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Title: DETERMINING APPROPRIATE ACCELERATED AGING
TESTS FOR KERUING PLYWOOD

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The main objective of this study was to determine appropriate accelerated aging methods for exterior plywood made with Southeast Asian hardwood face veneers. A secondary objective of this study was to determine the durability of exterior plywood made with keruing (12 Dipterocarpus spp.).

To reach these objectives I made plywood using three phenolic adhesives in a split-split plot design, varying assembly time (5, 20, 45 minutes) and species (16 Southeast Asian hardwoods) through four replications. Samples from these panels were subjected to vacuum/pressure soak (PS1-74); standard boil cycle (PS1-74) for 2, 5, 10, and 25 cycles; automatic boil cycle (ASTM D3434-75) for 20, 40, 100, and 200 cycles; weatherometer (ASTM G23-69) for 2400 hours; and wet/dry cycling for 2400 hours.

For these hardwoods, both the standard and automatic boil cycle aging methods were good discriminators of bond durability.

The standard boil method required 10 or more cycles to assure that unsatisfactory bonds would be detected. The automatic boil method required 40 or more cycles. The vacuum/pressure, weatherometer and wet/dry cycle methods were poor discriminators of bond durability.

All keruings examined formed uniformly excellent bonds with a low molecular weight resin (adhesive B); they formed bonds of variable quality with a moderately high molecular weight resin (adhesive A).

Determining Appropriate Accelerated Aging Tests for Keruing Plywood

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

DETERMINING APPROPRIATE ACCELERATED AGING TESTS FOR KERUING PLYWOOD

I. THE NEED FOR ACCELERATED TESTS OF PLYWOOD GLUEBONDS

Textured exterior siding for residential construction is a rapidly growing market for plywood. Face veneer for exterior siding must be free from defects that can cause delamination or are visually unattractive. Southeast Asian hardwoods mostly are defect free and plentiful, whereas high quality veneers of North American species are scarce. Because Southeast Asian hardwoods appeared to be desirable for siding, they were used widely in the early 1970's. Soon, veneer mills in Southeast Asia had more veneer on order than they could produce (Page, 1974).

The rapid rise in demand for imported hardwood veneer can be attributed largely to what has happened to domestic timber supplies. Domestic supplies of high quality veneer have declined steadily because younger timber stands are being harvested. Logs from young trees have more knots and other defects. However, veneers from younger trees are not useless; they are very suitable for plywood cores where the defects are not seen. But these core veneers can be used only if face veneers are available.

In spite of the apparent high quality of Southeast Asian hardwoods and their great demand in the past, few mills currently are using them. Some imported hardwood face veneers began to peel from exterior siding panels within one to three years after installation on houses. The problem was sufficiently serious that the Federal Housing Administration proposed to exclude all of these hardwoods from exterior plywood (Ripley, 1972). Lauan (*Shorea*, *Parashorea*, and *Pentacme*), called meranti in Indonesia and Malaysia, has performed quite well in exterior use (Wellons and Krahmer, 1973) and should not be excluded from siding markets. On the other hand, no company has succeeded in forming exterior quality bonds with kapur (*Dryobalanops* spp.) bonded to Douglas-fir. Keruing veneer (*Dipterocarpus* spp.) also has had a mixed history of good and poor bond performance.

Many factors may be responsible for the poor performance of keruing and kapur. These hardwoods frequently are dense; higher density woods tend to shrink and swell substantially, resulting in stress on the glueline. The pores of these hardwoods are quite large and uniformly distributed, allowing the adhesive to "bleed" away from the surface of an assembled panel. Nguyen (1975) found that high extractive concentrations on the surface of these hardwoods could be expected to cause gluing difficulty. Water and alcohol soluble compounds caused adhesives to gel in half of the normal time, resulting in poor adhesive penetration into the wood fiber walls. The extractives also may condense with the adhesive, intercept polymer condensation with the wood substrate and make a poorly bonded panel (Akaike et al., 1974).

A major concern of the plywood industry is that the poor performance of some of these hardwoods was not detected prior to market introduction. Bond durability usually is predicted by accelerated aging. The industry now wonders whether the accelerated aging methods specified by the plywood standard (PS 1-74, National Bureau of Standards 1974) do or do not predict exterior plywood durability with hardwood face veneers. Caster and Perrine (1974) noted that the standard methods did not predict the poor performance that was indicated by other methods with keruing face veneers. If the performance of keruing was not reliably predicted by the standard methods, these methods need to be changed. Several non-standard aging methods currently are being used by industry to replace the standard ones.

Study Objectives

The main objective of this study was to determine which accelerated aging methods best detected unsatisfactory[1] gluebonds in exterior plywood made with Southeast Asian hardwood face veneers.

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[1] An unsatisfactory bond can not withstand the bond degradation energies found in normal use.

A secondary objective was to determine the durability of exterior plywood made with keruing (Dipterocarpus spp.) face veneers using optimum production conditions. The accelerated aging methods compared in this study were: vacuum/pressure (PS1-74); standard boil cycle (PS1-74); automatic boil cycle (ASTM D3434-75, American Society for Testing and Materials 1976a; weatherometer (ASTM G23-69, American Society for Testing and Materials 1976b; and wet/dry cycling. Samples from these tests were compared with matching samples mounted on an exterior exposure fence and examined after six months. Future reports will compare these accelerated methods with longer term outdoor exposure.

II. AVAILABLE TESTS OF GLUEBOND DURABILITY

Adhesive-bond degradation has been attributed to heat energy, chemical energy, and mechanical energy (Gillespie and Lewis, 1972). Any glued product experiences all or some of these degradation energies in use. Thus, a proper aging test must match the degradation energies found when the product is in use. After matching the application, the test then increases the rate of degradation sensibly by increasing the rate of energy input.

A. Requirements for Accelerated Aging Methods

1. Correlate With Outdoor Exposure

The real measure of performance is long-term exposure in climatic conditions. Accelerated aging methods must correlate with a known time period of natural aging. Long-term exposure conditions vary in different climates. For instance, adhesive performance is different in England, Nigeria, and the Arctic. Carruthers and Hudson (1955) found that high temperature and humidity conditions in the tropics accelerated aging relative to temperate climates. This was expected because heat and dimensional changes degrade adhesive bonds rapidly. Chow and Steiner (1974) aged exterior plywood in Arctic-like conditions and found much wood tissue damage that was caused by severe internal stresses in the panels. Thus, the accelerated aging of a plywood product must be designed to simulate the most severe conditions that can be expected in a given region of use.

2. Simple to Interpret

Commercial plywood panels may vary in the number of gluelines for different products. To make aging methods interpretable, panels must be simplified. Booth and Maxwell (1957) found that thicker panels (five ply) of higher density species deteriorate faster than standard test panels (three ply) because greater stress develops in the thicker panels. Although the five ply panel deteriorates faster, it is complicated by having four gluelines to evaluate. The advantage of the standard three ply panel is that it fails in the face or back glueline of the panel. Commercial use of Southeast Asian hardwoods is as face veneer over a domestic species for core and back veneer. Because one objective of this study was to determine the durability of the hardwood-softwood glueline the test must evaluate that glueline. If delamination occurs in any other glueline, no information is gained about the durability of the hardwood-softwood glueline. Thus, I used hardwood veneer for both the face and back of my experimental panels.

3. Faster Than Natural Aging

The purpose of accelerating aging is to predict glueline durability in service. Therefore, testing must simulate rapidly the most severe conditions of a product's use. Protective coatings, such as paint, generally are not used because they absorb some of the degradation energy.

4. Reproducible

The results of accelerated aging must be reproducible. The weathering cycle generally is reproduced easily. However, the method of evaluating the results is more difficult to reproduce. Current standards (PS1-74) specify that aged plywood specimens be tested in shear by applying tension parallel to the glueline. Some investigators have tested glueline performance in other modes, such as cleavage (perpendicular to the glueline). Northcott (1952) used a wedge to cleave specimens. Stanger and Blomquist (1965) found wedge cleavage to be effective because the grain was oriented to concentrate stress on the glueline. They said that the shear test can cause either the wood or the adhesive to fail and is therefore less specific than wedge cleavage. Friction, however, between the wedge and the wood could be a major factor in this test. Strickler (1968) avoided friction by cutting a "V" notch into a standard specimen (Figure 1), attaching a cable to either end, and pulling the specimen apart.

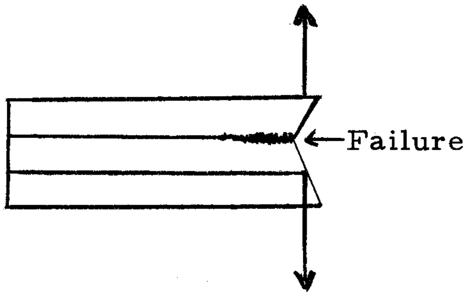

Figure 1. Cleavage specimen.

Wedge cleavage measures the cohesive strength of the glue and, possibly, adhesion between the glue and the wood. Plywood failure rarely, if ever, is due to cleavage forces and because of this, cleavage tests generally are not performed.

Following aging and shearing (or cleaving), specimens must be dried and evaluated for their performance. Two methods of evaluation are used: wood failure and breaking load. Breaking load was found by Carroll et al. (1969) to be heavily influenced by lathe checks and other uncontrollable variables. These uncontrollable variables tend to make reproduction of breaking loads difficult. Wood failure is an estimate of the percentage of wood that failed (as opposed to adhesive) in a one square inch area of a plywood specimen. When wood failure is high, the adhesive is known to be at least as strong as the wood. Northcott (1955) observed that wood failure results can be difficult to reproduce because no measure of wood failure is universally accepted. The American Plywood Association (APA) maintains standardized sets of sheared plywood specimens for which wood failure has been determined. These are used to assure that its members estimate wood failure in the same manner. Other testing organizations use these same standards. Bryant et al. (1959) found that wood failure was sensitive to core species, types of face stock, density of face stock, type of glue, and assembly time. They found breaking load to be insensitive to all of these variables. Thus wood failure, in spite of its shortcomings, is the best method available for evaluating plywood performance.

Following some aging methods, no mechanical test is used. Instead, the amount of delamination of the glueline is estimated or directly measured. These measurements might seem as reproducible as percentage wood failure, but are hampered by the difficulty of determining areas of delamination that are not visible at the edge of a sample.

B. Mechanical Stress

Kreibich and Freeman (1965) have used artificial stress to age adhesive bonds, by accelerating the effects of mechanical energy. After the stress treatment, they sheared the specimens, observing wood failure and breaking load. Panels having every ply oriented in the same direction were used. Plywood is manufactured so that adjacent plies are oriented perpendicular to each other, creating mechanical stress from shrinking and swelling. Artificial stress results from a measurable, controlled load. In a later study, Kreibich and Freeman (1970) compared the performance of several adhesives of known durability using stressed and unstressed panels. The unstressed panels were ranked in a different order of adhesive durability than expected. The stressed panels were ranked in the proper order of adhesive durability, indicating the need for stress in the test procedure because the unstressed panels did not perform as expected. From experience, the reliability of the test using unstressed panels was questioned.

C. Dry Heat

Dry heat aging methods accelerate bond degradation by accelerating the effects of heat energy. This type of method has been suggested to be effective for determining durability of interior adhesives (Gillespie and River, 1975, Sasaki *et al.*, 1976). However, panels bonded with exterior adhesive responded little to this method. The response that did occur with exterior adhesives was due to wood degradation.

D. Moisture

1. Cold Water Soak

The effects of wood moisture content variation can be accelerated by soaking. Gillespie (1965) and others developed swelling stresses in wood panels by soaking them in water. Interior grade adhesives are designed to be used in protected environments, such as homes. They are not designed to be waterproof, so they respond to tests such as this. Exterior adhesives are designed to resist boiling water, so a cold soak is ineffective in accelerating exterior adhesive breakdown.

2. Humidity

The effects of wood moisture content variation also can be accelerated by rapidly varying relative humidity. Several workers (Knight and Newall, 1954, Carruthers and Hudson, 1955) simply placed plywood specimens in an open-sided shed that had relative humidity variation due to weather changes; there was no control of this variation. Controlled climate rooms can be used to control the variation. The main degradation energy acting in a humidity test is mechanical because of the internal stresses that develop in the panel as it shrinks and swells. Exterior plywood adhesives so readily resist humidity changes that such tests are ineffective in predicting their durability.

3. Vacuum/Pressure Soak

Alternating cycles of vacuum and pressure rapidly soak a glueline. England (1954) was one of the early workers to use this method. Blomquist (1954) proposed that severe internal stresses would develop when plywood was soaked in water during cycles of vacuum (25 inches Hg) and pressure (75 psi). The energies involved are similar to those found in normal use. Only one hour is required for the standard vacuum/pressure soak prescribed by PS1-74 to degrade most unsatisfactory bonds between domestic softwood veneer. This standard aging method is used frequently by industry because of its short duration.

4. Boiling Water

Many accelerated aging methods use boiling water as the weathering agent. Exterior plywood is rarely boiled in normal use, but soaking does occur and boiling accelerates soaking. Boiling causes, in addition to swelling (mechanical energy), some hydrolysis (chemical energy) and thermal stress (heat energy). Lecher (1946) concluded that at least 12 hours of continuous boiling are required to distinguish between exterior and interior type adhesives.

C. Cyclic Boil

Another standard method of aging plywood (prescribed by PS1-74) uses alternating cycles of boiling and drying. Specimens are boiled four hours, dried 20 hours, and boiled four more hours after which they are tested in shear and wood failure estimated. Plywood specimens degrade after less boiling in this test than in the continuous boil test or other soak tests because the drying cycle accelerates the aging process. All three degradation energies are present in the cyclic boil method. However, heat accelerates cure of phenolic resin adhesives so undercured gluebonds may not be detected.

Many workers have used other boil-dry-boil methods (Perkins, 1949; Blomquist and Olson, 1955, and Hart, 1956), but the boil cyclic procedure described remains as the standard. Some preliminary work in industry shows that extending the standard boil test to 25 cycles of boiling and drying would better predict hardwood plywood durability.

The boil-dry-boil methods require at least daily service. An automated procedure that predicts durability with the same or greater accuracy as the standard boil-dry-boil method long has been sought to alleviate the problem of routine service. Walser and Colbeck (1967) developed an automated test having 10 minutes in boiling water, 4 minutes in ice water and 60 minutes in a forced draft oven at 225°F. They rapidly moved their specimens from boiling water to ice water which probably developed a partial vacuum in the specimens and helped in wetting them. Northcott _et_ _al_. (1968) compared many different cyclic schemes and found that the standard boil-dry cycle was the best system for accelerating bond degradation. However, a much shorter test in their study gave similar results. This test used 10 minutes boil, 3.75 minutes ice water immersion, and 60 minutes in a forced draft oven at 225°F. Kreibich and Freeman (1968) automated the latter test and were able to distinguish between known durable and non-durable adhesives. Caster and Perrine (1974) used a modification of Kreibich and Freeman's test to make the following automated test: 10 minutes in boiling water, 4 minutes exposed to forced air at room temperature and 57 minutes exposed to forced air at 225°F. Caster and Perrine justified the replacement of ice water with room temperature air on the hypothesis that temperature difference between steps, and not temperature itself, creates a thermal shock which develops internal stresses and ages the panel. The chief advantages of this method are speed and dependability.

F. Weatherometer

Weatherometers have been used extensively to test the durability of protective coatings but they have been introduced only recently for testing plywood durability. Peterson (1963) was among the first to use a weatherometer for accelerating the aging of plywood. The Boise Cascade Company noted a correlation of weatherometer aging to exterior fence exposure during the last five years.[2] Twin carbon arcs served as a heat energy source and caused shrinkage during the drying cycle. A fine water spray caused hydrolysis and swelling during the wetting cycle. Thus, all three degradation energies are present.

The performance of a test specimen can be evaluated by measuring the percentage of the panel area free of delamination (percent area intact). The weatherometer requires an extensive time period (2400 hours is believed to approximate five years outdoor exposure) and it is relatively expensive to operate.

Wet/dry cycling, similar to the aging occurring in the weatherometer, might be a less expensive way to obtain the same results. Steam or infrared heating elements could be used instead of carbon arcs to reach temperatures comparable to the weatherometer. Ultraviolet radiation, the heat source in the weatherometer, has limited ability to penetrate wood so that radiation can not be causing bond degradation directly. Therefore, wet/dry cycling merely should be substituting heat sources and duplicating the other test conditions.

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[2] Personal communication - Mr. O. T. Stenberg.

G. Chemical Degradation

1. Acid Hydrolysis

Hydrolysis is one of the degradation reactions occurring in many of the accelerated aging methods. Since this reaction may occur during bond degradation, some workers have studied techniques that use acid hydrolysis directly to degrade bonds. Freeman and Kreibich (1968) found that phenol formaldehyde (exterior) adhesives were essentially non-hydrolyzable in acid. They measured bond breakdown indirectly by monitoring the amount of formaldehyde released by hydrolysis. Troughton (1969) also found that little hydrolysis occurred with exterior adhesives. This aging method is only successful when using interior adhesives which are much more susceptible to hydrolysis.

2. Thermal Softening

Thermal softening is also being considered as a bond durability predictor. This method uses heat energy. Chow (1973) developed a thermal softening technique, as follows: scrape adhesive from the glueline, place it in a column under load, raise the temperature, and record the flow which then takes place. He believed that adhesives which have a high softening temperature should be more durable, but the process is very time consuming.

H. Conclusion

In Summary, Table 1 illustrates the aging methods that appear to be the most useful for this study, both because of their speed and their ability to degrade unsatisfactory exterior adhesive bonds.

The vacuum/pressure soak is the current standard method and should be compared to the others.

The alternate cycling of boiling and drying is a standard method (PS1-74) but, based on experience to date, may need to be extended well beyond the two cycles specified by the plywood standard.

The automatic boil cycle that was developed by Caster and Perrine (1974) greatly accelerates aging and uses all three bond degradation energies.

The weatherometer is reported to correlate with outdoor exposure and requires less time than outdoor exposure.

Wet/dry cycling is similar to the weatherometer but uses steam heat and is less expensive to operate.

Outdoor exposure is the only reliable indicator of plywood durability because it tests durability under actual conditions experienced in use.

Table 1. Aging methods used to degrade plywood bonds

Aging Method	No. of Tests	Cycles	Shear Test Speed
Vacuum/pressure	2	1 (60 minutes)	Fast or slow
Standard boil cycle	4	2, 5, 10, 25 (1 day each)	Fast
Automatic boil cycle	4	20, 40, 100, 200 (71 minutes each)	Slow
Weatherometer	1	1200 (2 hours each)	Not applicable
Wet/dry cycling	1	1200 (2 hours each)	Not applicable
Total accelerated methods	12		
Outdoor fence (Tacoma, Washington)	5	(6, 12, 24, 48, 72 months)	

III. EXPERIMENTAL DESIGN

To reach my objectives, I have made plywood using three adhesives in a split-split plot design with four replications. Table 2 is a brief description of that design. This design should indicate statistical differences between the aging methods and factors such as adhesive, species, and assembly time. To select the best accelerated aging method, I compared all accelerated methods to the six month test fence exposure by regression of the form $y=bx$ where y is the result of the accelerated method and x is the result of six month exposure. Both the slope of this regression and the residual mean squares were used to select the best method. In the future, these accelerated methods will be compared with extended outdoor exposure in order to verify the results based on short time exterior exposure. I also determined the solid wood properties of these species in order to interpret the performance of the species, if possible, in the gluing study.

A. Dependent Variables

The performance of each accelerated aging method was evaluated by either percentage of the sample area intact (area free of delamination) or breaking load and wood failure, depending on the test method used. The weatherometer and wet-dry cycle methods

Table 2. Summary of experimental design

Factor	Levels Included					
Adhesive		A		B		C
Species of face veneers	17	Douglas-fir 2 merantis 2 kapurs 12 keruings	8	Douglas-fir 2 merantis 2 kapurs 3 keruings	8	Douglas-fir 2 merantis 2 kapurs 3 keruings
Assembly time	3	5 minutes 20 minutes 45 minutes	3	5 minutes 20 minutes 45 minutes	3	5 minutes 20 minutes 45 minutes
Accelerated aging methods		12 as described in Table 1		12 as described in Table 1		12 as described in Table 1
Replications		4		4		4

specified measuring area intact. All other accelerated methods required measurement of breaking load and estimation of percentage wood failure. Samples from the exposure fence were cut into shear specimens, then sheared, measuring breaking load and wood failure.

B. Independent Variables

1. Adhesives

Three different commercial phenolic adhesives were included in the study in three separate gluings. The use of three different adhesives was not an attempt at determining the best adhesive but rather, was an attempt at encompassing the types of adhesives being used with these hardwoods. The properties of the phenolic resins used in these adhesives are summarized in Table 3.

Table 3. Characteristics of phenolic resins used in adhesives

Characteristic	Adhesives		
	A	B	C
% phenolic solids	45	40	56
pH	11.2	10.5	9.8
molecular weight	moderate	low	low and moderate combined
viscosity, centipoise	1100	800	700

2. Species of Face Veneer

Seventeen species were included in this study, as indicated in Table 4. Because one of the main objectives was to examine keruing's acceptability for exterior plywood, 12 species were included from that trade group. Six of the keruings were segregated and identified only as keruing. Because the species identification was not confirmed, I have called them mixed keruing. Red meranti was included because of its reputation for minimal difficulty in forming exterior bonds. Red balau, a more dense meranti than normally used in plywood, was included to evaluate density effects within the meranti trade group. Two kapur species were included because of their reputed difficulty in gluing. The aging methods should rank

Table 4. Species used in gluing study

Trade Group	Scientific Name	Species No.	Supplier
Douglas-fir	Pseudotsuga menziesii (Mirb) Franco	(0)	Roseburg Lumber & Champion International
meranti			
red meranti	Shorea curtisii	(21)	Mentiga
red balau	Shorea ochrophloia	(4)	Pacific Veneer
kapur	Dryobalanops aromatica	(20)	Mentiga
	Dryobalanops oblongifolia	(22)	Mentiga
keruing			
West Malaysia	Dipterocarpus sublamellatus	(16)	Mentiga
	Dipterocarpus cornutus	(18)	
	Dipterocarpus crinitus	(23)	
	Dipterocarpus costulatus	(26)	
	Dipterocarpus kerii	(27)	
	Dipterocarpus verrucosus	(28)	
Sumatra	6 mixed Dipterocarpus species	(10-15)	Boise Cascade Co.
Total	17 species		

red meranti and kapur according to their reputations. If these species are ranked in the expected order of durability, the keruing species also would be expected to be ranked in the proper order of durability.

I used fewer keruing species with adhesives B and C because a massive number of specimens would have been generated by a complete replication of the gluing as with adhesive A. Instead, I selected keruing species that represented the range of physical properties encountered.

3. Closed Assembly Time

Assembly time is the time period between application of the adhesive and placing the assembled panel in the hot press. A range of closed[3] assembly times was desirable in order that some of the panels be mismanufactured deliberately, either by over penetration of adhesive in the wood when pressure was applied (short assembly time) or by dry out of the glueline (long assembly line). Such unacceptable panels should be detectable after the accelerated aging of the panels.

4. Aging Methods

The aging methods used in this study are listed in Table 1 and were discussed in Chapter II.

5. Replication

Four replications were included in this study. Previous work had shown that four replications of the experiment should detect differences of five percent wood failure. Within each adhesive, the

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[3] Closed assembly time--the time between assembling and hot pressing the panel.

gluing of one replication was completed before beginning the next replication, assuring that any variability over time could be accounted for. To further assure that the maximum amount of variability would occur between replications, the order of gluing the species was randomized separately for each replication.

IV. EXPERIMENTAL PROCEDURE

A. Species Selection

Through arrangements of the American Plywood Association (APA), each tree used for this study was identified in the field as to genus, and in most instances, species. When the tree was felled, a representative of the Regional Forestry Department of that Southeast Asian country took leaf and wood specimens in order to confirm the field identification. Six trees of keruing (genus *Dipterocarpus*) were never positively identified as to species based on leaf samples and identification beyond genus based on the wood sample was not possible.

The veneers needed for this study were peeled in Southeast Asia by the companies listed in Table 4. Twenty sheets of "A" grade veneer (4'x8'x1/8") were peeled from each tree and kiln dried at temperatures not above 320°F. The veneer was then shipped to Oregon State University.

B. Solid Wood Properties

1. Sampling Procedure

For each species in the study, ten pieces of lumber (2"x4" or 1"x4") were cut, as indicated, from a four foot bolt (see Figure 2, coming from the same tree as the veneer.

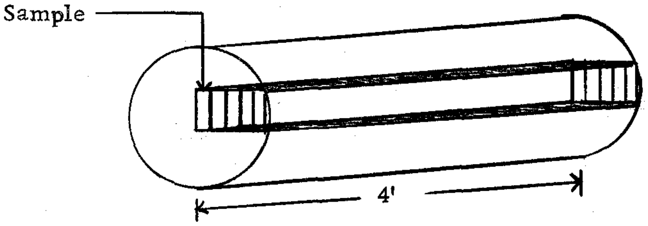

Figure 2. Cutting pattern for lumber

Two boards were selected from each bolt and confirmed to be flat sawn. Each board was then cut as indicated in Figure 3 into sections.

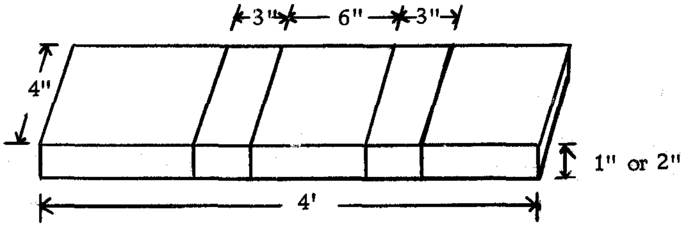

Figure 3. Cutting pattern for wood samples

The three inch sections from each board were combined and ground in a Wiley mill to pass a one square millimeter screen. This constituted the first replication for extractive and pH measurements. The second board was treated in an analogous manner in making the second replication. The remaining six inch sections from the two boards were for determining shrinkage and specific gravity, using the following sequence.

2. Shrinkage and Specific Gravity Procedure

(a) Measure radial, tangential, and longitudinal dimensions of each wood sample to ±0.001" when green.

(b) Weight the green wood samples to ±0.1 grams.

(c) Oven dry the wood samples at 105°C to constant weight and record the oven dry (O. D.) weight.

(d) Measure the dimensions after drying in the same manner as described in (a).

(e) Calculate green and dry volumes.

(f) Calculate specific gravity

$$\text{Sg (green)} = \frac{\text{Weight O. D.}}{\text{Volume green}}$$

$$\text{Sg (O. D.)} = \frac{\text{Weight O. D.}}{\text{Volume O. D.}}$$

(g) Calculate green moisture content

$$\text{MC\%} = \left(\frac{\text{Weight green} - \text{Weight O. D.}}{\text{Weight O. D.}}\right) \times 100$$

(h) Calculate tangential and radial shrinkages:

$$\text{Shrinkage (X)} = \left(\frac{\text{X green} - \text{X O. D.}}{\text{X green}}\right) \times 100$$

where X = tangential or radial dimension

3. Extractive Content

The wood meal from the lumber samples was used for duplicate extractive determinations as follows:

(a) Oven dry a cellulose extraction thimble, record the O. D. weight, equilibrate it at ambient conditions, and record the air dry weight.

(b) Place approximately 20 grams of air dry wood meal in the thimble and record the weight of meal used to ±0.001 grams.

(c) Determine wood meal moisture content from a matching sample.

(d) Extract the air dry sample and thimble in benzene for nine hours in a soxhlet extractor having four to six solvent exchanges per hour.

(e) Air dry the sample overnight.

(f) Evaporate benzene extract quantitatively to dryness and weight amount of extractive recovered after oven drying at 105°C.

(g) Repeat steps (d)-(f) using diethyl ether.

(h) Repeat using ethanol.

(i) Repeat using distilled water.

(j) Oven dry extracted sample and thimble at 105°C recording dry weight.

(k) Calculate extractive content as:

$$\left(\frac{X_{(i)}}{\text{O. D. weight extracted wood}}\right) \times 100$$

where X_1 = weight benzene solubles recovered

X_2 = ether solubles, etc.

4. pH and Buffering Capacity

Using wood meal from each species prepared as described previously, two sets of duplicate samples were analyzed as follows.

(a) Boil distilled water to remove dissolved carbon dioxide, cool to room temperature, and mix 5±0.001 grams of air dry wood meal to 50 milliliters of the carbon dioxide free water.

(b) Determine sample moisture content from matching wood meal samples.

(c) Measure pH of each to ± 0.1 units using a calibrated glass-calomel electrode system.

(d) Titrate one sample with 0.1N HCl and allow slurry to reach equilibrium by stirring.

(e) Continue tritation until 2.0 pH is reached recording titer at intervals of approximately one pH unit.

(f) Titrate second sample with 0.1 N NaOH analogously until a pH of 12.0 is reached.

(g) Graph pH as a function of millimoles of acid or base added per gram of O. D. wood.

C. Panel Manufacture and Analysis

1. Veneer Preparation

Veneer for four replications of each specie was selected as free as possible of knots, streaks, cross grain, etc. because the aging methods would detect the flaws preferentially.

The veneer sheets (1/8"x52"x100") were cut in half, providing matched face and back veneer for each panel and trimmed to 51" along the grain x 42" cross grain. These paired veneers were then cut into three pairs of matched pieces (17"x42") prior to panel layup, and each pair assigned to one of the three assembly times. The veneer cutting pattern is shown in Figure 4.

Douglas-fir core veneer (1/10"x17"x126" along the grain) was also as free as possible of flaws. The core veneers were cross cut into three pieces so that veneer from the same sheet of core was used for all three assembly times.

After cutting and labeling, all veneer was conditioned in a controlled climate room to 5±1 percent moisture content for two weeks or more prior to gluing.

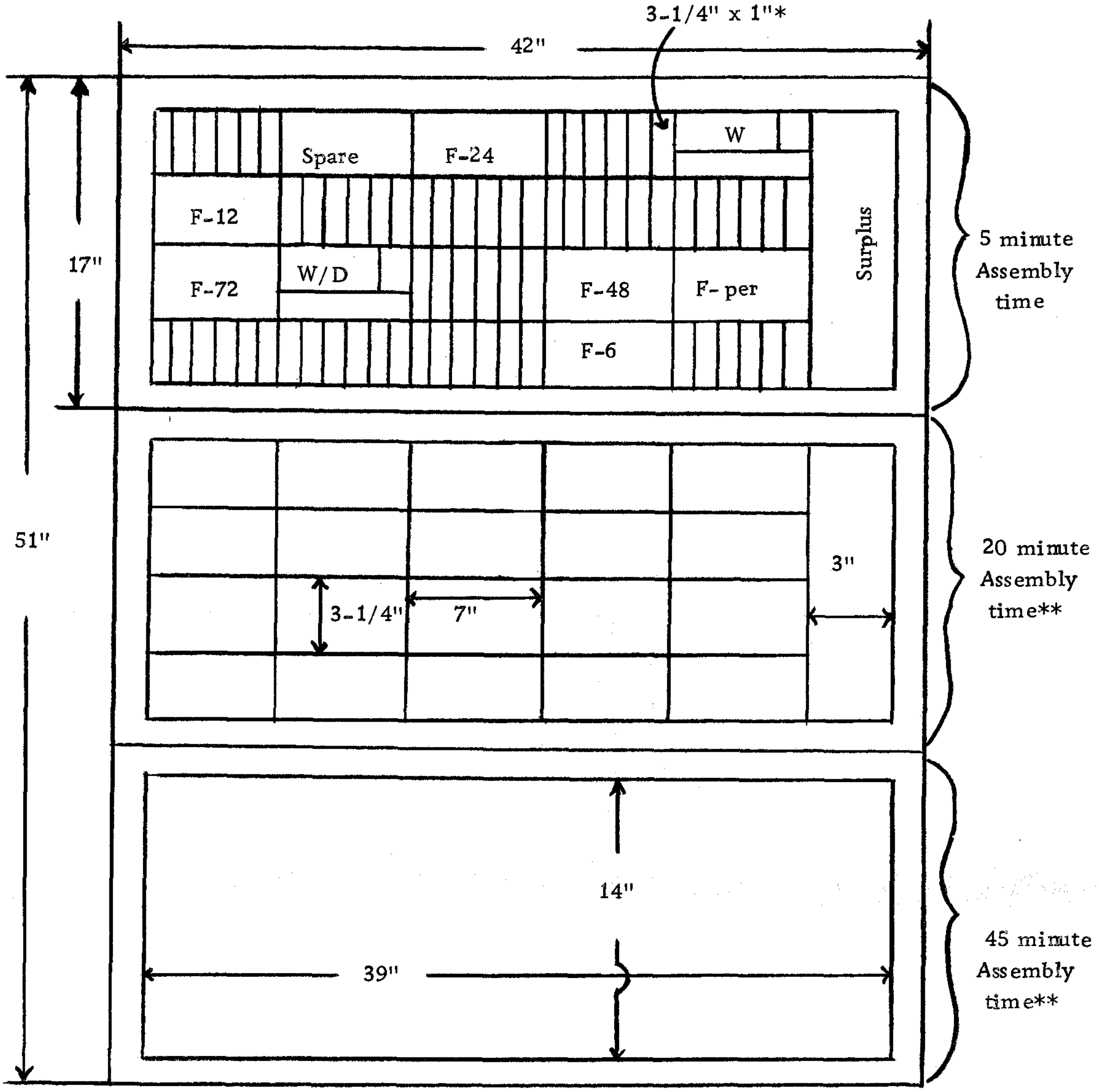

Figure 4. Cutting pattern for plywood panels

F = Outdoor exposure
W = Weatherometer cycles
W/D = Wet/dry cycles

* Shear samples randomly assigned to vacuum/pressure, standard boil and automatic boil cycle methods.

** Cutting pattern for 20 and 45 minutes analogous to 5 minutes, except different random arrangement

2. Gluing

Plywood panel manufacture occurred at the APA laboratory located in Tacoma, Washington. Adhesive[4] was mixed from resin[5] and applied to core veneer at the rate specified in Table 5 with a conventional rubber roll glue spreader. Face, back, and core veneers were assembled immediately into three ply, 3/8'' panels with the tight side[6] facing outwards, and allowed to wait for the prescribed closed assembly time. The three panels representing the three assembly times were pressed at the same time using the following conditions:

temperature = 300°F; pressure = 200 psi; press closing time = 1/2 minute; time at full pressure = 5-1/2 minutes.

All panels were stacked while hot for at least 24 hours prior to texturing.

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[4] Adhesive - Neat resin that has been extended and prepared according to the resin manufacturer's recommendations.

[5] Resin - A phenol formaldehyde material prepared by the resin manufacturer.

[6] Tight side - The side of the veneer facing outwards on the log when the veneer was peeled. The opposite side, the loose side, is next to the knife during peeling.

Table 5. Adhesive Formulation

Adhesive mix	A	B	C
Resin used	A	B	C
% resin solids in mix	32.4	29.4	39.0
% caustic solids added to mix	1.4	0.0	0.0
% filler and extender solids in mix	10.8	13.3	8.5
Type of fillers and extenders used	walnut shell flour wheat flour	walnut shell flour wheat flour	walnut shell flour wheat flour polyvinyl alcohol diatomaceous earth
Application rate			
liquid adhesive #/MDGL*	75	76	46
resin solids #/MDGL	24.3	22.3	17.9

* #/MDGL = pounds per 1000 sq. ft. of double glueline.

3. Sample Preparation

Following plywood manufacture, the face surface of each panel was textured, removing about 0.03 inches of the surface, duplicating as closely as possible commercially available exterior siding plywood.

Each textured panel was then cut into 20 blanks (3-1/4''x7'') as indicated in Figure 4 and stored in bags. Any surplus from the panel was also placed in the bag.

Nine blanks were selected randomly from each bag representing each panel for the following tests: 1 - weatherometer, 1 - wet/dry cycling, 6 - one per length of outdoor exposure, and 1 - spare sample. Weatherometer samples were then cut to 2-5/8"x4" and mounted on five ply plywood backing. Wet/dry cycle samples were cut to 2-5/8" x4" and placed in wire trays which allowed water drainage during the aging. Outdoor exposure blanks (3-1/2"x7") were mounted on the APA test fence in Tacoma at 45° to the horizontal and facing southward.

The 11 blanks remaining from each panel were cut to make 66 standard shear specimens as indicated in Figure 5. Core lathe check[7] orientation was determined. Grooves were then cut through the face veneer and two thirds of the way to the next glueline after orienting the sample so that the lathe checks were closed when shear tested. The grooves were place 1±0.005 inches apart. These grooves force failure to occur in the test area between them.

After cutting all 66 shear specimens from each panel, they were sorted randomly into sets of six shear specimens for each aging method, making ten sets for the ten methods that prescribed their use, and an eleventh set of six retained as spare samples. Each set

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[7] Lathe check - Fractures that occur when the wood is peeled; they cause one side of the veneer to be "loose".

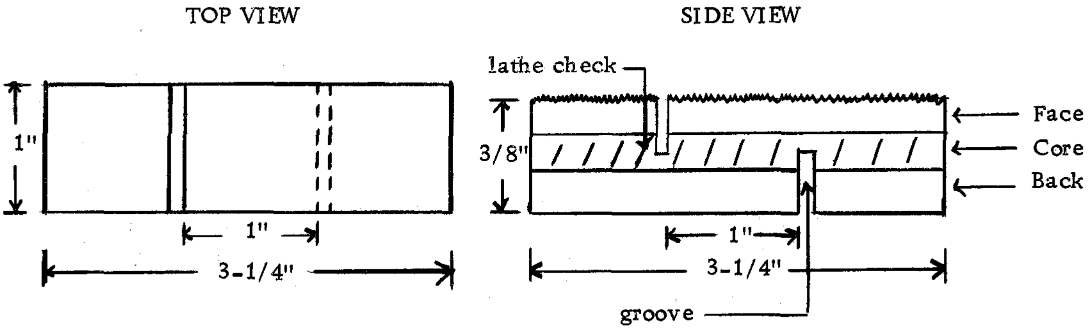


Figure 5. The standard shear specimen

of six shear specimens was drilled outside of the test area, tied together with wire, and subjected to one of the ten aging methods.

4. Accelerated Aging

(a) Vacuum/Pressure Soak. I submerged standard shear specimens from each panel in water at 70°F while in a pressure vessel. A vacuum of 25 inches of mercury was drawn and maintained for 30 minutes, followed immediately by a pressure treatment of 70-75 psi for 30 additional minutes. Specimens were then removed and sheared while wet by tension loading to failure with secure grips (no slippage). The test speed was 16 inches per minute for the fast method (PS1-74) and 600-1000 pounds per minute for the slow method (ASTM D-906). The load at failure (breaking load) was recorded and the percentage of wood failure was estimated after the specimens had air dried.

(b) Standard Boil Cycling. Sets of six standard shear specimens were selected for this cyclic procedure. They were boiled in water for four hours (cycle 1), dried for 20 hours at 145±5 °F, and boiled again (cycle 2). This boiling and drying process was repeated for the specified number of cycles. Following accelerated aging, the samples were cooled to room temperature in water, sheared by the fast method (16 inches per minute), with breaking load and wood failure evaluated as described in the vacuum/pressure method.

(c) Automatic Boil Cycling. Sets of six standard shear specimens were selected, drilled as described in Figure 6 and shipped to the Weyerhaeuser Company for the aging. A rod was passed through the 1/4" holes in the set of six with spacers between specimens to allow water and air circulation. The specimens then were exposed to cycles of ten minutes in boiling water, 3.75 minutes of forced air circulated at room temperature and 57 minutes of forced air circulated at 225 °F. This process was continued for the specified number of cycles. After the last cycle, the dry samples were returned to Oregon State University, subjected to the vacuum/pressure soak specified by PS1-74, and tested by the slow method (600-1000 pounds per minute, ASTM D-906). The breaking load and wood failure were estimated.

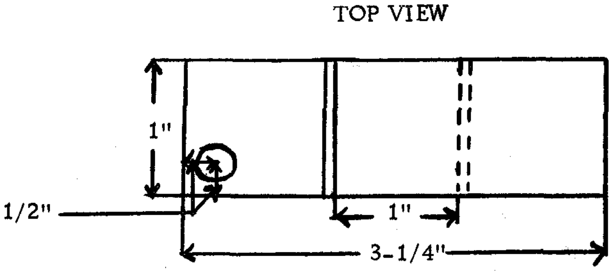


Figure 6. Drilling pattern for automatic boil cycle specimens

(d) Weatherometer Cycling. The weatherometer samples were placed in the weatherometer (twin arc, Atlas model DMC) and aged in the following manner:

dry - 102 minutes of radiation from a carbon arc (enclosed) at 175°F.

wet - 18 minutes of radiation from a carbon arc (enclosed) plus cold water spray, reducing temperature to 95°F.

Every 400 hours, samples were removed, dried for 24 hours at 145°F, and the area intact was estimated. Approximately half of the specimens were aged in weatherometers of the Boise Cascade Company, Boise, Idaho. The remaining were aged at Oregon State University.

(e) Wet/Dry Cycling. The samples for wet/dry cycling were placed in the chamber and aged in the following manner:

dry - 102 minutes of steam heating, regulated to 175°F.

wet - 18 minutes of cold water spray, reducing temperature to 95°F.

Every 400 hours, samples were removed, dried for 24 hours at 145°F, and the area intact was estimated.

(f) Outdoor Exposure. The six month test fence samples were removed and evaluated after exposure. The remaining samples will be removed after the prescribed time (12, 24, 48, and 72 months) and evaluated. The area intact was estimated from the sample blank (3-1/4"x7") after air drying. These sample blanks were then cut into six standard shear specimens, subjected to the vacuum/pressure soak prescribed by PS1-74, sheared by the fast method, recording breaking load and wood failure.

5. Wood Failure Estimates

Wood failures were estimated using the APA standard method (see Appendix A). Each wood failure reading represented the average of two readers. Their estimates of wood failure were never allowed to differ by more than ten percent.

D. Statistical Procedure

1. Sample Distribution

The sampling intensity from every aging method needs to be the same so that comparison of aging methods can be made simply. Six standard shear specimens were cut from each sample blank for each aging method requiring them, but only one blank was used for the other aging methods. This apparent discrepancy in sampling intensity was accounted for by averaging the six values of wood failure and breaking load obtained from the standard shear specimens, making the sampling intensity of all aging methods the same.

2. Preparing Data for Analysis

My analysis assumed that the responses of the samples to the aging methods were normally distributed. This was a reasonable assumption for the distribution of breaking loads. Area intact and wood failure were measured as percentages, which are not normally distributed. I used the arcsine transform to convert the percentage data to a nearly normal distribution using the following formula:

$$X_{\text{transformed-degrees}} = \text{Arcsine } (x_{\text{percent}}/100)^{1/2}.$$

This transformation is illustrated graphically by Figure 7. Note that 100 percent wood failure is 90° after transformation.

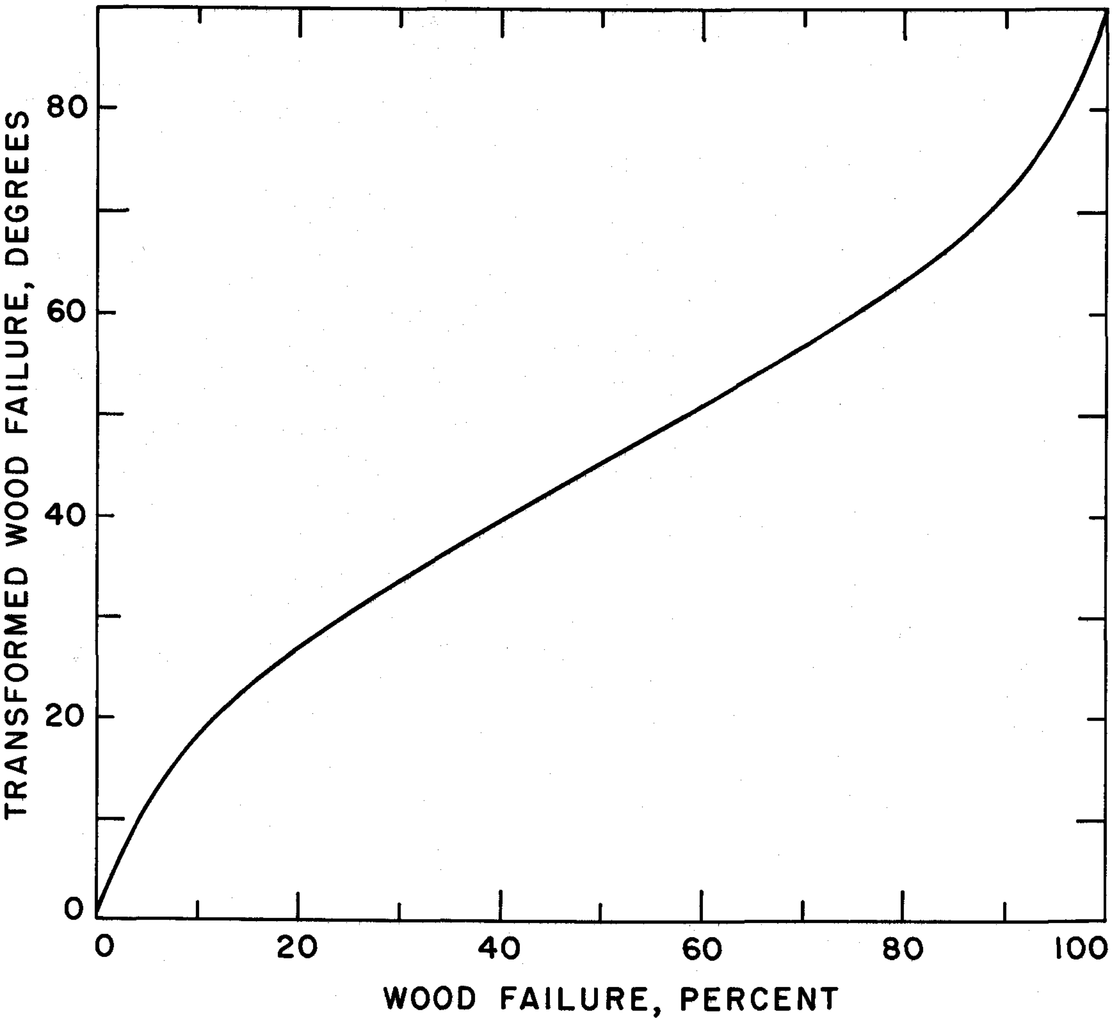


Figure 7. Arcsine transform of percentage data.

3. Analysis of Variance

With the data thus prepared for analysis, I analyzed the contribution to variance caused by each of the independent variables used with adhesive A on each of my dependent variables (area intact, wood failure, breaking load). One analysis of variance used the transformed percentage data from adhesive A, the other used the breaking load data. The F values from both of these analyses were used to compare the sensitivity of breaking load and wood failure to process variables. Adhesive A is more nearly typical of the adhesives being used for producing exterior plywood today so I am particularly interested in the responses from plywood made with this adhesive.

Adhesives A and B were then combined in an analysis of variance of wood failure as a function of the eight species used with both adhesives, excluding the results from the weatherometer and wet/dry cycling. These two adhesives were combined in this analysis to determine if significantly different responses to the aging methods occurred with these adhesives as well as to detect differences in the two adhesives. Adhesive C was excluded from this comparison because the computer program for statistical analysis could not accept that much data and because I had discovered that adhesive C was not used at optimum conditions, causing all adhesive bonds to be marginal or worse. Data from adhesive C was analyzed separately. The lack of effectiveness of the weatherometer and wet/dry cycling in predicting performance was determined by analysis of adhesive A alone, so these methods were not included in subsequent analyses, in order to limit the analyses to a size acceptable to the computer.

Adhesives A and B were again analyzed, but using eight keruings and only two aging methods (vacuum/pressure-fast, 40 cycles of the automatic boil). This analysis was based on additional experiments which yielded more specific information about differences in keruing's performance with adhesives A and B.

4. Regressions

I regressed wood failure following six months outdoor exposure for all species against either area intact or wood failure following accelerated aging, using the results of either adhesive A, B, or C. Regressions of transformed results were expected to intersect at 90° because durable panels should give that value, regardless of the aging method. By subtracting the transformed values from 90, I obtained regressions that passed through the origin, eliminating the intercept coefficient, i.e., $y=bx$

where $y = 90^\circ - \text{Arcsine}(\text{wood failure of accelerated test})^{1/2}$

$x = 90^\circ - \text{Arcsine}(\text{wood failure of six months exposure})^{1/2}$.

V. DISCUSSION AND RESULTS

Species, adhesive, and assembly time were the plywood production parameters varied in this study. Each of these parameters was expected to influence bond quality and, in turn, aging method, so species, adhesive, and assembly time need to be discussed before aging methods.

A. Effect of Species

Breaking load and wood failure were the two independent variables used to evaluate the effect of all dependent variables, including species. However, an analysis of the species effect verified that breaking load was an inappropriate measure of plywood bond quality after accelerated aging.

1. Breaking Load

Breaking load following accelerated aging did not rank the species in the order of bond quality observed for breaking loads after six months of outdoor exposure, and neither ranked the species in the order normally observed in application. The breaking load results obtained in this study (illustrated by Figures 8 and 9 using adhesive A) suggest that keruing forms equally as durable bonds as Douglas-fir or red meranti. Experience has shown that keruing is

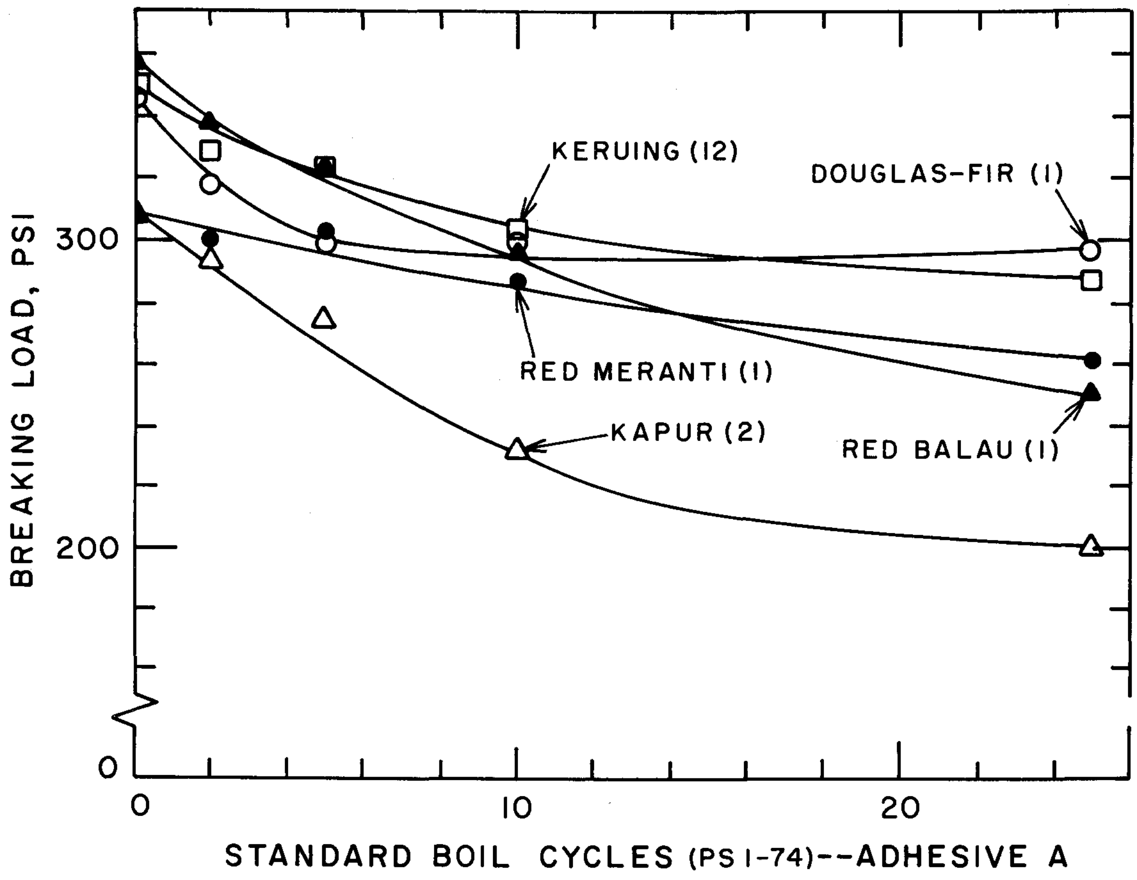


Figure 8. Breaking loads for standard boil cycle method - adhesive A

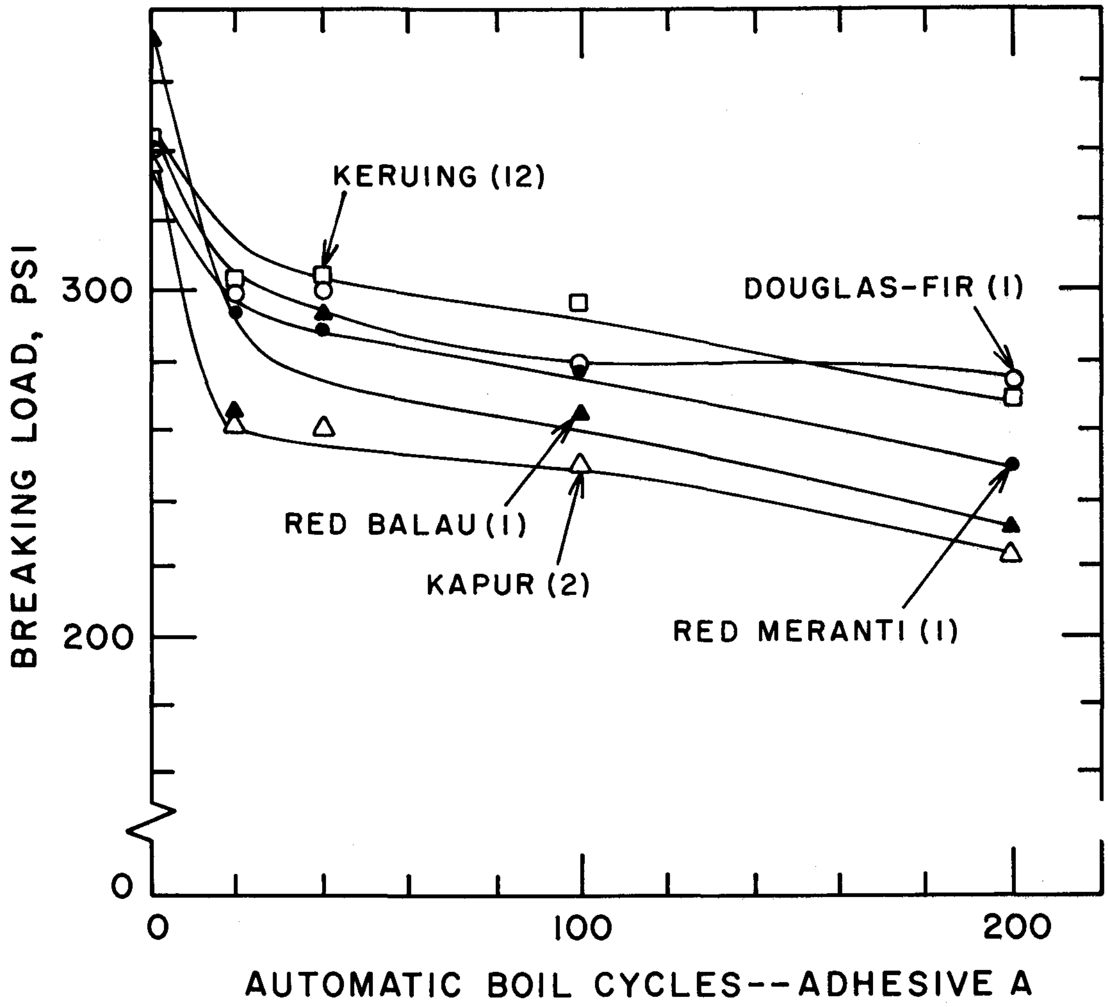


Figure 9. Breaking loads for automatic boil cycle method - adhesive A

less satisfactory than Douglas-fir and red meranti with an adhesive such as A.

The statistical analysis of these results with adhesive A (Table 6) verified that significant differences did occur between species. That effect occurred primarily because of low average breaking loads with kapur and red balau. Kapur was known in advance of this study to provide poor bonds (Wellons and Krahmer, 1974). However, the low breaking loads with kapur and red balau (Figures 8 and 9) are artificially low because specimens that did not survive the accelerated aging were arbitrarily given a zero breaking load. Those kapur and red balau specimens that did survive had essentially the same breaking loads as those of all other species. This indicates that breaking load did not detect the poor bonds in kapur panels that had not yet delaminated.

Instead of measuring bond quality, breaking load seemed to measure primarily the strength of the veneers. High density species generally have high strength. Thus, keruing may have appeared more durable than would be justified by experience. Standard boil and automatic boil cycling reduced wood strength, causing breaking loads to decrease as the number of aging cycles increased. Caster and Perrine (1974) used breaking load to predict bond quality. However, their specimens were parallel laminated. Bryant (1959) found, as indicated by these results, that breaking load was not sensitive to

Table 6. Analysis of variance of factors influencing breaking load with adhesive A

Sources of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F	Probability*
Replication	255446.08	3	85148.73		
Species	656046.70	16	41002.92	2.16	97.95
Error (A)**	912556.19	48	19011.60		
Assembly Time	100318.96	2	50159.48	19.40	100.00
Time x Species	93576.26	32	2924.26	1.13	68.41
Error (B)**	263672.25	102	2585.02		
Tests	1472132.80	9	163570.31	487.07	100.00
Species x Tests	281327.94	144	1953.67	5.82	100.00
Time x Tests	6394.84	18	355.27	1.06	61.18
Species x Time x Tests	91022.11	288	316.05	0.94	25.77
Error (C)**	462428.03	1377	335.82		
Total	4594922.80	2039			

* Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Error (A) - Rep x Species
Error (B) = Time x Rep + Species x Time x Rep
Error (C) = Test x Rep + Species x Test x Rep + Time x Test x Rep + Species x Time x Test x Rep

bond quality when cross-laminated specimens were used. Instead, lathe checks and other uncontrollable variables dominated. Because breaking load did not seem to measure adhesive bond durability, I did not use it to evaluate the effect of other variables on bond quality.

2. Wood Failure

Wood failure did discriminate between durable and non-durable adhesive bonds. As shown in Figures 10-15 and Table 7, large differences in average wood failure values occurred between some species. Furthermore, these values ranked the species in an order

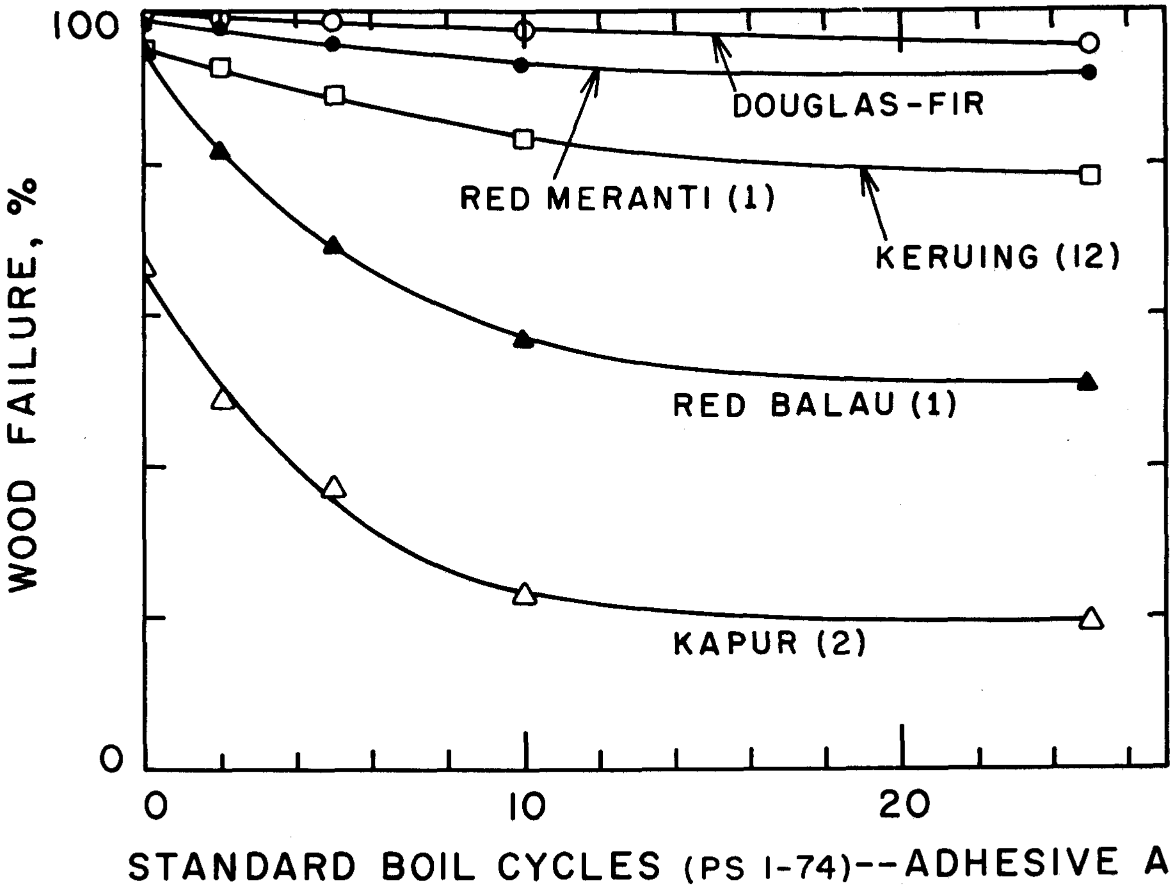


Figure 10. Wood failures for standard boil cycle method - adhesive A

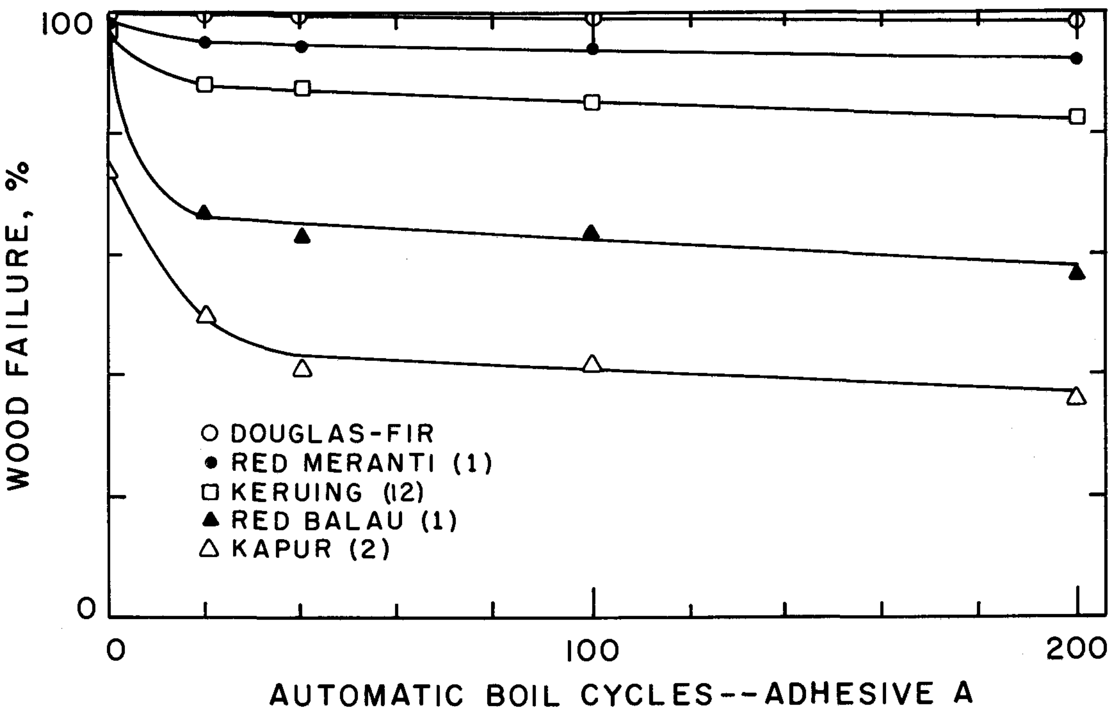


Figure 11. Wood failures for automatic boil cycle method - adhesive A

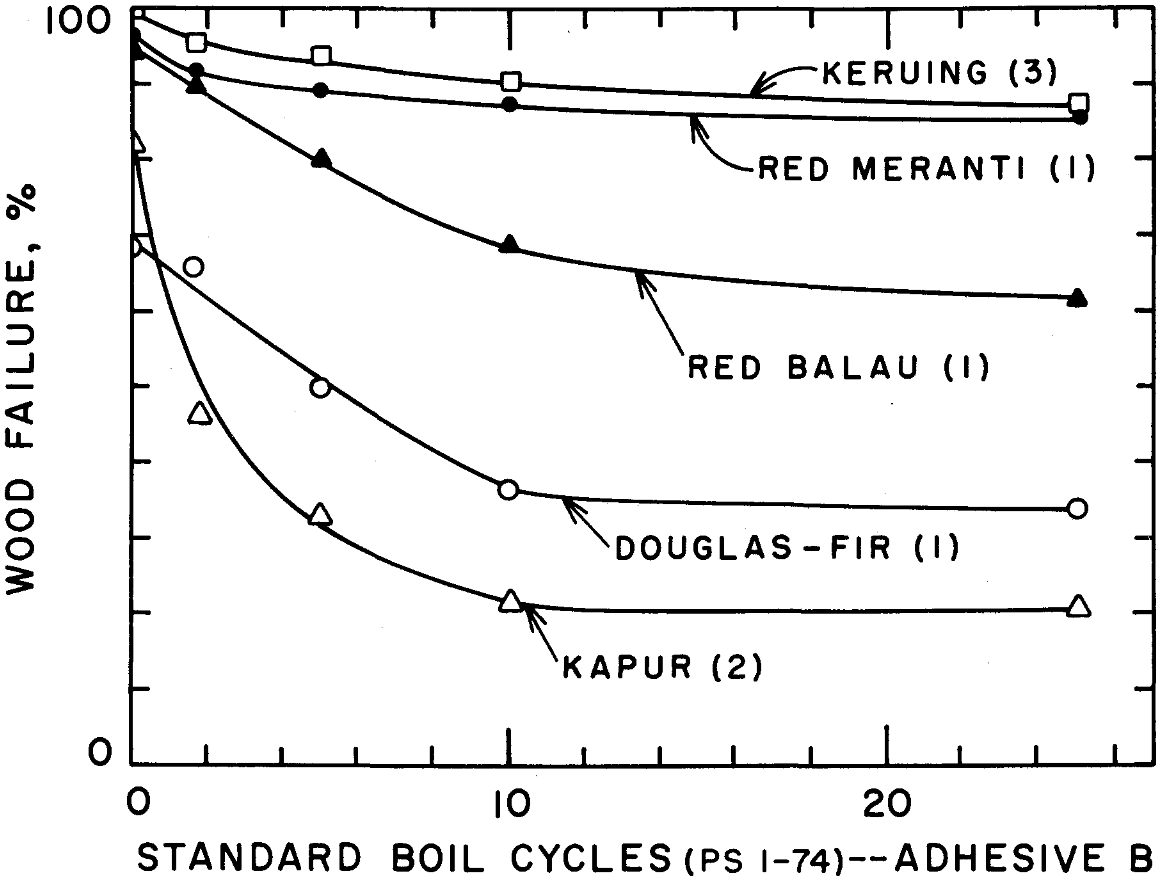


Figure 12. Wood failures for standard boil cycle method - adhesive B

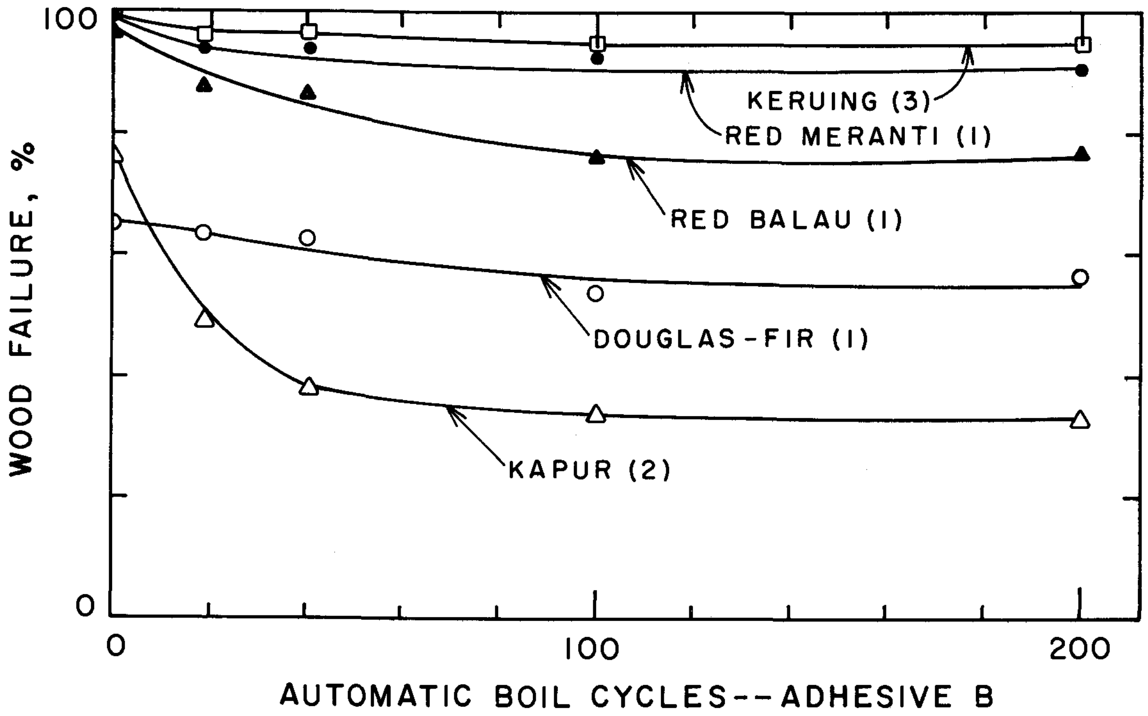


Figure 13. Wood failures for automatic boil cycle method - adhesive B

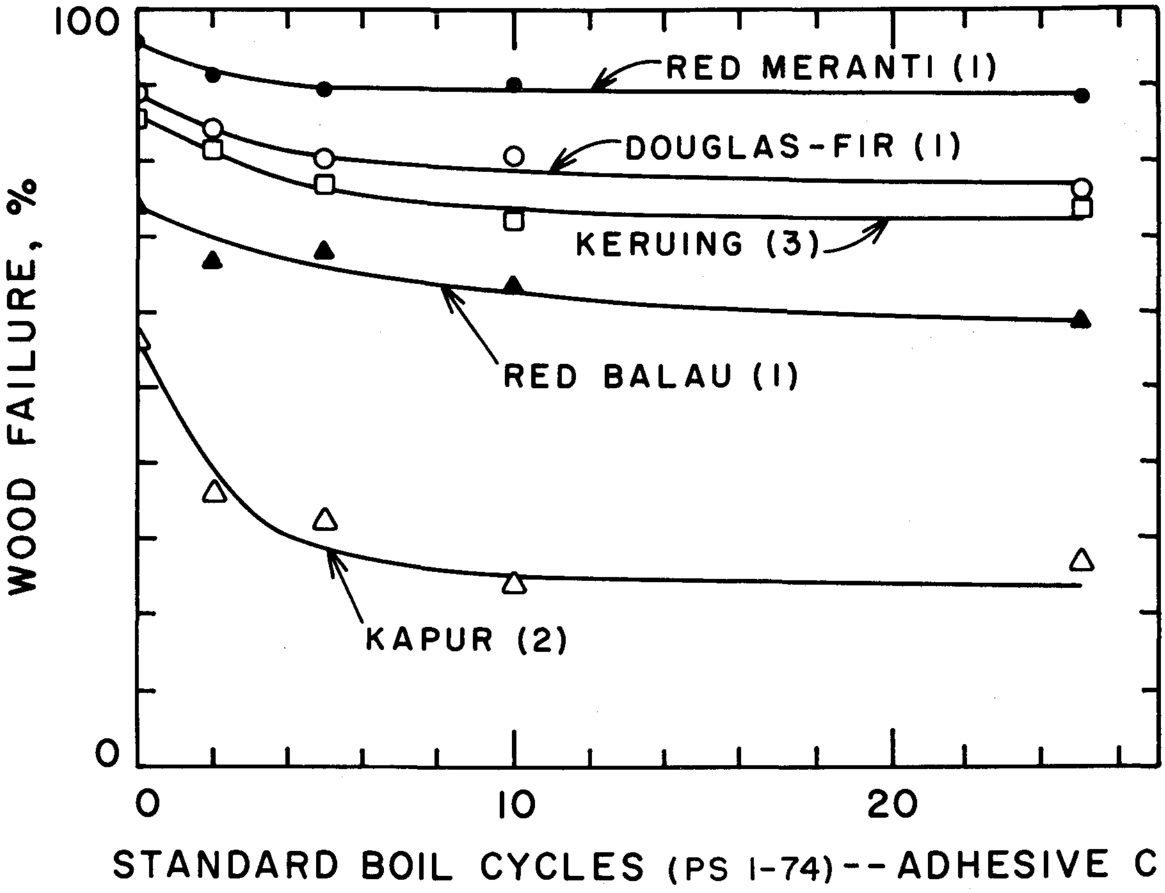


Figure 14. Wood failures for standard boil cycle method - adhesive C

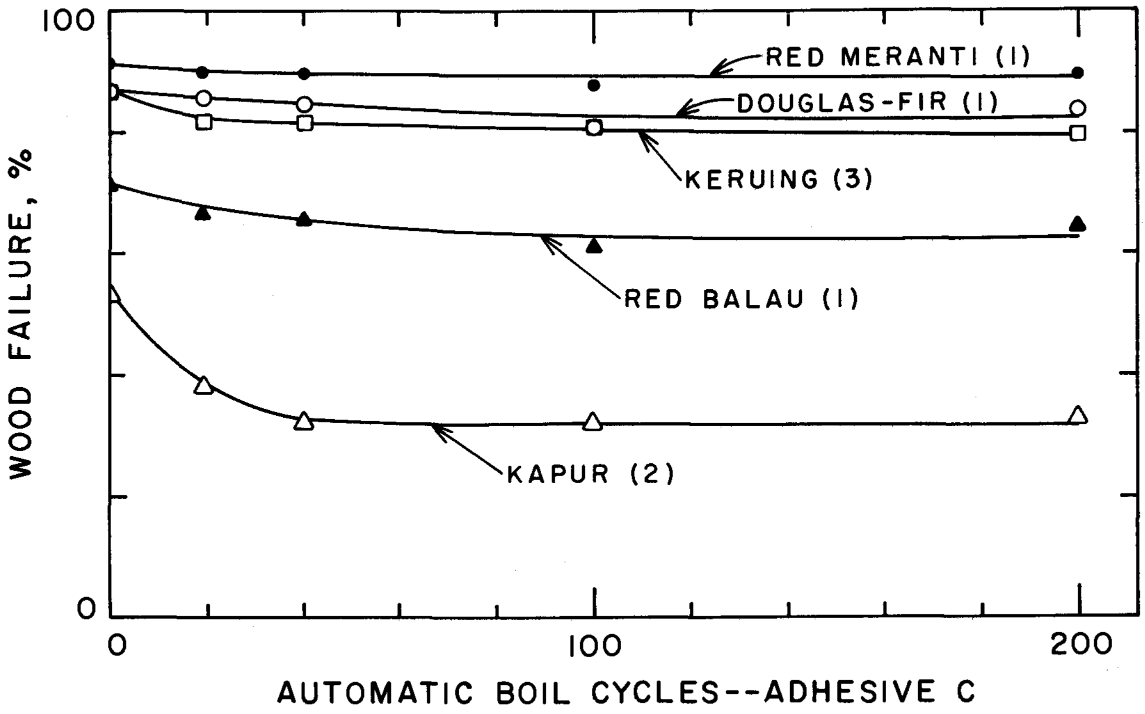


Figure 15. Wood failures for automatic boil cycle method - adhesive C

of durability consistent both with experience and with performance in the six months exposure test.

Species was a significant source of variation with all adhesives (Tables 8-10). The species effect, as indicated by Figures 10-15, was essentially the same irrespective of adhesive or aging method. The major differences between species are illustrated statistically by single degree of freedom comparisons between groups of species with adhesive A (Table 11).

Douglas-fir and red meranti formed very durable adhesive bonds, as expected. The major exception occurred with adhesive B. The Douglas-fir veneers used with that adhesive were moistened accidentally just prior to gluing, raising their average moisture content to almost 12 percent. Acceptable glue bonds were not expected at that high a moisture content.

Red balau, the abnormally dense meranti (see for example specific gravity in Table 12) was substantially less gluable than red meranti. See for example Contrast 1 in Table 11. Among the properties of the veneers reported in Table 12, only density (and the related shrinkage percentage) was greatly different between these two species of meranti. However, a comparison based on such limited observations is not adequate to claim that high density causes poor bonding.

Table 7. Area intact or wood failure in samples aged by the weatherometer, wet/dry cycling, and outdoor exposure.

		Average % Area Intact After 2400 Hours of Weatherometer			Average % Area Intact After 2400 Hours of Wet/Dry Cycling			Average % Wood Failure After 6 Months Exposure		
Species		Adh A	Adh B	AdhC	Adh A	Adh B	Adh C	Adh A	Adh B	AdhC
Douglas-fir	(00)	100	100	100	100	100	100	100	81	92
red meranti	(21)	100	100	100	100	100	100	97	96	94
red balau	(4)	100	100	91	100	100	100	76	97	77
	(28)	100	-	-	100	-	-	97	-	-
keruing	(16)	100	-	-	100	-	-	80	-	-
from	(27)	100	100	100	100	100	100	95	99	91
West	(26)	97	-	-	99	-	-	63	-	-
Malaysia	(18)	99	-	-	100	-	-	85	-	-
	(23)	100	100	100	100	100	100	99	99	87
	(12)	100	-	-	100	-	-	97	-	-
	(11)	100	-	-	100	-	-	97	-	-
keruing	(10)	99	-	-	100	-	-	72	-	-
from	(13)	100	-	-	100	-	-	99	-	-
Sumatra	(14)	100	-	-	100	-	-	90	-	-
	(15)	100	100	98	100	100	100	83	98	86
	(20)	98	98	97	100	100	100	55	53	52
kapur	(22)	79	78	88	97	99	100	36	47	20

Table 8. Analysis of variance of factors influencing wood failure and area intact with adhesive A

Sources of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F	Probability*
Replication	20367.10	3	6789.03		
Species	387847.17	16	24240.45	23.15	100.00
Error (A)**	50254.99	48	1046.98		
Assembly Time	3130.40	2	1565.20	7.20	99.88
Time x Species	15406.09	32	481.44	2.22	99.86
Error (B)**	22166.61	102	217.32		
Tests	162410.51	11	14764.59	314.27	100.00
Species x Tests	81236.25	176	461.57	9.82	100.00
Time x Tests	2166.95	22	98.50	2.10	99.79
Species x Time x Tests	15689.43	352	44.57	0.95	27.52
Error (C)**	79068.51	1683	46.98		
Total	839743.99	2447			

* Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Error (A) = Rep x Species
Error (B) = Time x Rep + Species x Time x Rep
Error (C) = Test x Rep + Species x Test x Rep + Time x Test x Rep + Species x Time x Test x Rep

Table 9. Analysis of variance of factors influencing wood failure with adhesives A and B

Sources of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F	Probability*
Replication	5347.64	3	2694.56		
Species	460843.45	7	65834.78	32.82	100.00
Error (A)**	42121.64	21	2005.79		
Glue	3872.86	1	3872.86	2.31	85.84
Species x Glue	95845.80	7	13692.26	8.18	100.00
Error (B)**	40166.88	24	1673.62		
Assembly Time	8100.31	2	4050.16	9.87	99.99
Species x Time	30972.52	14	2212.32	5.39	100.00
Glue x Time	14190.80	2	7095.40	17.29	100.00
Species x Glue x Time	7937.49	14	566.96	1.38	82.21
Error (C)**	39385.90	96	410.27		
Test	96893.78	9	10765.98	200.56	100.00
Species x Test	32225.31	63	511.51	9.53	100.00
Glue x Test	2181.04	9	242.34	4.51	100.00
Species x Glue x Test	8409.53	63	133.48	2.49	100.00
Time x Test	3364.70	18	186.93	3.48	100.00
Species x Time x Test	6686.45	126	53.07	0.99	48.41
Glue x Time x Test	1735.99	18	96.44	1.80	97.92
Species x Glue x Time x Test	5347.64	126	42.44	0.79	4.53
Error (D)**	69567.97	1296	53.68		
Total	977933.73	1919			

* Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Error (A) = Species x Rep

Error (B) = Glue x Rep + Glue x Species x Rep

Error (C) = Time x Rep + Glue x Time x Rep + Species x Time x Rep + Glue x Species x Time x Rep

Error (D) = Test x Rep + Glue x Test x Rep + Species x Test x Rep + Glue x Species x Test x Rep + Time x Test x Rep + Glue x Time x Test x Rep + Species x Time x Test x Rep + Glue x Species x Time x Test x Rep

Table 10. Analysis of variance of factors influencing wood failure with adhesive C

Sources of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F	Probability*
Replication	12539.35	3	4179.78		
Species	196565.70	7	28080.82	3.92	99.31
Error (A)**	150481.99	21	7165.81		
Assembly Time	1195.41	2	597.71	3.68	96.74
Species x Time	2538.44	14	181.32	1.12	63.42
Error (B)**	7798.37	48	162.47		
Test	13987.42	9	1554.16	38.13	100.00
Species x Test	7317.34	63	116.15	2.85	100.00
Time x Test	1004.30	18	55.79	1.37	86.07
Species x Time x Test	3211.84	126	25.49	0.63	0.08
Error (C)**	26409.62	648	40.76		
Total	423049.78	959			

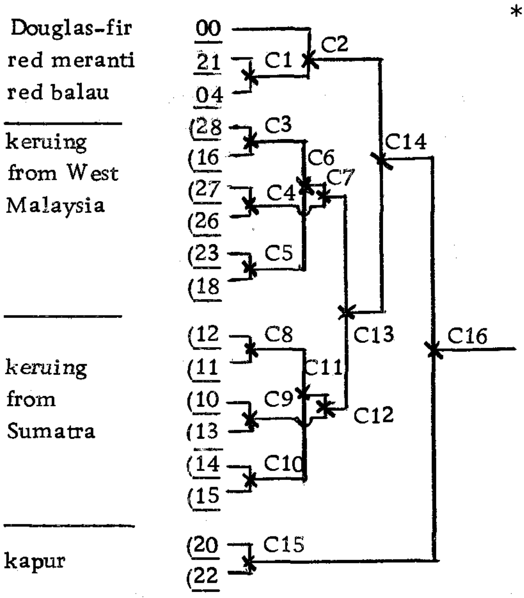
* Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Error (A) = Species x Replication
Error (B) = Time x Rep + Species x Time x Rep
Error (C) = Test x Rep + Species x Test x Rep + Time x Test x Rep + Species x Time x Test x Rep

Table 11. Single degree of freedom comparison of species with adhesive A using transformed percentage data

Contrast	Average Difference for Contrast	Sum of Squares **	F***	Probability****
C 1	18.9	25679.90	24.50	100.00
C 2	13.9	18479.60	17.70	99.99
C 3	11.6	9609.22	9.18	99.61
C 4	25.5	46954.50	44.80	100.00
C 5	7.0	3553.08	3.39	92.82
C 6	0.6	56.23	0.05	18.23
C 7	13.2	33583.40	32.10	100.00
C 8	0.8	46.04	0.04	16.53
C 9	14.2	14456.10	13.80	99.95
C10	3.6	936.13	0.89	65.05
C11	7.3	7749.52	7.40	99.09
C12	3.1	1846.32	1.76	80.91
C13	2.7	3037.46	2.90	90.50
C14	1.0	350.76	0.34	43.46
C15	13.3	12682.10	12.10	99.89
C16	28.7	208821.00	199.00	100.00

* Species contrasts were as follows:



*** Degrees of Freedom = 1 x 48

**** Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Equation for calculating sums of squares:

$$SS = \frac{n(\Sigma \lambda_i M_i)^2}{\Sigma (\lambda_i)^2}$$

n = number of items averaged, 3 x 4 x 12 = 144
i = coefficient for comparison
M_i = means being compared

Table 12. Properties of Southeast Asian hardwoods

Common Name	Scientific Name	Spp. No.	$S_{g\,dry}$ [1]	% Sh_T [2]	% Sh_R [2]	% Extractives Soluble in [3]			pH	Buffering Capacity [4]
						Benzene + Diethyl Ether	Ethyl Alcohol + Water	Total		
meranti										
red meranti	*Shorea curtisii*	(21)	.40	4.91	4.78	1.03	1.32	2.35	3.31	0.34
red balau	*Shorea ochrophloia*	(4)	.80	8.39	5.65	1.80	2.48	4.28	4.90	0.37
kapur	*Dryobalanops aromatica*	(20)	.69	9.38	5.94	0.61	6.52	7.13	3.47	0.60
	Dryobalanops oblongifolia	(22)	.70	10.03	8.92	0.42	6.98	7.40	3.38	0.60
keruing										
West Malaysia	*Dipterocarpus verrucosus*	(28)	.67	10.11	6.38	1.95	1.46	3.41	5.06	0.23
	Dipterocarpus sublamellatus	(16)	.73	9.81	7.56	0.69	1.73	2.42	4.48	0.30
	Dipterocarpus kerii	(27)	.81	13.16	9.52	2.71	2.88	5.59	4.09	0.28
	Dipterocarpus costulatus	(26)	.91	13.11	8.80	10.25	2.21	12.46	4.39	0.34
	Dipterocarpus cornutus	(18)	.97	11.81	10.60	3.31	1.57	4.88	4.46	0.34
	Dipterocarpus crinitus	(23)	.97	12.98	9.93	0.68	2.48	3.16	3.66	0.28
Sumatra	Six *Dipterocarpus species*	(12)	.59	9.82	6.59	0.76	0.97	1.73	4.43	0.46
		(11)	.61	9.35	4.92	1.54	2.44	3.98	5.35	0.34
		(10)	.67	9.76	5.48	1.12	2.77	3.89	5.25	0.28
		(13)	.69	11.90	5.70	1.02	1.45	2.47	4.71	0.28
		(14)	.79	9.76	5.25	0.89	3.88	4.77	4.37	0.33
		(15)	.84	10.98	5.97	0.92	6.23	7.15	4.29	0.49

[1] Specific gravity based on dry weight and volume

[2] Shrinkage (tangential, radial) based on green dimension

[3] Based on dry weight of unextracted wood

[4] The number of millimoles of NaOH added per gram of wood to raise the pH to 10.0.

Kapur gave the expected low wood failures after all aging methods (see Contract 16, Table 11), confirming previous experience. The combination of higher density, extractive content and buffering capacity are consistent with the conclusions of Nguygen (1975) that these factors inhibit bond durability.

Keruing faced panels were marginal in bond quality, with adhesives A and C, but acceptable with adhesive B. The average wood failure values with adhesives A and C after extensive accelerated aging were about 80 percent, compared to 85 percent wood failure required by the Construction and Industrial Plywood Standard, PS1-74. However, that average consisted of keruings that were both as durable as Douglas-fir and as non-durable as kapurs. See for example Figures 15 and 16.

The extreme variability in bond quality with keruing and adhesive A can not be explained by the properties of those species. When keruings of similar density (Contrasts 3, 4, 5, 8, 9 and 10 of Table 11) were compared for bond quality, significant differences occurred, suggesting that factors other than density affect bond quality. Furthermore, when keruings of dissimilar density (Contrasts 6 and 11 of Table 11) were compared, significant differences were not always found, reinforcing the fact that density alone does not explain variation in bond quality. Orthogonal comparisons of density and extractive content were not possible, but the data suggest

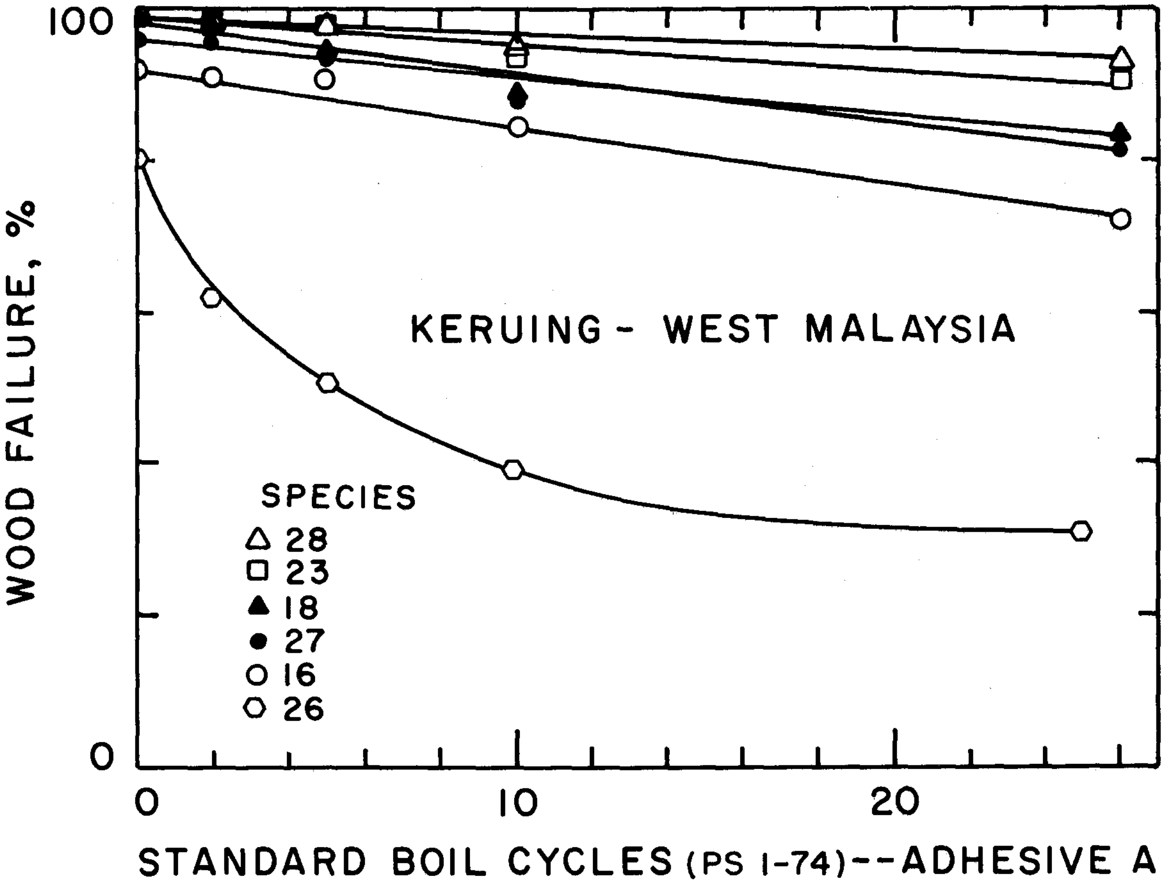


Figure 16. Wood failures for keruings from West Malaysia after standard boil cycle aging

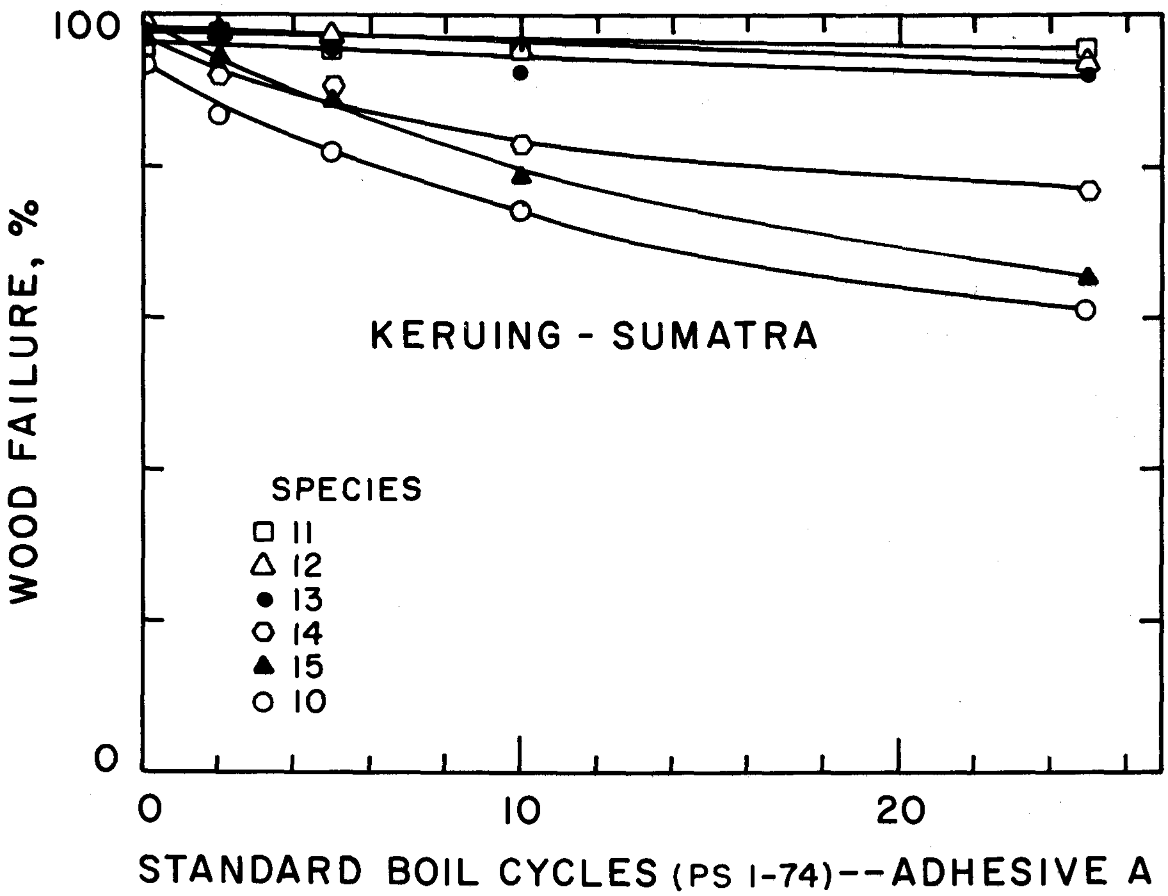


Figure 17. Wood failures for keruing from Sumatra after standard boil cycle aging

that considering both factors will not explain the variation in bond quality either.

B. Effect of Adhesives

Because this study was not designed specifically to evaluate differences between adhesives, few statistical comparisons are possible between adhesives A, B and C. Furthermore, comparisons of adhesive C to the other two might not have been valid, even if possible, because none of the gluing conditions were optimal for that adhesive. Controlling spread of adhesive C at 45 lbs/MDGL was difficult even with laboratory conditions. Subsequent to this study, the supplier of adhesive C reported that adhesive spreads now used in plywood plants are about 5 lb/MDGL greater than had been recommended for this study. Such an increase in adhesive spreads would make it possible to control spread rate and improve wood failures slightly, but not dramatically.

From the limited comparisons possible with this study, it seems that the adhesive used to make a panel caused few differences in the average performance of all species. This is illustrated by the non-significant "glue" terms in the statistical comparison of adhesive A and B (Table 9). Stated another way, none of the adhesives formed satisfactory bonds with kapur or red balau and all formed satisfactory bonds with red meranti.

The statistical comparison of adhesives A and B reported in Table 9 contained a significant species by glue interaction. Although the major cause of this interaction was, as previously discussed, the reduced bonding of Douglas-fir with adhesive B, one of the three species of keruing appeared to be bonded better with adhesive B.

Because I was particularly interested in the performance of keruing, I glued five more species of keruing with adhesive B, allowing a comparison of adhesive A and B on eight species of keruing. I had little confidence in the earlier analysis that was based only on three keruings. These additional panels were made in the same manner as described previously (refer to gluing procedures for details). For these additional panels I used only two aging methods, 40 cycles of automatic boil (which will be shown later to be one of the better accelerated aging methods) and vacuum/pressure (fast).

Keruing was better bonded with adhesive B than with adhesive A, based on the additional data (Table 13). "Species," "glue," and the "species by glue" interaction were all significant with these eight keruings (Table 14). These results are consistent with the fact that adhesive B resulted in uniformly excellent bonds with all keruings examined, whereas the bonds with adhesive A were variable.

Table 13. Wood failure with keruing after 40 cycles of automatic boil aging using adhesives A and B

Adhesive	A			B		
Assembly Time	5 min	20 min	45 min	5 min	20 min	45 min
Species of keruing						
10	83	76	62	95	97	99
14	87	91	86	95	97	99
15	87	93	83	97	100	100
16	80	91	84	98	91	98
23	95	98	98	96	98	99
26	48	58	54	92	94	100
27	94	97	98	95	99	99
28	97	100	98	97	100	100
Average	84	88	83	96	97	99

C. Effect of Assembly Time

Assembly time may affect adhesive penetration. Excessively long assembly time causes underpenetration because the adhesive dries out and does not bond adequately with the wood. Excessively short assembly time causes overpenetration or too much adhesive "bleeding" away from the glueline, not leaving enough adhesive to bind the panel together.

As expected, assembly time causes significant differences in the performance of all adhesives as illustrated by every analysis of variance of wood failure data (Tables 8, 9, 10). Species by assembly time also was significant in the analyses of adhesives A

Table 14. Analysis of variance of factors influencing wood failure with keruing and adhesives A and B after vacuum/pressure and 40 cycle automatic boil aging

Sources of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F	Probability*
Replication	2007.66	3	669.22		
Species	10009.26	7	1429.89	17.37	100.00
Error (A)**	1729.21	21	82.34		
Glue	7196.28	1	7196.28	37.00	100.00
Species x Glue	5020.49	7	717.21	3.78	99.33
Error (B)**	4557.07	24	189.88		
Assembly Time	340.84	2	170.42	2.75	93.10
Species x Time	1113.44	14	79.53	1.28	76.60
Glue x Time	888.96	2	444.48	7.16	99.87
Species x Glue x Time	1374.49	14	98.18	1.58	90.12
Error (C)**	5957.23	96	62.05		
Test	2080.11	1	2080.11	82.28	100.00
Species x Test	973.91	7	139.13	5.50	100.00
Glue x Test	1458.97	1	1458.97	57.71	100.00
Species x Glue x Test	1202.64	7	171.81	6.80	100.00
Time x Test	88.95	2	44.48	1.76	82.43
Species x Time x Test	139.18	14	9.94	0.39	2.40
Glue x Time x Test	124.94	2	62.47	2.47	91.18
Species x Glue x Time x Test	324.30	14	23.16	0.92	46.10
Error (D)**	3640.81	144	25.28		
Total	50228.75	383			

* Probability that the difference occurred as a result of treatment rather than by chance. Probabilities greater than 99.99 are rounded to 100.00.

** Error (A) = Species x Replication
Error (B) = Glue x Rep + Glue x Species x Rep
Error (C) = Time x Rep + Glue x Time x Rep + Species x Time x Rep + Glue x Species x Time x Rep
Error (D) = Test x Rep + Glue x Test x Rep + Species x Test x Rep + Glue x Species x Test x Rep + Time x Test x Rep + Glue x Time x Test x Rep + Species x Time x Test x Rep + Glue x Species x Time x Test x Rep

and B (Tables 8, 9), meaning that some species responded to assembly time more than others. In particular, kapur seemed sensitive to long assembly times.

Adhesive by assembly time also was a significant term with adhesives A and B (Tables 9, 14), meaning that the assembly time effect was different with these adhesives.

A long assembly time (45 minutes) caused adhesive A to make slightly poorer bonds than the other two assembly times (82 versus 87 percent wood failure for the analysis using all species groups). Adhesive A had a moderate molecular weight which caused it to need more water in the glueline prior to pressing. A short assembly time (5 minutes) caused adhesive B to make poorer bonds than the other assembly times (73 versus 86 percent wood failure for the analysis using all species groups). Adhesive B had a low molecular weight, which caused excessive flow of the adhesive when a short assembly time was used.

Analysis of variance for adhesives A and B using keruing only (Table 14) did not show a significant assembly time effect, because all keruings responded in the same manner with adhesive B.

Adhesive C did not show a significant species by assembly time interaction (Table 10) because adhesive C was at low glue spreads, which tended to form poor bonds with all species regardless of assembly time. Therefore, with adhesive C, the short assembly time bonds were not ideal and the longer assembly time bonds were even worse.

D. Effect of Aging Method

1. Analyses of Variance

Analyses of variance were used to determine significant differences between test methods and factors influencing them. These analyses could not determine which tests were more effective at predicting bond durability. I used regressions of accelerated aging methods versus six months outdoor exposure to determine which methods were most effective at predicting performance. These regressions are discussed in a later section.

The aging methods were significantly different from each other in detecting poor adhesive bonds (Tables 8, 9, 10, 14). These differences were obvious in Figures 10-15 and Table 7. However, species by test was also a significant term in every analysis of variance, meaning that the effect of aging methods varied from species to species.

Orthogonal contrasts between aging methods were made for every species glued with adhesive A, to determine the cause of the species by test interaction. These contrasts are listed in Table 15. In analyzing this table, look across the columns at the contrasts for

Table 15. Significance of differences* between test methods with each species using transformed percentage data from adhesive A

		Probability That Contrast Occurred as a Result of Aging**										
Species		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Douglas-fir	(00)	***	***	***	95.01	***	***	***	97.07	***	***	***
red meranti	(21)	***	***	***	99.18	***	***	93.14	***	100.00	***	100.00
red balau	(4)	***	100.00	***	100.00	***	98.93	98.17	95.27	100.00	100.00	100.00
	(28)	***	***	92.15	99.63	***	***	***	***	***	***	99.96
keruing	(16)	***	***	99.66	100.00	95.72	***	99.16	***	100.00	***	100.00
from	(27)	***	99.63	***	100.00	***	***	97.81	***	100.00	***	100.00
West	(26)	***	97.99	***	100.00	***	***	99.99	***	100.00	***	100.00
Malaysia	(23)	***	99.42	***	100.00	***	***	99.62	***	100.00	***	100.00
	(18)	***	93.10	***	100.00	***	***	93.58	***	100.00	***	100.00
keruing	(12)	93.50	***	***	99.77	***	***	***	91.55	***	***	***
from	(11)	***	***	***	99.63	***	***	***	***	100.00	***	100.00
Sumatra	(10)	96.39	92.84	99.69	100.00	***	***	99.91	98.84	100.00	***	100.00
	(13)	99.88	***	97.61	97.90	***	***	***	***	***	***	100.00
	(14)	95.80	***	***	100.00	91.29	***	95.77	92.20	100.00	***	100.00
	(15)	97.80	99.72	98.99	100.00	***	***	99.96	***	100.00	99.35	100.00
kapur	(20)	***	99.86	***	100.00	***	98.76	***	100.00	100.00	99.84	100.00
	(22)	98.49	98.50	***	100.00	99.93	90.67	99.81	100.00	100.00	100.00	100.00

* F ratios calculated on 1 and 1683 degrees of freedom using sum squares obtained from the following equation:

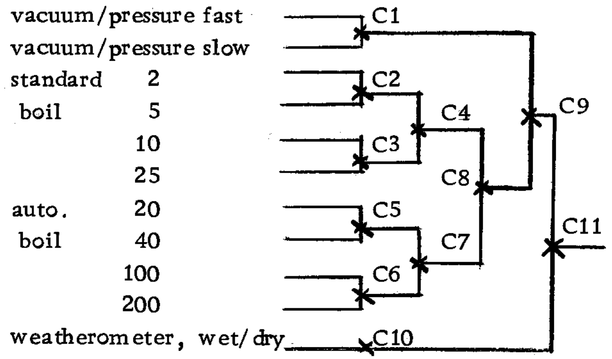
$$SS = \frac{n(\Sigma \lambda_i M_i)^2}{\Sigma(\lambda_i)^2}$$

n = number of items averaged, 3 x 4 = 12

λ_i = coefficient for comparison

M_i = mean being compared

** Contrasts between aging methods were as follows:



each species. Red balau and kapur had significant differences in nearly every contrast. Because these species were poorly bonded, all aging methods degraded their bonds, but some methods caused much more degradation than others. Douglas-fir and red meranti had very few significant differences. Because those species were well bonded, few aging methods degraded their bonds. Some keruings differed significantly in many aging methods; others did not. Those keruing species that were poorly bonded had the significant differences in aging methods and those that were well bonded did not. This held true whether the keruings came from West Malaysia or Sumatra. Thus the species by test interaction was caused by the fact that some species formed highly durable bonds that were not affected greatly by any aging method. Only those species having non-durable bonds allowed distinction between aging methods.

The significant differences between test methods can be seen by looking down the columns of Table 15. Contrast 1 shows that the fast vacuum/pressure method generally was not significantly different from the slow method, meaning that wood failure was independent of test speed. Contrast 4 shows that extending the number of standard boil cycles caused significant decreases in wood failure (illustrated in Figures 10, 12, 14). Contrast 7 shows that extending the number of automatic boil cycles also decreased wood failure somewhat (Figures 11, 13, 15). However, automatic boil cycling caused more bond degradation during the first 20 cycles and that continuing beyond this point had less effect. Contrast 8 shows that for most species, the standard boil method was not significantly different from the automatic boil method. Contrast 9 shows that the wood failures after standard and automatic boil cycling were significantly lower than the wood failures from the vacuum/pressure methods. Contrast 11 shows that all methods using wood failure were different from the weatherometer and wet/dry cycling which used area intact (Table 7).

Adhesive interacted significantly with aging method (Tables 9, 14) when adhesives A and B were used. This occurred because some aging methods could discriminate between good and poor bonds and others could not. Because adhesive B made higher quality bonds on the average than adhesive A, the aging methods were less discriminating with adhesive B.

Assembly time also interacted significantly with aging method when adhesives A and B were used (Tables 8, 9); adhesive C did not interact significantly (Table 10). Analogous to the interaction of test with adhesive, if an assembly time reduced bond quality, the tests were more discriminating. Because adhesive C was not used at optimal glue spreads, bond quality was reduced at all assembly times, causing no interaction with aging method.

Species by adhesive by aging method was another significant interaction term in Tables 9 and 14. This interaction, although complicated, again reinforces the same concept--some aging methods were capable of discriminating between good and poor bonds and others were not.

2. Regressions

Outdoor exposure for six months followed by the vacuum/pressure-fast aging method was assumed to correctly discriminate between good and poor bonds. The average wood failures (reported in Table 7) ranked the species in the same order as found by industrial experience, reinforcing the assumption that this aging is a good base for comparison for the accelerated aging methods.

To select the most appropriate aging method, several factors must be considered. Assuming the wood failure requirement of PS1-74 applies to the six month outdoor exposure data, any species averaging lower than 85 percent wood failure after six months of outdoor exposure must also average less than 85 percent wood failure following accelerated aging. Because the regressions pass through the origin, this means the only acceptable aging methods are those whose regressions have a slope that is less than 1.0. In addition, the best accelerated aging method is one which is highly correlated and has the smallest slope when regressed against outdoor exposure. The smaller the slope, the more rapid the aging during the accelerated method.

A typical regression of wood failures after six months outdoor exposure against wood failures after accelerated aging, using the model described in the procedures, is illustrated by Figure 18.

Regressions of the vacuum/pressure fast and vacuum/pressure slow data with all adhesives had slopes greater than 1.0, plus higher residual mean squares and lower correlation coefficients than the boil cycle methods (Table 16). Vacuum/pressure was a relatively ineffective aging method.

The area intact measured after weatherometer or wet/dry cycling was very large for all species, including kapur (Table 7). The slopes of these regressions were much larger than 1.0, the residual mean squares were quite large, and the correlation coefficients were very low, making these aging methods completely ineffective (Table 16). Area intact, as I measured it, could detect delaminations that occurred only at the edges of the sample and, therefore, did not represent the area intact of the entire sample. Using the proportion of panels that delaminated after aging as a measure of performance (Table 17) increased the responsiveness of the weatherometer aging. However, these results still were not as well related to actual performance as wood failures from the standard and automatic boil methods.

Most regressions with the standard boil cycle data had slopes

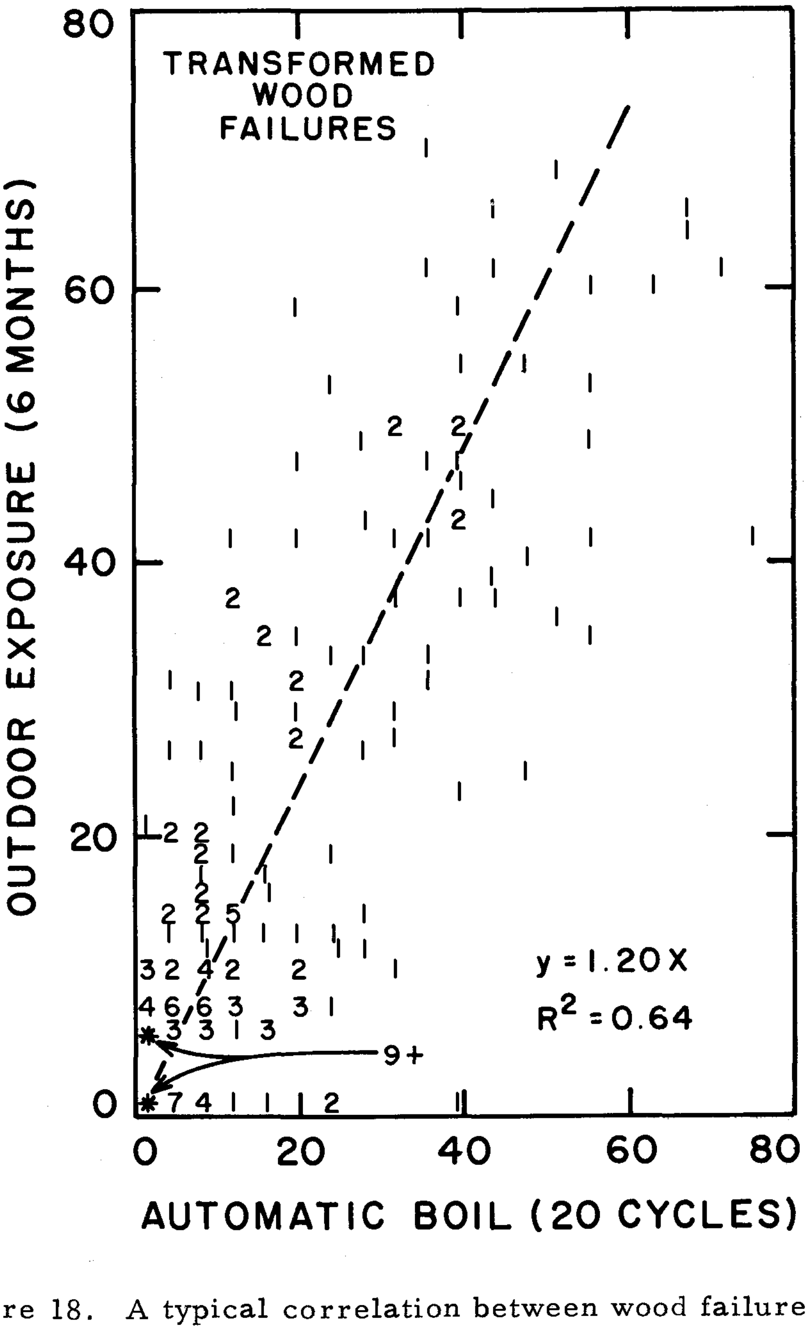


Figure 18. A typical correlation between wood failures after accelerated aging and outdoor exposure

Table 16. Regression coefficients for transformed wood failure after accelerated aging method (X) vs. six months outdoor exposure (Y)

Adhesive	A			B			C		
Test	B*	Residual Mean Squares	Simple Correlation Coefficient R	B*	Residual Mean Squares	Simple Correlation Coefficient R	B*	Residual Mean Squares	Simple Correlation Coefficient R
Vac/press fast	1.35	1.9×10^2	0.72	1.22	2.9×10^2	0.81	1.20	0.7×10^2	0.86
Vac/press slow	1.55	2.3×10^2	0.70	1.06	3.0×10^2	0.68	1.43	1.1×10^2	0.87
2 cycle std. boil	1.06	1.6×10^2	0.79	0.83	1.5×10^2	0.82	0.98	0.7×10^2	0.86
5 cycle std. boil	0.90	1.4×10^2	0.79	0.72	1.6×10^2	0.82	0.89	0.7×10^2	0.85
10 cycle std. boil	0.75	1.3×10^2	0.80	0.61	1.9×10^2	0.88	0.83	0.7×10^2	0.86
25 cycle std. boil	0.67	1.5×10^2	0.75	0.57	2.2×10^2	0.75	0.98	0.6×10^2	0.88
20 cycle auto. boil	0.98	1.4×10^2	0.80	0.85	1.5×10^2	0.82	0.98	0.6×10^2	0.88
40 cycle auto. boil	0.89	1.3×10^2	0.81	0.81	1.5×10^2	0.84	0.96	0.5×10^2	0.91
100 cycle auto. boil	0.85	1.4×10^2	0.79	0.71	1.7×10^2	0.80	0.92	0.6×10^2	0.87
200 cycle auto. boil	0.77	1.4×10^2	0.78	0.71	1.7×10^2	0.81	0.94	0.6×10^2	0.87
Weathometer	1.43	4.6×10^2	0.47	1.19	5.2×10^2	0.59	1.72	3.9×10^2	0.61
Wet/Dry	5.26	5.6×10^2	0.39	3.96	5.9×10^2	0.54	3.13	5.1×10^2	0.48
16 cycle manual boil	0.69	0.9×10^2	0.72						

*Y=BX

Table 17. Proportion of panels delaminated after aging

Species		% Samples Delaminated* After 2400 Hours in Weatherometer			% Panels Delaminated* After 2400 Hours of Wet/Dry Cycling			% Panels Delaminated* After 6 Months of Outdoor Exposure		
		Adh A	AdhB	Adh C	Adh A	Adh B	Adh C	Adh A	Adh B	Adh C
Douglas-fir	(00)	0	0	0	0	8	0	0	0	0
red meranti	(21)	0	0	0	0	0	0	0	0	0
red balau	(4)	50	0	8	8	0	0	0	0	0
keruing from West Malaysia	(28)	8	-	-	0	-	-	0	-	-
	(16	17	-	-	8	-	-	0	-	-
	(27	8	8	0	0	0	0	0	0	0
	(26)	58	-	-	8	-	-	0	-	-
	(18)	25	-	-	0	-	-	0	-	-
	(23)	8	0	0	0	0	0	0	0	0
keruing from Sumatra	(12)	0	-	-	0	-	-	0	-	-
	(11)	0	-	-	0	-	-	0	-	-
	(10)	25	-	-	0	-	-	0	-	-
	(13)	8	-	-	0	-	-	0	-	-
	(14)	8	-	-	0	-	-	0	-	-
	(15)	42	8	0	0	0	0	0	0	0
kapur	(20)	42	33	33	0	0	8	0	0	0
	(22)	75	67	58	8	25	50	0	0	17

less than one, had lower residual mean squares and fairly high correlation coefficients (Table 16). However, the two cycle boil did not reduce the wood failures of non-durable panels sufficiently to fail the 85 percent wood failure requirement in the commercial standard (PS1-74) i.e., they had slopes greater than 1.0. Five cycles of the standard boil method barely detected unsatisfactory panels with all three adhesives. However, these plywood panels were made under carefully controlled conditions, relative to normal manufacturing, so I believe that ten cycles of the standard boil would better discriminate between acceptable and unacceptable bonds in commercial plywood.

Regressions with the automatic boil cycle data also had low slopes and good correlations (Table 16). The 20 cycle automatic boil did detect unsatisfactory performance. However, a 40 cycle automatic boil might better predict performance in normal manufacturing conditions, using the same arguments as for the 10 cycle standard boil method.

Although both 10 cycles of standard boil and 40 cycles of automatic boil were effective at degrading inadequate gluebonds, they differ in cost and speed. The standard boil method is less expensive to operate on a limited basis because no elaborate equipment is required. However it requires considerable labor and could be excessively expensive if large numbers of samples must be analyzed.

The automatic boil method is faster in obtaining results (standard boil cycling - 10 days, automatic boil cycling - 2 days), a critical factor for most industrial situations and will age 2000 specimens at a time. But the machine developed by Weyerhaeuser to automate boil cycling cost $30, 000 to build.

For limited numbers of samples, such an expensive machine might not be justifiable. I therefore searched for an alternate accelerated aging method. By using the following aging sequence, I obtained 16 cycles of boiling and drying in one day by manually exposing standard shear samples to the conditions specified:

Day 1 - 8 cycles of boil (10 minutes), cool in ambient air (5 minutes), dry at 225°F (60 minutes);

Overnight - dry at 145°F

Day 2 - 8 cycles same as day 1.

This 16 cycle manual method was used on a limited number of spare samples from adhesive A. It readily degraded marginal bonds (see Table 18 and regression coefficients in Table 16) and correlated with outdoor exposure as well as the other boil cycle methods. Thus this technique may prove useful to smaller companies not able to afford an expensive aging machine.

Table 18. Wood failure after 16 cycles of manual boil aging

Assembly Time	5 min	20 min	45 min
Species			
4	49	52	51
10	58	52	51
13	94	99	92
15	81	84	70
16	68	71	74
20	51	35	30
21	98	95	84
26	27	31	29
27	73	89	73
Average	73	75	67

VI. CONCLUSIONS

Based on these results and their statistical analysis, the following conclusions were reached.

1. Extended cycles of both the standard and automatic boil aging methods degrade marginal gluebonds and both correlate equally well with outdoor exposure. To assure that they will discriminate between durable and non-durable bonds, the standard boil method requires 10 cycles (10 days) and the automatic boil method requires 40 cycles (2 days).
2. The two cycle standard boil method, as described in the commercial standard (PS1-74), is not a sufficient discriminator of bond quality for Southeast Asian hardwood faced plywood.
3. The 16 cycle manual boil method was as effective a discriminator of bond quality as 40 cycles of the automatic boil method, based on limited data.
4. The vacuum/pressure, weatherometer and wet/dry cycle methods are poor discriminators of bond quality for Southeast Asian hardwood faced plywood. Shear test speed is irrelevant when measuring wood failure.
5. Breaking load does not determine bond quality with cross-laminated specimens whereas wood failure does determine bond quality with cross-laminated specimens.

6. All the keruings examined in this study form uniformly excellent bonds with adhesive B; they form bonds of variable quality with adhesive A.

7. Red balau and kapur form unsatisfactory bonds with the adhesives used in this study.

LITERATURE CITED

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APPENDIX

APPENDIX A

PROPOSED STANDARD METHOD FOR ESTIMATING PERCENTAGE WOOD FAILURE ON PLYWOOD SHEAR SPECIMENS

Scope

1. This method covers the determination of percentage wood failure of plywood shear specimens prepared and tested as outlined in ASTM D 906-64, "Strength Properties of Adhesives in Plywood Type Construction in Shear by Tension Loading."

Apparatus

2. (a) A dual element desk lamp equipped with one 15 watt Daylight and one 15 watt Cool White fluorescent tube shall be used for estimating purposes. Outdoor light interference should be avoided.

   (b) A ruler or other measuring device calibrated to 0.1 inch is recommended as an aid to measuring the area of torn wood fibers.

Preparation of Test Specimens

3. Percentage wood failure shall be estimated with specimens in a dry condition.

Procedure

4. (a) Specimens will be hand held, tipped at a 45° angle to the desk surface, and the long axis of the specimen shall be parallel to the light tubes. A plane through the two fluorescent light tubes in the lamp shall be parallel to the desk surface and shall also form an angle of 45° to the surface of the test specimens. Very slight movement of the specimen (not rotation) is permissible to enable the eye to discern differences in color and texture which may exist.

   (b) Wood fiber failure of each specimen shall be estimated to the nearest 5%, with a maximum of 100% based upon the one-inch-square test area.

(c) Both halves of the specimen are held to the light in the manner prescribed in 4(a) to orient the estimator with relative positions of wood and glue failure. The estimator shall note bare areas in the glue spread which shall not be counted as wood failure.

(d) Solid wood failure within the test area shall be measured with the ruler or other measuring device. The estimator shall measure wood failure occurring on both halves of the specimen, taking care not to count wood failure from matching areas more than once.

(e) Scattered areas of fine fiber shall be counted by the estimator mentally grouping them into an area that can be estimated. Division of the test surface into measured areas with the aid of the ruler may be of assistance in this regard. With respect to hair-like or single cell fibers attached by one end, only the part actually in contact and adhered to the glueline shall be counted as wood failure. Loose fibers not adhered to the glueline shall be brushed or blown off prior to commencing the estimating process.

(f) Isolated wood particles (such as sawdust or slivers which fell onto the glueline during the gluing process) appearing as wood failure, but which have not actually been torn from a ply during testing, shall not be counted as wood failure even though glued in place.

(g) Evaluation of wood failure may be checked by estimating the amount of glue failure present within the test area. The total amount of glue and wood failure should equal 100%.

(h) Specimens containing localized defects permitted within the plywood grade (such as burls, core voids, etc.) in or adjacent to the test area, shall not be counted in the average. Any failing panel containing such defects in one or more specimens shall be subjected to a retest.

(i) By agreement between interested parties, other localized defects such as glue wipes, chips, core laps, etc. also may be a basis for discarding the test specimen.

(j) Test specimens showing glueline delamination in excess of 1/8 inch deep and one inch long in any area of the specimen shall be rated as 0% wood failure.

Calculation

5. The panel average percentage wood failure will be the total of the individual specimen values divided by the number of specimens tested from that panel.