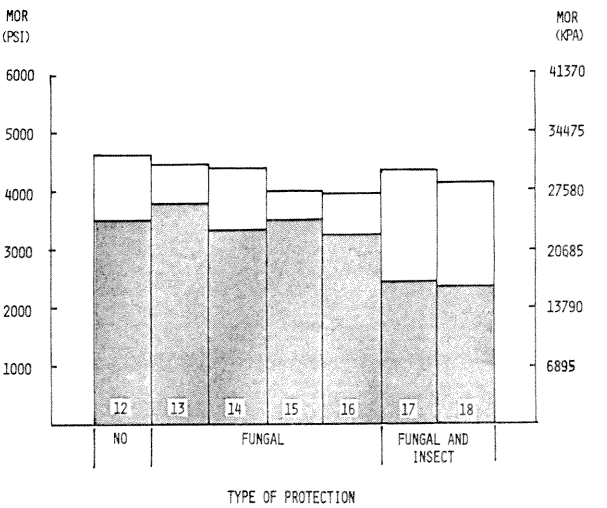

Figure 4.--Modulus of rupture of liquid phenolic resin bonded waferboard before □ and after ■ ASTM accelerated aging.

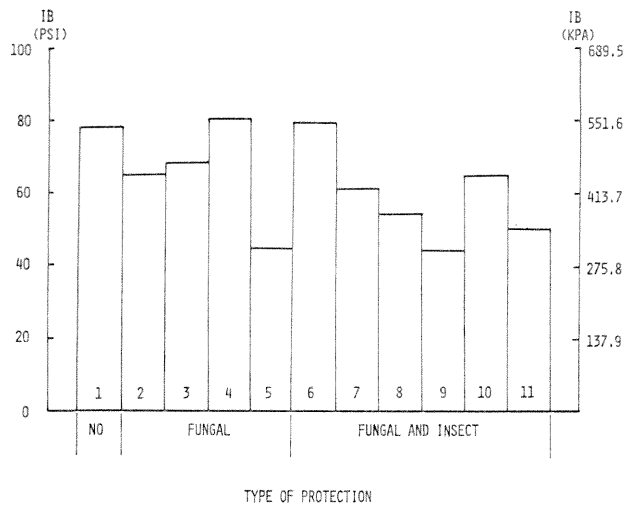

Figure 5.--Internal bond of powdered phenolic resin bonded waferboard.

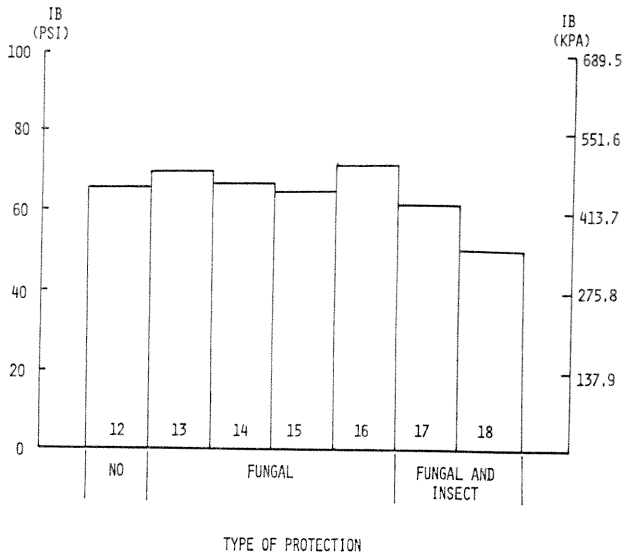

Figure 6.--Internal bond of liquid phenolic resin bonded waferboard.

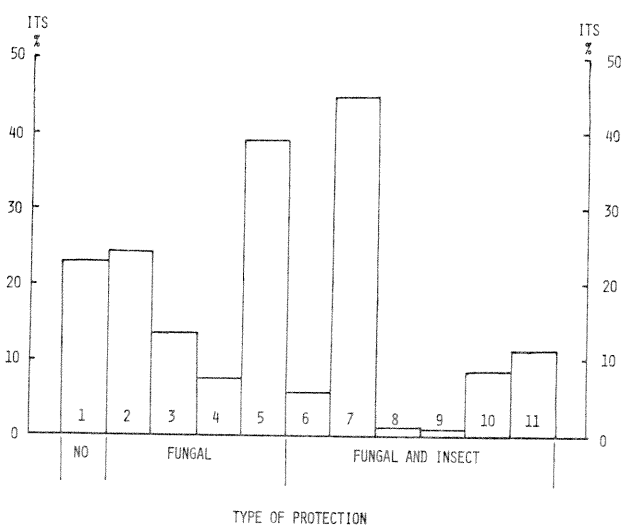

Figure 7.--Irreversible thickness swelling of powdered phenolic resin bonded waferboard after ASTM accelerated aging.

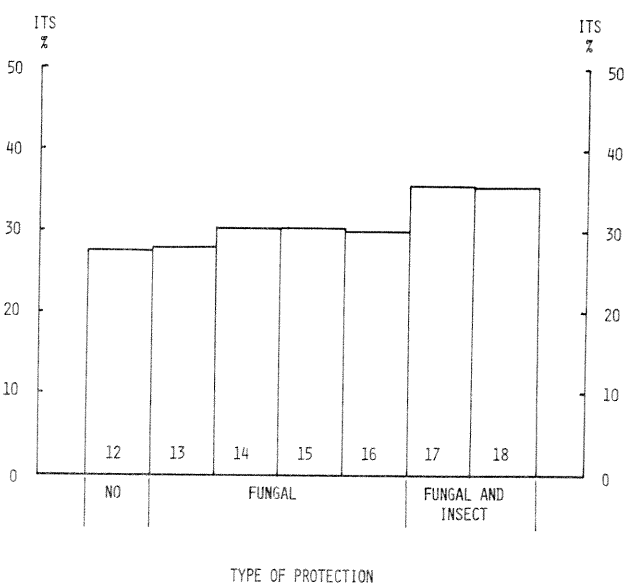

Figure 8.--Irreversible thickness swelling of liquid phenolic resin bonded waferboard after ASTM accelerated aging.

EVALUATION OF PRESERVATIVE EFFECTS ON MECHANICAL PROPERTIES AND BIODURABILITY OF ASPEN WAFERBOARD[1/2/]

E. L. Schmidt, H. J. Hall, and R. O. Gertjejansen[3/]

Abstract.-- Experimental aspen waferboards, bonded with liquid or powdered phenol formaldehyde resins and treated by various methods with a wide selection of preservatives, were tested for fungal resistance in accelerated laboratory trials. Mold growth on the surface as well as weight and strength losses due to the action of decay fungi were determined. Testing of board strength after decay in high and moderate-hazard exposure conditions required modification of decay tests used for solid wood. A range of protection was noted with no preservative system exceeding the efficacy of the inorganic salt formulations. Averaged over all treatments, strength loss and weight loss are well correlated.

INTRODUCTION

Waferboard may become increasingly important as a structural panel product for residential and commercial construction. Canada has several waferboard plants, and there presently are several in production in the United States. However, more waferboard/flakeboard/oriented strandboard type plants may be built in the very near future. Projected demand for aspen waferboard includes many applications where durability against moisture and the deleterious effects of fungi and insects are necessary. Construction practices, paints, or sizings used to minimize moisture problems must be strictly maintained in service to effectively prevent damage by biological agents, and therefore cannot be completely relied upon as permanent protection. In addition, decay in any portion of a structural sheet of waferboard would involve high replacement costs (Hann et al. 1962). Therefore, the evaluation of aspen waferboard treated with various preservatives in both laboratory and field tests is important in assessing the potential service life of waferboard in high-risk or occasional-risk uses. Waferboard and flakeboard with decay and mold resistance would have potential application in numerous uses such as sheathing or subflooring in mobile homes and recreational vehicles, and construction of ice-fishing shelters. Treated waferboard would also find use in certain watercraft components and for some exterior uses within the United States. For example, in Puerto Rico 1/4" Canadian waferboard is being pressure treated with CCA and used for interior wall partititions. Although studies have evaluated the weatherability and 1-year exposure durability of flakeboards made from ACA-treated Ghanian hardwood flakes (Hall and Gertjejansen 1979, and Laudrie et al. 1979). Additional information on other treatments is wanting.

A previous report evaluated the effects of several preservatives, 2 resin types, and various treating methods on the mechanical and thickness swelling properties of aspen waferboard (Hall et al. 1982). Utilizing some of the same material, laboratory biodeterioration and concurrent strength losses were analyzed and reported in this report.

MATERIALS AND METHODS

Soil block testing (ASTM 1413) is a commonly accepted U.S. standard test that would subject waferboard to a decay hazard more severe than would be encountered in most service situations. However, the test is beneficial in assessing the comparative performances among candidate preservatives with a reasonable expenditure of time and materials. The test method uses weight loss of treated samples for primary evaluation, but, as has been stressed by leading foreign workers in particleboard deterioration (Becker and Deppe 1970, Griffioen 1969, Kerner-Gang and Becker 1968), evaluations based on reduction of strength properties are more germane to waferboard's

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intended structural use. Therefore, both weight loss and a crushing test that reflects the internal bond strength were determined for control and weathered samples. In addition, control and weathered bending samples were exposed in large soil-pan vessels to pure cultures of decay fungi. Previous results employing this method have indicated that significant strength reductions may occur even in treated particleboard exposed to actively growing fungi (Schmidt et al. 1978).

For evaluation of the lesser decay hazard in above-ground use of treated waferboard, a non-soil test ('contact block test') based on procedures of Behr (1977, 1978) was selected. The test was designed to simulate, in the laboratory, the resistance of treated materials to decay in above-ground service situations (i.e., no soil). The ability of a decay fungus which is well established on untreated wood, to spread to a treated piece of board in direct contact should reflect efficacy of a preservative to prevent decay in a wet environment out of soil contact.

Phenolic bonded particleboards that have failed in wet service conditions are often heavily invaded by fungi similar to those causing stain in lumber. Treated panel materials used in damp conditions may suffer paint failure or develop surface molding which can cause odor and allergy problems. Therefore, any proposed commercial treatment for waferboard should include evaluation of the stain and mold resistance on control and weathered samples.

Squares of treated waferboard (2" wide) were surface disinfested by a 2-second dip in boiling water, dipped in spore suspensions of test fungi, and suspended over water in sealed glass jars. After six weeks of incubation, samples were removed and rated for fungal overgrowth on the faces (0 = no growth; 1 = trace; 2 = 6-20%; 3 = 21-50%; 4 = 51-80%; 5 = 81-100% overgrowth).

RESULTS

Mold and Stain

Penicillum sp. was inhibited (i.e., the obvious area of sample overgrowth remained less than 20% or rate 2 on the fungus rating scale) on control (i.e., nonleached) samples dipped in surface-treatments 7 and 8, or treated in some fashion by ACA or CCA (with the notable exception of the CCA/wax treatment 13) (fig. 1). The TBTO treatments (15, 16) outperformed the Cu/Fl additions (17, 18). Although the accelerated aging process decreased the efficacy of the surface dip treatments, certain inorganic salt treatments (10, 11, 14) and the higher TBTO loading (15) retained mold inhibition.

The *Cladosporium* sp. (previously isolated from molded CCA-treated lumber) was not controlled by any of the treatments on leached (acclerated aged) materials.

Stain caused by *Aureobasidium pullulans* that is commonly encountered on weather-exposed wood was controlled by treatments 5, 6, 7, 8, 10, 11, 12, and 13 on non-aged samples. Interestingly, the development of this fungus on aged materials made from powdered resin was consistently, and in 2 cases (1, 14) dramatically, lower than on boards made from liquid resins or on non-aged controls. One possible explanation is the heat and moisture cycles associated with aging may condense some free phenols that are effective in preventing fungus growth on the surface. And this process occurs to a greater degree in boards made from powdered resin than from liquid resin. Also, the free fungicidal phenols may be redistributed to the sample surface during drying to a greater degree with powdered resin systems.

Contact Block

Gloeophyllum trabeum, the fungus frequently responsible for decay in wood members not in ground contact, decayed all samples except treatments 9-18, to levels similar to the untreated controls (fig. 2). The dip-treated samples (7, 8) as well as those containing TBTO (15, 16) decayed to a greater degree after accelerated aging. *Poria placenta* decay of samples in this test closely matched that of *G. trabeum* with the exception of untreated board made with liquid resin (2) and those containing TCMTB (3, 4), which were substantially more susceptible to *G. trabeum*.

With many aboveground uses envisioned for treated waferboard, the results of this test may better predict the performance of the preservatives than do the more severe decay tests (soil-block, soil-pan) in which untreated susceptible materials are more severely decayed.

Soil Block/Edge Crushing Strength

Instead of the 3/4-inch cubes recommended in ASTM D 1413, 1-1/2-inch square sample blocks were incubated in 16-ounce vessels. After weight loss determinations, the blocks were crushed on edge at a load rate of 0.05-in/min. The proportional limit (PL) was obtained for the incubated blocks and compared to previously wetted, but sterile, control samples containing the same preservative treatment. The edge crushing test method has been used to assess decay in solid wood (Toole 1969, 1971), and to study internal strength of non-decayed, preservative free particleboard (Kufner 1975). It was employed in this study to detect preservatives which might protect the wood in waferboard from decay during fungus testing (i.e., little or no weight loss), but result in large reductions in wood-glue bond strength. Comparison of PL obtained in the test with internal bond (IB) values in commercial aspen waferboard has shown a good correlation (r^2 = .7, Hall-unpublished). Therefore, the test can yield similar results of an IB evaluation without the face degradation from fungus impeding the gluing of an IB specimen.

Considering both brown rot fungi results (fig. 3), the susceptible aspen waferboard (treatments 1 and 2) was made resistant to decay (i.e., < 10% weight loss) by treatments 10-18. Upon aging ('A' extension line or side-line tab on histogram) protection level was lowered insignificantly in the ACA, CCA samples (10-14), but weight loss or decay significantly increased in other treatment-resin combinations--notably treatments 15 and 16 with TBTO.

Overall regressions and correlations between percentage weight loss and reduction in PL were also calculated (table 1). As evidenced by the high correlation coefficients, the relationships between weight loss and reduction in PL conformed well to the linear curves. In fact, the lowest correlation coefficient (0.82) found in the aged samples subjected to *P. placenta* would be considered a good relationship. A reason for this relationship to have a lower correlation coefficient was PL losses of aged specimens being less than unaged specimens in treatments 6, 10, 11, 12, 13, 14, and 18 (fig. 4). The PL loss is a result of an increased cross-sectional area from the large thickness swelling component. Based on these results, the brown rot fungi reduced the internal strength of waferboard (as reflected in determination of PL loss) proportionately to their ability to decay the wood, rather than destruction of the wood-glue bond.

Soil Pan Decay and Static Bending Properties

Waferboard samples cut into 17" long static bending strips were incubated in fungus cultures grown on soil and aspen shavings for three months. After equilibration, weight loss modulus of rupture (MOR) and modulus of elasticity (MOE) were measured. Combination of these data will assist in detecting treatment which might permit substantial reductions in bending properties after only small weight loss. The regression equations and associated correlation coefficients were obtained for a weight loss-MOR relationship (table 2). As in the case of the soil block-edge crushing trials, high correlation coefficients were obtained for the data.

Although there was little or no weight loss in certain treatments (e.g., 10-18 control samples (fig. 5), MOR losses ranged from 30-80% (fig. 6). These losses could be due to the organic acids given-off by the large area of test fungi in the polypropylene trays. Small holes commonly found in the aluminum foil covers after three months of insulation were presumably created by acidic condensates. The hydrolytic environment might have lower MOR values of waferboard strips even though little weight loss occurs.

Where weight losses of samples exceeded 15% (e.g., 1-9), resulting MOR reductions ran 70% or more. Such results indicate that in a high decay hazard usage of structural waferboard, it should be well protected against decay (i.e., little or no weight loss permitted) to insure continued strength in service.

MOE values from the decay-treated bending strips reflect the decreases due to decay (e.g., 1-9) and also the detrimental effects of leaching (e.g., *G. trabeum*-15, 16) (fig. 7).

SUMMARY

No preservative system tested surpassed the ACA/CCA group, treatments 10-14, in fungus protection. The CCA added to wax permitted the greatest fungal attack within this group with a maximum 13% weight loss to *G. trabeum* in aged samples in the soil block test. Also, mechanical properties of this CCA/wax treatment were inferior to other methods of incorporation (see Hall et. al. 1982). In terms of integrating one of these waterborne salt treatments into manufacture of treated waferboard, the addition of ACA to the wax emulsion provides excellent fungus protection while minimizing cost increases associated with a separate treatment operation (e. g., pretreating or pressure treating). By simply venting the rotating drum of excess ammonia during the ACA/wax spray addition, pollution problems would be minimized. The ACA solution permitted addition levels of 0.25 pcf to the board furnish without adding excess water which would require redrying of wafers. Presumably, work with ACA-wax compatibility systems could develop formulations permitting higher loadings (.4-.5 pcf) which may be required in ground contact situations.

In terms of moderate decay protection where the leaching hazard would be occasional (e.g., roof decking) the TBTO and Cu/Fl formulations, treatments 9, 15, 16, 17, and 18, performed well in the contact block test. The Cu/Fl was somewhat more leach-resistant than the TBTO, and the carrier solvent for the TBTO did have a noticeable odor (even after three months in testing) which might be objectionable in human habitats.

The surface dip treatments (7 and 8) did provide some mold protection and reduced decay a small amount in the contact block test; but, this decay protection was lost upon aging.

The formaldehyde/sulfur dioxide treatment, 6, did not protect boards from the brown rot fungi, and had deleterious effects on the water resistant nature of the phenol formaldehyde glue (PF).

The TCMTB treatments 3 and 4 offered little protection when incorporated into PF resin. Possibly the protection loss was due to the pH of the resin influencing the fungicidal compound (Buckman Labs - personal communication).

The poor performance of the Difolatan, treatment 5, was unexpected based on proven performance in other agricultural applications. However, since the chemical has failed to control fungus stain on susceptible hardwoods such as sweetgum while performing well on pine, the wood species may be a critical factor.

The untreated boards made with liquid PF resin were generally more resistant to decay than those

made from powdered resin, but upon aging or leaching, no difference was observed.

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Table 1.--Regression equation based on the soil/block/edge crushing tests

Fungus and condition	Regression equation[1/]
Glocophyllum trabeum controls	y = 2x - 1.8 (r = .86)
G. trabeum aged	y = 1.6x + 10.9 (r = .84)
Poria placenta controls	x = 1.5x + 13.4 (r = .93)
P. placenta aged	x = 1.6x - 3.2 (r = .82)

1/y = % PL loss; x = % weight loss

Table 2.--Regression equation based on soil/pan/ static bending tests

Fungus and condition	Regression equation[1/]
Glycophyllum trabeum controls	y = 2.4x + 26.5 (r = .87)
G. trabeum aged	y = 2.2x + 19.9 (r = .93)
Poria placenta controls	y = 3.9x + 12.9 (r = .92)
P. placenta aged	y = 2.1x + 21.3 (r = .84)

1/y = % MOR loss; x = % weight loss

Codes for Treatments (Active ingredients and details on concentrations given in Table 2 of Hall, et al.)

1. Untreated - Powdered resin (P)
2. Untreated - Liquid resin (L)
3. Busan 30 - Low level, L
4. Busan 30 - High level, L
5. Difolatan, P
6. $CH_2O + SO_2$, P
7. Troysan Polyphase, P
8. PQ 675, P
9. Wolmanit C10, high, P
10. ACA, pretreated wafers, P
11. ACA, pressure treated, P
12. ACA, w/wax, P
13. CCA, w/wax, P
14. CCA, pressure treated, P
15. Basileum SP70, high, L
16. Basileum SP70, low, L
17. Wolamnit C10, low, L
18. Wolmanit C10, high, L

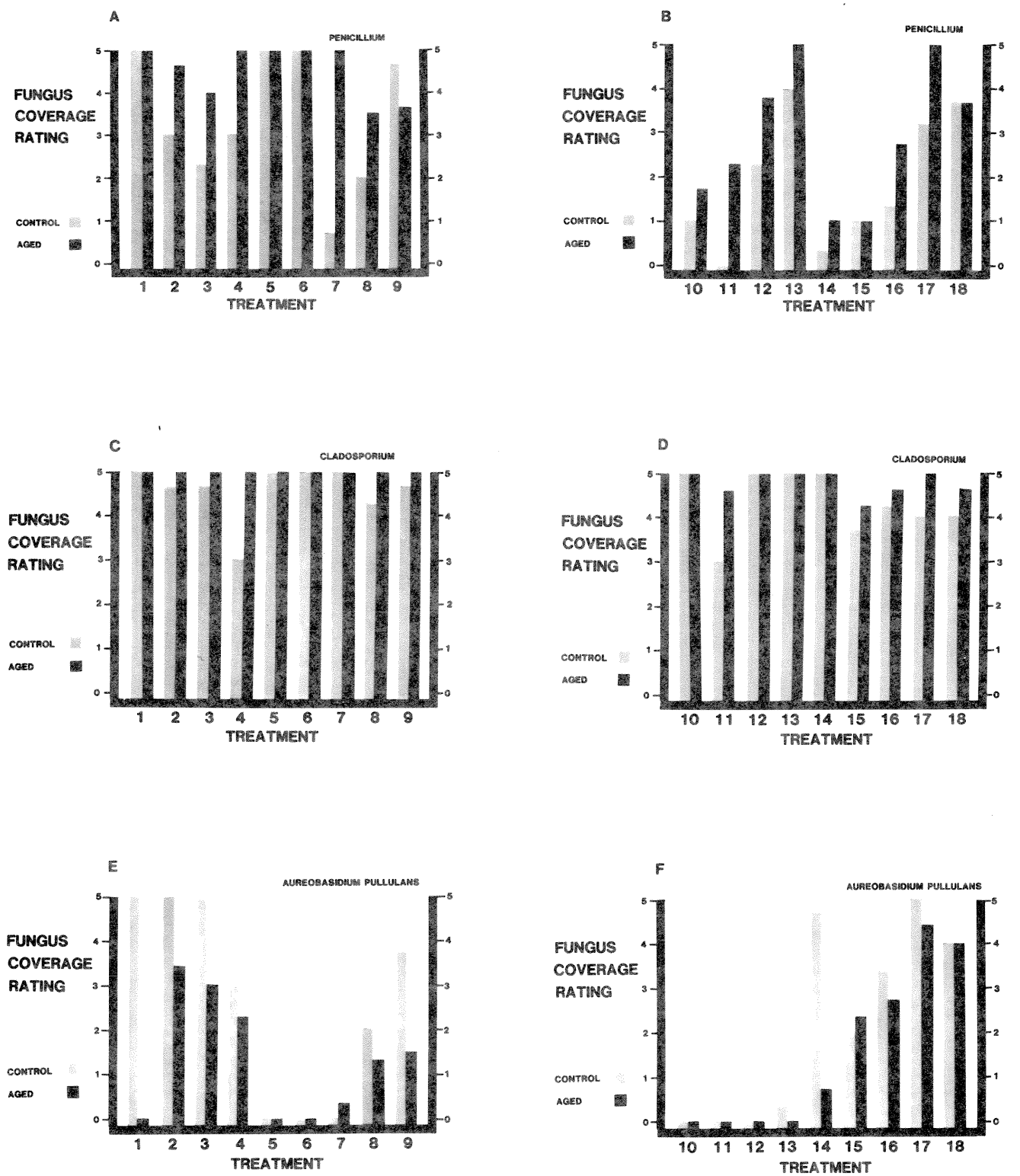

Figure 1.--Mold test of treated aspen waferboard. A, B. *Penicillium* sp., C, D. *Cladosporium* sp., E, F. *Aureobasidium pullulans*.

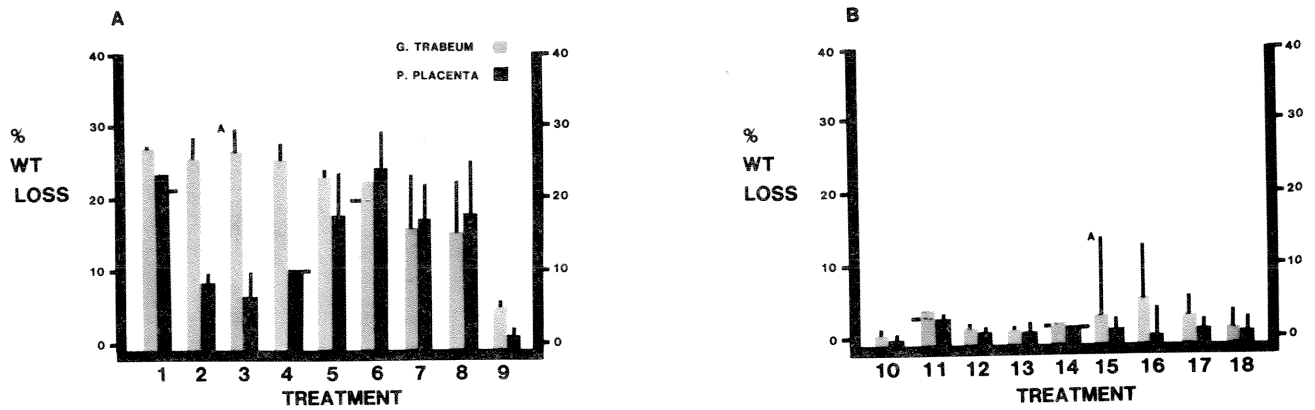

Figure 2.--(A, B). Contact block test of treated aspen waferboard. ('A' - extension line marks weight loss of accelerated-aged samples.)

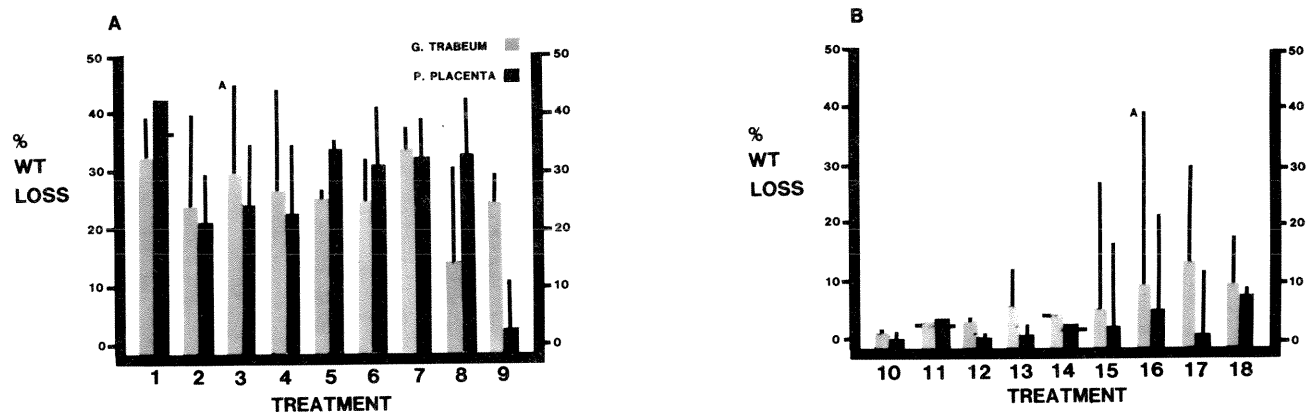

Figure 3.--(A, B). Soil block test (modified ASTM 1413) of treated aspen waferboard. ('A') - line or tab marks weight loss of accelerated-aged samples.)

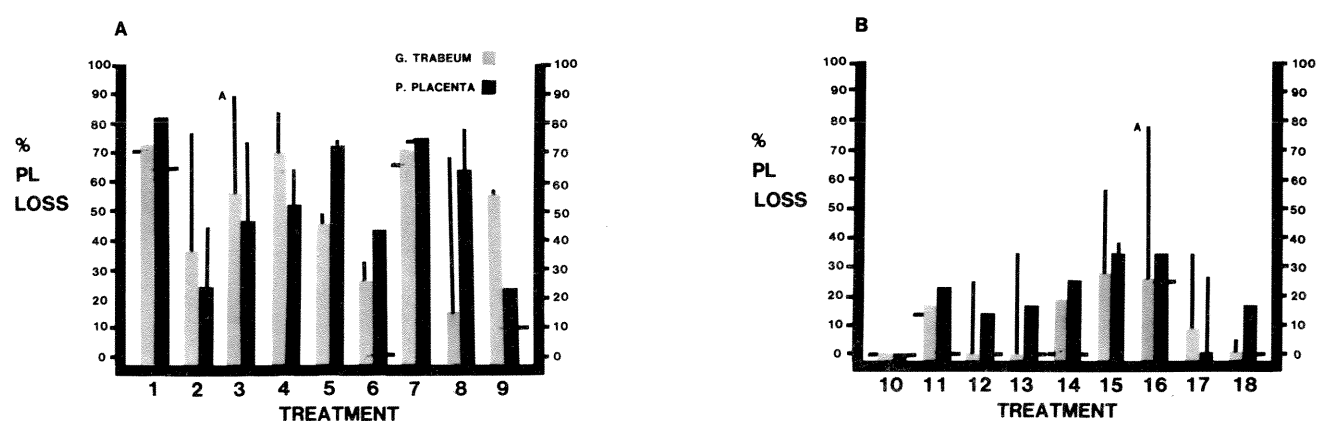

Figure 4.--(A, B). Loss in porportional limit (PL) of treated aspen waferboard samples crushed on edge after soil-block testing as compared to sterile, wet controls. ('A' indicates loss of accelerated-aged samples.)

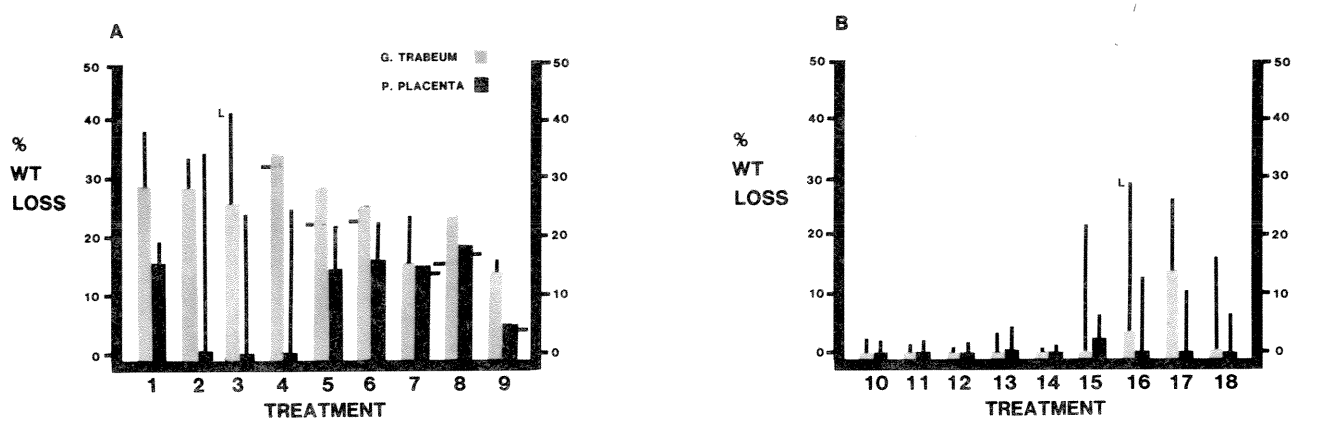

Figure 5.--(A, B). Weight loss of static-bending samples in the soil-pan decay test. ('L' - line on tab indicates sample weight loss for leached replicates.)

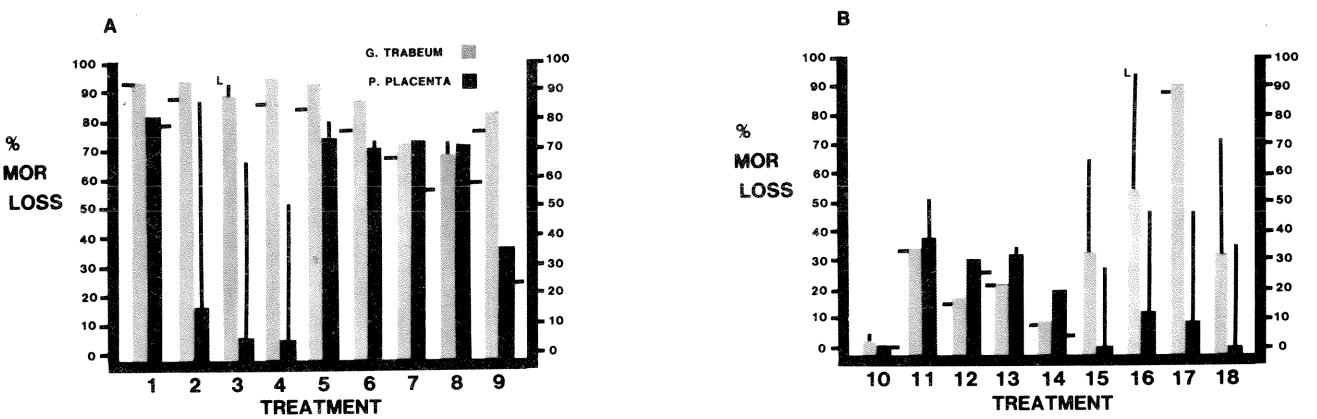

Figure 6.--(A, B). Modulus of rupture (MOR) loss (as compared to sterile, wet controls) of static bending samples after soil-pan decay testing. ('L' - line or tab indicates leached sample MOR loss.)

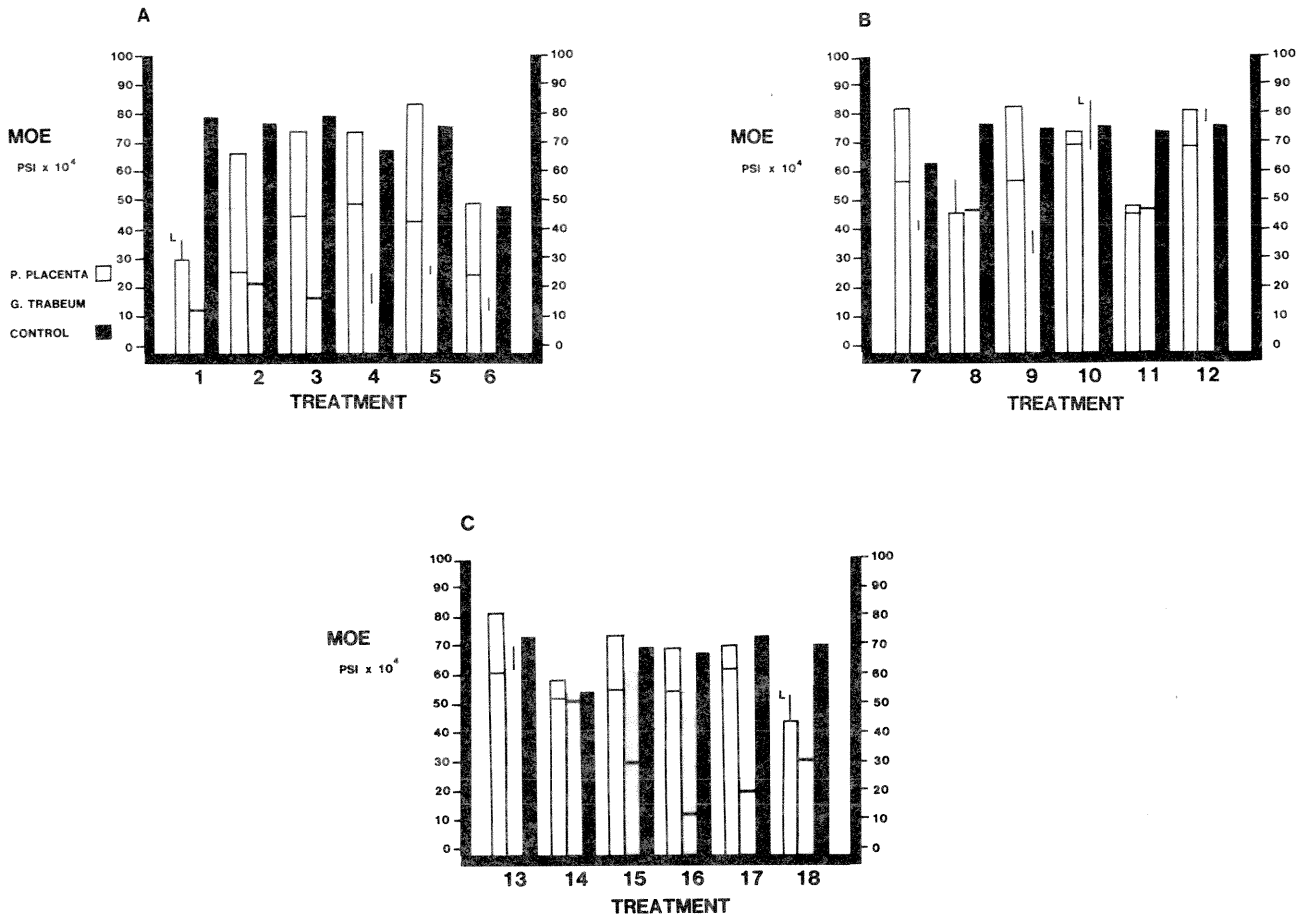

Figure 7.--(A, B, C). Modulus of elasticity (MOE) of static bending samples after soil-pan decay testing. (Control samples refer to wet but sterile samples; 'L' line indicates MOE of leached sample.)

DURABILITY OF COMPOSITE WOOD PRODUCTS[1/]

Roy D. Adams[2/]

Abstract.--A high strength aligned wood flake material has been developed and used to fabricate some exterior products. Using accelerated weathering tests the durability of both material and products has been found to be good. Acceptance of the products will require extensive field and service tests which are proceeding.

INTRODUCTION

During the past several years the Institute of Wood Research has developed a number of composite wood products. These products have as a basis a unique high strength composite wood material (CWM). Although CWM has potential in many structural applications the emphasis to date has been placed on exterior products used by the electric utilities. Developments have included utility poles - COMPOLES™, crossarms - COMARMS™ and lighting standards - COMLITES™.

Composite Wood Material

Composite wood material is an engineered man-made material comprised of aligned elongated flakes, treated with chemicals to provide protection against biodeterioration and bonded together using a water resistant adhesive, such as phenol-formaldehyde or isocyanate. Material properties can be manipulated to suit a particular end use by changing components and/or processing conditions. For example, resin levels of 8 percent, based on the oven-dry weight of the wood, have been used to achieve the required durability and strength properties. The material has unique characteristics, retaining the desirable properties of solid wood, such as high strength-to-weight ratio, machinability, low heat conductivity and high electrical resistance, while reducing some of the undesirable properties, such as nonuniformity of properties, knots and grain deviation.

Composite Wood Products

The material has been fabricated into various configurations depending on the product. Components are bonded together using water resistant resorcinol-formaldehyde adhesive. Two of these configurations are given in figures 1 and 2 which show the hollow octagonal COMPOLE™ and the hollow section of the COMARM™, respectively.

Poles have been produced in 40 foot lengths with a maximum base diameter of approximately 14 inches and a maximum wall thickness of three inches. As the CWM panels were one inch thick, lamination was required for production of the prototype poles. Crossarms have been produced with a 3.75-by-4.75 inch cross section and an 8 foot length. The design of the COMPOLE™ has been described in detail in a report to the Electric Power Research Institute (Adams et al 1981).

The products discussed are exterior products and one must have confidence that they will retain sufficient strength properties for the anticipated service life, some 30 to 40 years. Two major factors have the potential to reduce the service life, weathering and biodeterioration. The product must be durable against both of these factors. However, in controlling the attack by biological organisms it is important that adverse effects on material strength do not occur, either before or after weathering.

It is impractical to wait 30 to 40 years before introducing such products into the marketplace. Product assurance can be obtained by accelerated test procedures and by comparisons with other products or material known to have this life expectancy, i.e., treated solid wood. This paper discusses some of this testing.

ACCELERATED WEATHERING OF COMPOSITE WOOD MATERIAL

Effect of Adhesive Type

A critical aspect in manipulating CWM properties is the use of an adhesive suitable for extended outdoor exposure. It has been established that phenol-formaldehyde (PF) resins are extremely durable wood adhesives (Gillespie and River 1976). Consequently, this adhesive was initially selected as a prime candidate for CWM. The literature also indicated that isocyanate adhesives could provide some unique properties although at that time little work had been done on their use as wood adhesives (Deppe 1977). The isocyanates enhance strength properties, increase moisture resistance and can be cured at lower temperatures.

1/Paper presented at Workshop on Durability, Pensacola, Florida, October 5-7, 1982.

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Materials and Procedures

Early in the development of CWM two adhesive types were used extensively. The specific adhesives were:

i) PF - Borden Cascophen PB-65
ii) Isocyanate - Mobay Mondur E-441

Small specimen strength properties of CWM made with aspen flakes and 8 percent resin level were found at three sets of environmental conditions. One percent wax emulsion was sprayed onto the flakes during panel production to improve durability. Test specimens (12 x 2 x 0.5 inches) were cut from the panels so that the long direction was parallel to the flake alignment. These specimens were allowed to reach equilibrium moisture content for one of the three sets of conditions, and were then tested in bending. Average values were obtained from ten replicates.

Results and Discussion

Both bending strength (MOR) and EMC had a positive correlation with density and therefore values were adjusted to a nominal density of 40 pcf. These values are given in table 1 which shows that the isocyanate-bonded material is appreciably stronger than phenolic-bonded material under the same environmental conditions. This strength difference increases from approximately 20 percent at the low EMC to 40 percent at the high.

The data in table 1 show that the EMC in the isocyanate-bonded CWM is lower than in the phenolic, indicating the higher moisture resistance. This difference in EMC values can explain part of the strength difference but not all, thus emphasizing that the isocyanate adhesive gives better bonding at the same adhesive level. It was also observed during this experiment that the isocyanate-bonded material absorbed moisture at a slower rate, which is another good feature for exterior products.

Effect of Preservatives

In the introduction it was mentioned that the inclusion of preservative materials is necessary to provide protection against biological organisms. All of the currently used preservative systems in the United States have been evaluated as potential CWM preservatives. These are:

Pentachlorophenol
Creosote
Chromated Copper Arsenate
Ammoniacal Copper Arsenate

Since these are well established biocides, the initial criterion used to determine their effectiveness in the composite material was to evaluate their effect on bending strength.

Two methods of preservative application have been considered. These are 1) spraying the preservative onto the flakes before adhesive is applied, and 2) full cell pressure treatment of the material after manufacture. The former has been IWR's preferred method. This allows preservative to be sprayed on each flake providing a more uniform and complete distribution of preservative throughout the material. If the material is damaged in any way or checks occur, then only treated material is exposed. Pressure treatment does not give this distribution.

Two groups of data are discussed in this section. The first group was generated early in the development of CWM. At that time little was known about the effects of preservatives on initial strength and properties after weathering, particularly for isocyanate-bonded material. This study was conducted to determine if preservatives could be incorporated in a composite wood flake material without detrimental effects on properties. The second group was taken from panels which were prepared to supply decay stakes for in-ground testing in IWR's Florida and Panama test plots.

Materials and Procedures

For the first group, three panels measuring 18 x 18 x 0.5 inches were made for each adhesive and preservative combination. The panel characteristics and processing variables were as follows:

- Flakes

  --Species - aspen
  --Dimension of 0.02 inch thick x 1.6 inch long x 0.2 to 0.5 inch wide
  --Moisture content into press - 10 percent

- Board Properties

  --Nominal density of 40 pcf
  --Aligned flakes

- Adhesives - as before

- Dimensional Stabilization Agent

  --Wax - Borden Cascowax EW-403E, one percent by weight of oven-dry flakes

- Preservatives

  --Chromated copper arsenate (CCA), liquid concentrate, aqueous solution
  --Pentachlorophenol (PCP), methanol solution
  --Sodium pentachlorophenate (NaPCP), aqueous solution
  --Ammoniacal copper arsenate (ACA), aqueous solution

- Press Cycle

  --Close to stops in 1 minute
  --Press time of 15 minutes
  --Press temperature at 175°C (350°F)

The flakes were treated by spraying with the appropriate preservative solution. Following this, they were transferred to plastic bags and allowed to equilibrate overnight before being dried to the appropriate moisture content for panel production.

Seven test specimens measuring 2 inches wide by 0.5 inches thick by 12 inches long were cut from each panel so that the long direction was parallel to the flake alignment. These were then equilibrated at 21°C (70°F) and 50 percent relative humidity before being used for the initial strength test specimens or weathering test specimens. Samples made from clear aspen lumber and marine grade Douglas-fir plywood were included as reference material. The accelerated weathering cycle used was a 10 minute soak in boiling water followed by forced air drying for 7.8 hours at 105°C (220°F). The weathered specimens were exposed for 50 of these cycles.

Panel properties were evaluated by determining bending strength (MOR) and stiffness (MOE) over an 11 inch span. The dimensions before weathering were used for the weathered specimens. Values were adjusted to a nominal density of 40 pcf using a regression equation, and ten specimens were used to provide the average.

The second group of specimens were made from CWM panels 0.5 inches thick with a nominal density of 40 pcf. Conditions were similar to those described above. Only isocyanate adhesive was used and a variety of preservatives were sprayed onto the flakes. These preservatives are indicated in the table of results.

Test specimens (16 x 2 inches) were cut from these panels and a 10-inch span at one end was tested to obtain unweathered bending strengths. The broken end was cut off and used for specific gravity and moisture content determination. The remaining 11-inch specimen was subjected to 50 weathering cycles of 1.5 hour soak in boiling water followed by 4.5 hour drying at 105°C. The weathered specimens were equilibrated in the same conditions (21°C and 50% RH) as the unweathered specimens and then tested in bending. In this way the same specimens were used for weathered and unweathered results.

Results and Discussion

The data for the first study are given in table 2 and those for the second given in table 3. The results in table 2 provide additional comparisons between phenolic- and isocyanate-bonded material. There is considerably less MOR or MOE loss in the isocyanate specimens compared to the phenolic ones. It is apparent that when using the techniques and quantities in the study the isocyanate adhesives impart greater weathering durability with or without preservatives included.

The values in table 2 indicate that sodium penta can be added to CWM without a significant effect on strength or stiffness. Examination of the data shows that the average initial strength was somewhat lower but, after weathering, strength values were similar. The strength and stiffness losses due to weathering for this material were similar to that seen for penta treated Douglas-fir plywood, and for untreated aspen wood.

The addition of an inorganic salt-type preservative intensified the strength loss due to accelerated weathering. The data show that the MOR strength losses were in excess of 50 percent for the specimens which had CCA added to the flakes. To determine whether or not the effect of preservative salts on strength properties was unique to CWM or would also be found in solid wood, Douglas-fir plywood and aspen lumber samples were treated with CCA and subjected to the boil-dry test. The data show that the MOR strength losses were comparable to those found in CCA treated CWM. Therefore, we concluded that the main effect of CCA was on the wood and not the adhesive system. However, there was some reduction in strength before weathering. The effect of the accelerated test on MOE was less pronounced than that on MOR, although some substantial reductions were seen in phenolic-bonded CCA treated material and in the CCA treated plywood.

The data in table 3 agree with the earlier results indicating that several preservative systems can be blended into CWM without significantly affecting bending strength, either before or after accelerated weathering. CWM containing sodium penta, penta/creosote, penta in oil, ammoniacal penta or alkyl ammonium compounds (AAC) lost about the same amount of strength on weathering as treated solid wood. In contrast, CWM containing inorganic salt-type preservatives such as CCA and ACA experienced high strength losses after weathering.

As shown by the information in table 3 the addition of copper can have a deleterious effect on bending strength. This effect is demonstrated in comparisons of ammoniacal copper penta and ammoniacal penta as well as AAC plus copper chloride and AAC. The poor results found with the copper oxine were due to the presence of strong acid, which was required to solubilize the salt before preservative treatment.

The results obtained with salt-type preservatives may indicate that the boil-dry accelerated weathering test is not realistic, since wood is normally not subjected to these high temperatures during natural weathering. The use of a lower drying temperature in a vacuum-soak-dry weathering cycle reduced the strength loss of the salt treated material somewhat, but losses were still high. Since there are no data available on the effect of natural weathering on strength properties of salt treated wood, further studies are being conducted to determine whether or not these preservatives will be satisfactory for composite wood material.

Composite wood material decay/termite stakes have been prepared using various preservative systems. The initial work used the two adhesive systems, isocyanate and phenol-formaldehyde, while later work has concentrated on isocyanate. Most of the studies have used two species: aspen and balsam fir. Evaluation of resistance to decay fungi and termites is continuing in test plots in

Florida and Panama. A typical specimen is shown in figure 3. This work allows comparisons between preservative systems and also allows determination of threshold values for CWM, i.e., the minimum level of preservative required to provide durability.

ACCELERATED WEATHERING OF CROSSARM SECTIONS

Additional information on the durability of composite products was obtained from accelerated weathering of crossarm sections. Two daily weathering cycles were used, one was a vacuum/pressure/soak-and-dry cycle and the other was a condensation and U-V light cycle.

Materials and Procedures

Two COMARMS™ were produced, one from phenolic-bonded composite wood material and the other from isocyanate-bonded material. The crossarm configuration was shown in figure 2 with the length being 8 feet. Components were bonded with resorcinol-formaldehyde adhesive and the hollow core was filled with low density polyurethane foam. Sections approximately 30 inches long were cut from each end for the weathering tests.

One phenolic-bonded and one isocyanate-bonded section were subjected to 18 daily soak-and-dry cycles. In the daily cycle, specimens were exposed to a 30 minute vacuum followed by 100 psi pressure for 90 minutes while submerged in water. They were then dried at 102°C (215°F) for 22 hours. The sections were visually inspected after each cycle. After completion of the 18 cycles they were cut into 2 inch lengths for further observations.

The other two sections, one phenolic and one isocyanate, underwent daily cycles of 18 hours condensation (100 percent relative humidity) at 55°C (130°F) and 16 hours U-V light at 60°C (140°F). The sections were visually inspected after each cycle for the first 3 cycles, then they were inspected at regular intervals up to 50 cycles.

Results and Discussion

The specimens subjected to soak-and-dry cycles exhibited the majority of change during the first one or two cycles. This change was an obvious bulging of the sides of the crossarm due to the irreversible swelling in thickness of the sides, which was restrained at the gluelines by the smaller in-plane swelling of the top and bottom. There was some minor glueline separation. The surface of the phenolic CWM was rougher, with some flakes breaking away from the surface, compared to the isocyanate CWM.

As the cycling proceeded there was little day-to-day change. At the end of 18 cycles the gluelines had slightly more separation and there was minor checking in the CWM. Inspection of the slices showed that the glueline separation was only a small part on the outside with the interior of the gluelines sound. Overall the sections behaved exceptionally well considering the severe nature of this test, indicating that the COMARM™ sections have good durability.

The condensation/U-V light cycles were a less severe test which was also used to determine the effect of U-V light. No observable effects apart from color change were seen for many cycles. There was some minor glueline separation after 50 cycles which had not been observed after 35. At the conclusion of testing the CWM appeared solid with very few checks. The U-V light caused considerable darkening of the sections but this was only a surface phenomenon, as a scratch across the surface exposed white wood. In general, the sections appeared to stand up well to this accelerated weathering test.

FIELD AND SERVICE TESTING

The durability of several CWM systems is being evaluated by using short pole stubs inserted in the ground in Florida. They were installed in December 1979. After 3 years they showed good resistance to biodeterioration and, although experiencing some checking in the material, showed good weathering properties. In addition several COMARMS™ were installed above ground. A number of systems are performing well.

The products are undergoing extensive service testing. Approximately twenty 40-foot COMPOLES™ have been installed by various utilities mainly in the Midwest. The first was installed in Houghton, Michigan in September 1980. During installation the COMPOLES™ were treated similarly to solid wood poles with no difficulties encountered. The poles can be easily climbed and can be readily drilled if required.

The Electric Power Research Institute is sponsoring a project to evaluate the COMARMS™ in four areas of the United States. These are the Upper Peninsula of Michigan, the Pacific Northwest, the Interior Southwest and the Gulf States. Forty crossarms have been installed by a utility in each area. These will be inspected regularly and after five years half of the crossarms will be tested to determine strength properties to see what effect weathering has had on strength properties.

At the request of the City of Houghton, 24 lighting standards were produced. Most of these were installed in July 1982. Figure 4 shows several of these COMLITES™. The lighting standards were designed as a box beam approximately 5-by-5 inches in cross-section and 25 feet long. They were left hollow to allow the electric cable to pass down from the light to the ground. The surface of the material was grooved and stained to duplicate light standards already being used which were made from finger jointed and laminated southern pine. The composite lighting standards produced a very aesthetic product.

CONCLUSIONS

Using specific types of phenol formaldehyde and isocyanate adhesives we found that isocyanate-bonded material has superior initial strength and exhibits improved durability at the same adhesive level.

Several preservative systems can be incorporated in the material with minimal effects on initial strength or on strength after accelerated weathering.

Accelerated tests give an indication of how well a composite material will behave when comparison material is included. However, some anomalies may develop due to high temperatures involved in cyclic testing.

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Table 1.--Bending strength (MOR) and equilibrium moisture content (EMC) for phenolic-bonded and isocyanate-bonded material under three environmental conditions

Conditions		Phenol-formaldehyde		Isocyanate	
Temp.	RH	MOR[1/]	EMC[1/]	MOR[1/]	EMC[1/]
°C	%	psi	%	psi	%
21	50	12280	7.00	14790	6.37
27	70	10680	9.99	13860	8.97
21	90	8510	15.06	12250	12.65

1/ Adjusted to 40 pcf density

Table 2.--Average bending strength and stiffness values before and after accelerated weathering

Specimen[1/]	Preservative	Bending Strength[2/]		Strength	Bending Stiffness[2/]		Stiffness
		Control	Weathered	Loss	Control	Weathered	Loss
		psi	psi	%	psi x 10^6	psi x 10^6	%
I	None	15200	12050	20.7	2.25	2.19	2.5
P	None	11550	7940	31.3	2.04	1.64	19.5
I	Sodium Penta	13800	11820	14.3	2.28	2.06	9.7
P	Sodium Penta	12250	8170	33.3	2.10	1.88	10.8
I	CCA	14090	6620	53.0	2.30	2.07	10.0
P	CCA	11190	4300	61.6	2.13	1.54	27.7
I	ACA	13760	6970	49.3	2.33	2.02	13.4
P	ACA	11680	4140	64.5	1.99	1.72	13.5
DF Plywood	None	6190	5850	5.5	1.02	0.86	15.0
DF Plywood	CCA	6190	3250	47.5	1.02	0.74	27.0
DF Plywood	Penta	6270	4900	21.9	0.88	0.74	15.6
Aspen Wood	None	10450	8820	15.6	1.49	1.38	7.0
Aspen Wood	CCA	10450	5140	50.8	1.49	1.46	2.0

1/ I - isocyanate-bonded CWM
P - phenol-formaldehyde-bonded CWM
DF - Douglas-fir
2/ Adjusted to 40 pcf density

Table 3.--Average bending strength data for unweathered and weathered material treated with various preservatives

Preservative	Bending Strength[1/]		Strength Loss
	Unweathered	Weathered	
	psi	psi	%
Untreated	12150	9670	20.4
Sodium Pentachlorophenoxide	14360	11390	20.7
Pentachlorophenol/Creosote	12940	10010	22.6
Pentachlorophenol/P9 Oil	11850	9820	17.1
Ammoniacal Pentachlorophenol	12660	10140	19.9
Ammoniacal Copper Naphthenate	11400	7400	35.1
Ammoniacal Copper Pentachlorophenol	10950	7660	30.0
Ammoniacal Copper Arsenate (ACA)	10140	7690	24.2
Chromated Copper Arsenate (CCA)	11500	7920	31.1
Alkyl Ammonium Compound (AAC)	13100	9690	26.0
AAC + Copper Chloride	10330	7830	24.2
Copper Complex	11440	8980	21.5
Copper Oxine	5710	5190	9.1

1/ Adjusted to 40 pcf density

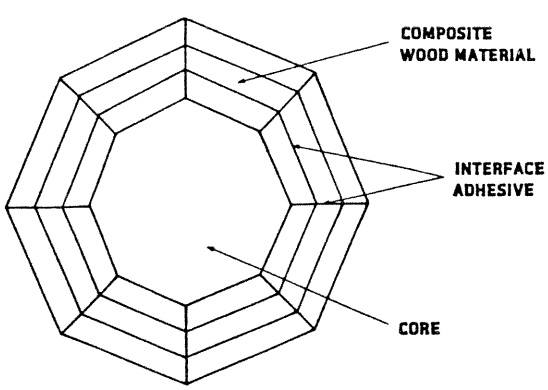

Figure 1.--Cross-section of composite wood utility pole showing laminations required to achieve wall thickness.

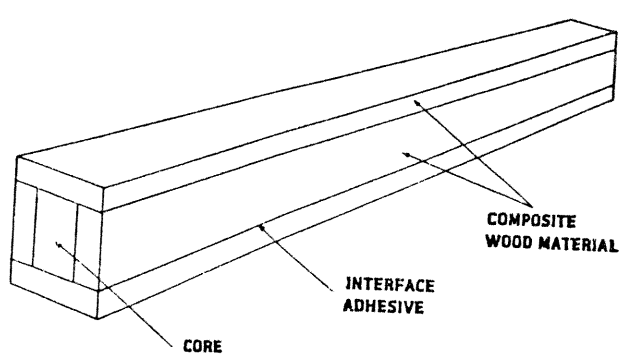

Figure 2.--Illustration of composite wood cross-arm.

Figure 3.--Composite wood decay stakes in Florida test plot, used for ground contact evaluation.

Figure 4.--Composite wood street lighting standards in Houghton, Michigan.

PRESERVATIVE TREATED SOUTHERN HARDWOOD FLAKEBOARD[1/2/3/]

Paul H. Short and Duane E. Lyon[4/]

Abstract.--Two preservatives, copper-8-quinolinolate-(PQ-56) and didecyl-dimethyl-ammonium (CWP-41) were evaluated for efficacy and effect on properties of flakeboards made from southern species. PQ-56 was the better preservative, but it adversely affected properties. CWP-41 did not affect properties, and may have adequate efficacy at higher treatment levels.

INTRODUCTION

Several factors have contributed to the acceptance of structural boards made from northern hardwood flakes. Included among these factors are: (1) the decreasing supply and increasing harvest cost of peelable logs for plywood production; (2) the ability to locate these board manufacturing plants closer to the large market areas of the U.S.; (3) the increasing acceptability of structural board products; and (4) the inherent benefits of this type board compared to plywood (Guss 1980). Coupled with these factors in the South is the availability of a mixture of low-grade hardwoods that may be suitable as a flakeboard furnish. This potential flakeboard furnish, which includes both low- and high-density wood species, needed to be economically utilized as an incentive for landowners to convert cut-over lands to southern pine production.

Unfortunately, these structural boards are subject to termite and fungal attack, especially in the high-risk areas of the southern and southeastern U.S. Although many insecticides and fungicides are currently being evaluated (Hall et al. 1982), research is lacking on the use of copper-8-quinolinolate (PQ-56) and didecyl-dimethyl-ammonium chloride (CWP-41) with flakeboard. It is believed that these two wood preservatives are most likely to remain acceptable to the U.S. Environmental Protection Agency. Consequently, the objective of this research was to evaluate the feasibility of treating exterior-grade hardwood flakeboard with these two wood preservatives.

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2/The authors wish to express their appreciation for the help given them by Dr. Terry L. Amburgey, Plant Pathologist, Mississippi Forest Products Utilization Laboratory, Mississippi State University, Mississippi State, MS.

3/Mention of company or tradename is solely to identify the material used and should not be interpreted as an endorsement by the Mississippi State University or the U.S. Department of Agric.

4/The authors are Associate Professors at the Mississippi Forest Products Utilization Laboratory, Mississippi State University, Mississippi State, MS.

PROCEDURE

Materials

The processing variables investigated are listed in Table 1. Three trees of each wood species in the 6- to 8-inch diameter class were harvested from the John Starr Memorial School Forest, Mississippi State University, located in northeast Mississippi. After debarking, the bolts were flaked in a Fibrexa drum flaker. Flakes were 2.50 inches long, 0.015-inch thick, and had random width. The flakes were dried to less than 5 percent moisture content in a kiln at 150°F.

Forasite 22-743, a water soluble phenol-formaldehyde resin was obtained from Reichhold Chemicals, Incorporated, and diluted to 40 percent resin solids prior to addition to the wood flakes. The diluted resin had a viscosity of approximately 150 cps and a pH of 9.5.

A wax emulsion, GMW-135, was obtained from Perkins Industries, and sprayed onto the flakes at a concentration of 48 percent wax solids.

The two preservatives, CWP-41 and PQ-56 were obtained from Chapman Chemical Company. The CWP-41 is manufactured by Lonza, Incorporated, and sold as Bardac 2250. PQ-56 and CWP-41 are manufactured as solutions with concentrations of 10 and 50 percent, respectively. The pH was 1.5 and 7.4 for the PQ-56 and CWP-41, respectively.

Flakeboard Manufacture

Flakeboard manufacturing conditions were:

Board size: 0.625-in. by 22 in. by 24 in.

Resin: Liquid phenol-formaldehyde spray applied at 6% (based on ovendry weight of flakes).

Wax: Wax emulsion spray applied at 1% (based on ovendry weight of flakes).

Mat moisture content: 13 - 14%.

Mat construction: Homogeneous

Press temperature: 340°F

Press cycle: Press to stops and hold at 570° psi for 1.5 min., reduce pressure to 285 psi and hold for 6.5 min.

Total press time: Approximately 9 min.

Postcure: Boards were heated in an oven at 212°F for 8 hours.

The appropriate weight of the kiln-dried flakes for three boards was blended with the required weight of each additive in a rotating drum blender equipped with spray nozzles. The required amounts of preservative, wax, and resin were added consecutively. Total blending time was approximately 15 minutes. A post-blending period of 15 minutes was included to remove excess moisture and to ensure adequate mixing of ingredients. This blending procedure was duplicated to provide sufficient material for six flakeboards.

After blending, the appropriate weight of flakes was manually felted into 22- by 24-inch mats. The felted mats were pressed to stops in an electrically heated press. Target densities were 45 and 50 pcf.

Flakeboard Properties

Table 2 lists the tests, exposure conditions and replications for each treated flakeboard type. All of the flakeboards were cut into test specimens, conditioned at 65% relative humidity and 68°F, and tested according to standard procedures (ASTM D 1037-72a). The in-plane crushing (C) stress was determined by loading 3- by 3-inch test specimens parallel to the face until failure. The value reported was the stress at the proportional limit per unit of cross-sectional area. The resistance of each board to decay, termite and mold was evaluated according to standard procedures with some modifications. All test specimens were 0.625 by 0.375 by 0.750 inches. There were three replications per treatment for each test. The procedures are described as follows:

Decay tests were conducted using the agar-block procedure (Amburgey 1976). Decay chambers were 8-ounce French square bottles containing 30 ml of 2% malt-agar (20 g Difco malt extract, 15 g Difco bacto-agar, 1000 ml distilled water). Sterilized decay chambers were laid on one side until the agar solidified and then inoculated with a pure culture of the brown-rot wood-decay fungus *Gloeophyllum trabeum* (Pers. ex Fr.) Murr. When fungal growth had covered the agar surface, a sterile, 2-mm-thick support was placed on the surface of the mycelium in each bottle to serve as a support for the test specimens. All test specimens and controls (0.75-in. cubes of southern yellow pine sapwood) were sterilized using ethylene oxide before being placed in the decay chambers.

Tests of resistance to subterranean termites were conducted according to AWPA Standard M12-72, except for block size. Southern yellow pine sapwood blocks (0.750-in. cubes) were used as controls.

Mold test specimens were momentarily immersed in an aqueous spore suspension of mold fungi obtained by mixing spores removed from pure cultures of: *Alternaria alternata* (Fr.) Keissler, *Trichoderma* sp., *Aureobasidium pullulans* (de Bory) Arnaud, *Aspergillus niger* van Tiegham, and *Ceratocystis* sp.

The inoculated test specimens were then placed in covered plastic crisper dishes (12 by 9 by 4 in.) containing a layer of 2 percent water-agar covered by a piece of southern yellow pine sapwood veneer. The specimens were placed on the surface of the veneer. The crisper dishes were incubated for 10 weeks in a controlled environment chamber. After 10 weeks, the percent of specimen surface covered by mold was determined.

Southern yellow pine sapwood blocks (0.750-in. cubes) were used as controls.

The mechanical and physical data were adjusted to average density values by the use of regression analyses. Although this procedure prohibits a comparison of means between treatments, the rather large variation in test results caused by inherent density variation makes a comparison of means almost useless. By adjusting the data to an average density, trends in the test results culd be evaluated.

RESULTS AND DISCUSSION

This study clearly demonstrates the need to consider carefully the loss of bond integrity that occurs when flakeboards are weathered. Property requirements for 2-BF flakeboard, American National Standard for Mat-Formed Particleboard, A208.1, (ANSI) requires a minimum internal bond (IB) strength of 50 psi. The only weathered flakeboards maintaining an acceptable IB strength were sweetgum boards which had an average IB strength of 70 psi at a density of 50 pcf. The addition of CWP-41 reduced the average IB strength to 60 psi. Consequently, the discussion of the results in the text is restricted to ranges in values and the significance of the findings. Complete test results may be obtained from the authors.

Unweathered Flakeboard Properties

1. Copper-8-quinolinolate Treated Flakes

Internal bond strengths of the unweathered, PQ-56 treated flakeboards are given in figures 1 and 2. Results show that the addition of this preservative decreased the IB strengths of the treated flakeboards. The amount of loss was dependent on addition level, flake species and flakeboard density. The largest loss occurred when pine flakeboards at a density of 52 pcf were treated at an addition level of 0.11 pcf. IB strength decreased from 200 to 10 psi, a 95% loss. The smallest loss (13%) occurred when white oak flakeboards at a density of 48 pcf were treated at an addition level of 0.02 pcf or where IB strength decreased from 80 to 70 psi. At the 0.02 pcf treatment level, all species except hickory produced flakeboards with IB strengths greater than the required 50 psi. At the 0.11 pcf treatment level, only sweetgum flakeboards had IB strengths greater than 50 psi.

In addition to the preservative treatment effects, results indicate a strong dependency of IB strength on species. This result may be due to a combination of variables, including species density, flake geometry, pH and buffering effects of the specific species.

The lower the density of the species, the higher the compaction ratio of the boards. Compaction ratio (CR) is defined as the ratio of board to species density. Compaction ratios for the various flakeboard types are listed in table 3. A linear regression of IB versus CR, IB = 155.0 (CR) -76.2, has a R^2 value of 0.95 for the 48 pcf boards. This correlation between IB and CR supports the belief that intimate flake contact appears to be the major factor affecting bond integrity in flakeboards. Hse et al. (1975), reported similar results. The amount of resin per board was constant within a density level, but the amount of resin per wood flake would depend on the specific gravity of the wood species and flake geometry. There were obvious differences in the flake geometry of the five species, but no attempt was made to correlate flake geometry to flakeboard properties. More research needs to be done in this area.

Flake pH and buffering effect were determined for each of the flake species. The results are shown in figure 3 and summarized in table 3. Pine flakes had the lowest initial pH, 4.5, and had the strongest buffering effect, 2.1 (Δ pH/millimoles NaOH). Apparently, the pine extractives depress the flake pH and contribute to the buffering effect at high pH. Hickory flakes had the highest initial pH, 5.6, and, along with sweetgum flakes, had the weakest buffering effect, 6.7 (Δ pH/millimoles NaOH). There appears to be a poor linear correlation between IB and initial pH (R^2 = 0.14), and also between IB and buffering effect (R^2 = 0.12). Consequently, initial flake pH and buffering effect are not major factors relating IB strength to species.

However, it is plausible that the combined acidic and buffering characteristics of the wood extractives and PQ-56 influence the chemical reactions that occur during bond formation between wood flakes. PQ-56 has a pH of approximately 1.5. As the pH of the resin medium is reduced, the alkaline buffer of the resin is neutralized, causing the resin cure rate to be reduced. Consequently, in the allotted press time bond formation in the pine flakeboards may not have had sufficient reaction time. Pine flakes had the lowest pH and exhibited the greatest buffering (table 3) and showed the greatest loss in IB strength when treated with PQ-56.

The decrease in IB strength of the various flakeboards also could be caused by localized acid hydrolysis of the wood substrate by the preservative. Whatever the cause, sweetgum flakeboard appears to be the only species tested which can be treated with PQ-56 at 0.11 pcf and maintain acceptable IB values.

In-plane crushing (C) stress of the unweathered PQ-56 treated flakeboards is given in figures 4 and 5. The pine and hickory flakeboards at a density of 48 pcf showed an average decrease of 53% in C stress. Note that these two flakeboard types also showed the greatest decrease in IB strengths when treated with PQ-56. Similar losses in C stress were observed for the higher density flakeboards, 53 pcf. But, the higher density boards had the greater C values due to the greater compaction ratios.

Except for pine flakeboards, the species dependency of the C values followed the same order as the IB values. The average lower C value of the pine flakeboards cannot be explained. Although this board property is based on a state of combined stresses, the linear relationship between IB and C values of untreated flakeboards has a R^2 value of 0.69. The C test is much quicker and appears to be more precise than the IB test. Also, the C test is indicative of the bond integrity of flakeboards without the dependency of rather high-quality board surfaces that are required for the IB test.

Thickness swell (TS) values of the unweathered PQ-56 treated flakeboards are given in figures 6 and 7. Without exception, the addition of this preservative adversely affected the TS properties of the treated flakeboards. At the 0.11 pcf addition level, TS for the 43 pcf boards ranged from 41% for the sweetgum boards to 60% for the pine boards. Increasing board density did not substantially change this trend. Except for the pine boards, increases in TS of flakeboards treated at the 0.02 pcf addition level were similar to increases observed for the higher addition levels. Apparently, the 0.02 pcf addition level is beyond a threshold value for interference with bond formation between flakes. This trend is exemplified by a fairly general increase of 29% in TS of the treated flakeboards.

Usually higher density boards swell more than lower density boards. Apparently, the difference between the two density levels was not large enough to observe the expected difference in associated TS values.

The variation in TS with respect to species could be caused by differneces in species density, flake geometry, etc. Generally, at a constant flakeboard density, boards made of lower density species will exhibit greater TS. This is due to the effects of the flake compression previously described. Results of thickness swell do not follow this expected trend, implying that flake geometry, chemical make-up, and/or some other processing parameter is the controlling factor. Consequently, the expected negatively correlated relationship between IB and TS was not observed.

Modulus of rupture (MOR) and modulus of elasticity (MOE) of the unweathered PQ-56 treated flakeboards are shown in figures 8 through 11. All unweathered flakeboards had average MOR values in excess of the minimum 3000 psi required by ANSI. Only white oak flakeboard at a density of 45 pcf did not have the minimum 500 x 10^3 psi MOE value required by ANSI. Except for pine flakeboards, the addition of PQ-56 did not greatly decrease the MOR or MOE. At both 45 and 49 pcf density levels, the pine flakeboards treated at 0.11 pcf retained approximately 46% and 80% of their MOR and MOE values, respectively. These reductions, being greater than 50%, make PQ-56 treated pine flakeboards unacceptable according to ANSI Standards.

The order of the species with respect to decreasing MOR was similar to that found for IB. This would be expected, considering that both bending strength and IB are positively correlated to the CR (Moslemi 1974). In addition to CR, MOR is also dependent on the differential density over the thickness profile (density profile), whereas IB is also sensitive to the quality of bond formed between flakes.

Flake geometry would have a major influence on both the density profile and quality of bond formed during the fabrication of the flakeboards. Maloney (1977) has reported that although relationships between flake geometry and board properties do exist, the relationships are not clearly defined.

Decay resistance of the unweathered PQ-56 treated flakeboards is shown in figures 12 and 13. The efficacy of the PQ-56 as a fungicide at the 0.11 pcf treatment level was very evident. Although the extent of efficacy was species dependent, the change in flakeboard density from 48 to 52 pcf had little effect. At a flakeboard density of 48 pcf and 0.11 pcf treatment level, average weight losses due to decay ranged from 6.4% for hickory boards to 0.3% for pine boards. Compared to controls, these values represent a 65% and 98% reduction in weight loss for the two species, respectively. Similar results were observed for the higher density flakeboards.

The well known natural decay resistance of white oak was evident (Scheffer and Cowling 1966). Untreated flakeboards at a density of 48 pcf had average weight losses due to decay ranging from 21.6% for sweetgum boards to 14.1% for white oak boards (fig. 12). The average weight loss for the untreated pine flakeboards at a density of 48 pcf was 17.9%, and the pine wood control blocks had an average weight loss of 16.7%. This, it appears that the medium-density pine flakeboard may have approximately the same decay susceptibility as southern yellow pine sapwood.

Termite resistance of the unweathered, PQ-56 treated flakeboards is shown in figures 14 and 15. This observation is reasonable considering the data on the use of PQ-56 fungicide.

All the flakeboards treated at 0.11 pcf had less than 4% weight loss, and less than 8% when treated at 0.02 pcf. These values represent substantial improvements in termite resistance considering that the untreated, 48 pcf flakeboards had weight losses ranging from 14.5% for pine boards to 5.5% for hickory boards. At the 0.11 pcf treatment level, pine flakeboards had a 3.3% weight loss, and the hickory flakeboards had a 3.0% weight loss. Both visual observations of blocks and weight losses of blocks caused by termite feeding indicate that PQ-56 at 0.11 pcf was very effective in protecting flakeboards from attack by subterranean termites. Thus, there was a 77% improvement in termite resistance of the PQ-56 treated pine boards. Hickory flakeboards, with their rather high natural resistance to termite attack, may not require treatment for termite control.

The results on termite resistance are based on weight loss data of treated and untreated flakeboards and a visual evaluation of test specimens as established by AWPA Standard M12-72. Although the visual evaluation is a subjective evaluation, the results of the visual evaluation complement the weight loss results (figs. 14 and 15).

The oaks and hickories appeared to have a relatively higher natural resistance to termite attack than the sweetgum and pine boards. Weight loss by termite attack was closely related to the species density; i.e., as flakeboard density increased, weight loss decreased (R^2 = 0.94). This trend also appeared to exist with increasing panel density. The higher density boards had the lowest weight loss due to termite attack. Increasing flakeboard density 8% decreased weight loss due to termite attack more than 30%.

Control samples of southern yellow pine wood blocks had an average weight loss of 13.7%. Thus, it appears that resistance of pine flakeboards to termite attack is similar to that for solid wood.

Mold resistance of the unweathered PQ-56 treated flakeboards is shown in figures 16 and 17. The effect of the two treatment levels were similar, and efficacy for controlling the growth of

mold fungi was evident. At a flakeboard density of 48 pcf, the surface coverage by the mold fungi of the untreated flakeboard test specimens ranged from 100% for pine boards to 15.0% for white oak boards. Untreated hickory flakeboards had a 22% surface coverage. At the same density level, the surface coverage of the 0.11 pcf treated flakeboards ranged from approximately 40% for pine to 6% for hickory boards. Compared to controls, these values represent an efficacy of 60% and 73% for the pine and hickory boards, respectively. Increasing the board density to 52 pcf improved the efficacy of PQ-56. Pine flakeboards had a surface coverage of approximately 23%, representing a 43% increase in efficacy by increasing board density 8%.

Mold fungi do not usually deteriorate the cell wall of wood but grow either on the surface or within the cell lumens, living mainly on sugars and starches found in ray parenchyma (Haygreen and Bowyer 1982). Although flake geometry is believed not to have an influence on the severity of attack by fungi on flakeboards (Moslemi 1974), flake geometry would be directly related to the surface density of the associated flakeboards. The greater the surface densification of the flakeboards, the more difficult it would be for mold hyphae to penetrate the flakeboard surface, Density profiles were not determined for the various flakeboards, but there is a direct relationship between MOR and mold coverage. The migration of extractives to the surfaces of the flakeboards during board consolidation in the hot press may also explain the increase in mold coverage of the higher density boards.

A summary of the efficacy of PQ-56 as a fungicide, termiticide and mildewcide for flakeboard is shown in table 4. As expected, the ranking of flakeboard by species with respect to improvement in resistance to biological deterioration was similar for both decay and termite tests. Although increase in mold resistance in PQ-56 treated samples was somewhat less than the other properties tested, mold resistance would not be as critical in most in-service applications. The siding market would be a noted exception. Considering these biological test results together with the observation that treated sweetgum flakeboards were the only boards with acceptable strength properties, it would be technically feasible to use PQ-56 as a preservative for flakeboards made with sweetgum.

2. Didecyl-Dimethyl-Ammonium Chloride Tested Flakes

Internal bond strengths of the unweathered, CWP-41 treated flakeboards are given in figure 2. For 52 pcf density flakeboards, this preservative reduced the IB strengths approximately the same amount for both treatment levels of 0.2 and 0.3 pcf. Internal bond strength was reduced from 210 to 180 psi for sweetgum, from 200 to 160 psi for pine, and from 100 to 70 psi for hickory boards. These values represent strength losses of 14%, 20%, and 30% for the three board types, respectively. But all treated flakeboards had average IB strengths greater than the minimum ANSI requirement of 50 psi. Test results appear to indicate that the difference between the treatment levels was not great enough to produce noticeable changes in IB strengths. Results do indicate that, at the addition levels tested, the CWP-41 preservative did not adversely affect IB results as much as did the PQ-56 preservtive. One reason for this could be that CWP-41 has a pH of approximately 7.4, thus it would cause less interference with the chemical reactions of the bonding mechanism and less localized hydrolysis than could have occurred with the relatively higher acidic PQ-56 preservative.

In plane crushing stress values of the unweathered CWP-41 treated flakeboards are given in figure 5. Only hickory flakeboards showed a decrease in the C stress value from 1360 psi to approximately 990 psi which is a 27% loss in the C stress value. The treatment did not reduce the C stress values of either the pine or sweetgum flakeboards. Actually, there did appear to be a slight tendency for the treatment to increase the C stress values of these two flakeboard types. Additional research needs to be conducted to verify this possibility.

Thickness swell values of the unweathered CWP-41 treated flakeboards are given in figure 7. The addition of this preservative to pine flakeboards did not affect the TS values. The preservative did adversely affect the TS values of both the sweetgum and hickory boards, but not to the same extent as did the PQ-56 treatments. The TS values increased from 7 to 25% for the 0.30 pcf treated sweetgum and from 25 to 38% for the treated hickory flakeboards.

Modulus of rupture and modulus of elasticity values of the unweathered CWP-41 treated flakeboards are given in figures 9 and 11, respectively. Neither the MOR nor MOE properties of the sweetgum and hickory flakeboards were adversely affected by the perservative treatment. There appears to be a slight improvement in these properties for the pine flakeboards when treated with CWP-41.

Decay resistance of the unweathered CWP-41 treated flakeboards is shown in figure 13. Both treatment levels of the preservative did not greatly change the amount of decay resistance of the treated hickory flakeboards. But there did appear to be some protection provided by the treatment to the sweetgum and pine boards. The amount of decrease in decay resistance was approximately 28% and 23% for the sweetgum and pine boards, respectively. Generally, there were no substantial differences between the efficacies of the two CWP-41 treatment levels.

Termite resistance of the unweathered CWP-41 treated flakeboards is shown in figure 15. There appears to be substantial improvement in the resistance to termite attack with the addition of

this preservative, especially at the 0.30 pcf level. But, the effect was only observed for the sweetgum and pine boards. Although the weight loss due to termite attack of the treated flakeboards was only about 3% for all three wood species evaluated, untreated hickory had an average weight loss of only 3%. As with the PQ-56 treated flakebords, visual evaluation data as established by AWPA substantiated the weight loss data.

Mold resistance of the unweathered CWP-41 treated flakeboards is shown in figure 17. The 0.30 pcf treatment level of preservative did increase the resistance to mold of the sweetgum and pine boards by approximately 38%. There appeared to be very little effect on the resistance to mold by the 0.20 pcf treatment level in all three species of flakeboards.

A summary of the efficacy of CWP-41 with flakeboard is shown in table 5. A comparision of the two preservatives, PQ-56 and CWP-41, indicates that the acidic preservative, PQ-56, is generally a better preservative at approximately one-third the loading rate than the neutral preservative, CWP-41 (tables 4 and 5). The cost of PQ-56 is aproximately 10-fold that of CWP-41. This rather large cost differential would economically justify much higher loading rates of the CWP-41 preservative.

Weathered Flakeboard Properties

Internal bond strength of test-fence-weathered, untreated sweetgum flakeboards is shown in figure 18. It became apparent during this study that the amount of variation in weathered IB samples was much larger than that of unweathered samples. Thus, the number of IB samples needs to be rather large for statistical analysis to be meaningful. Consequently, only trends in IB test results are reported. Results indicate that the sweetgum flakeboards were the only boards that had an average IB strength greater than 50 psi after a 3-month exposure. The untreated sweetgum flakeboards decreased from an initial IB of 210 psi to 70 psi after a 3-month exposure. This is only a 33% strength retention. After a 6-month exposure, the IB strength was below 50 psi.

The PQ-56 treated sweetgum boards, at both addition levels, had average IB strengths below 50 psi after 3-months on the test fence. The CWP-41 treated sweetgum boards had somewhat higher IB strength than the PQ-56 treated boards, but the values were only marginal.

Flakeboards Made with a Species Mixture

Properties of flakeboards made with a mixture of the wood species are shown in the respective figures previously noted. Table 6 contains the rule of mixture data of the untreated and unweathered flakeboards. Predicted board properties were determined using the rule of mixtures.

Generally, the mechanical, physical, and biological properties follow the rule of mixtures fairly well. For example, the untreated flakeboards had an actual MOR of 3420 psi and a predicted MOR of 3720, a 9% difference. The biological properties showed similar results. Weight loss due to decay was 19.4% compared to a predicted loss of 18.1%, a 7% difference. Weight loss due to termite attack was 10.0% and weight loss due to mold fungi was 32.0%, representing a 1% and 13% difference from the predicted values, respectively.

These results indicate that a specific property of a flakeboard made from a mixture of wood species can generally be predicted from data for individual species. Except for IB, TS, and mold resistance, the predicted values were within 10% using the rule of mixture.

CONCLUSION

These conclusions summarize the findings of the evaluation of the properties and durability of copper-8-quinolinolate (PQ-56) and didecyl-dimethyl-ammonium chloride (CWP-41) treated 2-BF flakeboard.

1. The acidic preservative, PQ-56, at a loading rate of 0.02 pcf adversely affects flakeboard quality.

2. The neutral preservative, CWP-41, at a loading rate of 0.30 pcf does not greatly affect flakeboard quality.

3. Static bending strength and internal bond strength of flakeboards are wood species dependent.

4. Of the five species evaluated, only sweetgum flakeboards had the best weathering durability.

5. Efficacy of the PQ-56 preservative at a loading of 0.02 pcf was demonstrated.

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Table 1.--Flakeboard variables[1/]

Variable	Level
Flakeboard density[2/]	2
A. 45 pcf	
B. 50 pcf	
Wood species (species code)	6
A. *Liquidambar styraciflua* L. Sweetgum (S)	
B. *Pinus taeda* L. Loblolly pine (P)	
C. *Quercus falcata Michx.* Southern red oak (RO)	
D. *Quercus alba* L. White oak (WO)	
E. *Carya* sp. Hickory, true (H)	
F. Mixture of species A - E (20%, wt. basis)	
Preservative treatment[3/]	5
A. Didecyl-dimethyl-ammonium chloride (CWP-41)	
1. 0.20 pcf	
2. 0.30 pcf	
B. Copper-8-quinolinolate (PQ-56)	
1. 0.02 pcf	
2. 0.11 pcf	
C. Control (0 pcf)	

Six boards were made for each combination of variables. Three replications of each board type were used for unweathered and weathered board analyses. Consequently, 198 flakeboards were processed.

1/All unlisted variables were set at levels based on commercial processing systems.
2/Boards at 50 pcf were made using only hickory, sweetgum, and pine flakes.
3/Preservative CWP-41 was added only to flakeboards at a density of 50 pcf.

Table 2.--The mechanical and physical property evaluations of PQ-56 and CWP-41 treated flakeboards

Exposure	Test	Duration	Replications/Board[1/]
Unweathered	MOR & MOE	0	2
	TS		2
	In-plane crushing		2
	IB		5
	Termite		3
	Decay		3
	Mold		3
Test-fence-weathered	IB	3, 6, & 9 months	5

1/Six boards were manufactured for each set of variables (Table 1). Three boards were used in the testing of unexposed test specimens, and three boards were used for the testing of exposed test specimens.

Table 3.--Flakeboard compaction ratios, pH, and buffering effects[1/]

Species code[2/]	Specific gravity	Compaction ratio (48 pcf board density)	pH	Buffering effect (pH/millimoles NaOH)
S	0.49	1.57	5.1	6.7
P	0.51	1.51	4.5	2.1
RO	0.68	1.13	4.9	6.1
WO	0.74	1.04	5.0	5.3
H	0.76	1.01	5.6	6.7

1/Wood species' specific gravity is based on weight when ovendry and volume at 12% moisture content (bark excluded).

2/See table 1 for species code.

Table 4.--Efficacy of copper-8-quinolinolate (PQ-56) with flakeboard[1]/

Biological agent		
Decay	Termite	Mold
---Percent---		
P (98)[2]/	S (86)	H (77)
S (97)	R (77)	S (68)
RO (93)	RO (74)	RO (64)
WO (86)	WO (52)	P (63)
H (65)	H (45)	WO (50)

1/Treatment level equals 0.11 pcf (active ingredient). Flakeboard density equals 48 pcf. Percentages are the amounts of improvement of treated samples compared to untreated control samples.
2/See table 1 for species code

Table 5.--Efficacy of didecyl-dimethyl-ammonium chloride (CWP-41) with flakeboard[1]/

Biological agent		
Decay	Termite	Mold
---Percent---		
S (28)[2]/	P (68)	P (38)
P (23)	S (66)	S (38)
H (6)	H (-17)	H (14)

1/Treatment level equals 0.3 pcf (active ingredient). Flakeboard density equals 52 pcf. Percentages are the amounts of improvement of treated samples compared to untreated control samples.
2/See table 1 for species code.

Table 6.--Rule of mixture data of untreated and unweathered flakeboards made of a 20 percent mixture of five wood species

Property	Value		Difference
	Actual	Predicted	
			Percent
MOR, psi	3420	3720	9
MOE, 10^3 psi	580	590	2
IB, psi	100	120	20
C, psi	1100	1020	7
TS, %	33	25	24
D, %	19.4	18.1	7
T, %	10.0	10.1	1
M, %	32.0	36.3	13

1/Property code: C = in-plane crushing
D = decay resistance
T = termite resistance
M = mold resistance

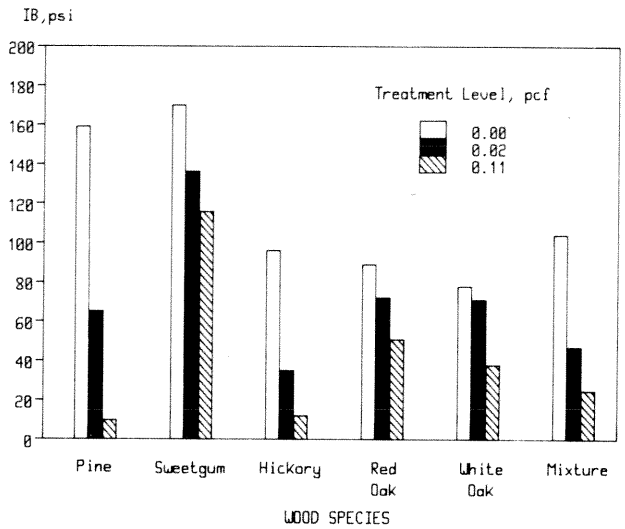

Figure 1.--Internal bond strengths of unweathered PQ-56 treated flakeboards at a density of 48 pcf.

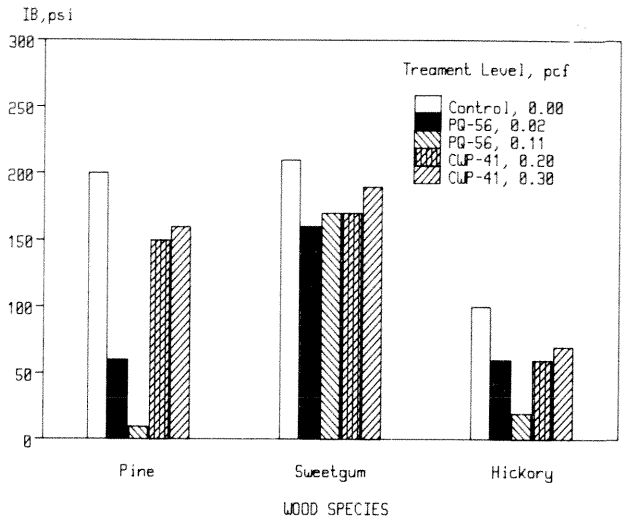

Figure 2.--Internal bond strengths of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 52 pcf.

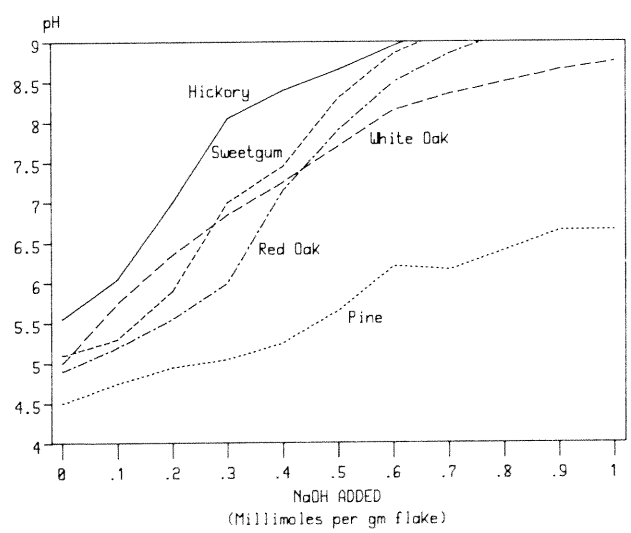

Figure 3.--Flake titration curves.

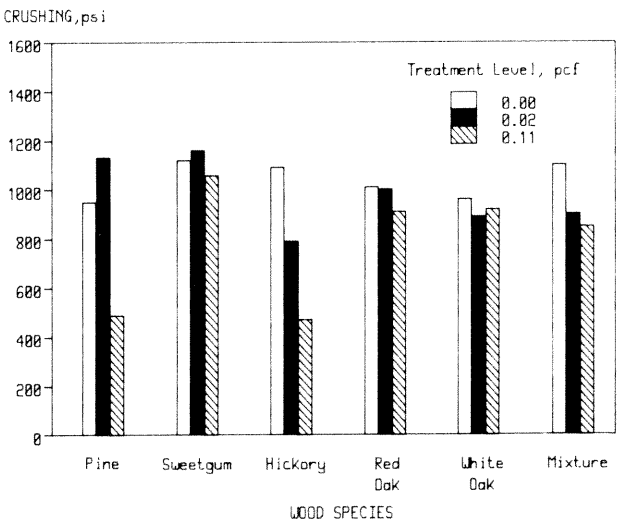

Figure 4.--In-plane crushing stress of unweathered, PQ-56 treated flakeboards at a density of 48 pcf.

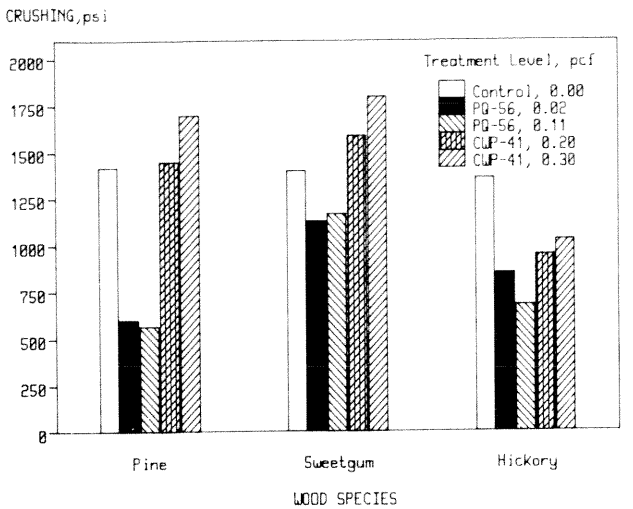

Figure 5.--In-plane crushing stress of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 53 pcf.

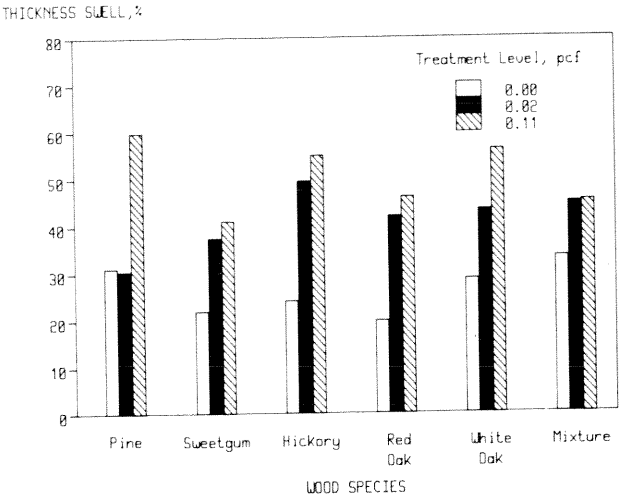

Figure 6.--Thickness swell values of unweathered, PQ-56 treated flakeboards at a density of 43 pcf.

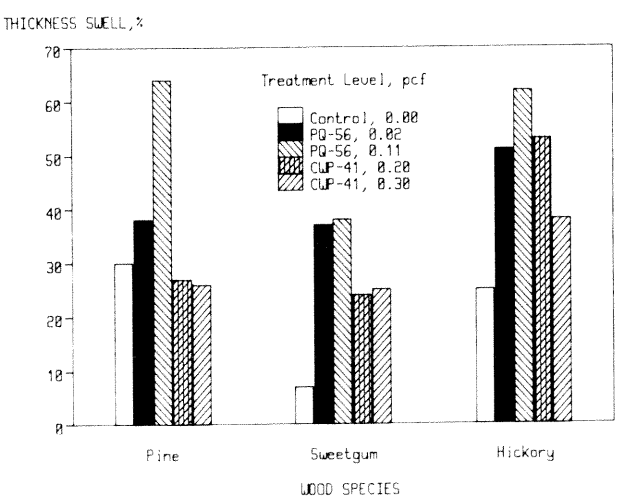

Figure 7.--Thickness swell values of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 48 pcf.

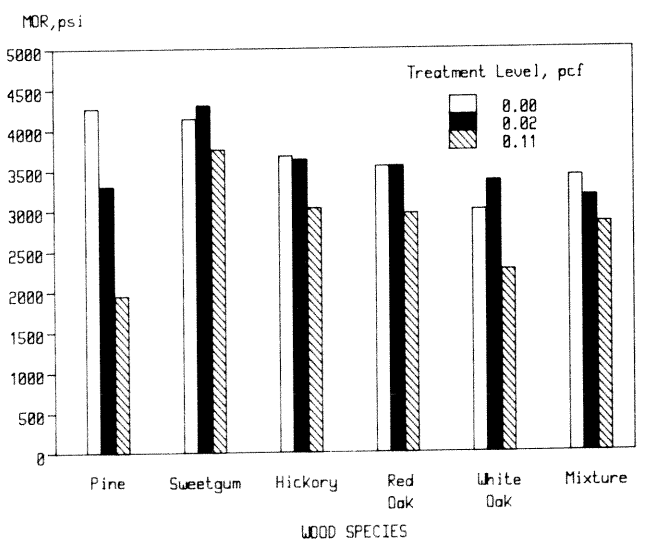

Figure 8.--Modulus of rupture of unweathered, PQ-56 treated flakeboards at a density of 45 pcf.

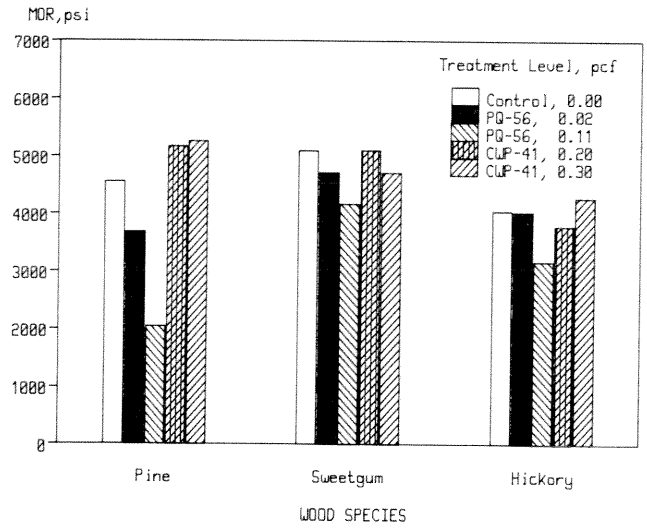

Figure 9.--Modulus of rupture of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 49 pcf.

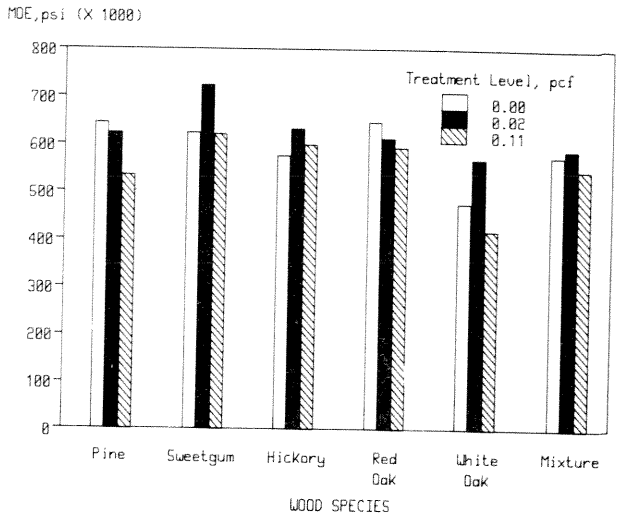

Figure 10.--Modulus of elasticity of unweathered, PQ-56 treated flakeboards at a density of 45 pcf.

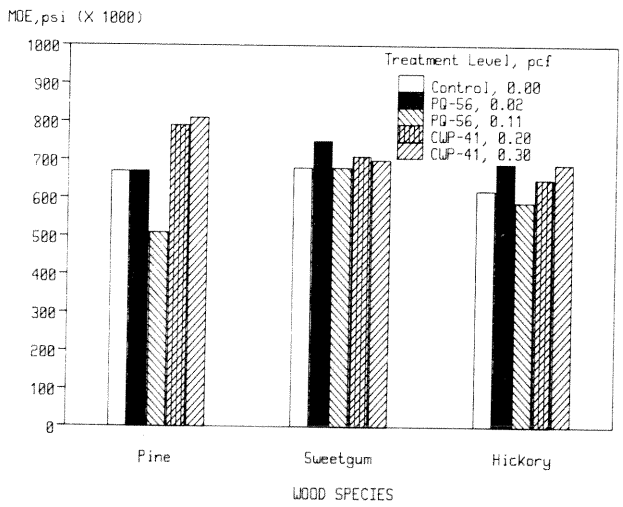

Figure 11.--Modulus of elasticity of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 49 pcf.

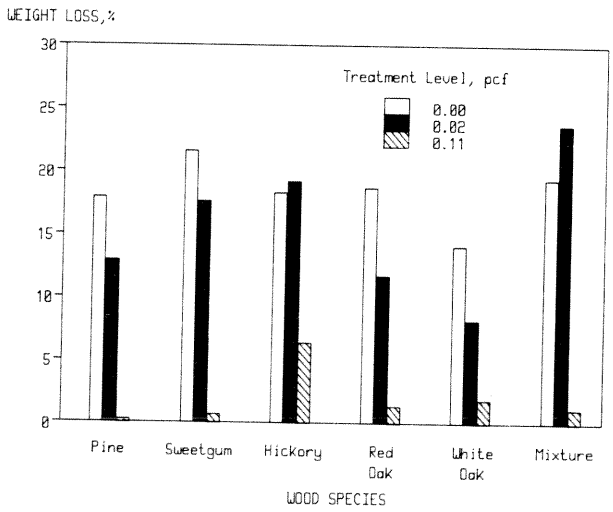

Figure 12.--Weight losses due to decay by *Gloeophyllum trabeum* of unweathered, PQ-56 treated flakeboards at a density of 48 pcf. Southern yellow pine control blocks had 19.3% weight loss.

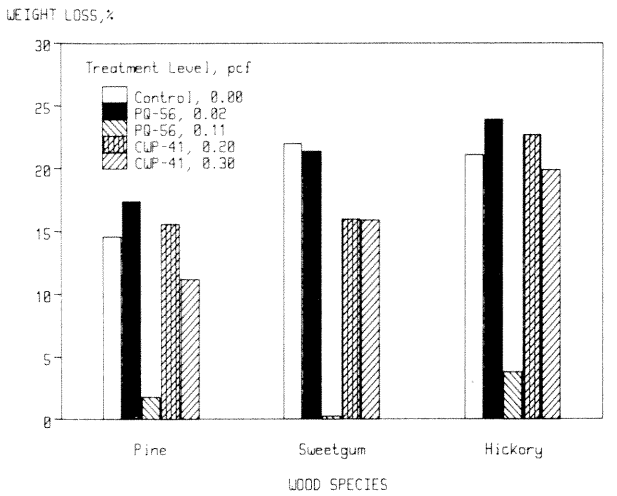

Figure 13.--Weight losses due to decay by *Gloeophyllum trabeum* of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 52 pcf. Southern yellow pine control blocks had 19.3% weight loss.

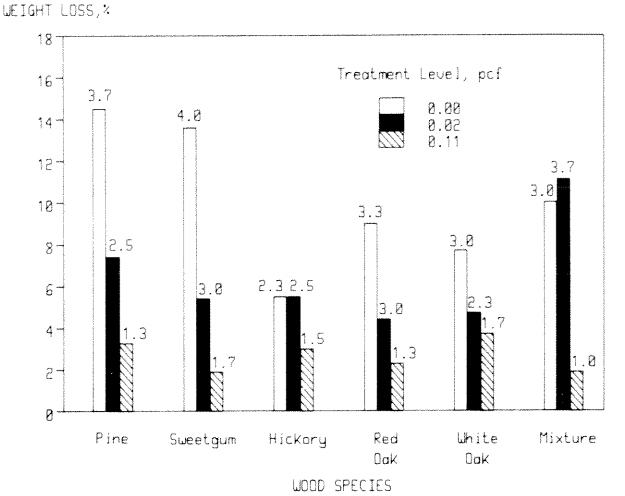

Figure 14.--Weight losses due to termite attack of unweathered, PQ-56 treated flakeboards at a density of 48 pcf. Southern yellow pine control blocks had 13.1% weight loss. Numerical ratings are average values based on visual evaluation of test samples; AWPA Standard M12-72.

1 = Sound surface
2 = Light attack
3 = Moderate attack
4 = Heavy attack
5 = Failure

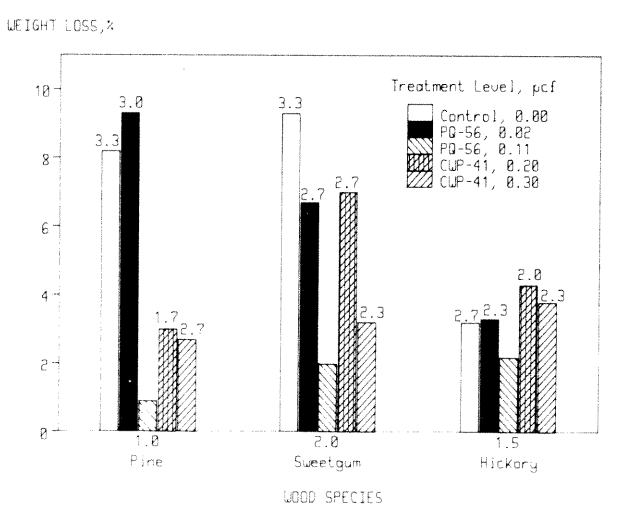

Figure 15.--Weight losses due to termite attack of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 52 pcf. Southern yellow pine control blocks had 13.1% weight loss. Numerical ratings described on Figure 14.

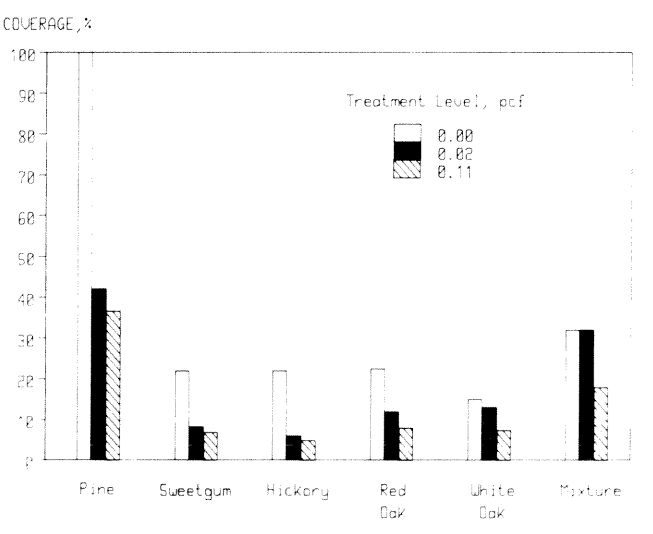

Figure 16.--Surface coverage due to mold of unweathered, PQ-56 treated flakeboards at a density of 48 pcf. Southern yellow pine control blocks had 100% coverage.

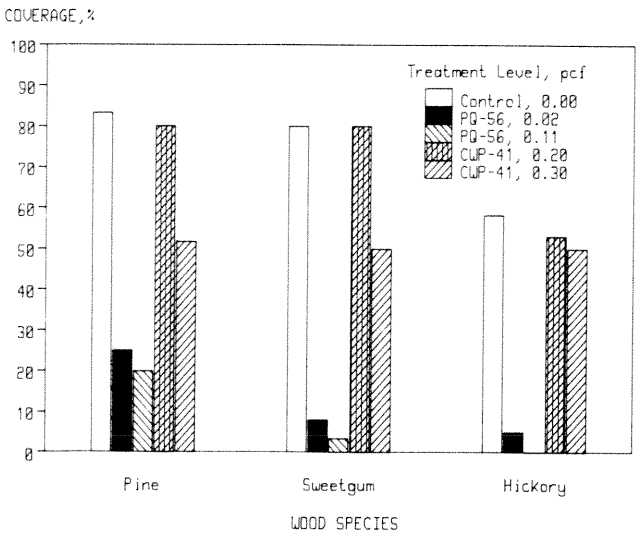

Figure 17.--Surface coverage due to mold of unweathered, PQ-56 and CWP-41 treated flakeboards at a density of 52 pcf. Southern yellow pine control blocks had 100% coverage.

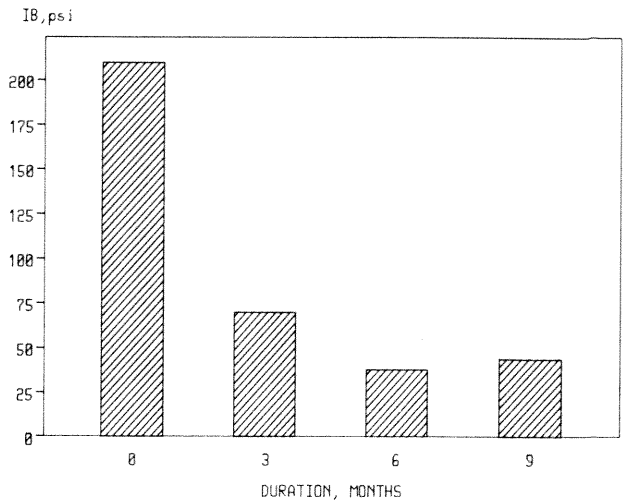

Figure 18.--Internal bond strengths of test-fence weathered, untreated sweetgum flakeboards at a density of 52 pcf.

RESEARCH NEEDS ON DURABILITY OF STRUCTURAL PANELS[1]/

by

E. W. Price and R. C. Tang[2]/

The development of structural panels has taken several years and many individuals. Durability and evaluation techniques are still a major concern of the industry, scientists, and users. The concluding session of the Workshop on Durability of Structural Panels, October 5-7, 1982, held in Pensacola, Florida, and sponsored by Southern Forest Experiment Station and Auburn University was devoted to a discussion on research needs. The discussion was concluded by obtaining a list of 10 durability problems and concerns voiced by the 26 participants. Without prioritization, the concerns voiced were:

- Real life performance requirements based on reliable field data are wanting.
- Current test methods are not adequate to predict real life performance.
- Products are or will be marketed that will not last for the expected service life.
- A centralized body is needed to coordinate efforts directed towards the understanding of durability problems and lead in establishing standardization for test procedures.
- An analysis to determine the influence of major degradation factors, such as weathering, biological creep, and stress rupture, is desired.
- Inconsistencies in product qualification procedures exist.
- Information, approaches, and solutions to durability problems or other building materials should be more effectively utilized.
- The user is not properly educated about the correct application to obtain maximum product performance.
- A greater participation of all parties (i.e., users, producers, general interest groups) is required in addressing the durability problems.
- Short term test methodology/approach for manufacturers to predict long term durability behavior of products is insufficient.

1/Summary of the discussion session at Workshop on Durability of Panel Products, Pensacola, FL, October 5-7, 1982.

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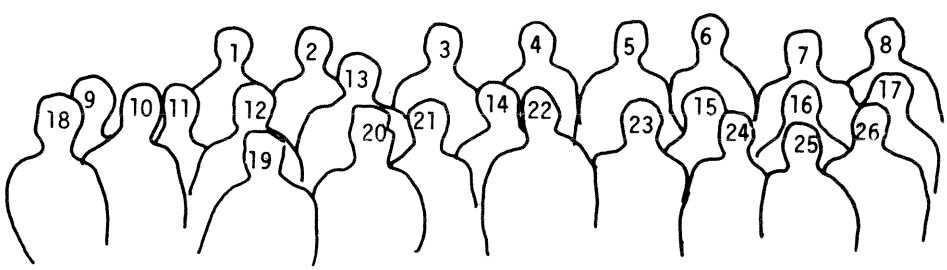

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Price, Eddie W., editor. Durability of structural panels. General Technical Report SO-53, New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1984. 185 p.

Twenty papers from the proceedings of a workshop are presented on the durability of a group of structural panels for use in roof, wall, and floor sheathing applications. The panel types are waferboard, flakeboard, strandboard, oriented structural board, and structural particleboard. A summary of the proceedings is given as the final presentation.

Additional Keywords: Dimensional stability, preservative treatment, load duration, biodeterioration, research needs.