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THE RECYCLING POTENTIAL OF OUT-OF-SERVICE UTILITY POLES FOR ENGINEERED WOOD PRODUCTS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Forestry, Wildlife, and Fisheries

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August 1997

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ABSTRACT

This study on the recycling potential of out-of-service poles for use in engineered wood products involved determination of basic properties of used southern pine (*Pinus* sp.) utility poles and also manufacture of glued-laminated beams from these poles. Most of the defect-free portions of 25-year treated poles still retained adequate strengths comparable to those of freshly treated poles and untreated southern pine. Creosote contents, however, diminished with pole ages. The reduction in creosote content was correlated with lower decay resistance, poorer dimensional stability, and lower lumber recovery, but better gluability. The spectrometry method for creosote content determination was explored as an alternative to the time-consuming standard toluene extraction method, and the results were comparable. Steam treatment could remove creosote to about 1.5 percent of its content regardless of initial creosote contents of the poles.

Two- and 3-ply laminated beams were fabricated by gluing laminae from both treated poles and from untreated southern pine. The strengths of 2-ply beams assembled with an edge-to-edge gluing method decreased with increasing number of laminae for treated poles as well as untreated southern pine. Strengths of 2-ply beams from treated poles were lower than those of 2-ply beams from untreated southern pine, but still comparable to strengths of defect-free southern pine lumber. In 3-ply beams, fabrication was done with end-to-end gluing method. Increasing the number of joints caused a steady reduction in strengths, with finger-jointed beams exhibiting lower strengths than scarf-jointed beams. The overall strengths of jointed beams were lower than those of unjointed beams. All beams from treated poles,

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either jointed or unjointed, had strengths lower than those from untreated southern pine beams of the same construction. However, 3-ply beams from treated poles with scarf-joints had strengths comparable to those of defect-free southern pine lumber.

Results of this study indicate that high performance engineered wood products in the form of laminated beams can be fabricated from out-of-service utility poles. Factors affecting strengths, such as residual creosote content, number of glued laminae, type of gluing, and number and type of joints are taken into consideration. Laminae with high strength and high creosote content should be placed on the surface, and low strength and low creosote in the inside, with little or no additional preservative treatment.

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INTRODUCTION

Electric utility companies in the United States have more than 150 million wooden poles in service carrying electrical transmission and distribution lines. Each year the ever-expanding basic electric and communication industries consume about six million treated poles. Approximately 75 percent of the annual consumption of poles consists of southern yellow pines, which are usually treated with creosote (Micklewright 1991). The preference of using creosote is due to its many advantageous properties: inexpensive, insoluble in water, high toxicity to wood-destroying organisms, and easy to apply. Wood treated with an oil-type preservative, such as creosote, is most suitable for outdoor use because the oil retards water movement in wood and is permanent.

Poles represent a significant investment for the electric utility, and their maintenance and replacement are a significant expense. One to two million poles are being replaced each year mostly because of mechanical wear, and not because of biodegradation. Most of these replaced poles are considered no longer serviceable (Bull and Lindenheim 1990) due to lack of an economically viable manufacturing process. As a result, utility companies are faced with a dilemma concerning the disposal of out-of-service poles which still contain residual creosote. Popular waste disposal options, such as combustion and landfilling, are becoming more and more costly because of strict regulatory requirements.

About 1.3 million cu. m. per year of creosote-treated railroad ties and 2 cu. m. per year of utility poles treated with pentachlorphenol and creosote are available for

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recycling (Felton and DeGroot 1996). Presently, reutilization of used utility poles is still limited to simple uses, such as landscape timbers, parking signs, and road barriers. Preparing those converted pole products, however, can produce residual amounts of wood waste (e.g. sawdust, flakes, and chips) which still contain creosote. This causes disposal problems to the environment; therefore, additional treatments must be applied to the discarded utility poles and their waste products so that they are free of residual preservatives.

Most research on recycling of treated wood has focused on making reconstituted railroad crossties (Keil 1976). A significant disadvantage of the reconstituted tie process is the weak adhesive-to-fiber bond properties in creosote-treated wood (Geimer 1982) since the hydrophobic nature of creosote interferes with normal bonding of an adhesive that requires wetting the surface of normally hydrophillic wood fibers. Furthermore, the large capital investment needed for a reconstituted tie manufacturing facility makes the process less feasible for successful commercial production.

Another development in recycling of crossties and poles is a process called "bioremediation" in which microbes "consume" the wood preservatives, leaving the wood to be reprocessed into cellulose-based products such as rayon. The cost of removing the preservatives in the wood, however, can be prohibitive and time-consuming. Also, technical information about the properties and potential uses of the resulting cellulose and lignin product are still unknown. Treatment of wood by chemicals has been reported to change the wood structure and permeability of

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wood, and hence the physical properties of wood (Choong et al. 1972; Tesoro and Choong 1976). Conversely, removal of these preservatives by physical, chemical, and microbiological processes further changes the properties of wood.

Converting weathered utility poles into more useful wood products without drastically changing the wood properties, i.e. by first reducing poles to smaller pieces of wood free of defect and with a minimum content of residual preservatives, would lead to a more efficient utilization of treated wood. This is an economically viable manufacturing process for potential value-added products that addresses environmental safety.

This research is divided into two phases: Phase I - Basic properties of out-of-service poles, which includes Chapter 1 (determination, distribution, and removal of residual creosote content), Chapter 2 (strength and dimensional stability properties, and lumber recovery), and Chapter 3 (decay resistance); Phase II -Development of useful engineered wood products, which includes Chapter 4 (gluability) and Chapter 5 (manufacture of glue-laminated wood beams).

It is the objectives of this study to provide the necessary information and background for the reutilization of out-of-service poles into value-added useful engineered wood products and for the development of a comprehensive life-cycle management of treated wood products.

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CHAPTER 1

RESIDUAL CREOSOTE IN OUT-OF-SERVICE POLES

Introduction

Creosote in utility poles may undergo physical and chemical changes due to weathering. In addition, the changes in creosote content may depend on its location with respect to vertical and horizontal positions within the poles. As a result, the residual creosote content and its distribution in utility poles must be known before these poles can be reutilized for useful engineered wood products.

The creosote content in treated wood is usually determined using the toluene solvent extraction method, in accordance with AWPA Standard A 6-83 (1984). This process, however, is very time-consuming; therefore, a better and more rapid method should be considered.

Even though weathering causes changes in creosote content, the residual creosote in old poles must be removed or reduced to an acceptable level before these poles can be reutilized. Therefore, an effective and relatively cheap way of removing creosote is necessary. This chapter reports efforts to deal with the residual preservative in waste poles, which involved the following: (1) determination of creosote content and its distribution in out-of-service poles by the standard method, (2) possible uses of electronic spectrometry for rapid and accurate determination of creosote content, and (3) removal of residual creosote using steam treatment.

Literature review

Creosote in utility poles

Creosote is impregnated into utility poles by the full cell method, which gives high retention of preservatives. The creosote is not chemically fixed inside the

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wood; rather, it is physically trapped in the cell lumen and held to the cell wall by adhesion forces and surface tension. Creosote, being oil-soluble, can not penetrate into the cell wall; therefore, during service, weathering may affect the patterns of how creosote remains in the poles (Nestler 1974). Weathering causes changes not only in creosote content, but also in its distribution in both vertical and horizontal directions inside the poles.

Determination of creosote content by colorimetric and spectrometric methods

The use of colorimetry is a direct method of measuring creosote content by dissolving the creosote in treated wood with a suitable solvent (Hudson 1961). The greater the amount of creosote in wood, the darker or more intense is the color of the solution. The creosote content is determined by matching the color of the solution with a set of standards representing a series with known amounts of creosote. The solvent must be one which is soluble in creosote, and also readily miscible with water. The best solvent for dissolving creosote is dimethylformamide (DMF). For a small amount of wood particles mixed with DMF, approximately 15 minutes is required for the solvent to dissolve the creosote completely. Thus, creosote content can be determined rapidly by this method. However, accuracy of results with the colorimetry is subjective, since it is dependent on the individuals who determine the color of creosote solution.

Electronic spectrometry is a modified colorimetry method. It is intended to reduce measurement subjectivity by substituting an electronic instrument for a human observer. This method is based on the interaction that occurs when light strikes through a medium by which part of the light is absorbed. If the medium is in

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the form of solution containing a chemical substance, the intensity absorbed will depend on the concentration of that substance. The greater the concentration, the higher the absorption intensity of the light (Ege 1987). Relationships can be established between a series of substance concentrations and their intensities of light absorption. This relationship can then be used to determine the unknown concentration of the same substance in comparison with known intensity of light absorption (Williams and Flemings 1973).

Light in general has a wide range of wavelengths, from ultraviolet (200-380 nm) to visible (380-800 nm) regions. In electronic spectrometry, the light can be in forms of a single wavelength or limited range of wavelengths within a region (limited spectrum). During spectrometry analysis, light absorption by a substance causes the transition of its electron from the ground state (low energy level) to the excited state (high energy level). The higher the difference in energy level, the greater the energy of light being absorbed, and the shorter the wavelength (Lambert et al. 1976).

If spectrometry is done on the substance solution using a single wavelength, only one intensity value of light absorption will be obtained. However, if it is done using a certain range of wavelengths, a continuous spectrum will appear that relates the intensity values to the wavelengths. In the spectrum, there can be a wavelength at which the intensity of light absorption is the highest, which is called optimum or maximum-absorbance wavelength. Usually the maximum-absorbance wavelength is preferred since the information obtained at that wavelength for spectrometry analysis gives more accurate and reliable results. But the wavelength is affected by several

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factors, such as type of solvent, functional groups, functional substitution, and chemical formula of the dissolved substance. For example, in a chemical formula, a substance containing a homologue series of aromatic compounds can cause the shifting of maximum-absorbance wavelength to a higher or longer value due to greater number of aromatic rings (Ege 1987). Therefore, in spectrometry, it is necessary to know the properties and characteristics of the preservative used.

Creosote as a wood preservative is derived from coal tar, which is the non-aqueous portion of the liquid distillate obtained during carbonization of bituminous coal. By distilling the coal tar, and collecting the liquid fraction from 175-200°C to 400-500°C, about 30 percent of the coal tar known as creosote is removed (Hickin 1971; Roche 1952).

According to Erickson (1960), the major components of coal-tar creosote are naphthalene (10-30 percent) and phenanthrene (9-14 percent), with smaller proportion of methyl-naphthalene (1-6 percent), acenaphthene (2-5 percent), flourene (2-4 percent), flouranthene (2-5 percent), tyrene (2-3 percent), carbazole (2-3 percent), anthracene (1-2 percent), diphenyl oxide (1 percent), 9,10 dihydroanthophene (0.1-0.3 percent). Tar acids and tar bases are further regarded as minor components.

Coal-tar creosote used in treating poles must meet certain specifications, shown in Table 1.1. However, after several years of service the chemical composition of creosote could undergo changes. Nestler (1974) reported a number of chemicals (Table 1.2) which have changed in compositions between pure coal-tar creosote and

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Table 1.1. Characteristics of coal-tar creosote[1]

Items	Values
Distillation fraction, % by weight	
up to 210°C	≤ 2.0
up to 235 °C	≤12.0
up to 270 °C	10.0 - 35.0
up to 315 °C	40.0 - 65.0
up to 355 °C	60.0 - 77.0
residue	17.0 - 25.0
Matters insoluble in xylene, %	≤ 0.1
Specific gravity at 38 °C	≥ 1.05

[1]AWPA Standard P 1-83 (1984)

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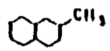
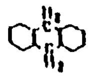
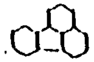
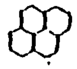
Table 1.2. Chemical compositions of pure creosote (A), and creosote from 31-year treated pole (B)[1]

Compounds	Boiling point (°C)	Molecular weight	Molecular structure	A		B	
				Total	Normalized	Total	Normalized
				(%)			
Naphthalene	202	128.12		15.8	34.0	0.12	2.6
Methylnaphthalene	242	142.20		3.0	6.5	0.19	4.1
Acenaphthene	278	154.21		3.1	6.7	0.34	7.0
Dibenzofuran	287	168.18		1.1	2.4	0.43	9.4
Fluorene	294	166.12		3.1	6.7	0.46	10.0
9,10-Dihydro-anthracene	313	180.25		0.2	0.4	-	-
Phenanthrene	340	178.12		10.7	23.0	1.84	40.0
Anthracene	340	178.23		1.5	3.2	-	-
Carbazole	352	167.21		2.4	5.2	-	-
Fluoranthene	382	202.26		3.4	7.3	0.73	15.9
Pyrene	393	202.26		2.2	4.7	0.48	10.5
Total				46.5	100.0	4.59	100.0

[1] Nestler (1974)

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the creosote in treated wood poles after being exposed for 31 years. Hence, in spectrometric analysis, these changes should be considered when determining creosote contents of treated poles.

Efforts to remove residual creosote from treated wood products

Attention has long been placed on removing or reducing creosote in weathered treated wood products which were considered no longer serviceable. Two methods have been applied: (1) bioremediation and (2) solvent extraction. Bioremediation is a biological process using organisms that can "consume" the preservative. An experiment done by Eslyn (1976) on creosote-treated marine piles showed that approximately 80 percent of the preservative can be eliminated, but the processing is time-consuming. Microorganisms used for his work was *Pseudomonas creosotensis.* Using water-nutrient broth, the incubation duration was nine days.

The LSU Institute for Environmental Studies has conducted solvent (methanol) extraction on severely weathered treated wood. This extraction could remove almost 100 percent of the creosote (Portier et al. 1994). However, the large-scale removal of creosote by this method involves use of expensive methanol solvent and costly extraction apparatus.

Steaming is often used in preservative treatment, especially by the vacuum-pressure method, to increase wood permeability (Eaton and Hale 1993; Hickin 1971) Steaming is also used to separate the volatile compounds in the wood extractives (Browning 1967). Therefore, steam treatment in theory should remove or reduce the creosote content in treated wood, but this method has not yet been tested.

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Steaming is also used to separate the volatile compounds in the wood extractives (Browning 1967). Therefore, steam treatment in theory should remove or reduce the creosote content in treated wood, but this method has not yet been tested.

Materials and Methods

Distribution of residual creosote in the poles

Wood species of the poles for this investigation were southern yellow pine (*Pinus* sp.); and those which had been out-of-service, with two duration groups: 5- and 25-years, were prepared. In addition, freshly treated poles of the same species were used for comparison purposes. Five different poles from each group were taken as replicates. Used poles were obtained from Entergy Gulf States Utility Company and brought to Lee Memorial Forest near Bogalusa, Louisiana for processing. All the poles were passed through a metal detector to remove metal objects. After metal removal, the poles were cut into 8- to 10-ft. long bolts. Three bolts (top, middle, and bottom sections) were selected from each pole. Each bolt was sawn into experimental specimens of lumber using a portable Wood Mizer at distance of 0.5-, 1.5-, 2.5-, 3.5-inches, respectively, as shown in Figure 1.1. During sawing, sawdust samples from each bolt were collected for preservative content determination.

Creosote content was determined using toluene extraction in accordance with AWPA Standard A 6-83 (1984):

$$\text{Creosote content (\% dry, extracted wood)} = 100*(W_1-W_2-W_3)/W_2 \qquad (1)$$

where:

W_1 = weight of wood sample before extraction (g)

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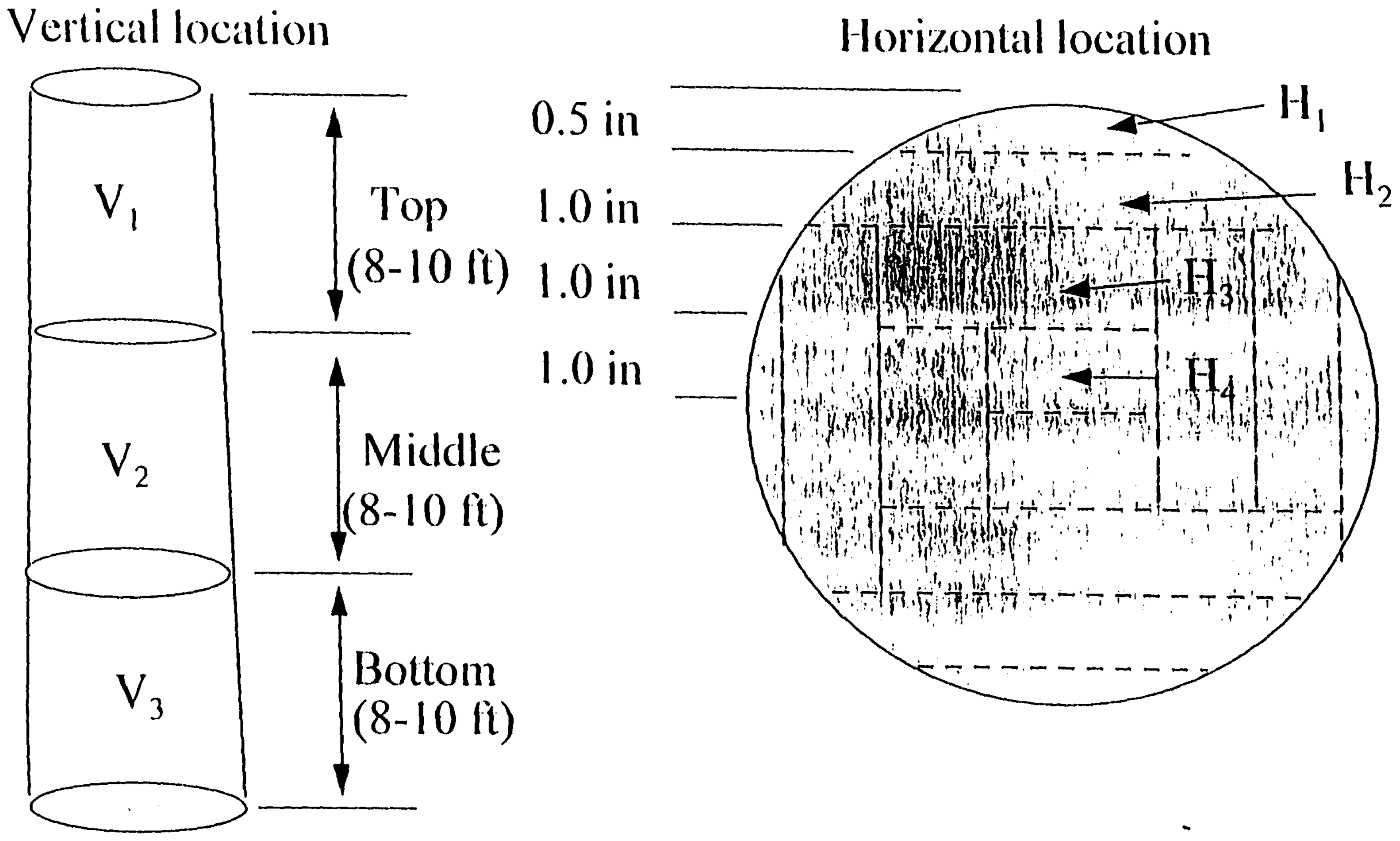

Figure 1.1. Pattern of cutting procedures in treated poles

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W_2 = weight of oven dry, extracted samples (g)

W_3 = weight of water in sample (g)

Evaluation of creosote content data was done using analysis of variance with factorial design. The variables studied were ages (service durations) of the poles, vertical location, and horizontal distance from pole surface. A summary of the experimental design is shown in Table 1.3.

Electronic spectrometry work

Approximately 2.0 g of sawdust with known moisture content and creosote content previously determined was mixed with 250 ml DMF solvent of spectrometric grade. The mixture was magnetically stirred for about 25 minutes. The DMF solvent, which is miscible in oil and water, dissolved creosote in the sawdust samples creating a brownish-colored solution.

After stirring, the creosote was separated from the sawdust particles by filtration under vacuum suction, followed by washing with pure DMF solvent. Washing was terminated when the color of the filtrate became colorless. The creosote solution was then diluted with DMF solvent to a concentration of about 22 mg/L. Then the creosote-DMF solution was subjected to a series of dilution processes, whereby the concentration of each diluted solution was calculated and recorded. The concentration ranged from 22.0 to 2.5 mg/L in steps of 2.5 mg/L. Solutions with the highest and the second highest concentrations were chosen and scanned spectrometrically with a Spectronic 1201 spectrophotometer to obtain average values of maximum-absorbance wavelengths.

In the same way, a series of dilution processes was carried out on DMF solution of pure creosote. The pure creosote was obtained from the LSU Institute for

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Table 1.3. Experimental design

Variables	Level	Characteristics
Service duration (between poles)	3	Freshly treated, 5 years, and 25 years
Vertical location (between bolts)	3	Top, middle, bottom
Horizontal location (within a bolt)	4	0.5, 1.5, 2.5, and 3.5 inches

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Environmental Studies. After dilution, solutions with highest and second highest concentrations were also spectrophotometrically scanned to obtain the average maximum-absorbance wavelength. DMF solutions of pure creosote were used for making a calibration curve which related creosote concentration to the light absorbance. The light absorbance was measured from the Spectronic spectrophotometer at approximately close to the overall average maximum-absorbance wavelengths of pure creosote and creosotes from freshly treated, 5-year and 25-year poles. The calibration curve was determined using the Lambert-Beer equation:

$$A = a*b*c \tag{2}$$

where:

A = light absorbance at average from maximum-absorbance wavelengths (λ) of pure creosote; and creosotes from freshly treated, 5- and 25-year poles

a = coefficient of extinction (L/mg-cm)

b = path length of the sample (creosote-DMF solution) (cm)

c = concentration of creosote in DMF (mg/L)

The calibration curve from pure creosote-DMF solution was used to determine the unknown concentration of creosote from the treated poles in DMF at known light absorbances and at average of maximum-absorbance wavelengths. In addition, light absorbances at that average wavelength were also measured on each of a series of DMF solutions of creosote from either freshly treated, 5-year, or 25-year poles. The relationship between creosote concentrations and its light absorbances was

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determined and evaluated as to whether the relationship was compatible among different pole ages (freshly treated, 5- and 25-years)

Removal of residual creosote by steam treatment

Samples of sawdust from the sawing of the utility poles used previously for creosote determination were collected in the same manner as in the spectrometry study. Each of these samples with predetermined creosote content and weighing about 5 g. was placed in a glass crucible, and then steam treated in a retort at atmospheric pressure and 100°C for as long as 3 hours. At intervals of 15 minutes, the samples in glass crucibles were removed from the retort, and washed with boiling water under vacuum suction to facilitate removal of as much creosote as possible. Then, the remaining creosote content in the samples was determined using the toluene extraction method. Steam treatment was terminated when the creosote content became stable. This was considered the final content.

Criteria used to evaluate the effectiveness of steam treatment were final creosote content and duration of treatment. Data of final creosote content were evaluated by analysis of variance with factorial design on the following variables: age of used poles, vertical location, and distance from surface (horizontal location). Data of steaming duration were analyzed in the same factorial design and variable factors as with the final creosote content, but the evaluation was by analysis of adjusted variance involving the initial creosote content as a covariate. As with the spectrometry study, sawdust from five different poles was used as replicates.

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Results and Discussion

Creosote content by toluene extraction method

Table 1.4. summarizes the residual creosote contents in various locations in utility poles which were freshly treated and which have 5- and 25-year service duration. The analysis of variance (Table 1.5) revealed that the effects of the main sources of variation (i.e., age of the poles, vertical location, and horizontal location) were highly significant (P=0.99), while the interaction of those three variables was significant (P=0.95). The significant interaction can be seen from a comparison of average creosote by the Tukey's test for significantly different means (Table 1.4), which shows that at a given pole age and vertical location, the creosote content had specific patterns of change with respect to horizontal distances from the surface.

The specific patterns of changes are also illustrated in Figure 1.2, which shows the distribution of residual creosote in all the experimental poles tested. As confirmed by the Tukey's test (Table 1.4), creosote content in freshly treated poles was much higher than in used poles. Poles with a 5-year service duration retained higher creosote content than with 25 years, indicating that many parts of the 5-year poles are still effective in their decay resistance. For aged poles, creosote content in the poles tended to increase horizontally from the surface to the pith. Values were highest for 3.5 inches from the surface, followed in decreasing order by 2.5-, 1.5-, and 0.5-inches from the surface. The results also reveal that the residual creosote tended to decrease with increasing vertical position in the poles with 5-year and 25-year service. These patterns, however, were inversed in the horizontal trend for

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Table 1.4. Average creosote content (%) in utility poles, and comparison (d) by Tukey's test for significantly different means

Service duration	Vertical location	0.5 (%)	0.5 (d)	1.5 (%)	1.5 (d)	2.5 (%)	2.5 (d)	3.5 (%)	3.5 (d)
Freshly treated	top	33.72[1]	A[2]	26.82	BC	25.66	BC	23.68	C
	middle	34.17	A	26.99	B	25.98	BC	24.11	C
	bottom	33.82	A	27.89	B	25.09	BC	23.64	C
5 years	top	8.49	EF	11.49	DE	13.07	D	13.79	D
	middle	10.98	DE	12.91	D	13.77	D	14.21	D
	bottom	11.65	DE	13.04	D	13.97	D	14.48	D
25 years	top	2.67	H	3.64	GH	4.09	G	11.41	DE
	middle	3.65	GH	3.70	G	6.06	FG	12.72	D
	bottom	3.76	G	3.83	G	5.69	FG	12.85	D

Sample location: Horizontal distance from surface (inches)

[1]Each value is average of 5 replications (poles)
[2]Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H)

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Table 1.5. Analysis of variance of creosote content in utility poles

Source of variation	DF	F -values	F-tables	
			$\alpha = 0.05$	0.01
Service duration (S)	2	24.57**	3.88	6.93
Error (a)	12			
Vertical location (V)	2	6.79**	3.06	4.75
Horizontal location (H)	3	16.96**	2.67	3.91
Interactions:				
S*V	4	3.24*	2.43	3.44
S*H	6	11.82**	2.16	2.92
V*H	6	1.77	2.16	2.92
S*V*H	12	1.98*	1.82	2.20
Error (b)	132	Y=15.49[1]	CV=10.04[2]	

[1]Overall average of creosote content (%)
[2]Coefficient of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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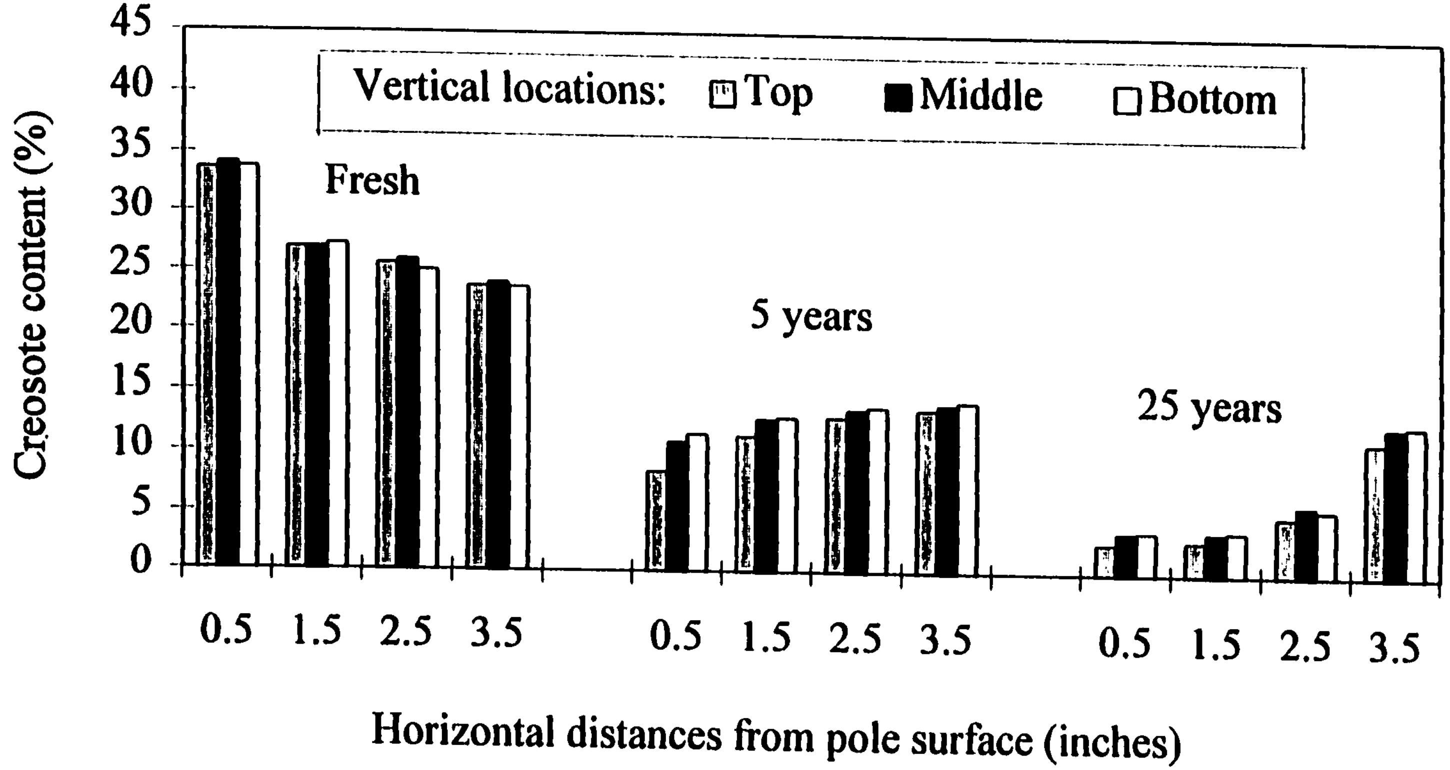

Figure 1.2. Distribution of creosote in treated poles

freshly treated poles which had the highest creosote content near the surface and lowest in the interior. The vertical trend showed no significant changes.

The loss of creosote from treated poles is mainly due to the effect of bleeding and leaching of creosote during service. Long-term weathering could be a significant factor affecting residual creosote content (Schneider, et al. 1995). In old poles, the low creosote content near the surface could be attributed to weathering. The surface of poles was exposed to high temperature during service, causing evaporation of the low molecular fractions. There was also movement of creosote due to differences in pressure between surface and inside. The weathering effect is more pronounced with poles that have been in service for 25 years, since their creosote contents are substantially lower than that of 5 years. Higher residual creosote content inside the old poles beyond 2.5-inch distance from the surface may be due to the presence of pit aspiration and bulking effect of extractives in the heartwood, inhibiting the passage of creosote and preventing the creosote from moving out of the heartwood. Pit aspiration in the cell walls was evident in freshly treated (Figure 1.3), in poles with 5-year (Figure 1.4), and with 25-year service (Figure 1.5). However, pit aspiration was less common near the surface of treated poles since the surface consisted mainly of sapwood. Also, steaming as a pre-treatment method prior to penetration of creosote tends to relieve pit aspiration on the surface. These phenomena explain the decreasing trend of creosote content from the outer to the inner portions of freshly treated poles. The higher creosote content in the bottom of old poles was mainly due to gravity which forced downward movement of creosote in standing poles during service.

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A

B

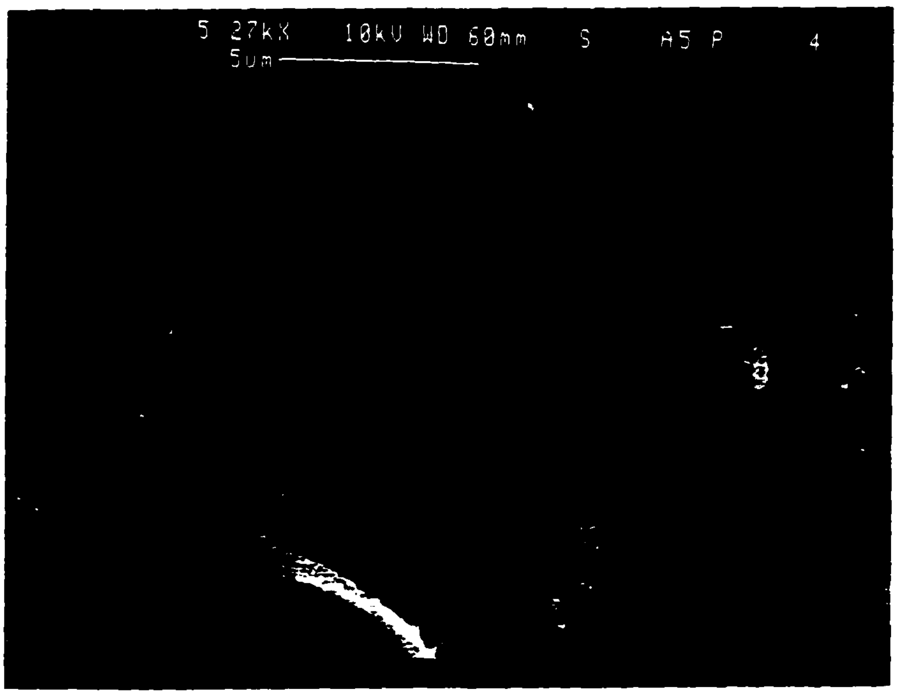

Figure 1.3. Aspirated pits on the cell wall of inner portion of freshly treated pole using scanning electron microscope: A (1190x) and B (5270x)

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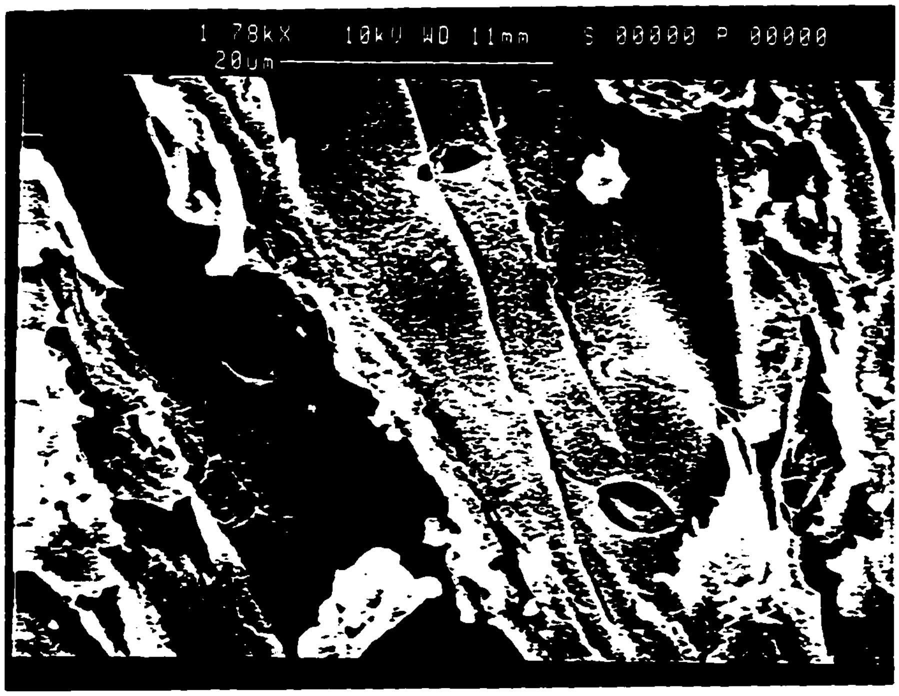
A



B

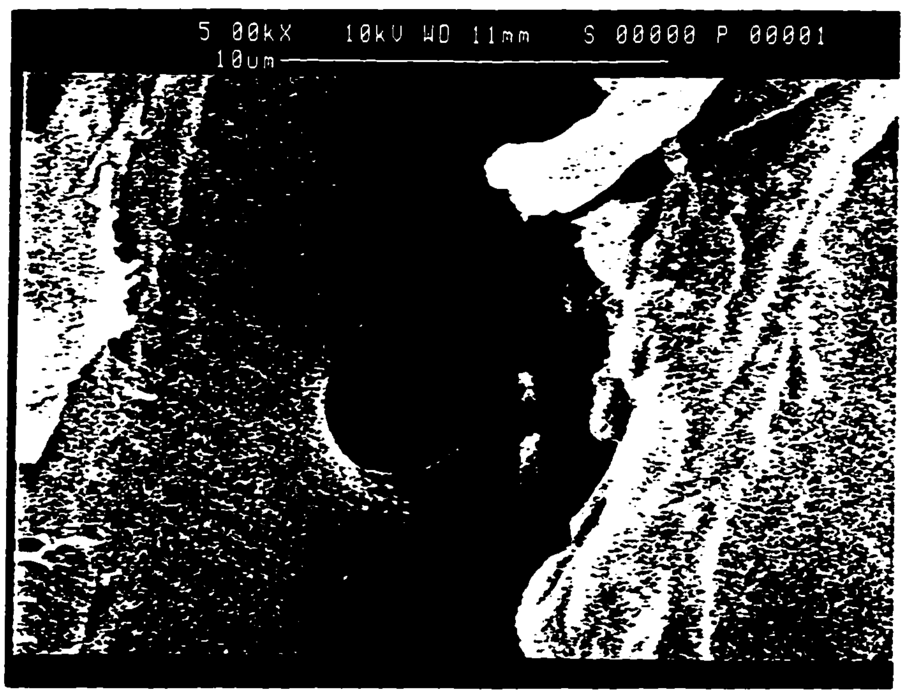


Figure 1.4. Aspirated pits on the cell wall of inner portion of 5-year pole using scanning electron microscope: A (1780x) and B (5000x)

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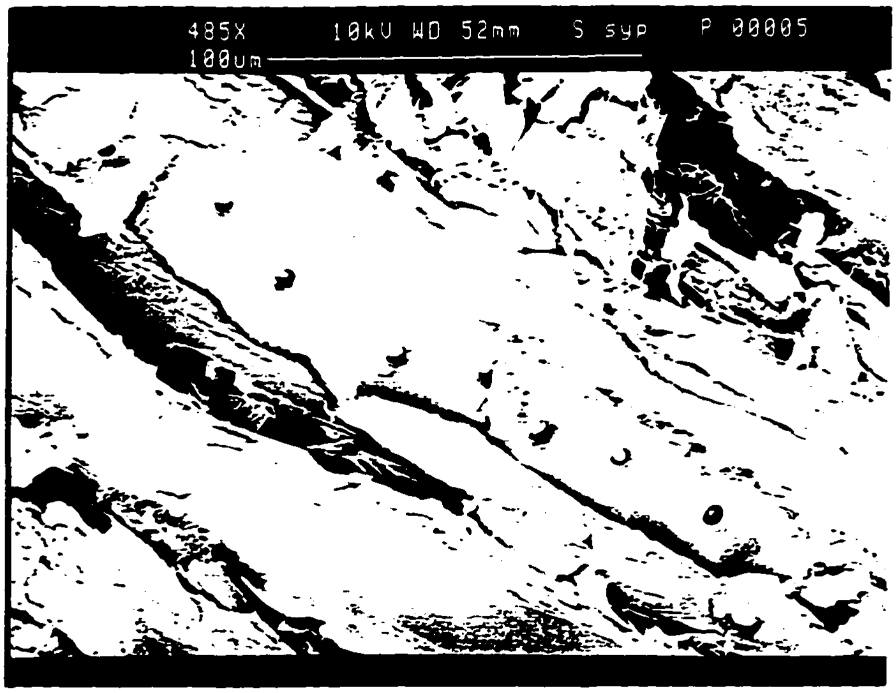
A



B

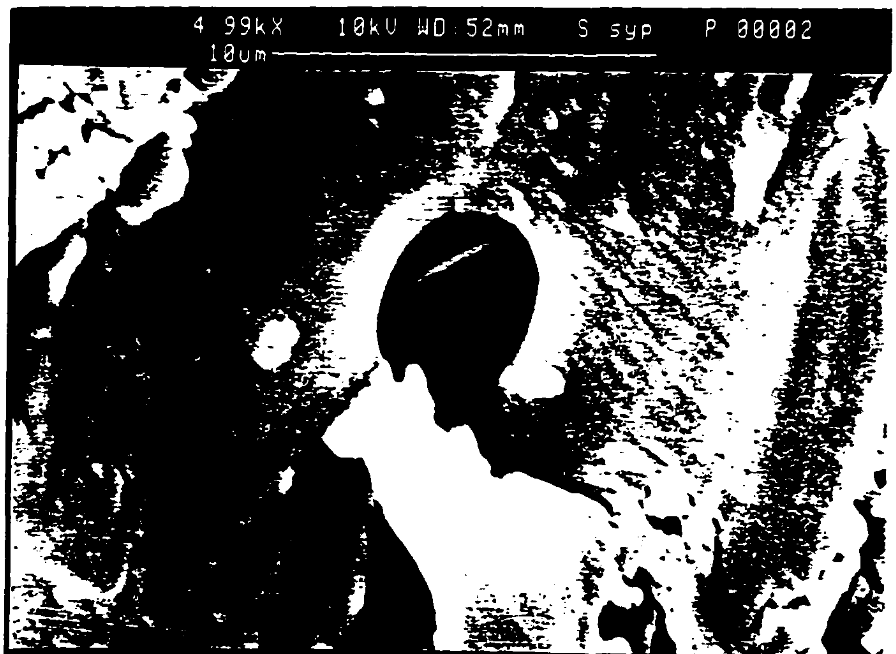


Figure 1.5. Aspirated pits on the cell wall of inner portion of 25-year pole using scanning electron microscope: A (485x) and B (4990x)

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Creosote content by electronic spectrometry method

The data on maximum-absorbance wavelengths of DMF solution of pure creosote and creosote extracted from treated poles are presented in Table 1.6. All the wavelengths were in the UV region (200-380 nm), whereby the overall average of maximum-absorbance wavelength was close to 280 nm. Therefore, a 280 nm wavelength was set on the spectrometer for making a calibration curve from DMF-pure creosote solution. The calibration curve, in the form of a linear regression equation, was based on plotted data between 280 nm light absorbances and pure creosote concentrations (Figure 1.6).

The calibration curve was later used to determine spectrometrically the creosote content in poles. Comparison of creosote contents from electronic spectrometry and toluene extraction are given in Table 1.7 and Figure 1.7. There is a relationship between the spectrometry method and the toluene extraction method. Spectrometric determination in 5- and 25-year poles show slightly higher values of creosote content than does the toluene extraction; nevertheless, the correlation (R=0.925) is significant at 5 per cent level. Thus, the spectrometry method with can be used for a rapid determination of creosote content in weathered poles with reliable results.

The slight difference in creosote content determination in the weathered poles between using electronic spectrometry and toluene extraction might be due to different maximum absorbance wavelengths of DMF solution of creosote from poles with different service durations, as shown in Figure 1.8. The analysis of variance (Table 1.8) indicates that the wavelengths were affected significantly by service

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Table 1.6. **Maximum-absorbance wavelength (nm) of DMF solutions of pure creosote and of creosotes extracted from the treated poles, and comparison (d) by Tukey's test for significantly different means**

Service duration	Horizontal distance from surface (in.)	Top (nm)	Top (d)	Middle (nm)	Middle (d)	Bottom (nm)	Bottom (d)
Freshly treated	0.5	260.84	E	261.64	E	261.74	E
	3.5	258.70	E	256.28	E	259.61	E
5 years	0.5	285.30	D	290.96	CD	289.16	CD
	3.5	279.80	D	285.20	D	282.74	D
25 years	0.5	303.56	A	303.10	AB	302.66	AB
	3.5	294.58	AB	292.76	ABC	291.95	ABC
Pure creosote				259.43			

[1]Similar letters indicate that no significant difference exists (A>B>C>D>E)

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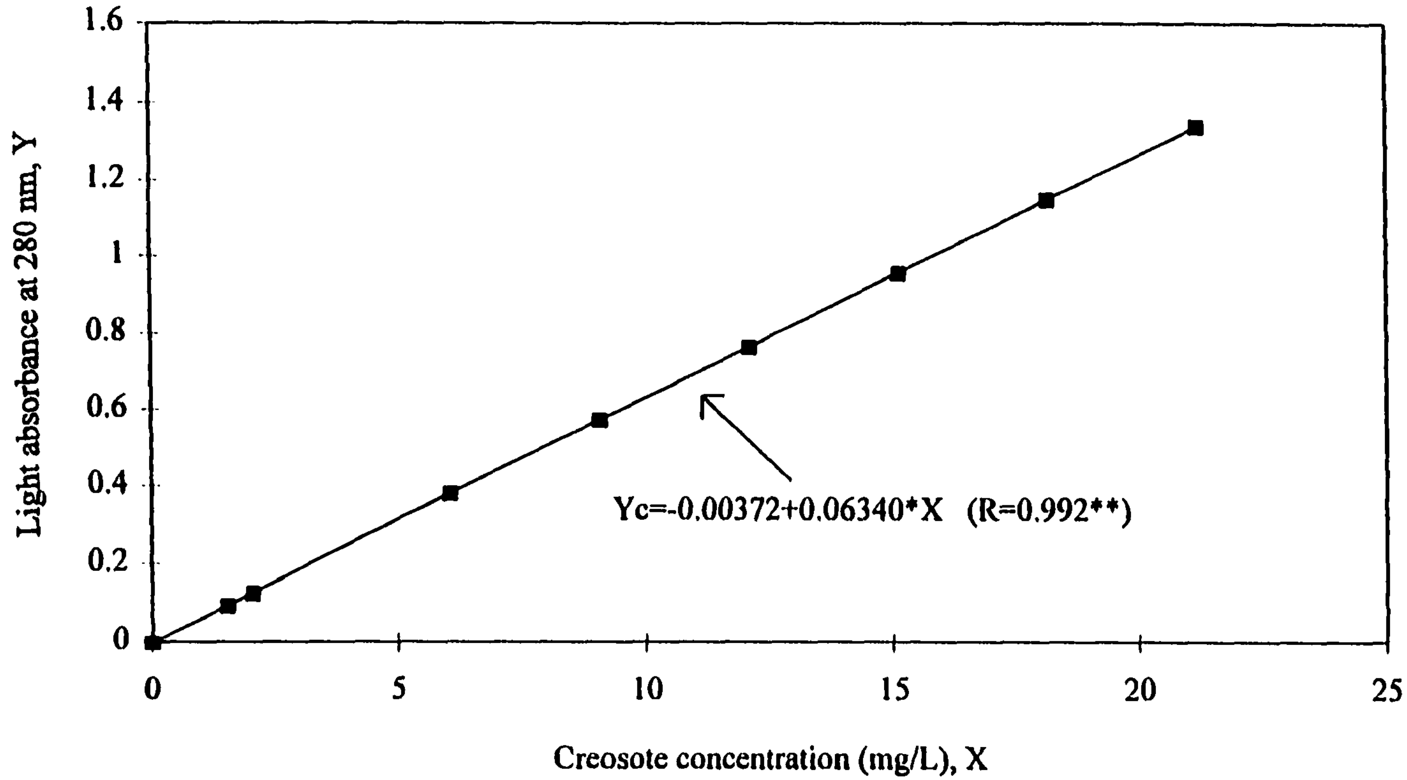

Figure 1.6. Calibration curve (Yc) for DMF-pure creosote solution

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Table 1.7. Comparison between determination of creosote content (%) in aged poles using toluene extraction (T) and using electronic spectrometry (E).

Service duration	Sample location								
	Vertical location	Horizontal distance from pole surface (inches)							
		0.5		1.5		2.5		3.5	
		T	E	T	E	T	E	T	E
		(%)							
Freshly treated	Top	34.51	35.07	26.12	25.61	24.99	25.55	22.14	21.62
	Middle	35.21	35.78	27.14	26.63	25.13	26.69	23.58	23.07
	Bottom	31.98	32.54	27.54	27.03	24.76	25.32	22.45	21.94
5 years	Top	9.11	10.43	12.45	13.49	13.77	14.99	14.12	15.66
	Middle	11.21	12.71	12.67	13.73	13.56	14.76	14.37	16.01
	Bottom	12.06	13.63	13.55	14.92	14.34	15.97	15.01	16.67
25 years	Top	2.75	3.23	3.79	4.16.	4.47	5.03	12.09	13.22
	Middle	3.65	3.88	3.81	3.98	6.14	7.02	12.55	13.77
	Bottom	3.85	4.09	4.11	4.33	5.97	6.79	12.97	14.11

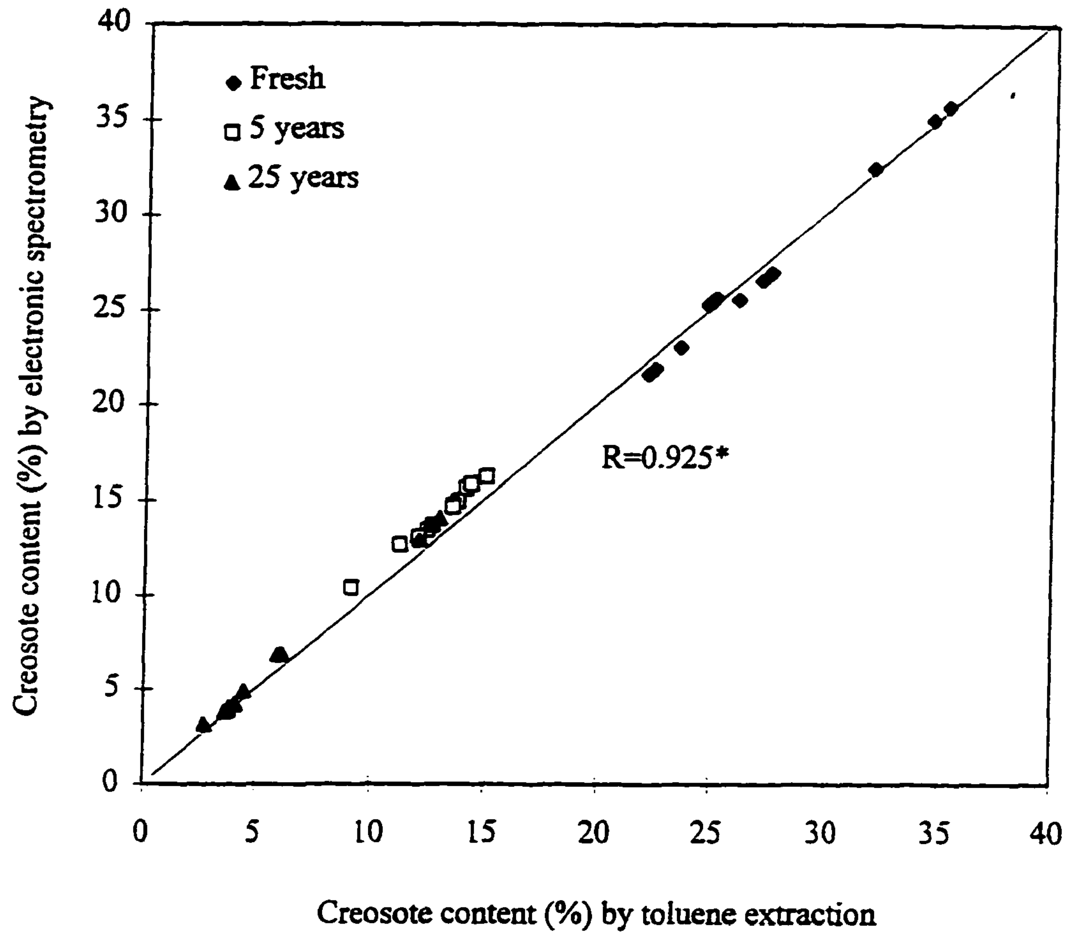

Figure 1.7. Creosote content determination showing relationship between electronic spectrometry and toluene extraction methods

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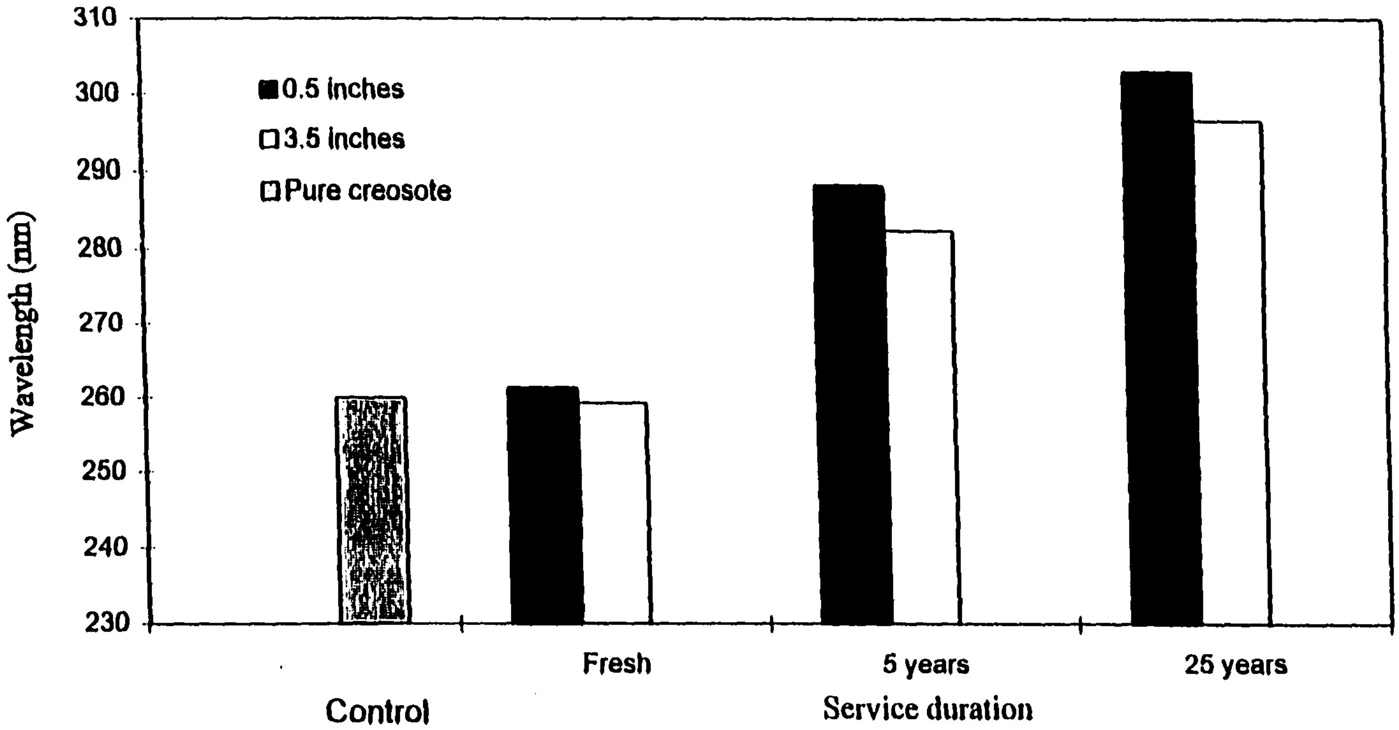

Figure 1.8. Maximum-absorbance wavelength of pure creosote and creosote extracted from poles using DMF solvent

duration, but not by either vertical or horizontal location. Comparison of the wavelengths by the Tukey's test (Table 1.6) indicates that the wavelengths were significantly different with respect to service duration, but not with different locations in the poles. The test shows that the wavelength was highest in poles with 25-year, followed in decreasing order by 5-year service, and by freshly treated poles. Higher wavelengths indicate that creosote compounds of high molecular weight (MW) contain more benzene or other aromatic rings (Williams and Flemings 1973). Previous experiment by Nestler (1974) revealed that creosote in weathered treated wood had lost significant amounts of low-boiling (volatile) fractions and retained high MW compounds, while creosote in freshly treated poles still contained some proportion of volatile or low MW fractions (Table 1.2). On the other hand, even though the maximum-absorbance wavelengths were not significantly different between the inner (3.5 inches from pole surface) and outer portions (0.5 inches from the surface), they tended to increase horizontally, especially in 5- and 25-year poles, from the pith to the surface ($0.80<P<0.95$), as shown by the F-values (=2.56) of interaction of variables between service duration and horizontal location (Table 1.8) and by the Tukey's test (Table 1.6). Again, this indicates that, as a result of weathering, the creosote in old poles near the surface had lost more volatile compounds than had the creosote near the pith.

In addition, plots among DMF concentrations of creosote from the poles (i.e. freshly treated, 5- and 25-years) and their light absorbance, at also 280 nm, to test the trend compatibility (Figure 1.9) show that at a given creosote concentration the light absorbances tended to be slightly different with different pole ages. This also

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Table 1.8. Analysis of variance of maximum-absorbance wavelength

Source of variation	DF	F -values	F-tables	
			$\alpha =$ 0.05	0.01
Service duration (S)	2	11.97**	3.88	6.93
Error (a)	12			
Vertical location (V)	2	1.69	3.15	4.98
Horizontal location (H)	1	3.27	4.00	7.08
Interactions:				
S*V	4	1.07	2.52	3.65
S*H	2	2.56	3.15	4.98
V*H	2	0.54	3.15	4.98
S*V*H	4	0.78	2.52	3.65
Error (b)	60	Y=281.41[1]	CV=9.28[2]	

Overall average of maximum-absorbance wavelength (nm)
[2]Coefficient of variation (%)
**denotes significance at 0.01 level

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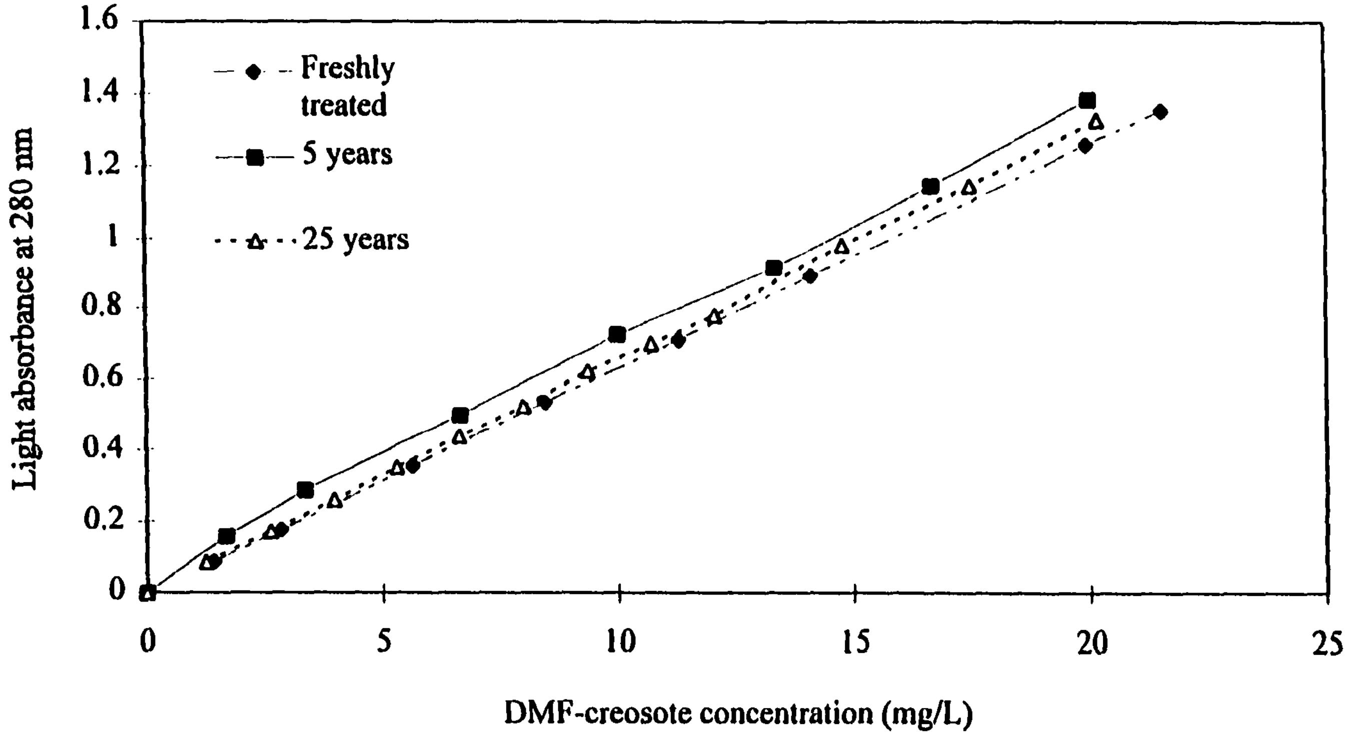

Figure 1.9. Relationship between DMF-creosote concentration and light absorbance

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confims that creosote in weathered poles underwent changes in proportion of its low- to high-boiling compounds, as compared to freshly treated poles.

Steam-removal of residual creosote

Data on removal of creosote for various service duration and locations in poles are presented in Appendix A.1. In general, steaming reduced creosote to a final content of about 1.5 percent regardless of initial content. Heat from the steam caused the volatilization of compounds in creosote and lowered the creosote's viscosity; consequently, the movement of creosote, which is not chemically held in wood , is greatly aided by steam treatment. However, the effectiveness of steam treatment is limited to about 1.5 percent final creosote content because creosote is oil-soluble and therefore immiscible in a polar substance (steam). Also, creosote at that low percentage level contains mostly the greater fraction of high-boiling compounds which are difficult to evaporate by steam (Andrew 1952; Wells and Bordenca 1955).

The analysis of variance (Table 1.9) shows that final creosote contents are not significantly different among all the variables tested; hence, the final content values can be averaged. The approximate steaming duration for various initial creosote contents could be determined, as shown in Figure 1.10, by interpolating it to the overall average (1.31 percent) regarded as effective final creosote content. As a result, when the experimental data of initial creosote contents are plotted against steaming duration (Figure 1.11), the relationship indicates that higher initial creosote content required longer steaming time. Removal of creosote from poles with longer service duration and from the inner portion of poles was more difficult. This is

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Table 1.9. Analysis of variance of final creosote content

Source of variation	DF	F-values	F-tables	
			α = 0.05	0.01
Service duration (S)	2	2.13	2.84	4.92
Vertical location (V)	2	2.08	2.84	4.92
Horizontal location (H)	1	2.55	3.09	7.04
Interaction:				
S*V	4	1.98	2.51	3.62
S*H	2	1.77	2.84	4.92
V*H	2	1.13	2.84	4.92
S*V*H	4	0.97	2.51	3.62
Error	72	Y=1.31[1]	CV=9.42[2]	

[1] Overall average of final creosote content (%)
[2] Coefficient of variation (%)

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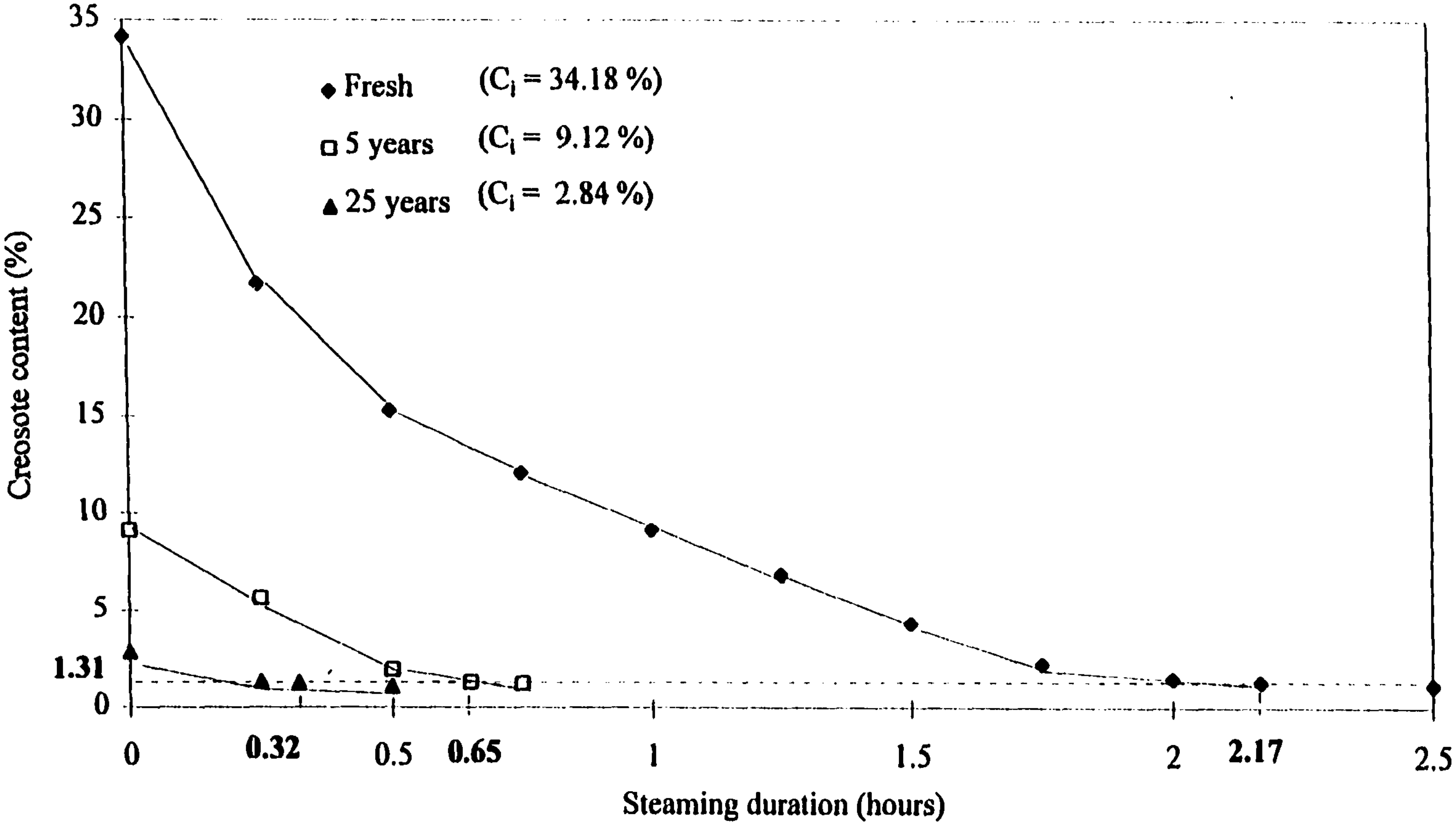

Figure 1.10. Approximate steaming duration required in three kinds of treated poles (i.e., 2.17 hours for freshly treated poles, 0.65 hours for 5-, and 0.32 hours for 25-year poles, respectively) to reach 1.31 % final creosote content - (C_i=initial creosote content)

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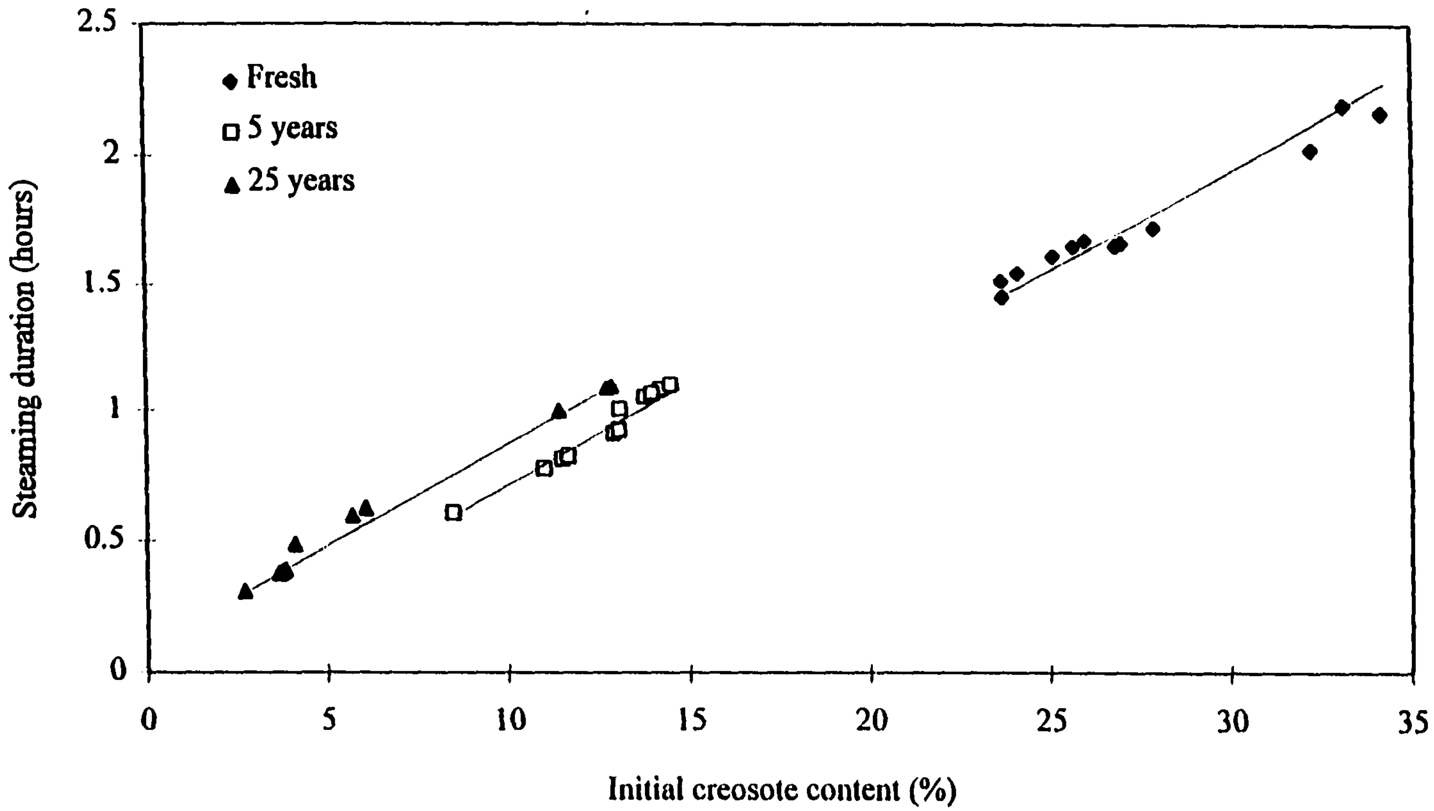

Figure 1.11. Relationship between initial creosote content and steaming duration to reach 1.31% final creosote content

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Table 1.10. Analysis of adjusted variance of steaming duration

Source of variation	DF	F-values	F-tables	
			α = 0.05	0.01
Main variables (M):				
Service duration (S)	2	14.98**	3.13	4.92
Error (a)	12			
Vertical location (V)	2	2.47	3.15	4.98
Horizontal location (H)	1	9.22**	4.00	7.08
Interaction:				
S*V	4	1.78	2.52	3.65
S*H	2	3.67*	3.15	4.98
V*H	2	1.34	3.15	4.98
S*V*H	4	0.91	2.52	3.65
Covariates:				
Initial creosote content	1	22.31**	4.00	7.08
Error (b)	59	X= 16.14[1]	Y=1.143[2]	CV= 7.23[3]

[1]Overall average of initial creosote content (%)
[2]Overall average of steaming duration (hr.)
[3]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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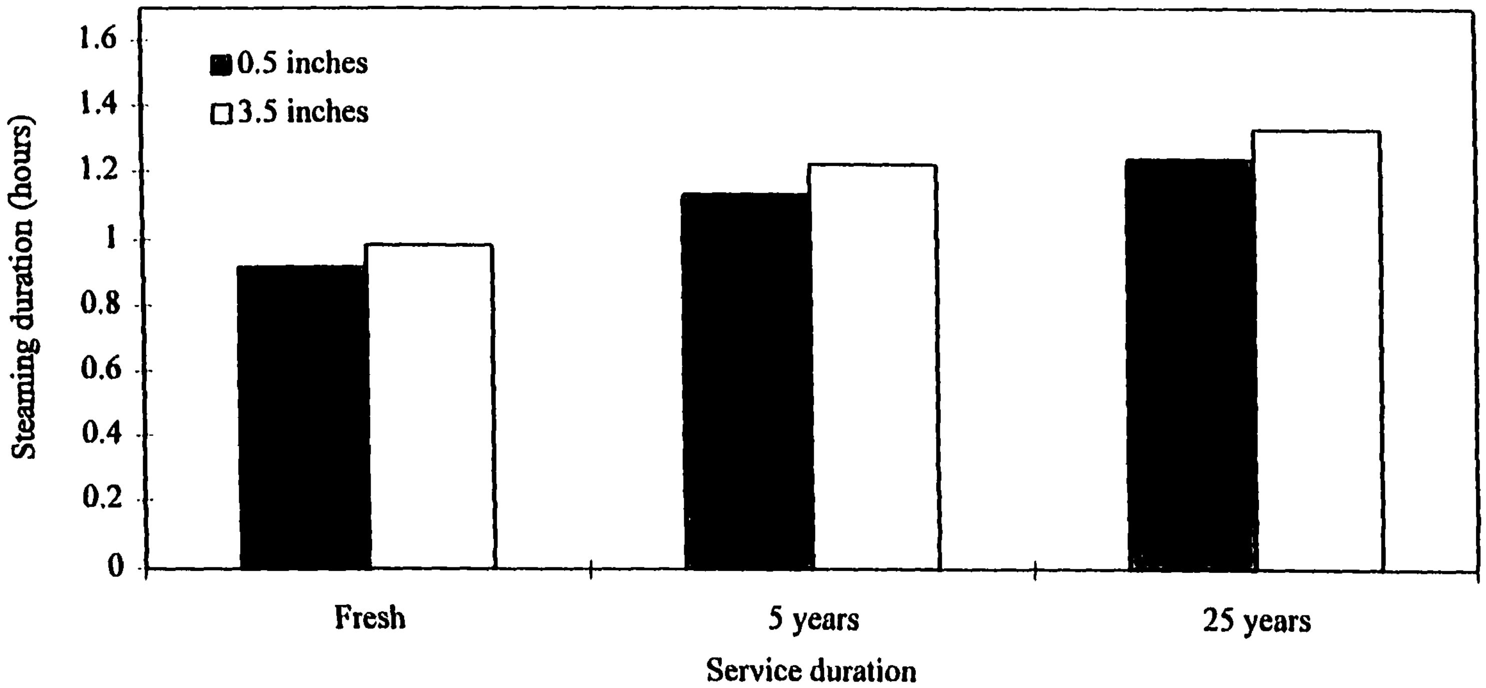

Figure 1.12. Steaming duration in sawdusts from three kinds of treated poles, by assuming that their initial creosote contents are the same (16.14%)

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shown by the significant effect of interaction between service duration and horizontal location on steaming duration using the analysis of adjusted variance (Table 1.10). This analysis, which assumed that the overall initial creosote contents were the same, revealed that longer time was required to steam sawdust samples from these poles (Figure 1.12). The difficulty of steaming 5- and 25-year weathered poles could be due to greater fractions of high-boiling compounds in creosote from those poles; while the difficulty to steam the inner portions could be linked to more aspirated pits on the cell wall from those portions.

Conclusions

The distribution of residual creosote was higher in bottom and inner portions of used poles than in upper and outer portions. Poles in service 5 years contained higher creosote content than those in service 25 years, but they have much lower creosote content than in poles which were freshly treated.

Electronic spectrometry could be applied for rapid determination of creosote content in treated poles. The results are compatible with those obtained by the standard, but time-consuming, toluene extraction method. Slight differences in results between spectrometry, especially in 5- and 25-year poles, and toluene extraction were due to long-term weathering of the poles in service. Weathering resulted in the increase of maximum-absorbance wavelength of creosote in old poles, in comparison with freshly treated poles.

The initial creosote contents in sawdust samples from poles are directly related to steaming time. Regardless of initial content, steaming reduced the creosote to 1.31 percent, which was less effective than solvent extraction. Also, creosote

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removal by steaming was more difficult for poles with longer service duration and for material from the inner portion. Steaming, however, is an efficient and cheap method of reducing the creosote content in treated poles.

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CHAPTER 2

STRENGTH PROPERTIES, DIMENSIONAL STABILITY, AND LUMBER RECOVERY

Introduction

Weathering of out-of-service poles affects not only the preservative, as described in Chapter 1, but also causes deterioration of the wood. The destruction is usually invisible in the incipient stage; hence, wood pieces can still be visually sound, but inside they may have undergone disintegration of cellulose and lignin causing changes in physical properties. It is also conceivable that after long-time weathering, most of the defect-free parts of the used poles could still retain adequate strength properties. This chapter reports the effect of residual preservative and long-term weathering on mechanical strength, dimensional stability, and lumber recovery of used poles.

Literature review

The outdoor wear in wood products can be due to a combination of many factors: (1) mechanical, e.g. cantilever action from the wind; (2) physical, due to repeated dimensional changes on wood surface; (3) photochemical, from exposure to light, oxygen, water, and atmospheric pollution; and (4) biological, due the action of organisms. In untreated wood, photochemical and biological degradation may not show visible defects, but they often result in lowering strength properties (Eaton and Hale 1993). The presence of residual preservative in treated wood, however, may prevent biological degradation.

Wood, being hygroscopic, responds readily to change in atmospheric humidity and temperature. Its unprotected surface absorbs moisture and swells in wet weather,

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and loses moisture and shrinks in dry weather. The repeated changes in dimension set up compressive and tensile stresses which eventually produce mechanical disintegration of the surface layer (Tsoumi 1991). Wood with large amounts of extractives tends to be dimensionally stable (Choong 1969) because the extractives in the cell walls provide a degree of bulking which prevents the cell wall from shrinking. Wood treated with an oil preservative, such as creosote, as distinguished from extractives inherent in the wood, will not prevent shrinkage because the preservative does not enter the cell wall; however, the preservative can inhibit the movement of moisture in wood. The reduction of creosote content as a result of weathering, consequently, may affect the dimensional change property of treated wood.

Lumber recovery factor (LRF) evaluates the conversion of a log. It is simply the ratio of board feet of lumber per cubic foot of actual log volume. If lumber were actually cut to nominal sizes with no losses in sawdust, and the logs were square, the LRF value would be 12 bd. ft./cu-ft. (Haygreen and Bowyer 1989). An actual LRF value, however, is dependent on many factors, such as methods of sawing, log diameter, and quality of logs. Weathering can affect quality of wood products; therefore, if out-of-service poles are to be processed into smaller pieces, their LRF values should be determined.

Materials and Methods

Lumber samples from the used poles described in Chapter 1 were used in this study. As with the sawdust samples, lumber pieces were taken from various vertical and horizontal locations in the poles (Figure 1.1) for each of the three service duration groups (i.e. freshly treated, 5- and 25-years). Five poles from each group were selected

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as replicates. In addition, untreated kiln-dried southern yellow pine (SYP) measuring 1- by 4-inches by 12-feet long were obtained from Miles Lumber Company in Bogalusa, Louisiana in dry-kiln condition.

Strength properties

Defect-free samples measuring 1- by 1- by 10-inches in size were selected. Evaluation of strength properties was done in accordance with ASTM Standard D 143-83 (1994). The samples tested were placed in an environmental chamber at 68°F and 65 percent relative humidity (RH) before they underwent a static bending test on an Instron universal testing machine to determine the modulus of rupture (MOR) and modulus of elasticity (MOE) :

$$\text{MOR (psi)} = 1.5\, P' * L/(w * d^2) \qquad (1)$$

where:

L = distance between supports or span (in)

P′ = breaking (maximum) load (lbs) applied at center of span

w = width of the sample (in)

d = depth of the sample (in)

$$\text{MOE (psi)} = P * L^3/(4 * w * d^3 * D) \qquad (2)$$

where:

P = load at proportional limit (in)

D = deflection at midspan resulting from P (in)

L = span (in)

d = depth of the sample (in)

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w = width of the sample (in^3)

Defect-free samples measuring 2- by 2- by 1-inch were also selected to determine solid-wood shear strength on the same Instron universal machine, in accordance with ASTM Standard D 143-83 (1994):

Shear (psi) = P/A (3)

where:

P = force required to shear the solid-wood block sample (lbs)

A = area of shear (in^2)

Latewood (LW) percentage was determined for its possible effect on strength properties. This was done by scanning the cross-section pieces of lumber with a Desk Scan II 1.61, and then the LW percentage was calculated by a programmable computer equipped with a Tif - Idrissi hardware. For comparison, several untreated SYP samples were selected for MOR, MOE, shear strength, and percent LW determinations in the same manner as those with treated samples.

Volumetric swelling

Defect-free samples of 2- by 2- by 1-inch (thickness) were prepared for dimensional stability test in accordance with ASTM Standard D 143-83 (1994). The samples were conditioned in an environmental chamber for 24 hours at 68°F and 65 percent RH (nominal 12.0 percent moisture content) from air-dry condition. At equilibrium, the volume of each of the samples was determined by measuring the dimensions (i.e. length, width, and thickness) with a caliper. Then, the samples were soaked in water for 24 hours, and their volumes again determined. The following formula was used to calculate the volumetric swelling (S_V):

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$$S_V\ (\%) = 100*(V_s - V_a)/V_a \qquad (4)$$

where:

V_a = volume of samples before soaking (in^3)

V_s = volume of samples after soaking (in^3)

Lumber recovery

From each pole in the experimental design (Table 1.3), three bolts were prepared. The length and midspan circumference of each bolt were measured. The bolt volume (V_b) and the bolt diameter (∅) were determined:

$$V_b\ (in^3) = 3*L*(C_m/\Pi)^2*0.26180 \qquad (5)$$

where:

L = length of the bolt (in)

C_m = midspan circumference of the bolt (in)

Π = 3.14286

and,

$$\varnothing\ (in) = C_m / \Pi \qquad (6)$$

Then, the total volume of defect-free lumber obtained from sawing the bolt with the portable Wood Mizer, as described in Chapter 1, was measured. The LRF value of each bolt was determined from the following formula:

$$LRF\ (bd.\ ft./ft^3) = 12*(\Sigma V_l / V_b) \qquad (7)$$

where:

ΣV_l = total volume of defect-free lumber (in^3)

V_b = volume of bolt (in^3)

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Results and Discussion

Strength properties

Data on strength properties and LW percentage of treated poles and untreated SYP lumber are summarized in Appendix B.1. The average strength properties are shown in Figure 2.1 for MOR, Figure 2.2 for MOE, and Figure 2.3 for shear strength, respectively, for each combination of service durations, horizontal distances from surface, and vertical locations of the poles as well as for the untreated SYP lumber. From analysis of variance (Table 2.1), the different service duration did not change MOR, MOE, and shear strength of defect-free wood in treated poles. This meant that after 25 years in service the internal structure of the pole parts still remained intact, indicating that the residual creosote still provides decay resistance. However, all strength properties were significantly different for different horizontal and vertical locations as indicated in the significant interaction between these two variables. The average strengths of treated poles decreased consistently from outer surface to pith in the horizontal direction, and from bottom to top in vertical direction. It is interesting to note that LW percentage as determined by scanning (Figure 2.4) shows a similar trend as that of strength properties in both horizontal and vertical directions. From the analysis of adjusted variance (Table 2.2), strengths were affected solely by LW percentage regardless of whether the samples were treated or untreated. The correlation between strengths and LW percentage was highly significant, as shown in Figure 2.5 for MOR, Figure 2.6 for MOE, and Figure 2.7 for shear strength. These significant correlations also confirm that at a given LW percentage, strengths of defect-free 5- and 25-year poles were comparable to those of freshly treated poles and untreated SYP.

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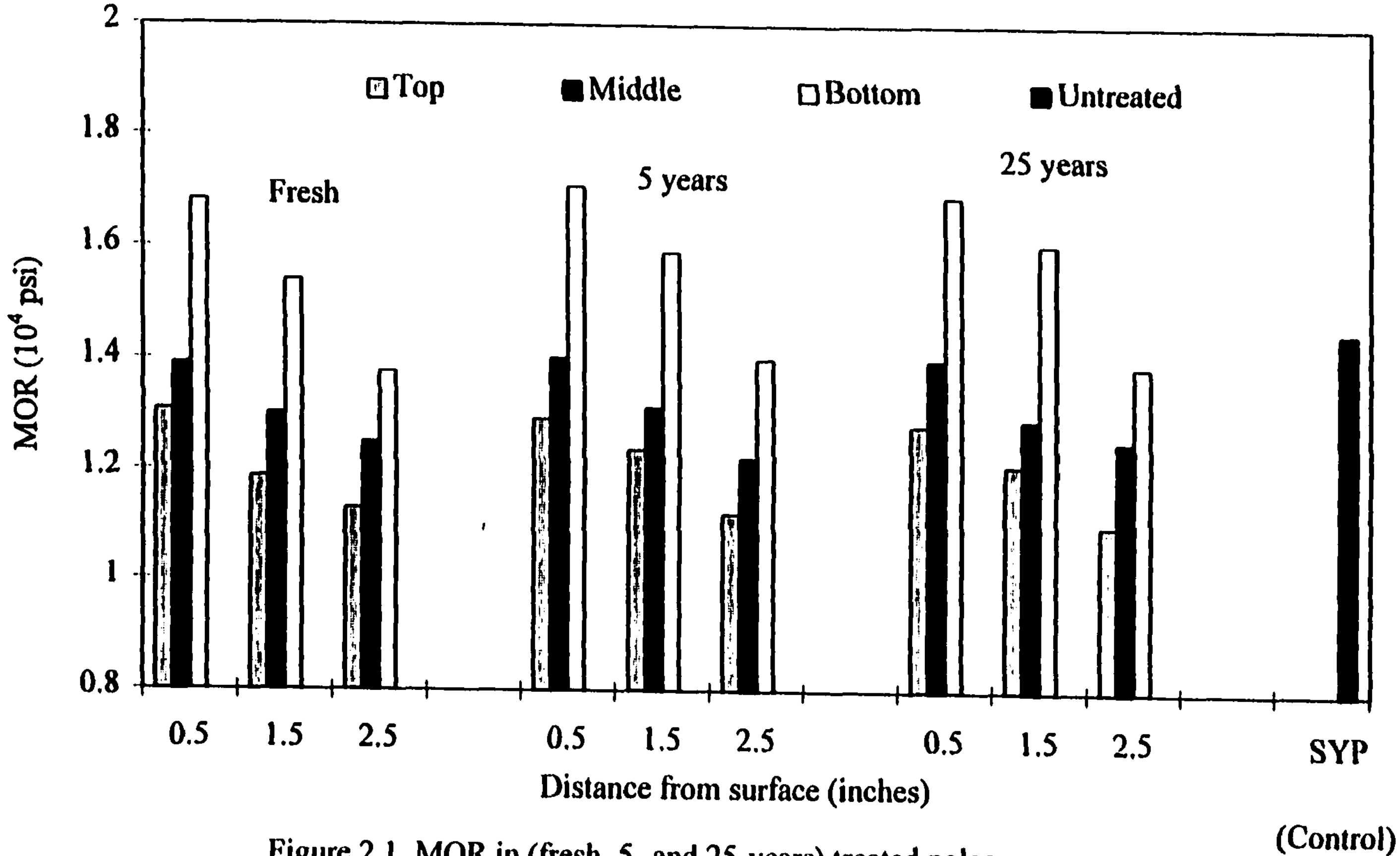

Figure 2.1. MOR in (fresh, 5- and 25-years) treated poles and in untreated SYP

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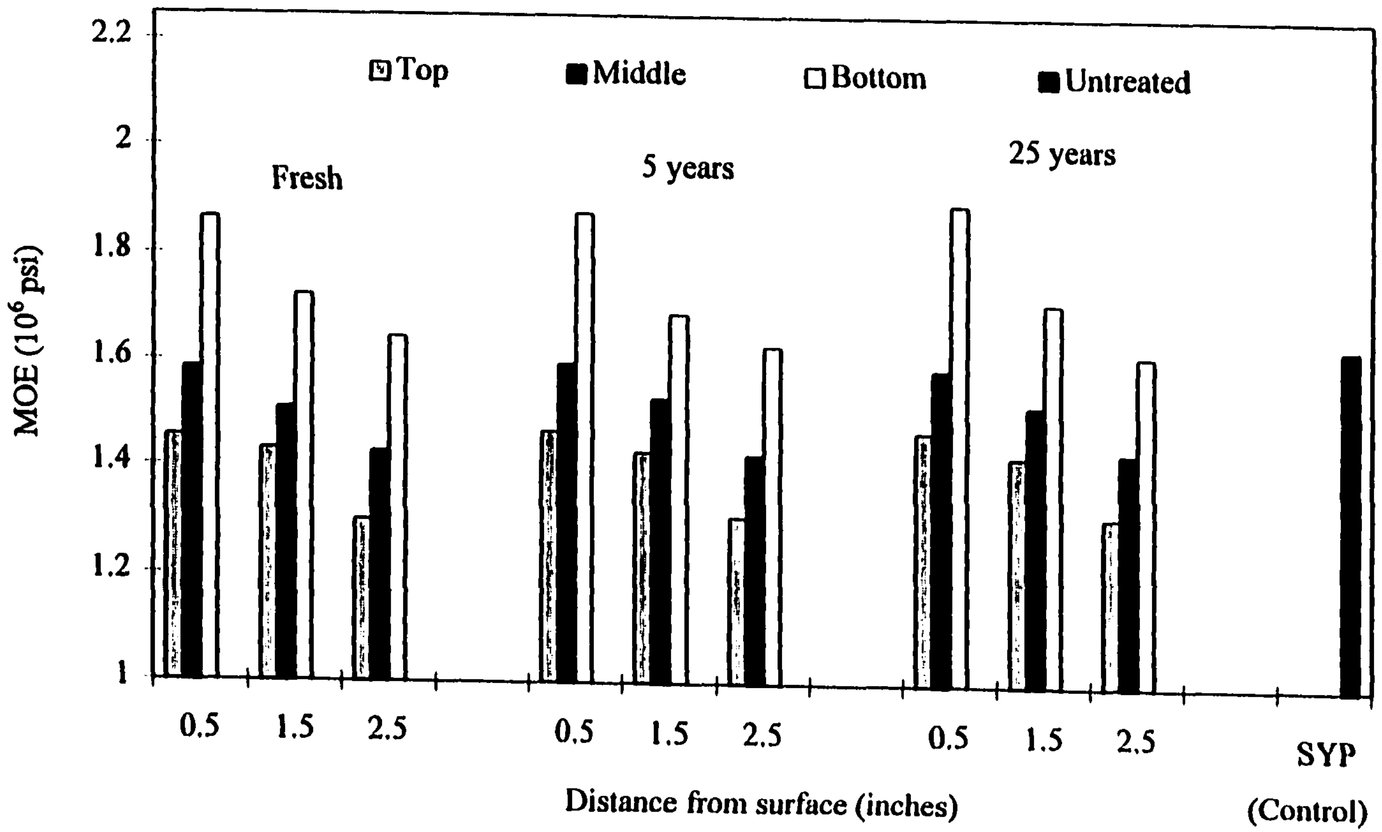

Figure 2.2. MOE in (fresh, and 5- and 25-years) treated poles and in untreated SYP

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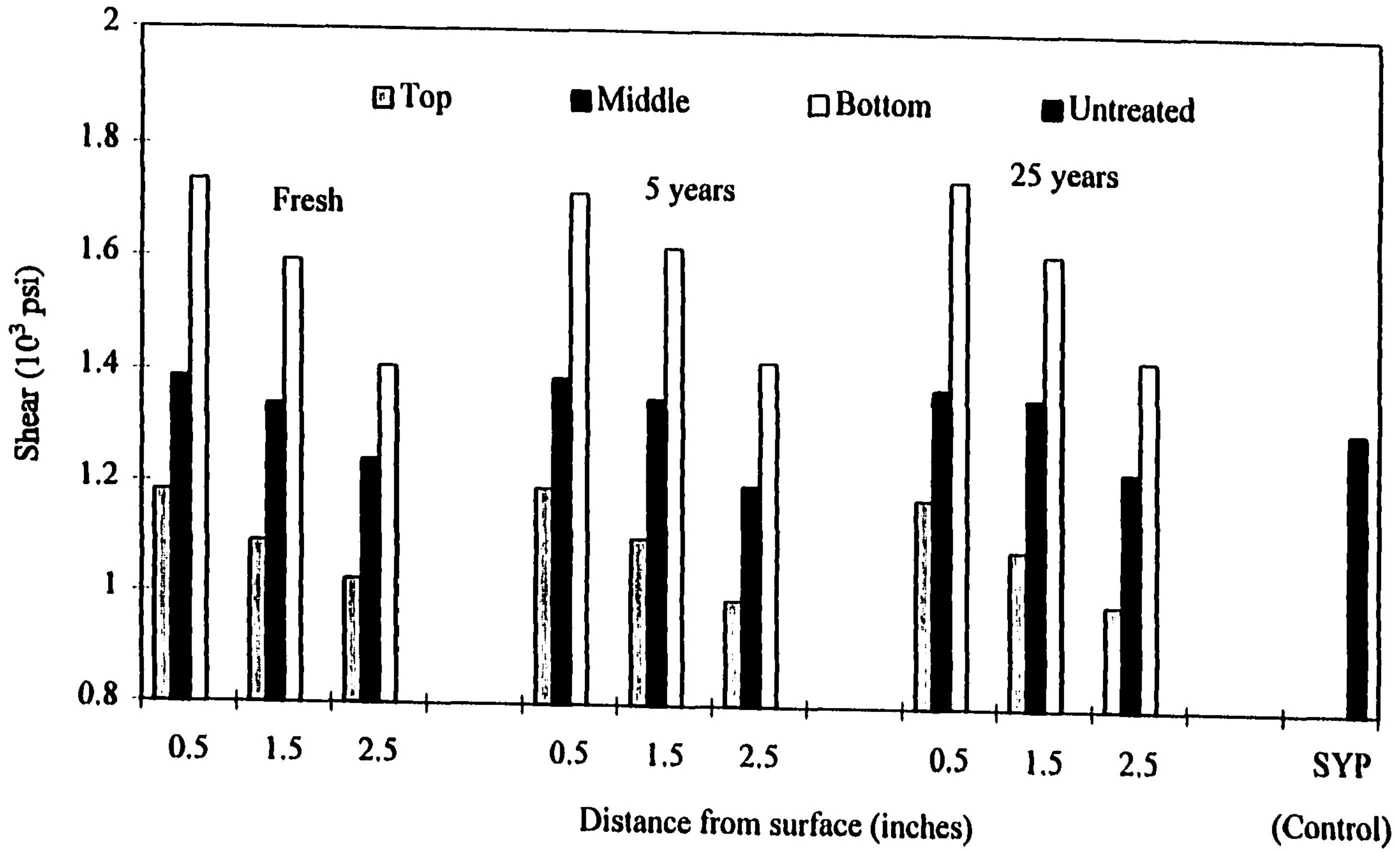

Figure 2.3. Solid-wood shear in (fresh, and 5- and 25-years) treated poles and in untreated SYP

Table 2.1. Analysis of variance of MOR, MOE, and solid-shear of treated poles

Source of variation	DF	F-values			F-tables	
		MOR	MOE	Shear	$\alpha = 0.05$	0.01
Service duration (S)	2	2.09	1.88	2.45	3.88	6.93
Error (a)	12					
Vertical location (V)	2	6.47**	5.78**	6.18**	3.09	4.82
Horizontal location (H)	2	6.32**	4.31**	4.58**	3.09	4.82
Interactions:						
S*V	4	1.22	1.89	2.13	2.46	3.51
S*H	4	0.89	1.45	1.98	2.46	3.51
V*H	4	3.44**	4.76**	6.58**	2.46	3.51
S*V*H	8	0.88	1.79	1.23	2.03	2.60
Error (b)	96					
Y[1]		1.353	1.651	1.329		
Unit		10^4 psi	10^6 psi	10^3 psi		
CV[2]		5.37	6.18	5.21		

[1]Overall average of the strengths (MOR, MOE, and shear) of treated poles
[2]Coeff. of variation (%) of the strength data
**denotes significance at 0.01 level

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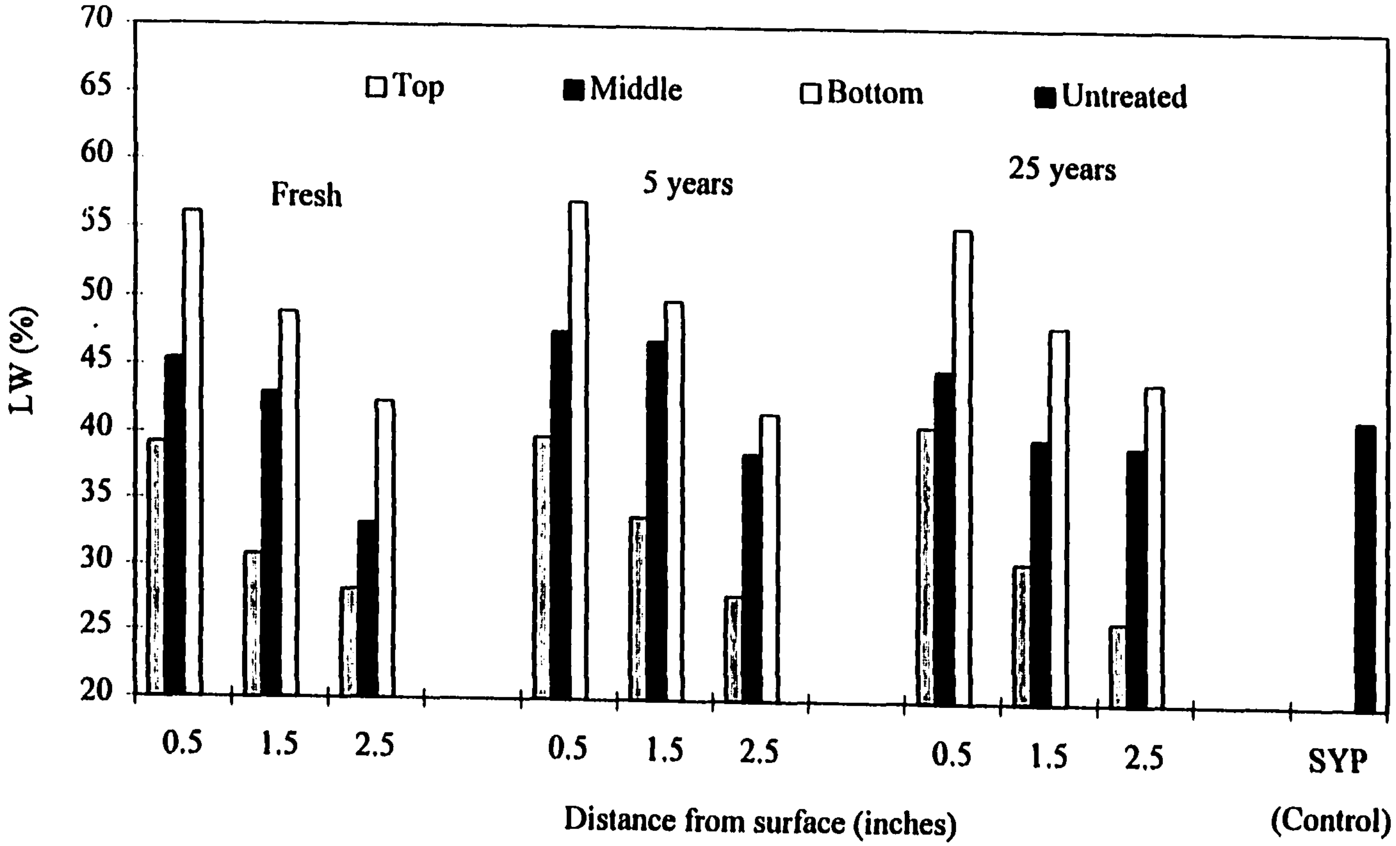

Figure 2.4. Distribution of latewood (LW) in treated poles

Table 2.2. Analysis of adjusted variance of MOR, MOE, and solid-shear

Source of variation	DF	F-values			F-tables	
		MOR	MOE	Shear	$\alpha = 0.05$	0.01
Main variables (M):						
Wood types[1]	3	0.25	0.54	0.24	2.88	4.42
Covariates						
LW percentage	1	22.43**	24.62**	45.47**	4.13	7.44
Error	30					
Y[2]		1.353	1.573	1.326		
Unit		10^4 psi	10^6 psi	10^3 psi		
CV[3]		7.97	8.09	6.91		

[1]Consists of treated poles (fresh, and 5- and 25-years) and untreated SYP
[2]Overall average of the strengths (MOR, MOE, and shear) of all wood types
[2]Coeff. of variation (%) of the strength data
**denotes significance at 0.01 level

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Volumetric swelling

Data for volumetric swelling of treated poles and untreated SYP, together with LW percentage and creosote content, are presented in Appendix B.2. The analysis of variance (Table 2.3) indicates that service duration, vertical and horizontal locations, and the interaction of these three variables, all significantly affected swelling. The variations in swelling (Figure 2.8) with respect to service duration were related to changes in creosote content due to weathering. These show the reverse in pattern with creosote content (Figure 1.2), indicating that swelling tended to increase with pole age, and consequently with decrease in creosote content. Low swelling, especially in freshly treated poles, was in part attributed to the high creosote content retarding the movement of water. Nevertheless, as shown in Figure 2.9. the swelling of weathered 5- and 25-year poles was lower than that of untreated SYP. The least swelling, as expected, occurred in freshly treated poles. Also, the inner portions of treated poles show better dimensional stability because they contained higher creosote content than the outer portions.

The significant interaction of the three variables (service duration, vertical and horizontal locations) might be due to the different effects of creosote content and LW percentage on swelling. Variation in creosote content, as described previously, was affected by different service duration and different vertical and horizontal locations of the samples; whereas, variation in LW percentage was caused by locations only.

Evaluation by multiple regression analysis (Table 2.4) confirmed that swelling was negatively affected by creosote content and positively affected by LW percentage. There was no significant interaction between LW percentage and creosote content,

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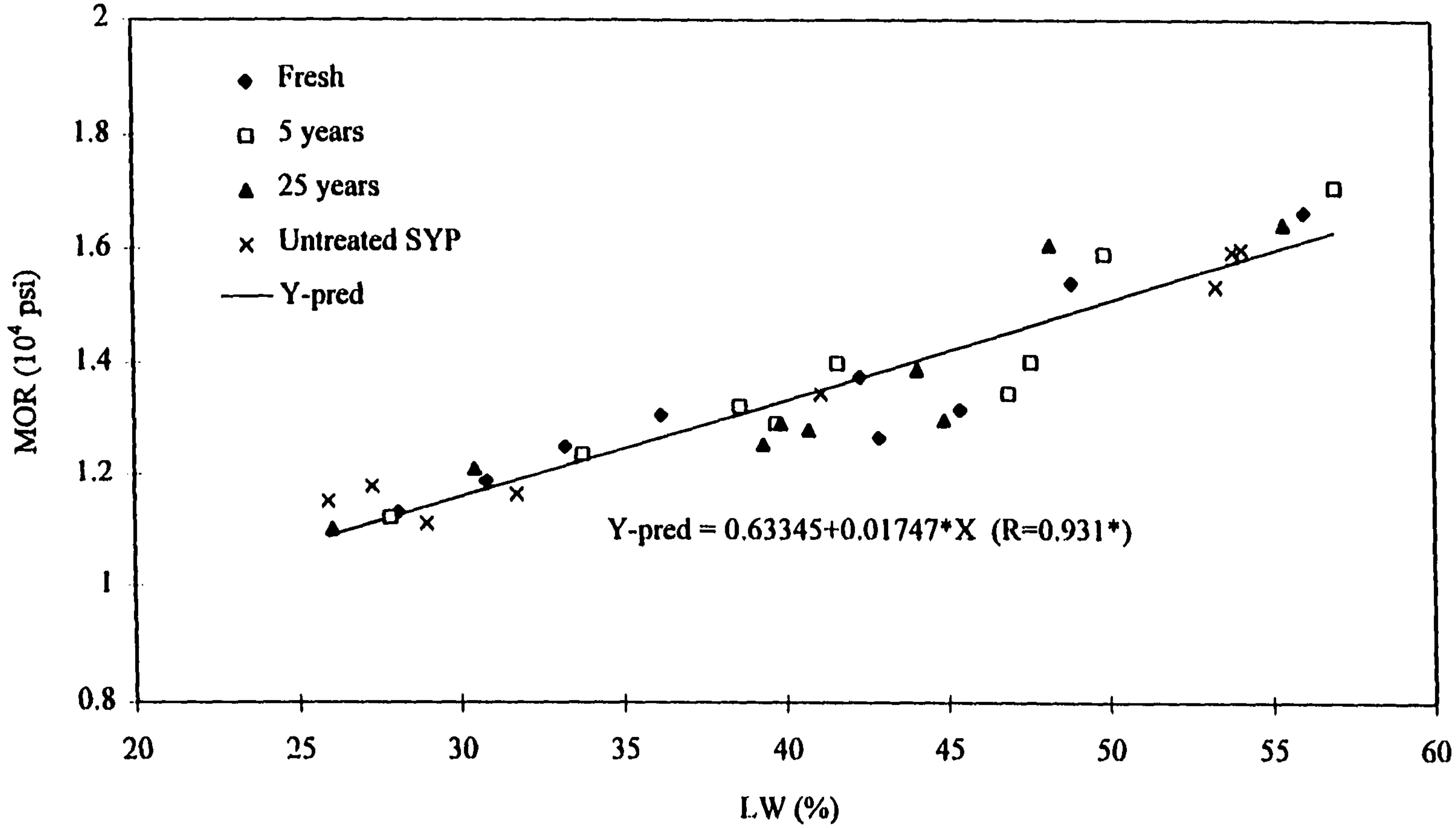

Figure 2.5. Relationship between LW percentage and MOR in (fresh, 5-, and 25-years) treated poles and in untreated SYP

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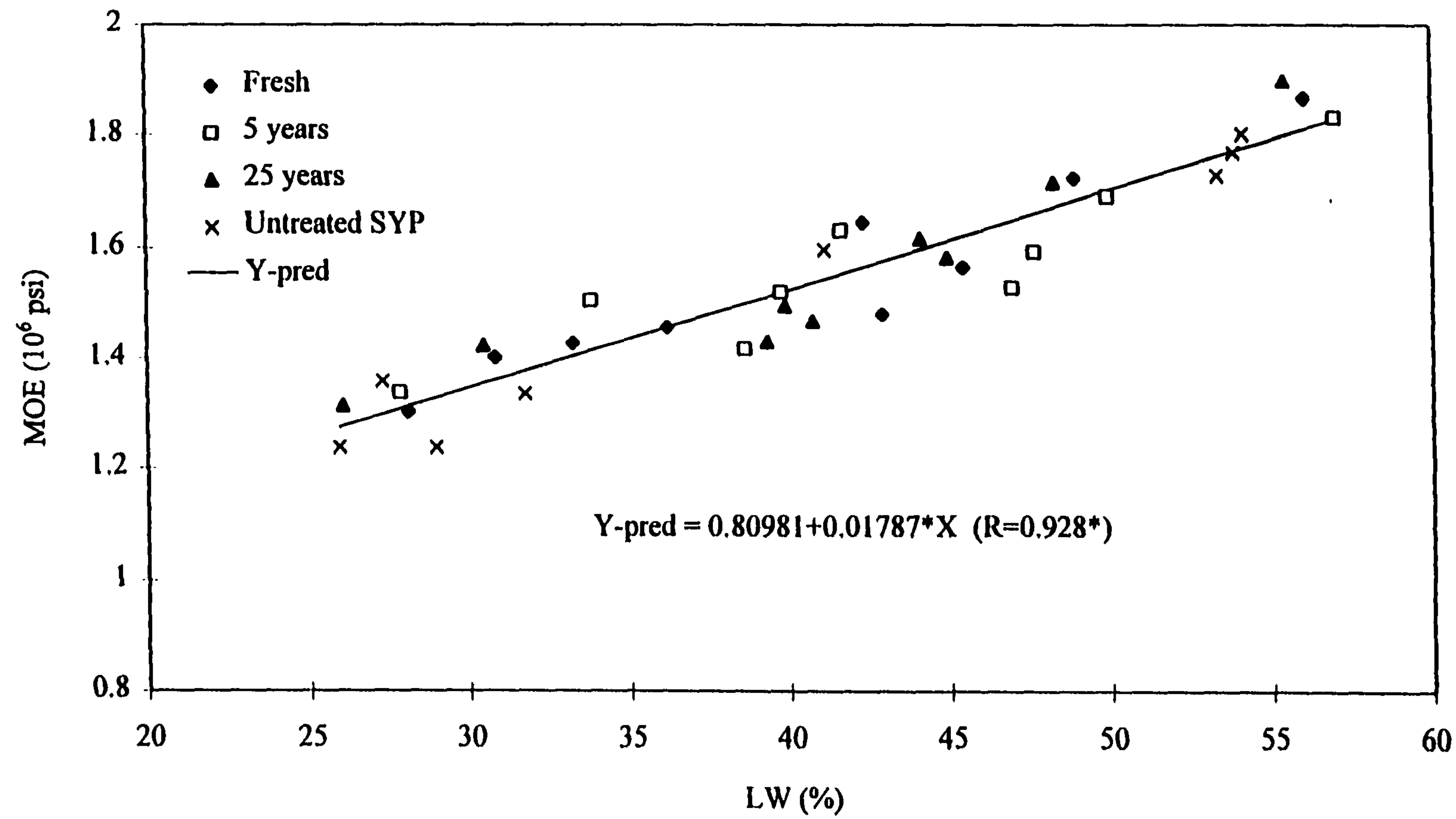

Figure 2.6. Relationship between LW percentage and MOE in (fresh, 5-, and 25-years) treated poles and in untreated SYP

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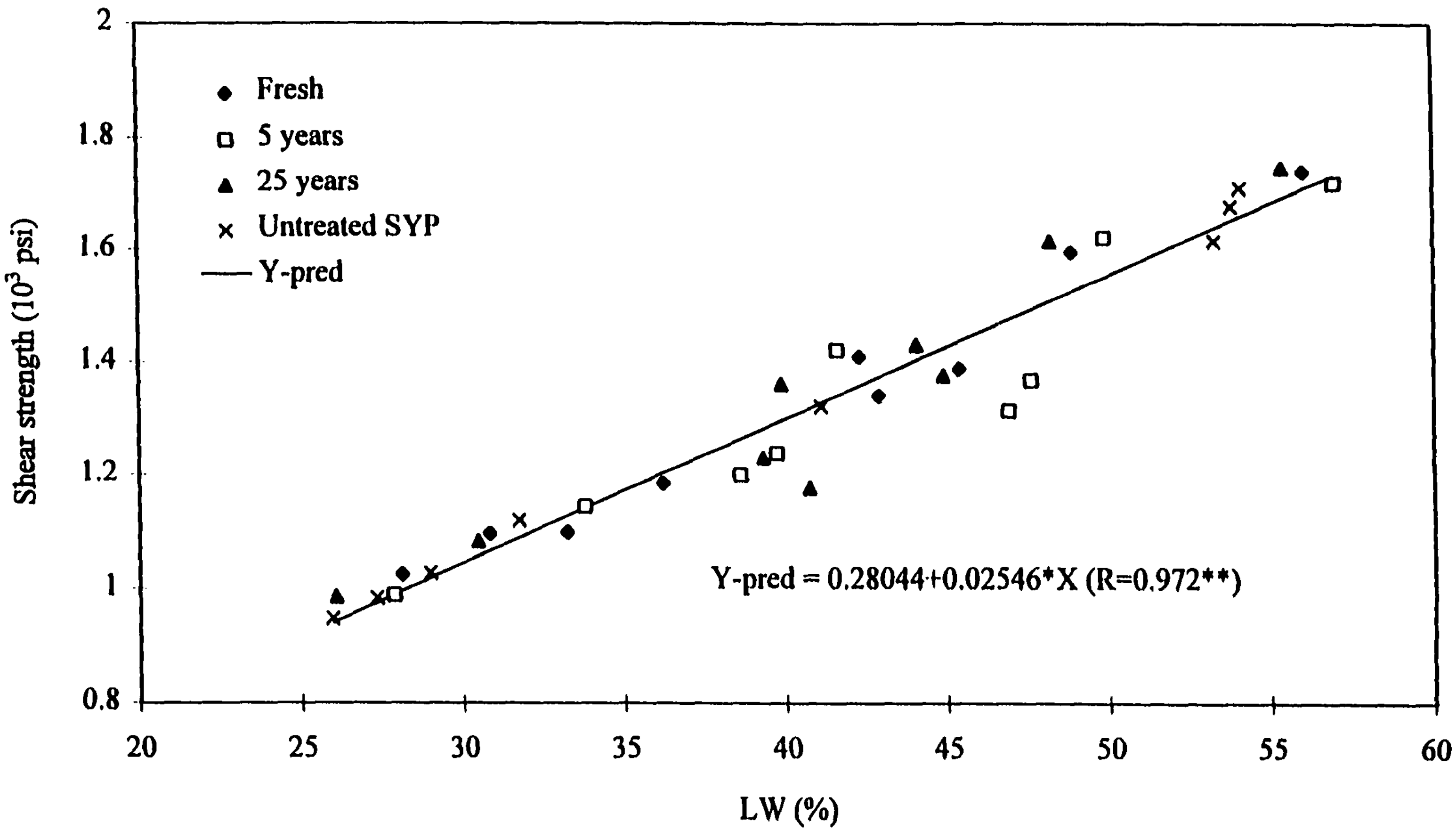

Figure 2.7. Relationship between LW percentage and solid-wood shear in fresh, 5-, and 25-years) treated poles and in untreated SYP

Table 2.3. Analysis of variance of volumetric swelling

Source of variation	DF	F-values	F-tables $\alpha = 0.05$	0.01
Service duration (S)	2	12.32**	3.88	6.93
Error (a)	12			
Vertical location (V)	2	8.32**	3.09	4.82
Horizontal location (H)	2	6.74**	3.09	4.82
Interactions:				
S*V	4	5.22**	2.46	3.51
S*H	4	4.35**	2.46	3.51
V*H	4	3.56**	2.46	3.51
S*V*H	8	2.58*	2.03	2.69
Error (b)	96	Y=4.856[1]	CV=7.22[2]	

[1]Overall average of volumetric swelling of treated poles (%)
[2]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively.

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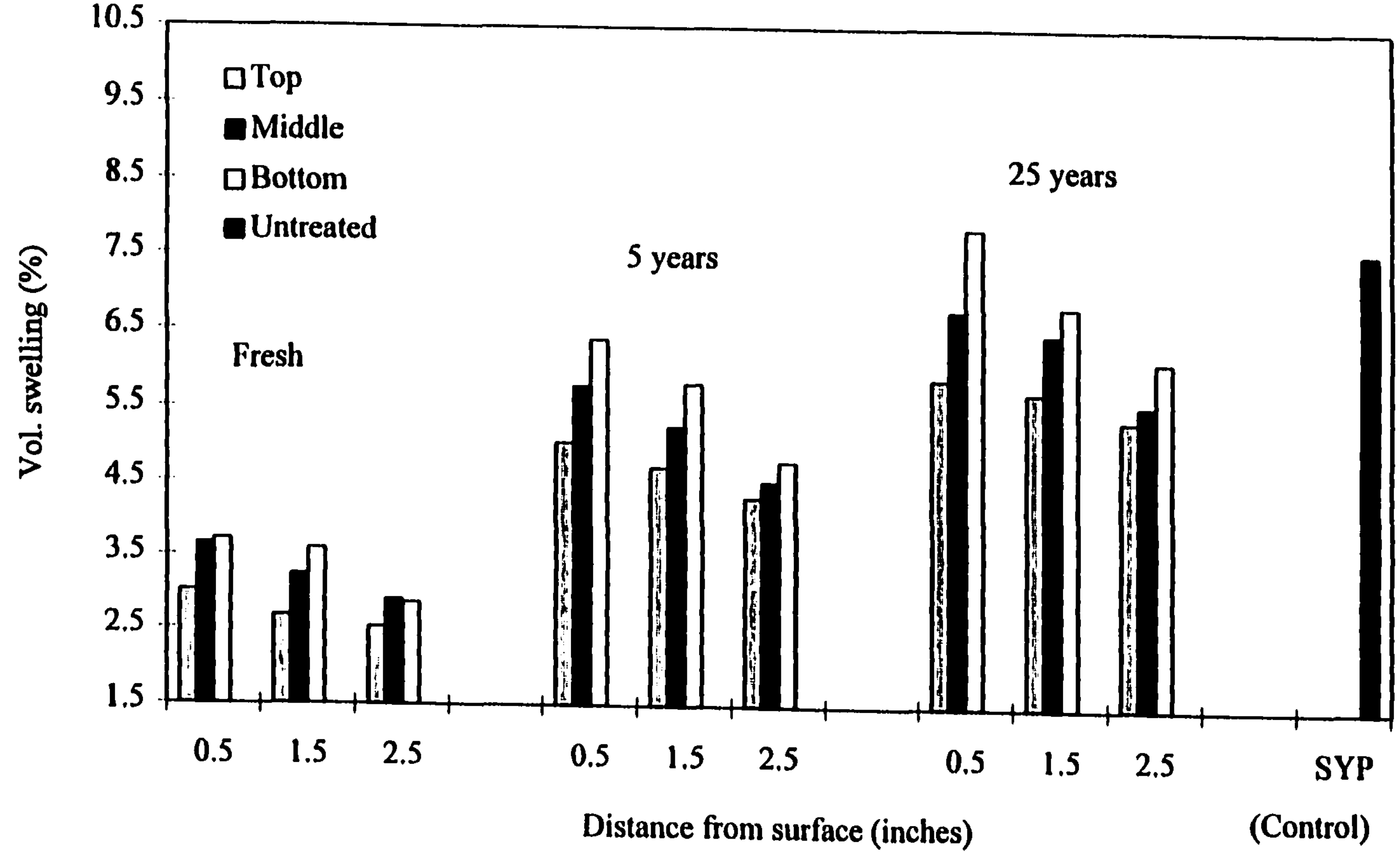

Figure 2.8. Volumetric swelling in (fresh, 5- and 25-years) treated poles and in untreated SYP, after 24-hour soaking in water

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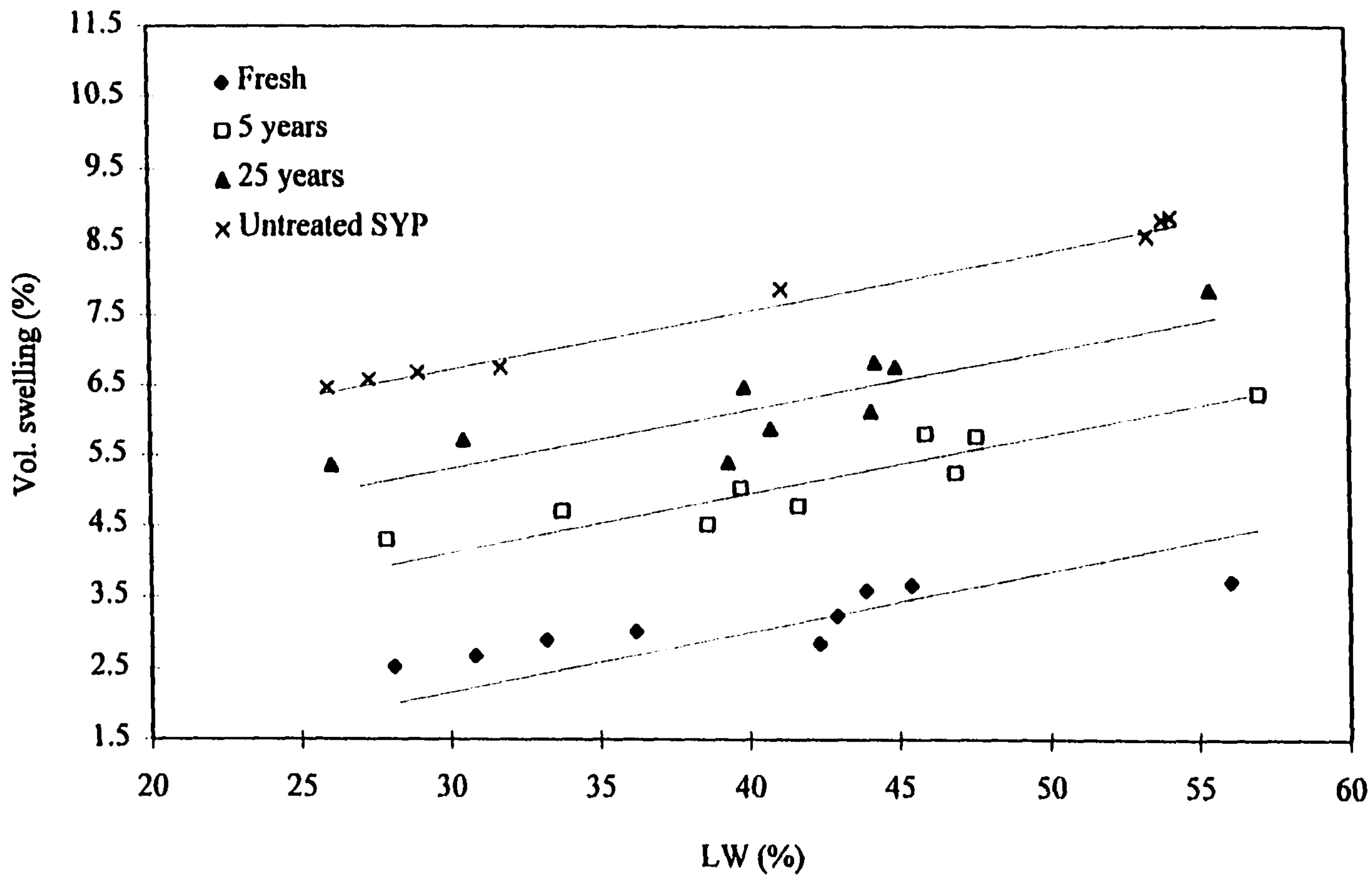

Figure 2.9. Relationship between LW percentage and volumetric swelling, from nominal 12.0 % moisture content, in (fresh, 5- and 25-years) treated poles and in untreated SYP

indicating that the increase in swelling with increased percent LW and creosote content tended to have the same slope (Figure 2.9). This is consistent with the literature, which indicated that higher LW percentage increases the wood density, and consequently the swelling (Stamm 1964; Walker et al. 1993). This phenomena explains the trend for swelling to decrease from the outer to inner portions and from the bottom to the top of all treated poles, especially in the 5- and 25-year service durations.

Lumber recovery factor (LRF)

Data of log measurement, lumber volume, and LRF of each bolt are presented in Appendix B.3. The LRF values range from 7.4 to 9.9 bd.ft/cu-ft, which are comparable to the average LRF among larger sawmills (Haygreen and Bowyer 1989). Analysis of adjusted variance (Table 2.5) indicates that the LRF was significantly affected by bolt diameter, service duration, and vertical location. The LRF tended to increase with increase in bolt diameter, as shown in Figure 2.10 for freshly treated poles, Figure 2.11 for 5-year poles, and Figure 2.12 for 25-year poles. The variations in LRF with respect to vertical position and service duration are shown in Figure 2.13. The LRF increased vertically from top to bottom of poles, which is consistent with previous investigation on SYP roundwood (Tsoumi 1991). The lower values of LRF in the bottom of 25-year weathered poles than those of freshly treated poles (Figure 2.13), as shown by significant interaction between service duration and vertical location (Table 2.5), may be due to the effect of greater stresses that developed at the base of the poles from weight, wind, and other lateral forces (Timber Engineering Company 1956). The overall LRF is higher in freshly treated poles than in 25-year poles. Weathering and loss of creosote in older poles could explain the lower LRF values in

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Table 2.4. Multiple regression analysis of volumetric swelling
($Y = bo + b1X1 + b2X2 + b12X1*X2$)

Variables	DF	Coefficient of regression (bi)	F-values	F-tables α = 0.05	F-tables 0.01
Intercept	1	3.9551			
LW percentage (X1)	1	0.0780	37.19**	4.13	7.50
Creosote content (X2)	1	-0.0131	12.66**	4.13	7.50
Interaction (X1*X2)	1	-0.0003	0.08	4.13	7.50
Error	34	Y=5.479[1]	CV=9.66[2]	$R^2 = 0.924$[4]	

[1]bi; i = 0 (bo), 1 (b1), 2 (b2), and 3 (b12)
[2]Overall average of volumetric swelling - including untreated SYP (%)
[3]Coeff. of variation (%)
[4]Coeff. of determination
**denotes significance at 0.01 levels

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Table 2.5. Analysis of adjusted variance of lumber recovery factor

Source of variation	DF	F-values		F-tables	
				$\alpha = 0.05$	0.01
Main variables:					
Service duration (S)	2	14.33**		3.88'	6.93
Error (a)	12				
Vertical location (V)	2	9.78**		3.42	5.66
Interaction (S*V)	4	12.45**		2.80	4.26
Covariates:					
Bolt diameter	1	17.06**		4.28	7.88
Error (b)	23	X= 10.13[1]	Y=8.51[2]	CV=12.21[3]	

[1]Overall average of diameter (in)
[2]Overall average of lumber recovery factor
[3]Coeff. of variation (%)
**denotes significance at 0.01 level

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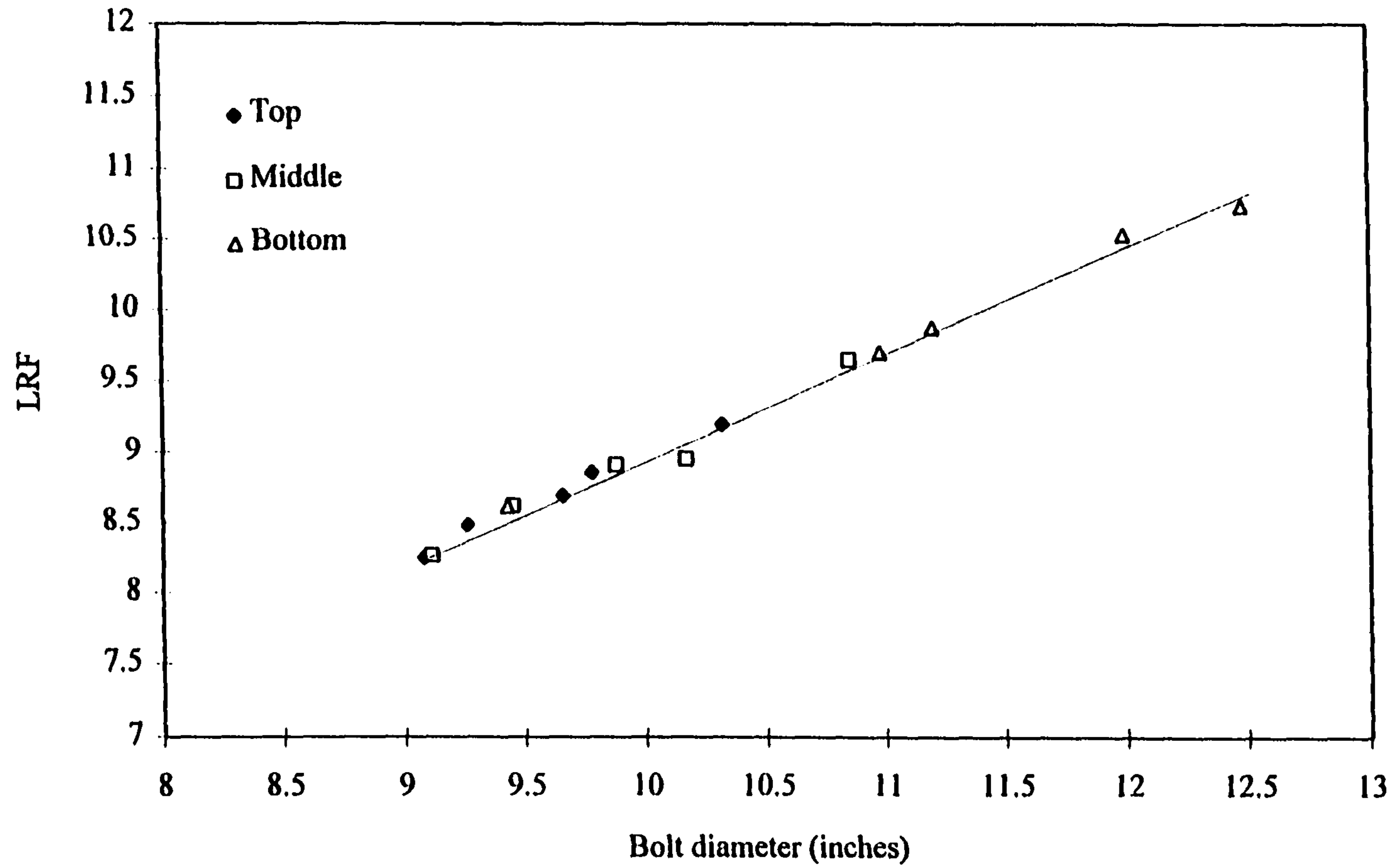

Figure 2.10. Lumber recovery factor (LRF) in freshly treated poles

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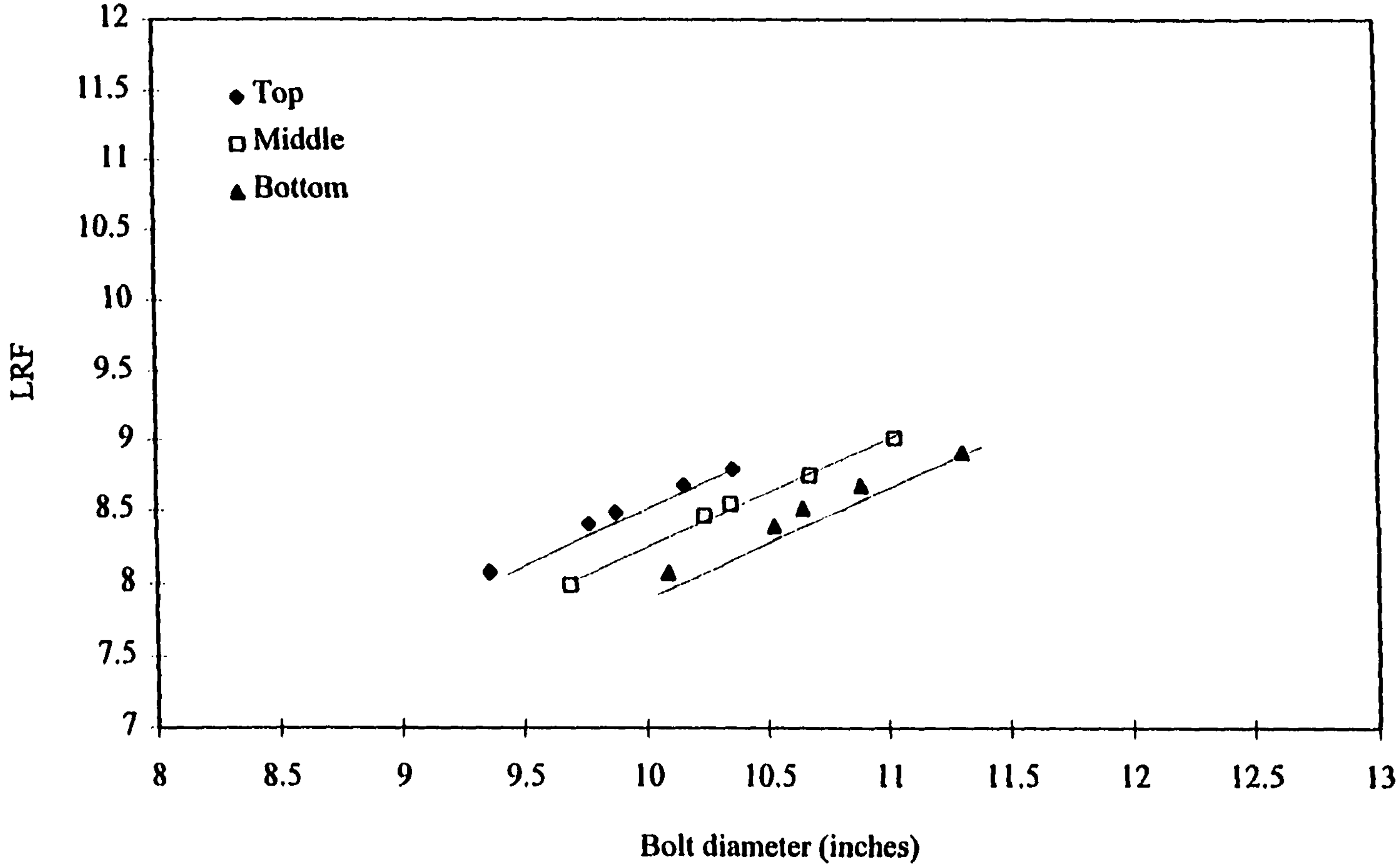

Figure 2.11. Lumber recovery factor (LRF) in 5-year old poles

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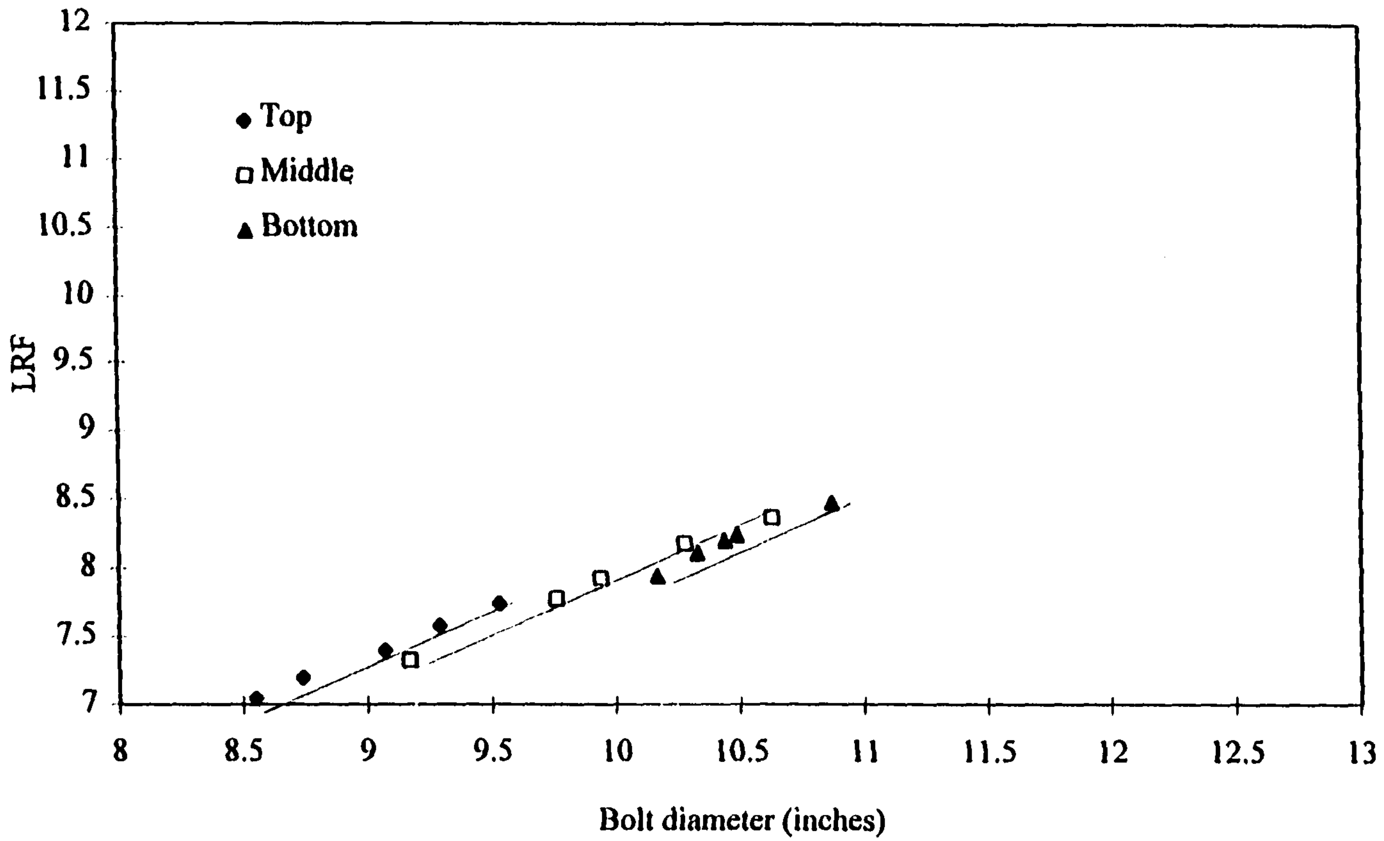

Figure 2.12. Lumber recovery factor (LRF) in 25-year old poles

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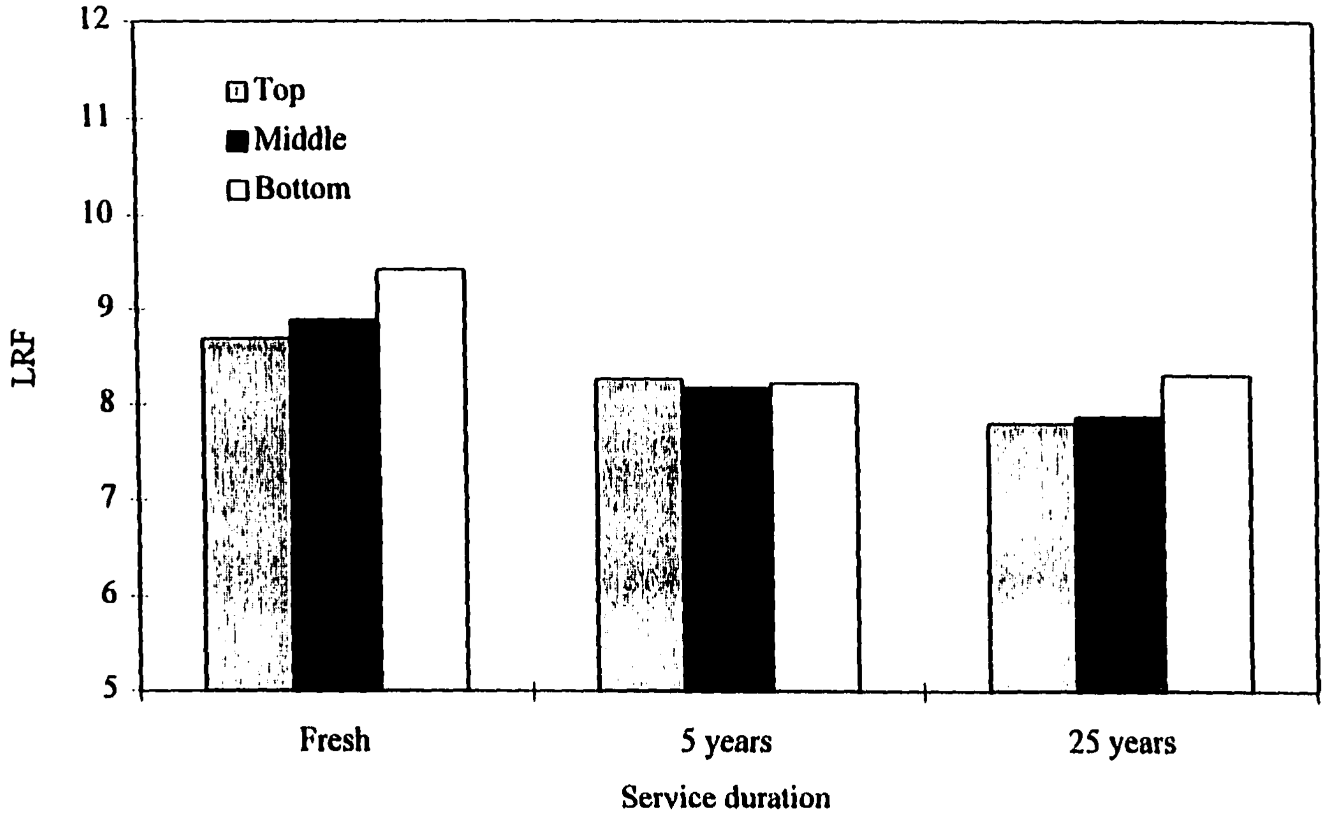

Figure 2.13. Lumber recovery factor (LRF) of treated poles interpolated at 9.60-, 9.88-, and 10.60-inch bolt diameters for top, middle, and bottom portions, respectively

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these poles. Weathering contributes to checking and splitting (Hunt and Garratt 1967), whereas creosote acts as lubricant (Eaton and Hall 1993) in minimizing the effect of weathering.

Conclusions

The visually defect-free parts of utility poles after 25 years in service still maintained strength properties which were mostly comparable to those of freshly treated poles and of untreated SYP. The variations in strengths with respect to horizontal and vertical position were due to variation in latewood content in the poles.

The variations in dimensional stability was related to creosote contents in treated poles. Swelling was least in freshly treated poles, and highest in 25-year poles and in untreated SYP. With respect to position, the inner and upper portions showed better dimensional stability.

The LRF values of treated poles ranged from 7.4 to 9.9. Longer service duration caused a reduction in LRF, which was significantly greater at the bottom than at the upper portions of the poles.

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CHAPTER 3

DECAY RESISTANCE

Introduction

Weathering in out-of-service poles can cause changes in the structure of wood and also in the distribution of preservative. The previous chapter describes the changes in residual creosote contents, which would affect the decay resistance of old poles. The objective of the study was to evaluate the extent of decay resistance of these poles.

Literature review

Long-term weathering factors including heat, leaching, and gravitational force can cause changes in creosote content and composition inside standing poles (Chapter 1). These changes may also affect the effectiveness of weathered creosote against wood-destroying organisms.

The soil-block test is commonly used to evaluate the effectiveness of preservatives in freshly treated as well as weathered wood products (Hunt and Garratt 1967). This test measures the decay resistance of treated wood at a given level of preservative retention. A fungus is introduced to infect and degrade wood substance (Duncan 1954). In creosote-treated wood, such as utility poles and crossties, the wood-rotting fungus *Neolentinus lepideus* Fr. is often used. It is a brown-rot fungus which destroys cellulose and hemicellulose, leaving lignin in the form of fine brownish residue. When wood is decayed by this fungus, it becomes dark in color with whitish mycelium and has a strong aromatic odor (Hickin 1971)

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The fungus *Neolentinus lepideus* Fr. is resistant to creosote and is commonly found in railway ties, utility poles, and other exposed treated wood which has received insufficient preservative during pressure impregnation treatment (Hunt and Garratt 1967; Richardson 1978). This fungus is also resistant to heat (up to 104°F) and drying. It grows optimally at 81-82°F temperature and wood moisture content near the fiber saturation point (Eaton and Hale 1993).

Materials and Methods

As in previous studies (Chapter 1), the poles for this investigation consisted of three duration groups, i.e. freshly treated, and 5- and 25-years. Five poles from each group were taken as replicates. Samples of visually defect-free wood were obtained from several vertical and horizontal locations as described in Table 1.3.

The test samples, with predetermined LW percentage, were prepared by sawing into blocks measuring 0.75- by 0.75- by 0.75-inch in size. They were stored in an environmental chamber at a constant temperature of 80°F and relative humidity of 70 percent for 24 hours, and weighed at equilibrium moisture content. Decay resistance was evaluated by the soil-block method in accordance with AWPA Standard M 10-77 (1984). Samples were subjected to decay by the fungus *Neolentinus lepideus* Fr., which was obtained from the American Type Cultural Collection with specification No. 12653 (Madison 535). For comparison purposes, 20 untreated reference SYP blocks were also prepared. After oven-drying and weighing, they were conditioned and subjected to decay in the same manner as the treated test samples. SYP feeder strips measuring 0.125- by 1.125- by 1.275-inch with the grain parallel to the long dimensions were used for each block.

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Sandy loam soil with a water-holding capacity of 22-25 percent was prepared by raising the pH from 5 to 8, and passing it through a soil sieve (U.S. No. 6) with 0.4-cm openings. Approximately 100 g of soil was placed into each wide-mouth, 240-ml capacity square bottle into which had been placed between 18-24 ml of distilled water to achieve 130 percent of water-holding capacity of the soil. A SYP feeder strip was added into the bottle, and an unlined cap was loosely screwed into place. The bottles were then sterilized in a retort at 212°F for 30 minutes, thoroughly cooled, and then inoculated with approximately one-inch square of fungus inoculum placed in contact with the edge of the feeder strip. The inoculated bottles were incubated in a conditioned room at 80°F and 70 percent relative humidity for about three weeks until the feeder strips were covered with mycelium. The bottles were then ready to receive the test blocks from either treated poles or untreated SYP.

The test blocks inside the sealed bottles were steam-sterilized in a retort at 212°F for one hour. They were cooled and placed one per bottle flat on the mycelium-covered feeder strips. The bottles with loosely screwed caps were then placed in the incubation room, and kept for an incubation period of 12 weeks.

At the end of the incubation period, the blocks were removed from the bottles, and the mycelium was carefully brushed off. The blocks were conditioned again, and then weighed at equilibrium. The following formula was used to determine the weight loss (WL):

$$WL\ (\%) = 100*(W_i - W_f)/W_i \qquad (1)$$

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where W_i is initial weight of the test block (before inoculation), and W_f is the final weight of the test block (after inoculation).

Decay resistance was evaluated by comparing the percentage of weight loss of treated and untreated (reference) samples after a 12-week incubation period.

Results and Discussion

Data of weight loss, initial creosote content, and percent latewood in treated poles and in untreated SYP are presented in Appendix C.1. The analysis of variance of weight loss in untreated SYP (Table 3.1) indicates that it was significantly affected by percent LW. As shown in Figure 3.1, the weight loss decreased with an increase in LW percentage. This phenomenon is explainable. The rate of decay by fungus is influenced by wood density, i.e. the higher the density the more cellulose there is for a fungus to destroy; therefore, weight loss is related to LW percentage since wood density is dependent on the content of LW. However, the magnitude of changes in weight loss was relatively small compared with the changes in weight loss due to reduction in creosote content below the 14 percent critical level (Figure 3.2).

The analysis of variance of weight loss in treated poles (Table 3.2) shows that the effect from all sources of variance (i.e. service duration, horizontal location and vertical location, and their interaction) were significant. The significant interaction means that the variation in weight loss due to service duration was dependent on the locations in the poles. In the Tukey's test (Table 3.3), poles with longer service duration had higher weight loss, indicating more intensive decay. Weathering, which caused reduction in creosote content as described in Chapter 1 (Figure 1.2),

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Table 3.1. Analysis of variance of percent weight loss of untreated SYP

Source of variation	DF	F-values	F-tables	
			α = 0.05	0.01
LW percentage	3	5.14*	4.49	8.53
Error	16	Y=42.88[1]	CV=6.22[2]	

[1]Overall average of untreated SYP weight loss (%)
[2]Coeff. of variation (%)
*denotes significance at $\alpha = 0.05$.

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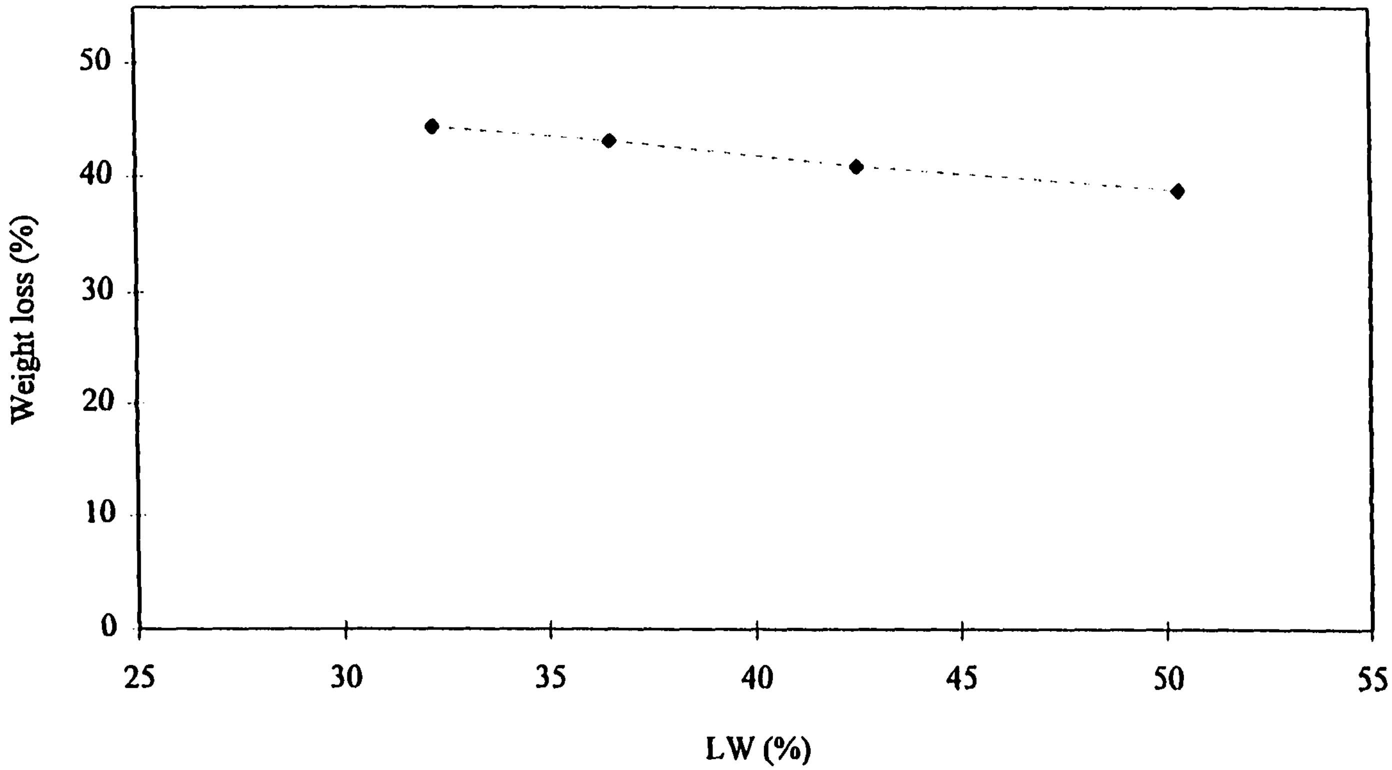

Figure 3.1. Relationship beteen latewood (LW) percentage and weight loss of untreated SYP

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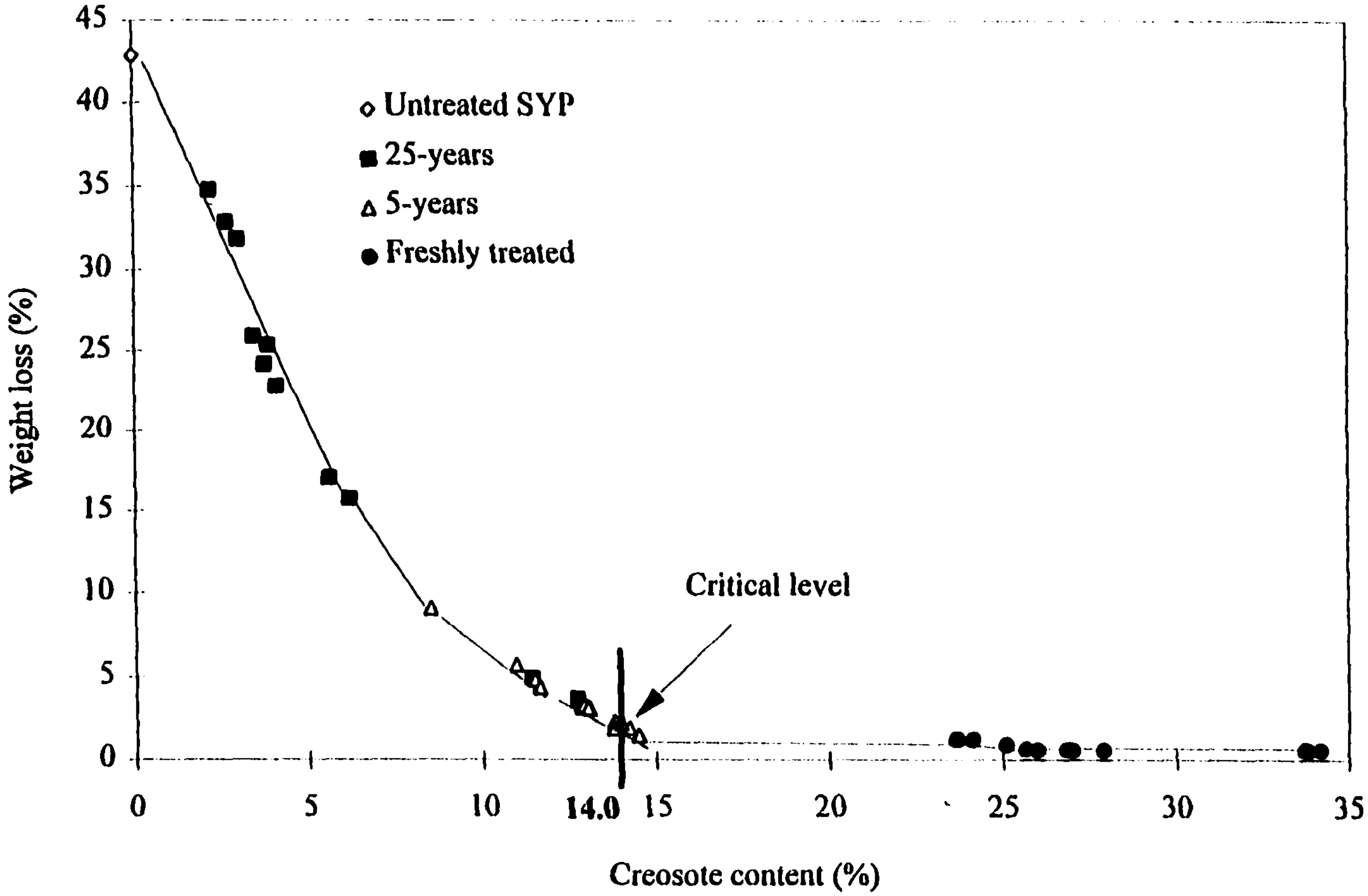

Figure 3.2. Relationship between creosote content and weight loss

Table 3.2. Analysis of variance of percent weight loss of treated poles

Source of variation	DF	F-values	F-tables	
			α = 0.05	0.01
Service duration (S)	2	24.92**	3.88	6.93
Error (a)	12			
Vertical location (V)	2	19.43**	3.06	4.75
Horizontal location (H)	3	8.74**	2.67	3.91
Interactions:				
S*V	4	6.98**	2.43	3.41
S*H	6	7.21**	2.16	2.92
V*H	6	4.39**	2.16	2.92
S*V*H	12	3.94**	1.82	2.20
Error (b)	132	Y=8.219[1]	CV=6.87[2]	

[1]Overall average of weight loss of treated poles (%)
[2]Coeff. of variation (%)
**denote significance at α = 0.01.

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Table 3.3. Comparison of weight loss (%) by Tukey's test (d) for significantly different means

Service duration of the poles	Vertical location	Sample location: Horizontal distance from surface (inches)							
		0.5		1.5		2.5		3.5	
		%	d	%	d	%	d	%	d[1]
Freshly treated	Top	0.63	O	0.65	O	0.67	O	1.27	NO
	Middle	0.62	O	0.59	O	0.61	O	1.26	NO
	Bottom	0.59	O	0.61	O	0.96	NO	1.28	NO
5 years	Top	9.05	J	4.86	L	3.11	LM	2.31	M
	Middle	5.72	KL	3.28	LM	2.60	M	1.95	MN
	Bottom	4.38	L	3.14	M	2.21	MN	1.50	N
25 years	Top	34.83	A	25.96	D	22.85	E	4.95	L
	Middle	32.91	A	25.41	D	15.77	FG	3.70	LM
	Bottom	31.91	AB	24.22	DE	17.07	G	3.17	M
Control (untreated SYP)		---------- 42.88 >>A ----------							

[1]Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H>I>J>K>L>M>N>O)

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made the exposed part of wood poles less protected, and therefore more vulnerable to biodegradation by fungi. In untreated SYP, the weight loss was much higher than in treated poles.

The Tukey's test also reveals that the weight loss of freshly treated poles was not significantly affected by vertical locations. The same trend applied to creosote contents (Figure 1.2). However, the weight loss in the inner portions of fresh poles was somewhat higher, whereas the creosote content was lower than in the outer portions. Figure 3.3 shows that the reduction in decay resistance, as measured by weight loss, was more pronounced in 25-year poles, less in 5-year poles, and least in freshly treated poles. The percent weight loss was greater in the upper and outer portions for both 5- and 25-year poles; but the creosote content in the same locations decreased horizontally outward and vertically upward. The significant reduction in weight loss in the outer portions, as compared with the inner portions (Figure 3.3), indicates that the loss of creosote enhanced the decaying activities of the fungus despite higher percentage of LW in the outer portions of poles.

It is interesting to note that the fungus-induced weight loss was negligible at creosote content above 14 percent level. It increased dramatically with the reduction in creosote content this level (Figure 3.2), indicating that at low creosote content there was much greater decay activity by the fungus. For example, the weight losses in the outer portions of 25-year poles ranged from 31.9 to 34.8 percent (Figure 3.3) and the corresponding creosote content ranged from 2.7 to 3.8 percent (Figure 3.2); on the other hand, weight losses in the inner portions ranged

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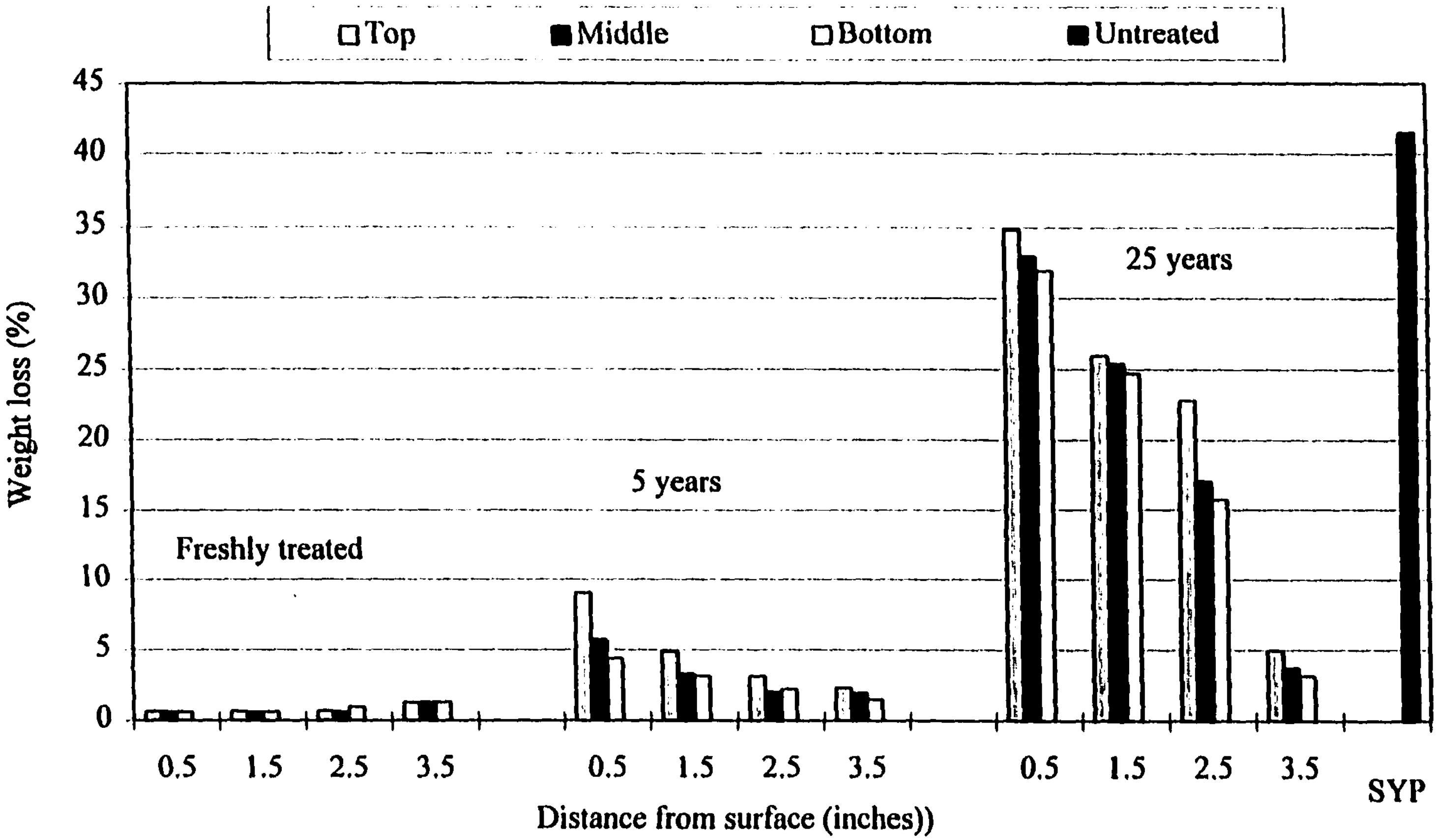

Figure 3.3. Weight loss with respect to vertical and horizontal locations in treated poles

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from 11.4 to 12.9 percent. This may be linked to the reduction of creosote in the outer portions, which was accompanied by some loss of its more volatile (i.e. low molecular weight) fractions described in Chapter 1. According to Stasse (1955), creosote of low molecular weight (i.e. low-boiling point fractions) tended to have greater partial solubility in water than high-molecular weight creosote. Therefore, fractions of high water partial solubility could more seriously damage the body fluid of organisms which they were intended to inhibit.

When pole averages are considered, the weight losses in freshly treated poles at 0.5-and 3.5-inch from the pole surface were 0.61 and 1.27 percent, respectively. For weathered poles, the weight losses were 6.4 and 1.9 percent in 5-year poles; and 33.2 and 4.0 percent in 25-year poles, respectively. For untreated SYP, the weight loss was much higher, i.e. 42.9 percent. It is apparent that the decay resistance of 5-year poles was closer to that of freshly treated poles; whereas, decay resistance in the outer portions of 25-year poles was closer to that of untreated SYP.

The results indicate that when out-of-service poles are reutilized for engineered wood products (EWP), pieces from the low decay-resistance wood poles with 25-year service should be located in the inner part of the EWP. Pieces from the high decay resistance 5-year poles are more suitable for the outer part of the EWP which is likely exposed to ground contact and other decay-inducing environmental factors.

Conclusions

The variation in decay resistance was related to creosote content in treated poles. Reduction in decay resistance was greatest in 25-year poles, much less in 5-

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year poles, and negligible in freshly treated poles. In the outer portions of 25-year poles, the decay resistance was very low and approached that of untreated SYP. Decay resistance was also higher at the bottom of treated poles, and least at the top.

In weathered poles, the creosote content at 14 percent was regarded as critical level. Below this level the decay resistance decreased considerably.

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CHAPTER 4

GLUABILITY

Introduction

Before out-of-service poles can be properly utilized for engineered wood products, their gluing properties must be known. In freshly treated poles, the creosote interferes with bonding due to poor contact between adhesive and wood substrate (Selbo 1958). As a result, fiber-to-glue bond strength in treated wood is lower than that in untreated wood.

After several years in service, the residual creosote in poles can undergo changes in its content and composition. These changes may affect the gluability of out-of-service poles. Therefore, the objective of this chapter is to study the effect of residual creosote on gluing properties of used utility poles.

Literature Review

Water-soluble adhesives have been applied with satisfactory results in gluing wood because the holocellulose in the cell wall contains hydroxyl groups which have a high affinity for water. Therefore, adhesives such as resorcinol-formaldehyde, polyvinyl acetate, and casein glue can enter the cell wall before they are cured (Koch 1975). Resorcinol-formaldehyde is a highly reactive adhesive which cures at room temperature. A modification of this adhesive is resorcinol-phenol formaldehyde produced by polymerizing two resins (resorcinol and phenol). The purpose is to lower the price as resorcinol is more expensive than phenol. Such an adhesive is thermosetting, in that it is converted to hard, insoluble, and infusible states by a catalyst. The reaction is not reversible, when cured. Both resorcinol- and resorcinol-

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phenol formaldehydes are widely used for laminating timbers and for assembly joints that must withstand severe outdoor conditions (Selbo 1975; Subramanyan 1981).

Polyvinyl acetate adhesive is thermoplastic, in that it softens at elevated temperature and hardens when cooled. It is prepared by polymerization of vinyl acetate monomers under controlled condition. A modification of this kind of adhesive is a thermosetting or catalyzed polyvinyl resin produced by adding agents such as di- or tri-valent salts or metal ions. These agents create crosslinking between the polyvinyl polymer chains, resulting in an adhesive that is more heat- and moisture-resistant. This kind of adhesive performs as well as the thermosetting resorcinol adhesive if used in dry conditions. However, they do not perform well in wet conditions; therefore, such adhesives are recommended only for interior applications (Murphey and Jorgensen 1974).

Casein glue is made by first precipitating the protein part of skim milk using mild acidic agents. On drying, the protein becomes a dry powder which has a strong affinity for water because it is proteinaceous with carboxylic acid groups. The casein powder is then dry-mixed with ingredients such as hydrated lime, sodium hydroxide, and zinc chloride. Curing occurs as a result of chemical reaction and loss of solvent. In the dry condition, casein develops a strong bond; therefore, it is widely used for structural joints and laminates in indoor usage (Freas 1954; Gillepsie, et al. 1978).

All these adhesives have performed well in gluing untreated wood. However, the performance of these adhesives in weathered creosote-treated wood is not known.

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Materials and Method

Samples for this study were obtained in the same manner as those for strength and dimensional stability evaluations as described in Chapter 2. The samples consisted of three service groups (freshly treated, 5 and 25 years), each with specific vertical and horizontal locations in the poles as shown in Table 1.3 and Figure 1.1. These samples were glued with three types of adhesive: resorcinol-phenol formaldehyde (RPF), polyvinyl acetate (PVA), and casein glue.

RPF adhesive was made by reacting a mixture of Cascophen LT-5210 resorcinol-phenol resin with FM-6210S paraformaldehyde hardener, both of which were obtained from the Borden Chemical Company in Springfield, Oregon. The proportion of mixture by weight was resorcinol-phenol : paraformaldehyde : water = 2.500 : 0.333 : 0.667. The paraformaldehyde was first dissolved in water solvent, then the solution was mixed with phenol formaldehyde in a mixer until a homogenous solution was obtained.

Cross-linked PVA was prepared by reacting CL-4379 PVA resin emulsion with a catalyst of K-4 trivalent salt ($AlCl_3$) at room temperature, using a weight ratio of 100 : 5, respectively, both of which were obtained from the National Casein Company in Tyler, Texas. Casein was also obtained from the same company in the form of dry powder. The powder contains non-casein matters such as calcium hydroxide (20 percent) and sodium fluoride (5 percent). Casein glue was made by dissolving the powder in water with a weight ratio of 1 : 2, and then thoroughly agitated in a mixer at room temperature.

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Gluing was carried out at room temperature by bonding together 2- by 1.75- by 0.75-inch samples of these creosote treated samples at 75 pounds per 1000 sq. ft. of joint area, and hydraulic pressure of 175 psi for 7 hours (Figure 4.1). After gluing, all the glued samples were conditioned in an environmental chamber at a temperature of 68°F and relative humidity of 65 percent for 24 hours. The gluability of test samples was determined on the basis of glue-line shear strength and percent wood failure in accordance with ASTM Standard D-905-86 (1994):

$$\text{Shear strength (psi)} = P/A \quad (1)$$

where:

P = force required to shear the glue line (lbs)

A = glue-line area (in^2)

and,

$$\text{Wood failure (\%)} = 100*(W/A) \quad (2)$$

where:

W = area of wood failure (done and measured after the shear test) (in^2)

A = total glue-line area (in^2)

Latewood (LW) percentage was also determined by the scanning technique described in Chapter 2, for each board, to study its possible effect on gluability. In addition, angle of growth rings (AGR) to the glue line on the shear block sample (Figure 4.1) was determined. Contact angle measurement between adhesive and the surface of wood substrate was performed with a Kernco apparatus for samples which were obtained from freshly treated, 5- and 25-year old poles, and from untreated SYP.

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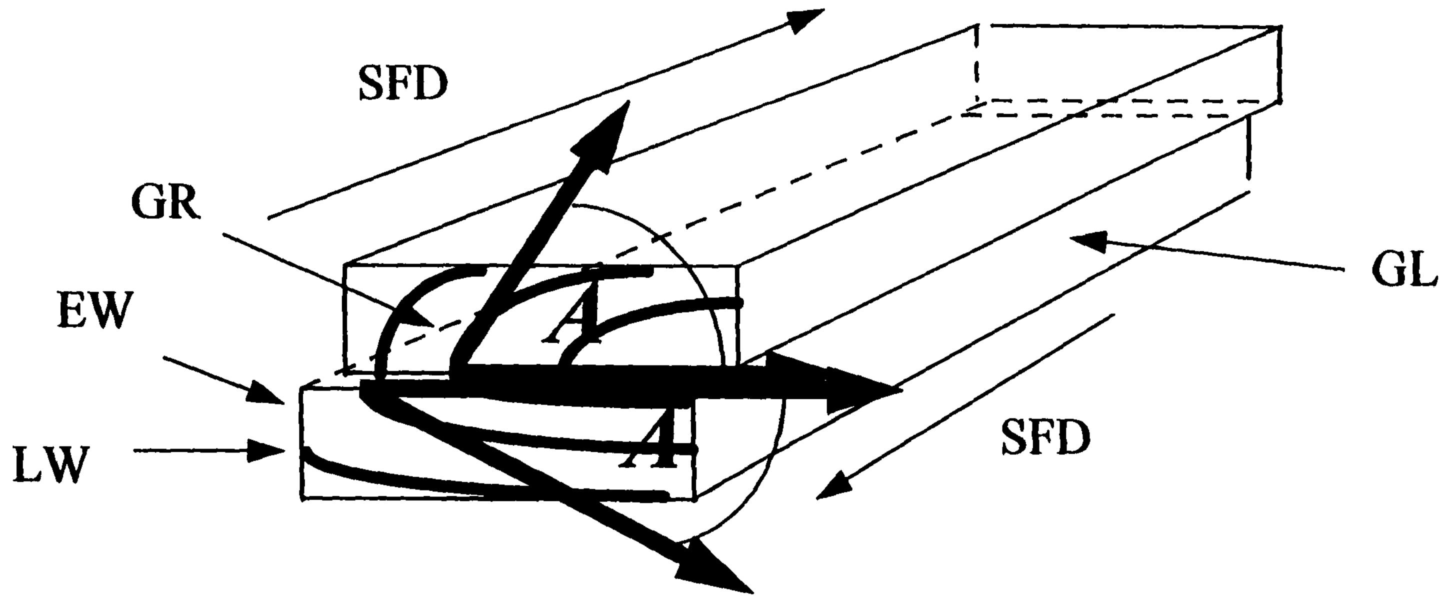

Figure 4.1. Measuring the angle (*A*) between growth rings and glue line on shear block test sample (EW=earlywood, LW=latewood, GR=growth ring, GL=glue line, and SFD=shear-force direction)

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Results and Discussion

Data of gluability in treated poles and untreated SYP are presented in Appendix D.1 for RPF adhesive, Appendix D.2 for PVA adhesive, and Appendix D.3 for casein glue. Analysis of adjusted variance indicates that glue-line shear strength (Table 4.1) and percent wood failure (Table 4.2) varied significantly with different service durations, vertical and horizontal locations, as well as with angle of growth ring.

Average glue-line shear strengths in treated poles and untreated SYP are summarized in Figures 4.2, 4.3, and 4.4 for RPF, PVA, and casein glue, respectively. The corresponding average wood failures are shown in Figures 4.5, 4.6, and 4.7, respectively. On average, gluability increased with service duration of treated poles. Values were highest for untreated SYP, followed in decreasing order by 25- and 5-year old, and freshly treated poles. The effect of service duration was mainly related to the decrease in creosote content due to weathering, as described in Chapter 1 (Figure 1.2). The creosote, being oil-soluble, inhibits wetting and penetration of adhesive which in turn results in inferior fiber-to-glue bond (Selbo 1958). This phenomenon is best illustrated from data on contact angle (Table 4.3), which shows that the angle tended to diminish significantly in all the three adhesives tested. The highest angle occurred in freshly creosote-treated pole, and the lowest in untreated SYP. The analysis of variance (Table 4.4) shows that the differences with respect to adhesives and wood substrates are significant. The decrease in contact angle indicates that adhesive wettability increased with decrease in creosote content.

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Table 4.1. Analysis of adjusted variance of glue-line shear strength using three types of adhesives (RPF, PVA, and casein)

Source of variation	DF	F-values			F-tables	
		RPF	PVA	Casein	α = 0.05	0.01
Main factor						
Service duration (S)	2	14.01**	20.63**	18.21**	3.88	6.93
Error (a)	12					
Vertical location (V)	2	32.04**	34.19**	29.81**	3.09	4.78
Horizontal location (H)	2	19.74**	21.49**	22.42**	3.09	4.78
Interactions:						
S*V	4	18.21**	16.85**	11.84**	2.46	3.51
S*H	4	15.47**	13.92**	16.98**	2.46	3.51
V*H	4	24.22**	18.74**	16.79**	2.46	3.51
S*V*H	8	9.17**	6.97**	8.24**	2.03	2.60
Covariates						
Angle of growth rings to the glue line (X3)	1	4.33*	4.06*	5.71*	3.91	6.83
Error (b)	95					
X3[1]		20.26	21.03	20.09		
Y[2]		1.1763	1.1407	1.1325		
CV[3]		9.73	10.21	8.97		

[1]Overall average angle of growth rings to the glue line
[2]Overall average of the shear strength (10^3 psi)
[3]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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Table 4.2. Analysis of adjusted variance of wood failure using three types of adhesives (RPF, PVA, and casein)

Source of variation	DF	F-values			F-tables	
		RPF	PVA	Casein	α = 0.05	0.01
Main factor						
Service duration (S)	2	34.71**	29.13**	27.61**	3.88	6.93
Error (a)	12					
Vertical location (V)	2	24.97**	22.18**	25.72**	3.09	4.82
Horizontal location (H)	2	18.72**	20.48**	19.48**	3.09	4.82
Interactions:						
S*V	4	16.93**	11.39**	12.28**	2.46	3.51
S*H	4	15.28**	13.28**	14.06**	2.46	3.51
V*H	4	9.47**	10.13**	8.79**	2.46	3.51
S*V*H	8	5.73**	6.78**	4.93**	2.03	2.60
Covariates						
Angle of growth rings to the glue line (X3)	1	5.49*	6.21*	6.09*	3.92	6.84
Error (b)	95					
X3[1]		20.26	21.03	20.09		
Y[2]		75.14	73.79	72.24		
CV[3]		10.71	9.61	9.32		

[1]Overall average angle of growth rings to the glue line
[2]Overall average of the wood failure (%)
[3]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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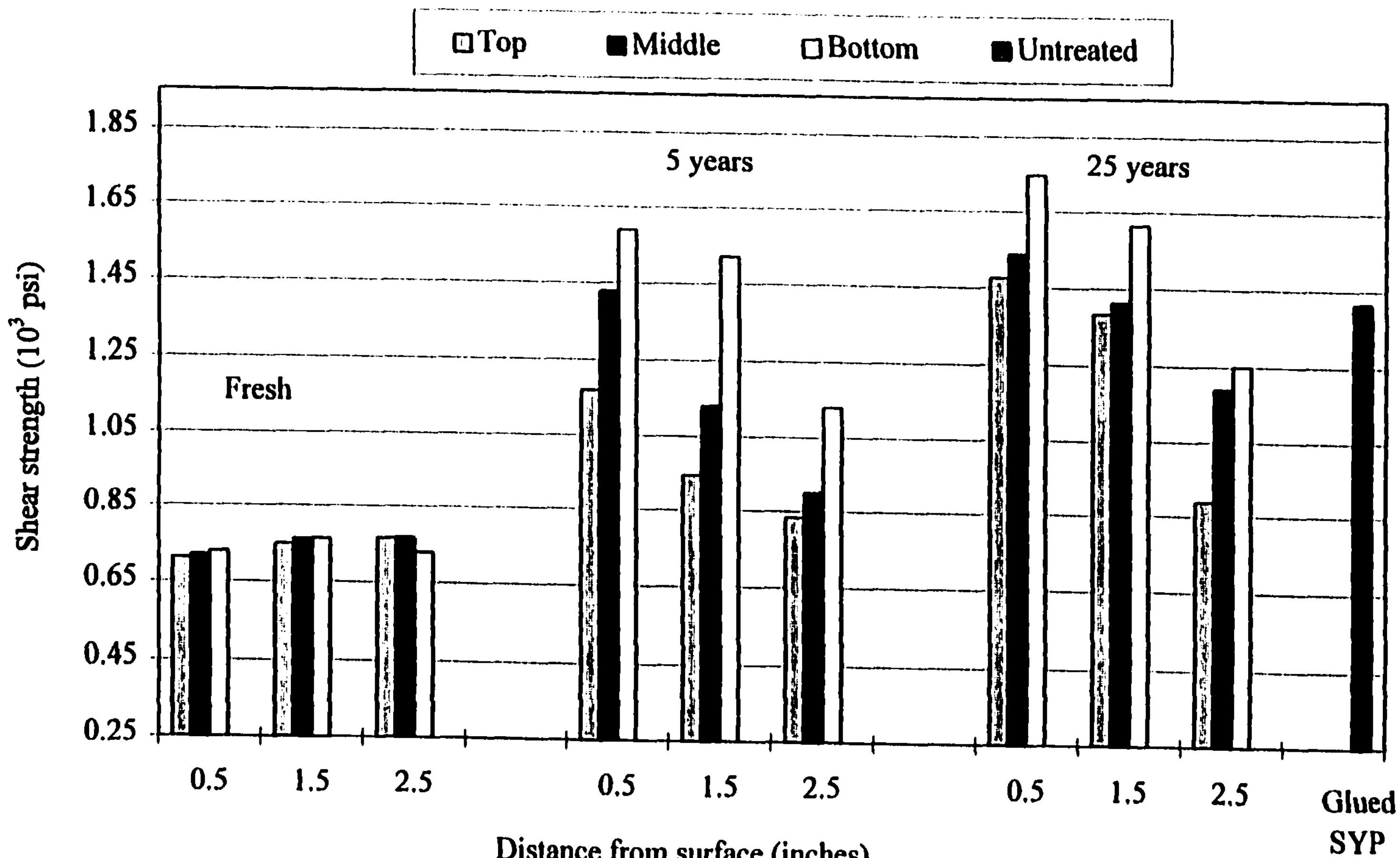

Figure 4.2. Glue-line shear strength of treated poles using RPF adhesive

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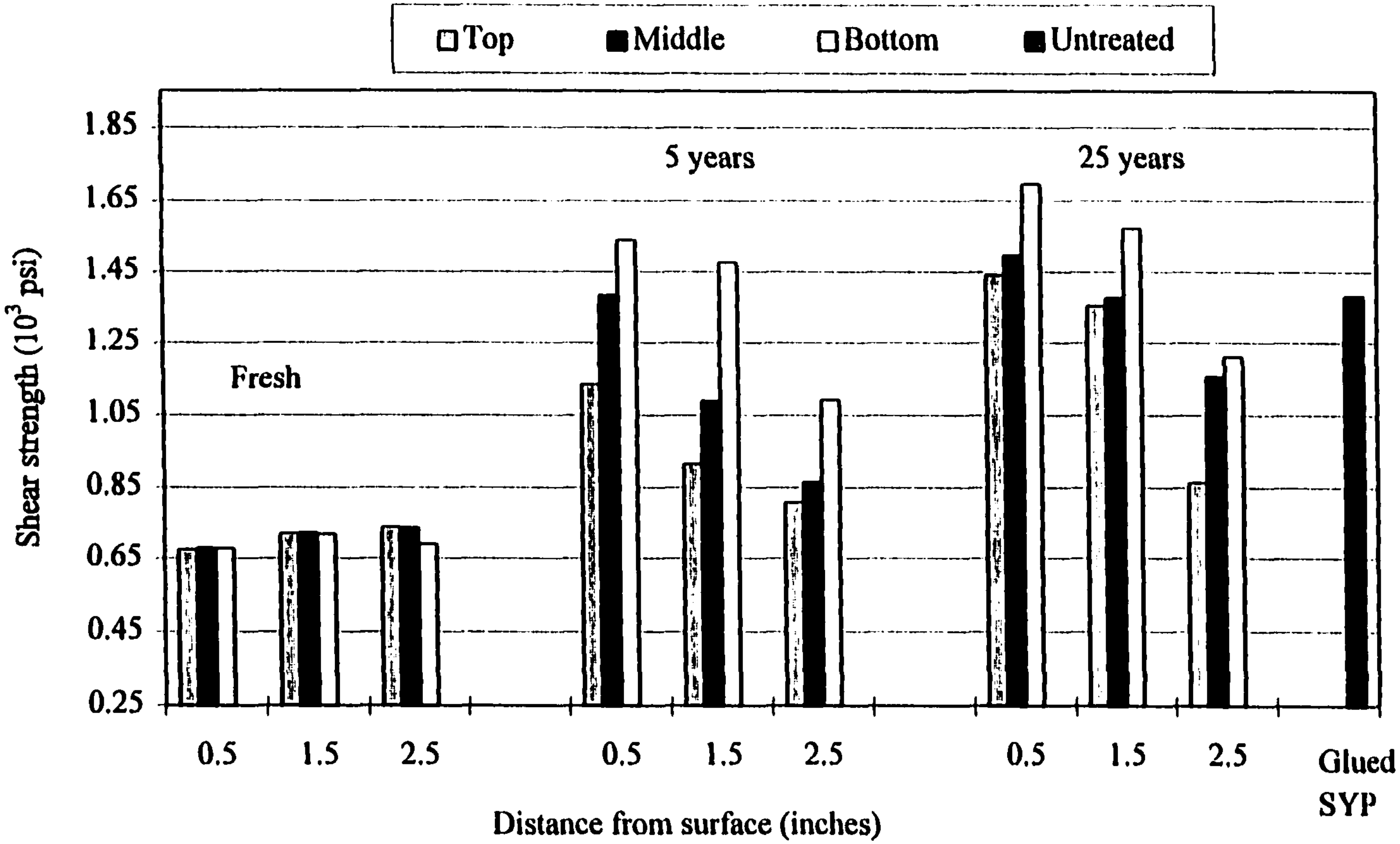

Figure 4.3. Glue-line shear strength of treated poles using PVA adhesive

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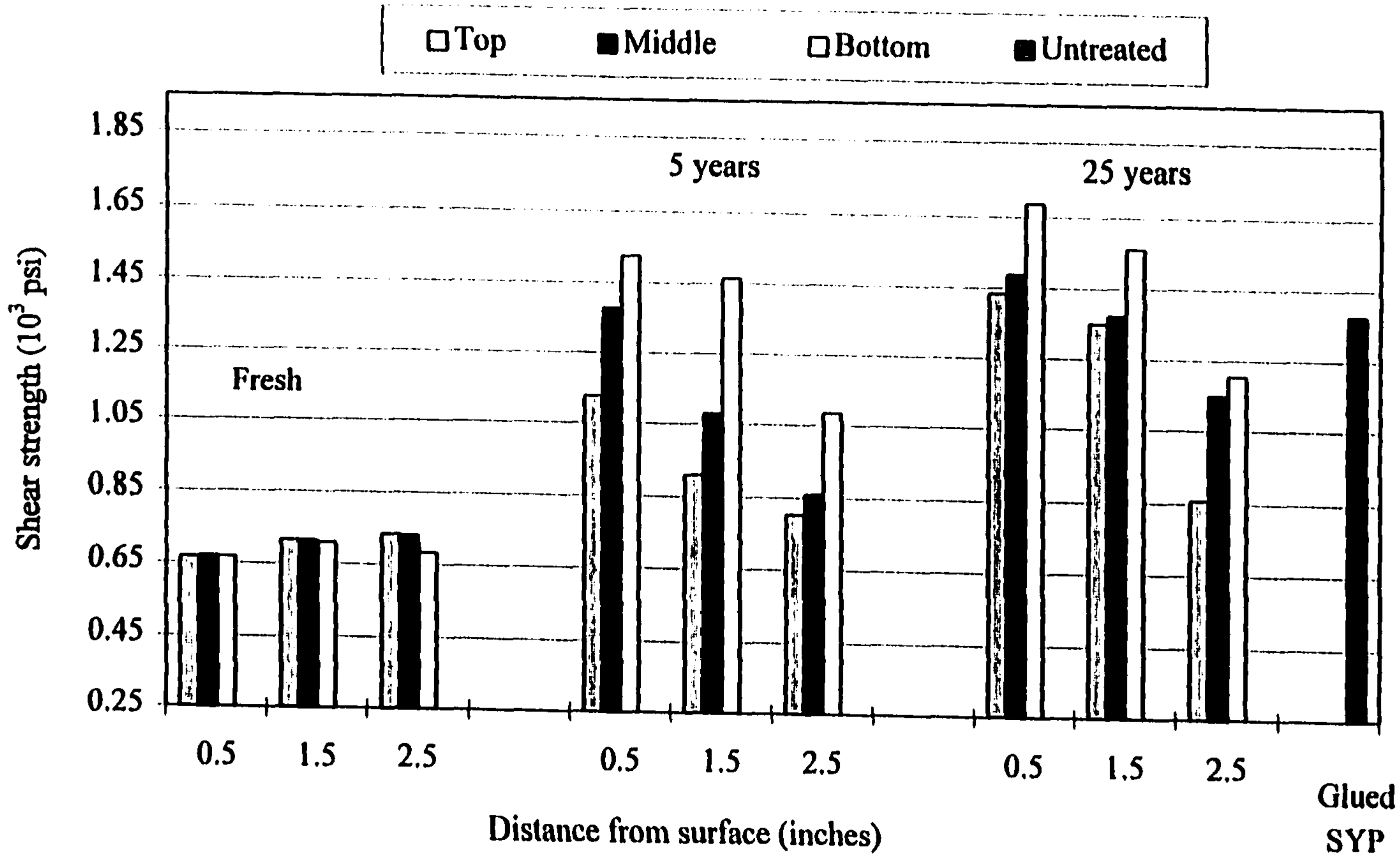

Figure 4.4. Glue-line shear strength of treated poles using casein glue

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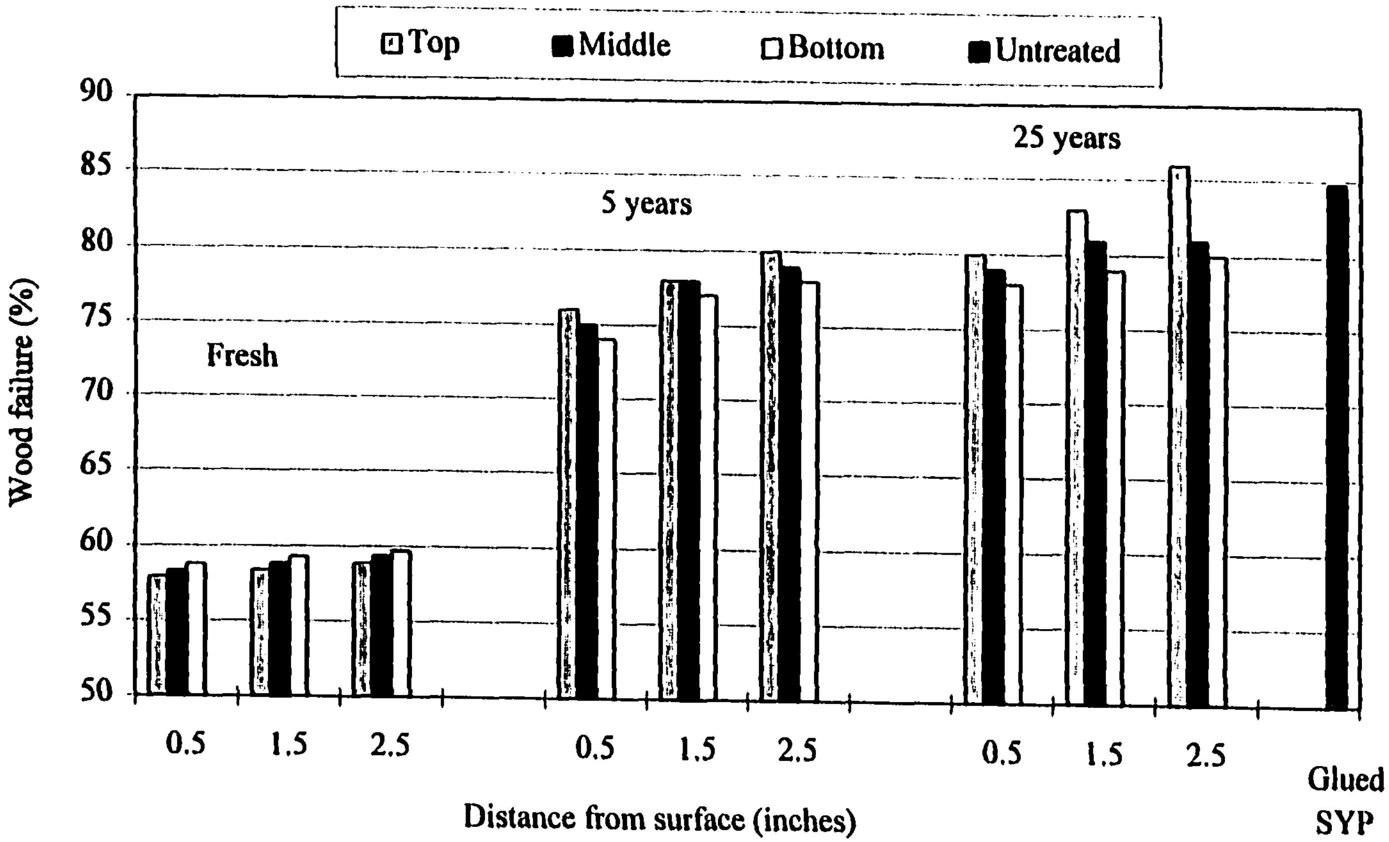

Figure 4.5. Wood failure of treated poles using RPF adhesive

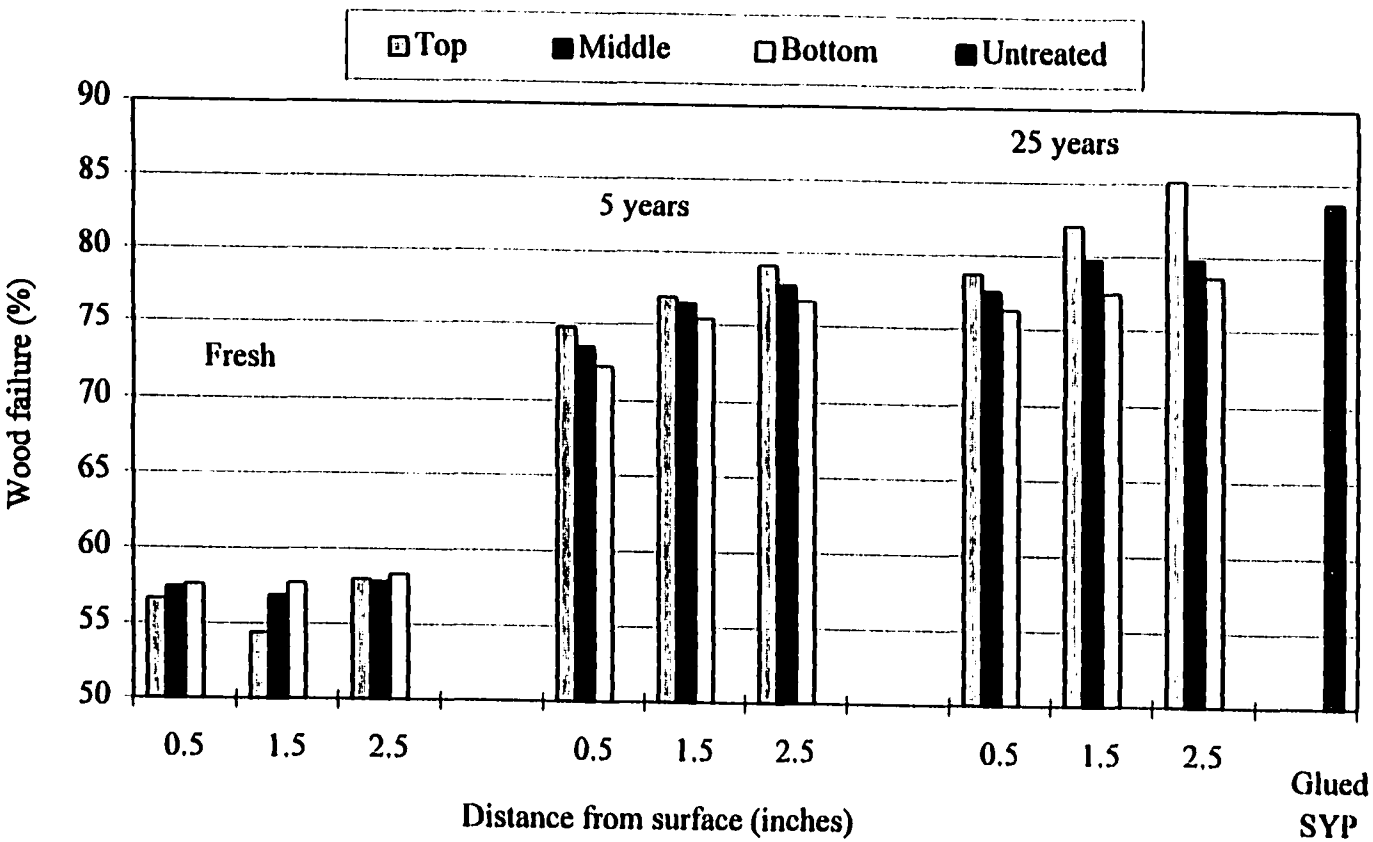

Figure 4.6. Wood failure of treated poles using PVA adhesive

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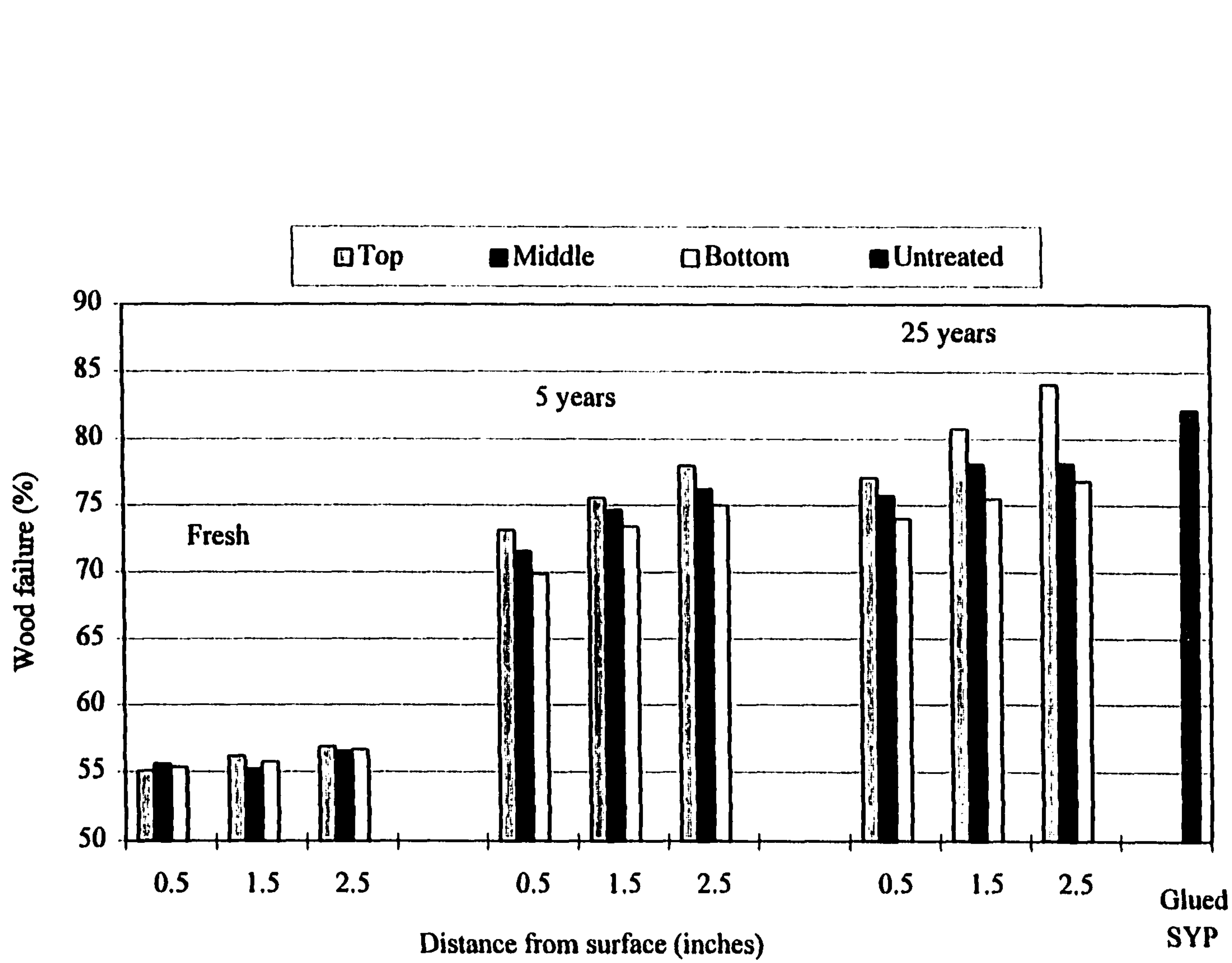

Figure 4.7. Wood failure of treated poles using casein glue

Table 4.3. Average contact angle of the three adhesives (RPF, PVA, and casein)

Wood substrates	Contact angle			
	RPF	PVA	Casein	Mean
Treated poles[1]				
Fresh	76.8	78.7	80.5	78.7
5 years	56.8	63.4	66.1	62.1
25 years	52.2	58.3	59.5	56.7
Untreated[1]				
SYP	47.9	54.1	54.3	52.1
Mean	58.4	63.6	65.1	

[1] Average of 5 replications

Table 4.4. Analysis of variance of contact angle

Source of variation	DF	F-calculated	F-tables	
			$\alpha = 0.05$	0.01
Types of adhesives (A)	2	14.53**	3.15	4.98
Wood substrates (S)	3	11.73**	2.76	4.13
Interaction (A*S)	6	5.28**	2.36	3.31
Error	59	(Y=62.4)[1]	(CV=5.54)[2]	

[1] Overall average of contact angle
[2] Coeff. of variation (%)
**denotes significance at 0.01 level

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Adhesive solution and wood substrate are polar, while creosote is non-polar; therefore, losing some of the creosote due to weathering could increase the polarity or reduce the hydrophobicity of wood surface, enhancing wettability (Garrey 1977). Higher wettability also enables the adhesive to spread and penetrate into the wood structure (Stamm 1964). The degree of adhesive penetration into the cell lumen and microstructure of the wood surface is shown in the photomicrographs for freshly treated poles (Figure 4.8), 5-year poles (Figure 4.9), 25-year poles (Figure 4.10), and untreated SYP (Figure 4.11). It is interesting to note that the deepest penetration with all three adhesives tested occurred in untreated SYP and the shallowest penetration in freshly treated pole, indicating that creosote, like extractives, inhibits preservative penetration by plugging the pits, thereby creating a barrier to adhesive movement.

The analysis also shows that location in the treated wood interacted with service duration to affect gluability. As shown in Figures 4.2 - 4.7, for 5- and 25-year poles, the shear strength increased and wood failure decreased from top to bottom in the vertical direction; while shear strength decreased and wood failure increased from the outer surface to the pith in the horizontal direction. For freshly treated poles, the differences in both vertical and horizontal directions were not significant, partly because the creosote inside fresh poles was relatively high in comparison with the creosote in aged poles (Figure 1.2).

Multiple regression analysis (Table 4.5) indicates that shear strength increased proportionately with increase in LW percentage, as shown by significantly positive coefficient of partial correlation ($R_p = 0.772^{**}$ for RPF, 0.781^{**} for PVA, and

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A.

B.

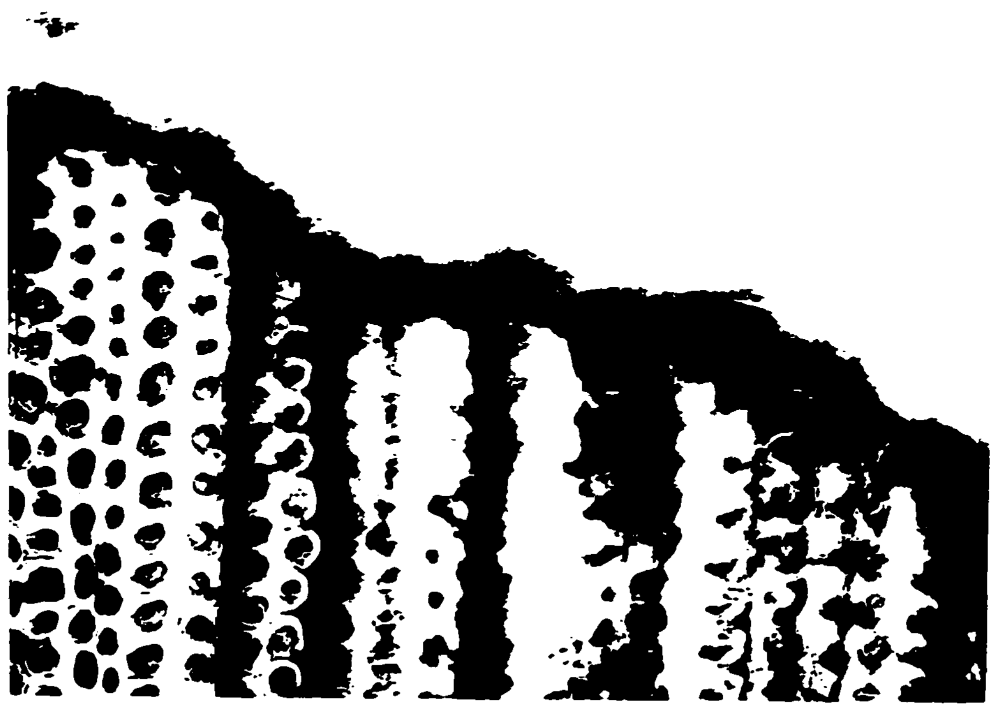

Figure 4.8. Photomicrograph (80 x) of cross section of glued pieces of freshly treated poles using RPF (A), PVA (B), and casein (C) adhesives, showing that penetration of adhesives into cellular structures was limited to the glued surface. (fig. cont'd.)

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C.

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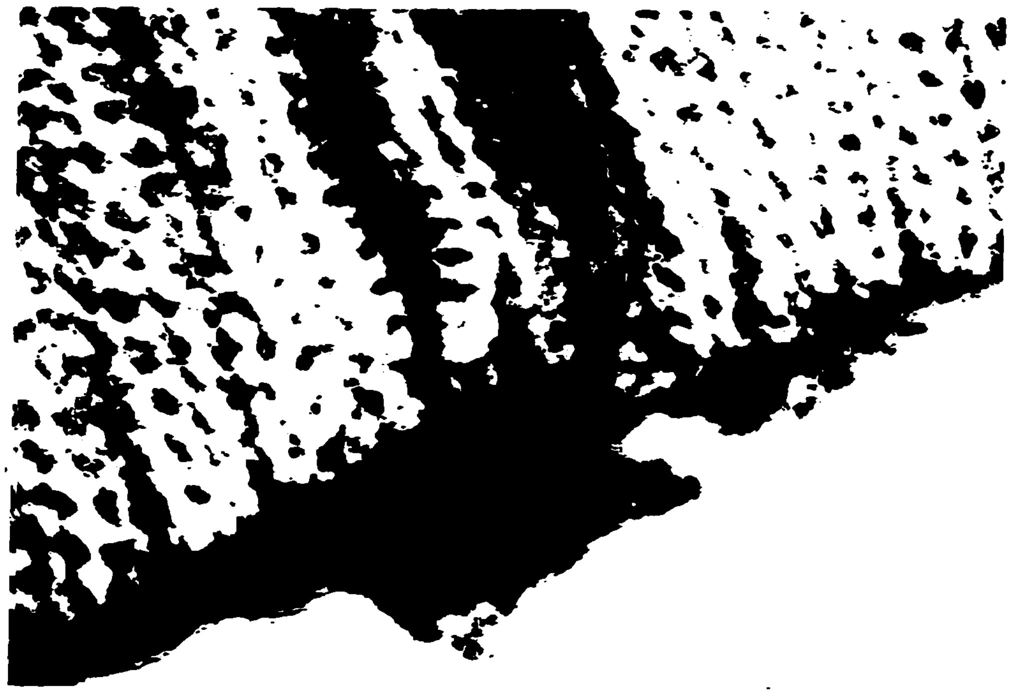
A.



B.

Figure 4.9. Photomicrograph (80 x) of cross section of glued pieces of 5-year poles using RPF (A), PVA (B), and casein (C) adhesives; showing that penetration of adhesives into cellular structures was significantly deeper than freshly treated poles. (fig. cont'd.)

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C.

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A.

B.

Figure 4.10. Photomicrograph (80 x) of cross section of glued pieces of 25-year poles using RPF (A), PVA (B), and casein (C) adhesives, showing that penetration of adhesives into cellular structures was deeper than 5-year poles. (fig. cont'd.)

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C.

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A.

B.

Figure 4.11. Photomicrograph (80 x) of cross section of glued pieces of untreated SYP using RPF (A), PVA (B), and casein (C) adhesives, showing that penetration of adhesives into cellular structure was the deepest. (fig. cont'd.)

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C.

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Table 4.5. Multiple regression analysis of glue-line shear strength
(Y= bo + b1X1 + b2X2 + b3X3)

Source of variation	DF	RPF		PVA		Casein	
		bi[1]	R_p[2]	bi	R_p	bi	R_p
Intercept, bo	1	0.8993	-	0.8972	-	0.8906	-
LW percentage (X1), b1	1	0.0180	0.772**	0.0172	0.781**	0.0169	0.812**
Creosote content (X2), b2	1	-0.0257	-0.885**	-0.0253	-0.876**	-0.0258	-0..892**
Angle of growth rings to the glue line (X3), b3	1	-0.0075	-0.473*	-0.0072	-0.487*	-0.0073	-0.671**
Error	31						
X1[3]		------- 40.32 -------		------- 41.28 ------		-------- 42.74 -----	
X2[4]		------- 11.62 -------		------- 11.62 ------		-------- 11.62 -----	
X3[5]		------- 20.26 -------		------- 21.48 ------		-------- 19.78 -----	
Y[6]		----- 1.1763 -------		------ 1.1407 ------		-------1.1325 -----	
CV[7]		------- 10.18 -------		------- 11.51 ------		--------- 9.67 -----	
(R^2)[8]		------- 0.844 -------		------- 0.822 ------		-------- 0.841-----	

[1]Slope (regression coefficient); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2]Partial correlation coefficient
[3]Overall average of LW (%)
[4]Overall average of creosote content (%)
[5]Overall average of angle of growth rings to the glue line
[6]Overall average of the shear strength (10^3 psi)
[7]Coeff. of variation (%)
[8]Coeff. of determination
** and *denote significance at 0.01 and 0.05 levels, respectively

0.812** for casein). Wood failure also increased proportionately with the decrease in LW percentage, as shown by significantly negative coefficient of partial correlation (Table 4.6) for all adhesives (R_p = -0.741**, -0.765**, and -0.789** for RPF, PVA, and casein glue, respectively). This relationship is expected because of close relationship between LW percentage and wood permeability. In the green condition of most softwood, the LW permeability is less than the EW (earlywood) permeability because the cell lumens in LW are smaller than in EW. However, after drying, most of the pits in the EW are aspirated. The pits in the LW are less likely to be aspirated because their margoes are thick and the pit membranes are rigid. Therefore, even though permeability is reduced after drying, the extent of reduction in the LW is considerably less than in the EW. In other words, the role of LW on permeability is greater than that of the EW when wood is dry (Walker et al. 1993).

During gluing, the LW permitted more lateral movement of adhesive inside the dry wood than did the EW. When the adhesive hardened, a stronger glue bond developed in the LW. The significant effect of LW on gluability has been reported in numerous studies (Koch 1975; Wellons 1981). Higher shear strength was accompanied by decrease in wood failure, or vice versa. A possible explanation is that since wood with higher EW content is weaker than wood with lower EW content (higher LW); therefore a glue-to-wood bond can be expected to be stronger than the strength of wood substance with higher EW content (higher wood failure).

In addition, AGR to the glue line affected gluing negatively (Tables 4.5 and 4.6), as shown by the negative values of partial correlation coefficients for both shear

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Table 4.6. Multiple regression analysis of wood failure
(Y= bo + b1X1 + b2X2 + b3X3)

Source of variation	DF	RPF		PVA		Casein	
		bi[1]	R_p[2]	bi	R_p	bi	R_p
Intercept, bo	1	90.6990	-	90.1058	-	90.5774	-
LW percentage (X1), b1	1	-0.1105	-0.741**	-0.1245	-0.765**	-0.1784	-0.789**
Creosote content (X2), b2	1	-0.8400	-0.874**	-0.8514	-0.881**	-0.8384	-0.843**
Angle of growth rings to the glue line (X3), b3	1	-0.0670	-0.482*	-0.0694	-0.563**	-0.0681	-0.682*
Error	31						
X1[3]		------- 40.32 -------		------- 41.28 ------		-------- 42.74 -----	
X2[4]		------- 11.62 -------		------- 11.62 ------		-------- 11.62 -----	
X3[5]		------- 20.26 -------		------- 21.48 ------		-------- 19.78 -----	
Y[6]		------- 75.14 -------		------- 71.79 ------		-------- 72.24 -----	
CV[7]		------- 8.74 -------		------- 9.13 ------		-------- 7.88 -----	
(R^2)[8]		------- 0.833 -------		------- 0.797 ------		-------- 0.816-----	

[1]Slope (regression coefficient); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2]Partial correlation coefficient
[3]Overall average of LW (%)
[4]Overall average of creosote content (%)
[5]Overall average of angle of growth rings to the glue line
[6]Overall average of wood failure (%)
[7]Coeff. of variation (%)
[8]Coeff. of determination
** and *denote significance at 0.01 and 0.05 levels, respectively

strength (R_p = -0.473* for RPF, -0.487* for PVA, and -0.671** for casein) and wood failure (R_p = -0.482* for RPF, -0.563** for PVA, and -0.682** for casein), respectively. The lower the angle, the more earlywood contacts with the adhesive. Since the earlywood has thin cell walls and large lumens, it is easily deformed and penetrated by adhesive (Koch 1975; Walker, et al. 1993). In the case of AGR, unlike the LW effect, higher wood failure, which was correlated significantly with lower AGR, was accompanied by increase in glue-line shear strength; and vice versa. A possible reason is that, at lower AGR, adhesive penetration into wood structure is deeper and more extensive; therefore, a stronger anchoring condition develops, resulting in better gluability.

The regression analysis (Tables 4.5 and 4.6) further confirmed quantitatively the adverse effect on gluing by creosote content, as shown by negative partial correlation coefficients for both shear (R_p = -0.885** for RPF, -0.876** for PVA, and -0.892** for casein) and wood failure (R_p = -0.874** for RPF, -0.881** for PVA, and -0.843** for casein), respectively. At a given LW percentage or a given AGR, gluability was better with lower creosote content.

Overall gluability results of RPF was superior to PVA and casein glue. This is shown by the results from gluing untreated SYP in Figures 4.12 and 4.13, and in Table 4.7. The high shear strength and high wood failure accompanying the use of RPF may be due to the contribution of paraformaldehyde, since it can react as a curing agent to form primary (valence) bonds with the wood substance (Subramanian 1981; Tsoumi 1991). On the other hand, PVA and casein bond wood by secondary

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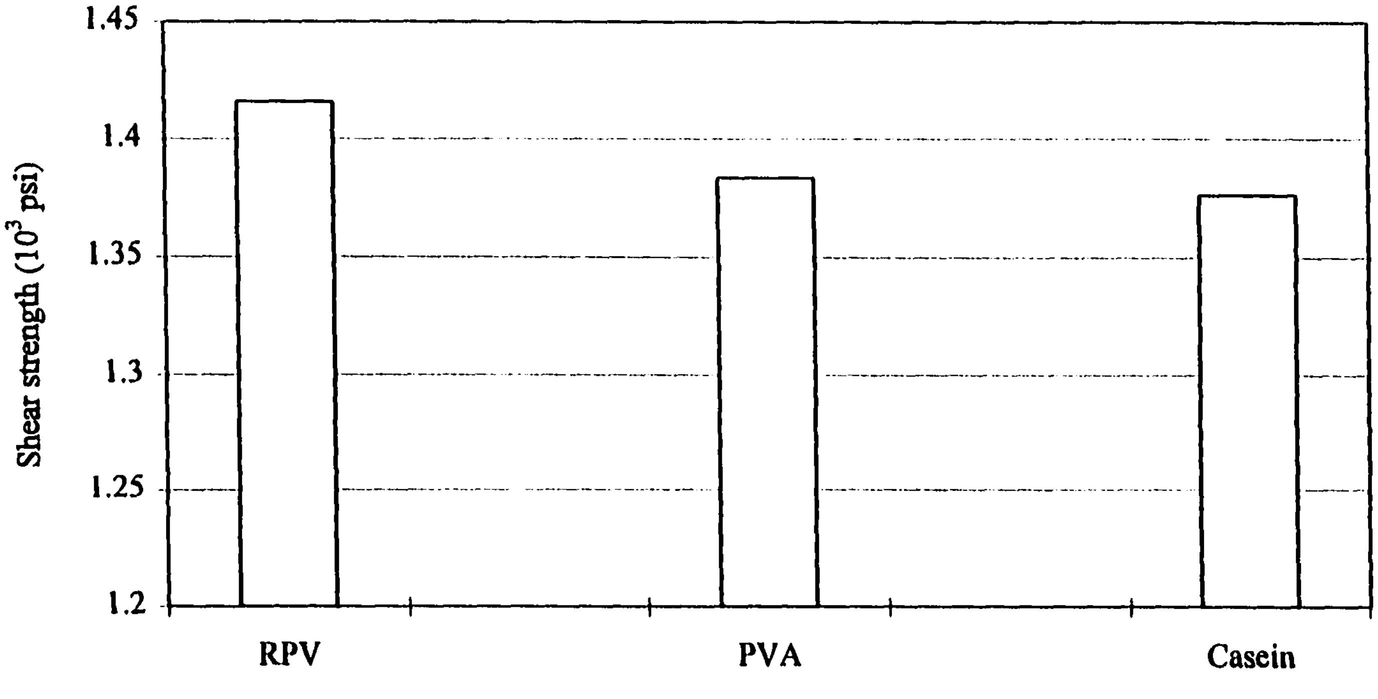

Figure 4.12. Glue-line shear strength of glued untreated SYP

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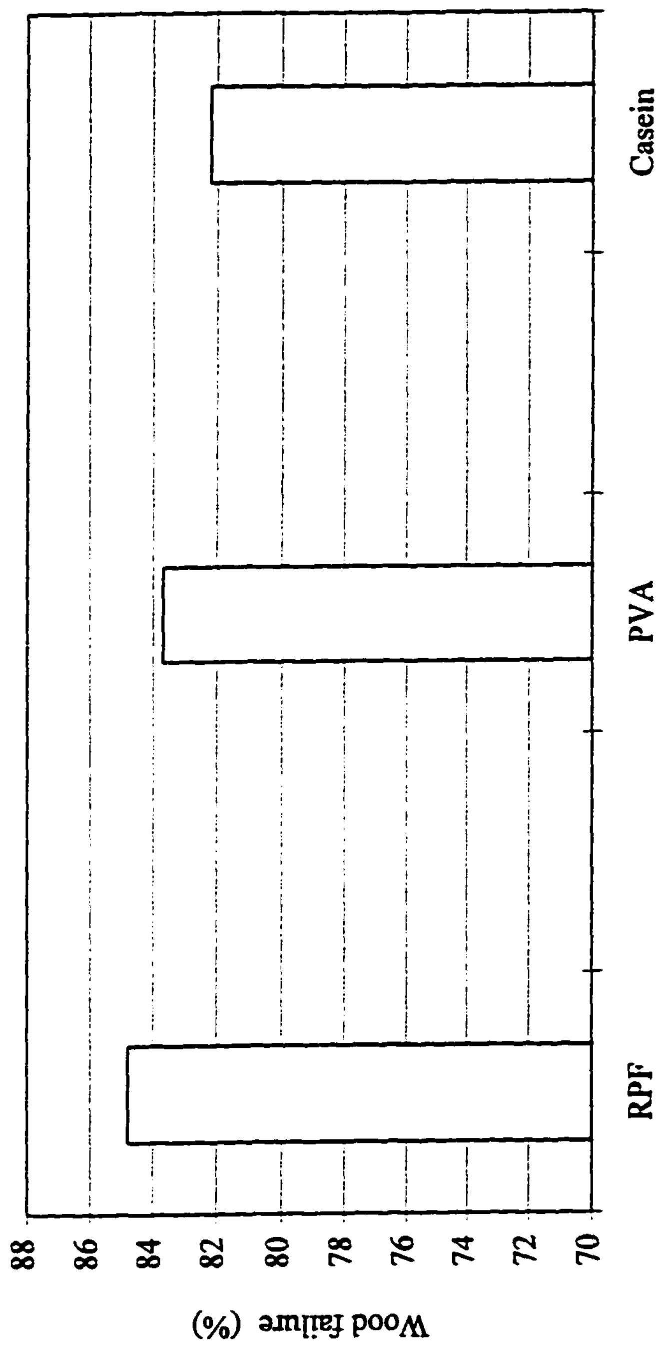

Figure 4.13. Wood failure of glued untreated SYP

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Table 4.7. Analysis of variance of glue-line shear and wood failure of glued untreated SYP

Source of variation	DF	F-calculated		F-tables	
		Shear	Wood failure	$\alpha = 0.05$	0.01
Types of adhesives	2	7.22**	5.61*	3.74	6.51
Replications	7	3.95*	3.17*	2.77	4.28
Error	14				
Y[1]		1.392 (10^3 psi)	83.55 (%)		
CV[2]		5.94	10.65		

[1]Overall averages of glue-line shear (10^3 psi) and wood failure (%)
[2]Coeff. of variation (%)
* and **denotes significance at 0.05 and 0.01 levels, respectively

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forces such as van der Waal's and hydrogen bonding, in addition to providing adhesion by mechanical forces.

Conclusions

Gluability depends on creosote content. The lower the creosote content, the better the gluability. Wood poles with low creosote content have gluing properties comparable to those of untreated SYP. Glue bonds are also affected positively by LW percentage, and negatively by the angle of growth ring to the glue line. This applies to all the three adhesives tested. From the gluing of untreated SYP, the best gluability results are with RPF, followed by PVA and then casein glue.

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CHAPTER 5

MANUFACTURE OF GLUE-LAMINATED STRUCTURES

Introduction

Glue-laminated structures are engineered wood products (EWP) which offer several advantages such as high strength, controllable quality, durability, dimensional stability, and ability to utilize wood pieces of variable dimensions. Therefore, the manufacture of laminated beams from discarded wood products such as out-of-service utility poles can be technically sound and economically feasible.

This chapter describes efforts to manufacture beams laminated with untreated SYP and with wood from discarded poles. Two types of laminated beams were fabricated. The first type consisted of 2-ply beams with various arrangements of edge-to-edge gluing. The second type consisted of 3-ply beams made with two kinds of end-to-end gluing, i.e. scarf and finger joints. The main purpose of this study was to evaluate: (1) the effect of laminae and joint designs on the strengths of beams and (2) the effect of residual creosote in aged poles on performance of beams.

Literature review

Glue-laminated beams can be defined as any structural member frabricated from wood products that have been reduced into smaller and thinner pieces or laminae (Guss 1995). The beams can be made of two or more layers of laminae with 0.5-inch or more in thickness, glued with an adhesive in such a way that the grain of all laminae is approximately parallel. These products have widespread uses such as chairseats, tabletops, arches, boat timbers, and laminated deckings (Selbo 1975).

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The significance of laminated products is evident from the fact that their production has increased from about 275 million bd. ft. in 1982 to 1500 million bd. ft. in 1991 (Guss 1995). The widespread use is due to the many advantages of laminated wood, such as improved utilization of wood since there is no limit imposed by size of accessible tree or grade of lumber, and improved mechanical and physical properties with less variability in strength. Smaller pieces of wood can be fabricated into larger and longer pieces by edge-to-edge and/or end-to-end gluing.

End-to-end gluing is particularly important in wood lamination because a long glued piece is more valuable than a short piece. End-glued joints have two common forms: scarf and finger joints (Gillepsie et al. 1978). A scarf joint is formed by cutting a long sloping face on the end section of lumber to be jointed. The strength of the jointed products depends on the slope; the flatter the slope, the stronger the joint. A slope of 1:12 achieves 90 percent efficiency compared with unjointed laminated product. Flatter slopes cause a greater loss of wood stock. A scarf joint with a 1:8 slope is usually considered optimum with 15-20 percent reduction in strength (Walker et al. 1993). Finger joints (Figure 5.1) are preferred over scarf joints because there is less loss of wood stock. The strength of finger joints, however, are affected by finger length, slope, and pitch width (Figure 5.2). Well made finger joints can be about 75 to 90 percent as strong as scarf joints if the slopes are the same (Koch 1975).

In the manufacture of laminated beams from treated wood, the preservative, especially oil-soluble creosote, interferes with adhesive bonding. Migration of creosote to the wood surface causes "bleeding" which is likely to occur after planing.

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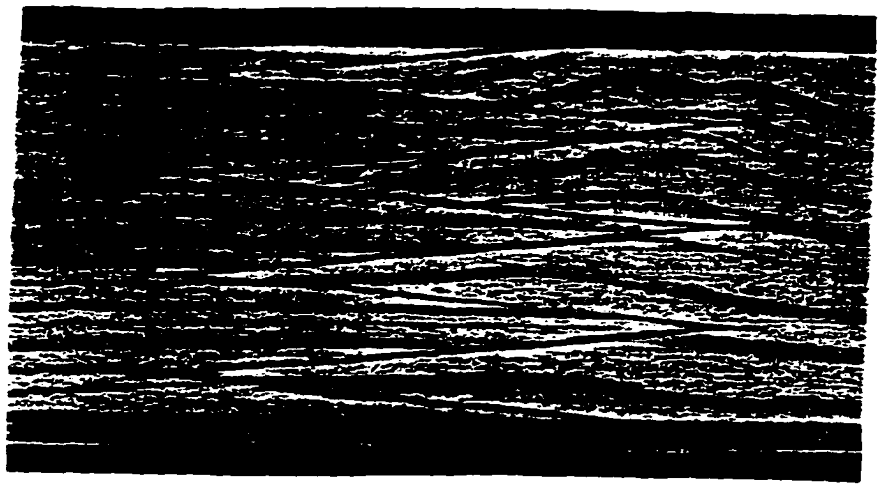

Figure 5.1. Example of finger joints, side view (Koch 1975)

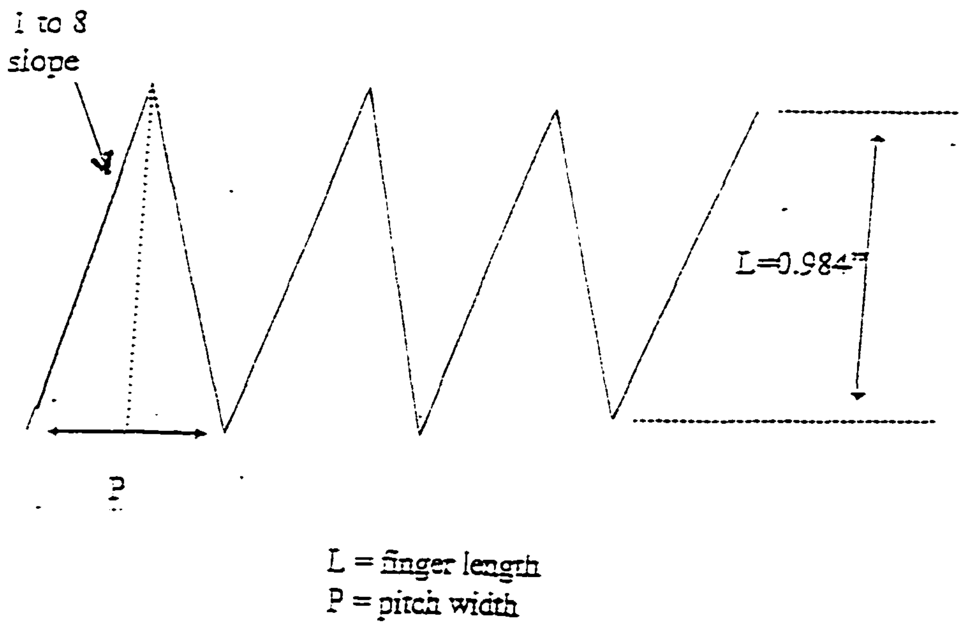

Figure 5.2. Common profile of finger joints (Walker et al. 1993)

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making good contact between adhesive and wood surfaces less perfect (Selbo 1958). However, treated lumber which has been exposed for weeks is more easily glued than freshly treated wood because the preservative could have moved out of the wood surface (Truax et al. 1953). Therefore, fabrication of used poles can result in a laminated structure that has mechanical and physical properties comparable to beams made from untreated wood.

Materials and Methods

Defect-free one-inch thick boards (laminae), measuring 4 inches in width and 96 inches in length, from untreated SYP and treated poles were selected to fabricate into 2- and 3-ply laminated beams. The stress wave time was measured on each untreated SYP board with a Metriguard instrument model 239A. The measurement was intended to evaluate possible variations in longitudinal stress wave speed due to different SYP board samples.

Manufacture of two-ply laminated beams

The 2- by 4-inch laminated beams were put together in four configuration models, designated: I, II, III, and IV, consisting of 2, 4, 5, and 7 laminae, respectively (Figure 5.3). The length of laminae was 96 inches, but the width varied from 0.66 to 4.00 inches. Details for each model are described in Table 5.1. The purpose of fabricating 2-ply beams with four models was to study the effect by using laminae with various sizes and variable numbers (areas) of glue lines on the strengths of beams.

In untreated SYP, each model was replicated 12 times; hence, a total of 48 laminated beams were fabricated. In treated old poles, 16 beams were fabricated

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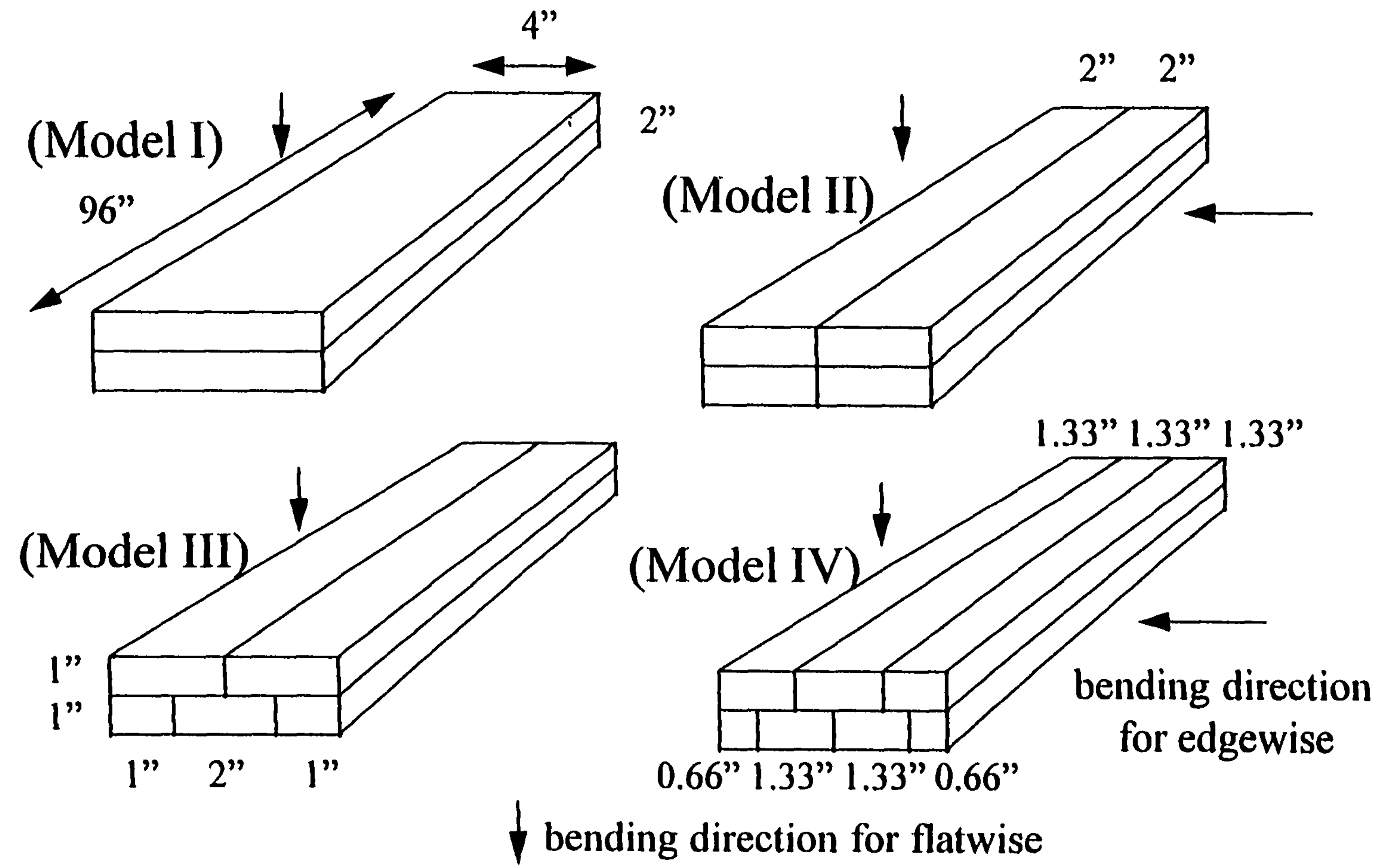

Figure 5.3. Two-ply laminated beams with four gluing-configuration models and variable number of glued laminae

Table 5.1. Specification of four configuration models for 2-ply beams

Configuration model[1]	Laminae		Glue-line area (in^2)		
	Number	Cross-section size	Horizontal	Vertical	Total
Flatwise direction					
I	(2)	1- by 4-inches	384	0	384
II	(4)	1- by 2-inches	384	192	576
III	3	1- by 2-inches			
	2	1- by 1-inches			
	(5)		384	288	672
IV	5	1-by 1.33-inches			
	2	1-by 0.66-inches			
	(7)		384	480	864
Edgewise direction					
I	(2)	1- by 4-inches	0	384	384
II	(4)	1- by 2-inches	192	384	576
III	3	1- by 2-inches			
	2	1- by 1-inches			
	(5)		288	384	672
IV	5	1-by 1.33-inches			
	2	1-by 0.66-inches			
	(7)		480	384	864

[1]For further details, refer to Figure 5.3

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with four replication on each configuration. In untreated SYP, each model was replicated 12 times; hence, a total of 48 laminated beams were fabricated. In treated old poles, 16 beams were fabricated with four replications. In fabricating these beams from untreated SYP, stress wave time was also measured on each of the laminae to evaluate whether width variation affected the speed of longitudinal stress waves along the constant length of laminae.

Gluing of the laminated assembly was performed using a resorcinol-phenol formaldehyde (RPF) adhesive with a glue spread at 75 lbs/1000 sq. ft. and with pressure at 175 psi. at room temperature. Lamination with boards from treated poles was performed in such a manner that the faces of laminae with low creosote content (8-11 percent) were placed inside the beam next to the glue line, while those with high creosote content (more than 11 percent) on the outside. All strength evaluations were made in a flexure bending in accordance with ASTM Standard D 198-86 (1994) using an Instron universal testing machine. Half of the laminated beams were tested flatwise (i.e. load applied perpendicular to 4-inch width surface), and the rest tested edgewise (load perpendicular to 2-inch width surface). Flatwise and edgewise tests were done to determine whether different depths of beams (2- vs. 4-inches), as shown in Figure 5.3, affected their strengths. As in the gluability study (Chapter 4), LW percentage of each SYP lumber and treated pole board, and angle of growth ring (AGR) to the glue line (Figure 5.4), were determined. Analysis of adjusted variance with factorial design was used for the data processing with the following variables as sources of variation: models (numbers of glued laminae), types of laminae (untreated

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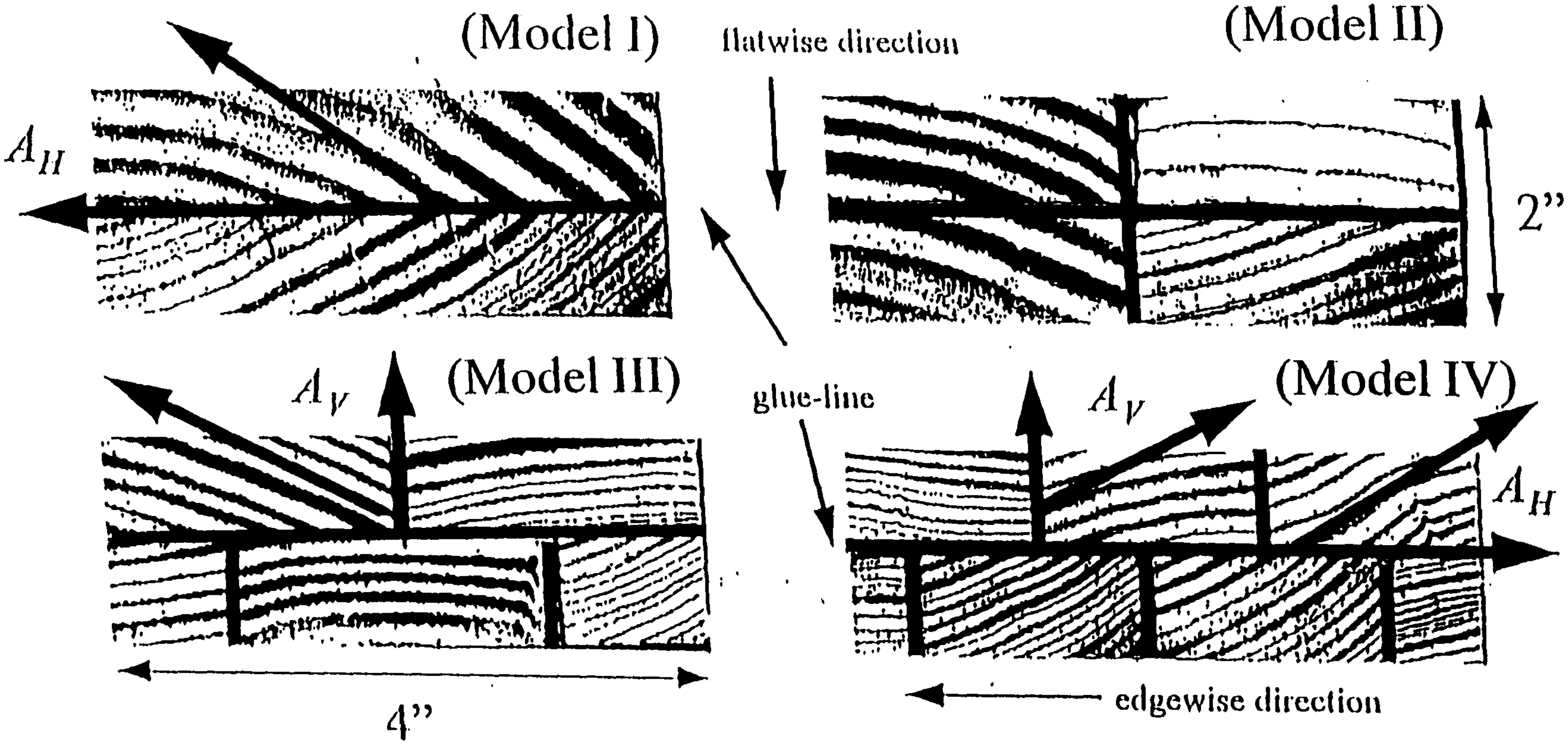

Figure 5.4. Results of cross-sectional scanning on each of four models (I, II, III, and IV), and angle of growth rings to horizontal (A_H) and vertical (A_V) glue-lines in the flatwise direction (in the edgewise direction, A_H and A_V become A_V and A_H, respectively)

and treated), and flexure direction (flatwise and edgewise). LW percentage and AGR were included in the analysis as covariates.

Manufacture of three-ply laminated beams

Laminated beams from untreated SYP were fabricated by placing laminae with lower value of stress wave time (higher longitudinal wave speed) at the surface (exterior), and those with lower wave speed in the interior. The reason is that the exterior part of the beam undergoes greater tensile and compression stresses, in bending, than the interior part. These beams were both without end-to-end gluing (Figure 5.5) and with end-to-end gluing. End-to-end gluing was used in fabricating 3-ply beams, with either scarf or finger joints (Figure 5.6), at a slope of 1:8. Lamination was done with six types of configurations, designated: 1A, 1B, 2A, 2B, 3A, and 3B, as shown in Figure 5.7. For a design A, the numbers of joints (either finger or scarf) were 4, 6, and 10; and for a design B, the numbers were 5, 8, and 12. In design A, two joints were located in the midspan of the beams (exterior laminae); whereas in design B there was only one or no joint in the midspan (interior laminae). Further details of 3-ply beams with end-to-end gluings are given in Table 5.2. Treated boards were fabricated in the same manner, using scarf joints with configurations 3A and 3B in end-to-end gluing. Laminations using treated poles was done in the same way as in 2-ply beams with regard to the faces of laminae, i.e. low creosote content in the interior, and high creosote content in the exterior. Laminated beams from untreated SYP were replicated eight times, while those from treated poles (i.e. unjointed beams, and scarf-jointed beams of 3A and 3B configurations) were replicated four times.

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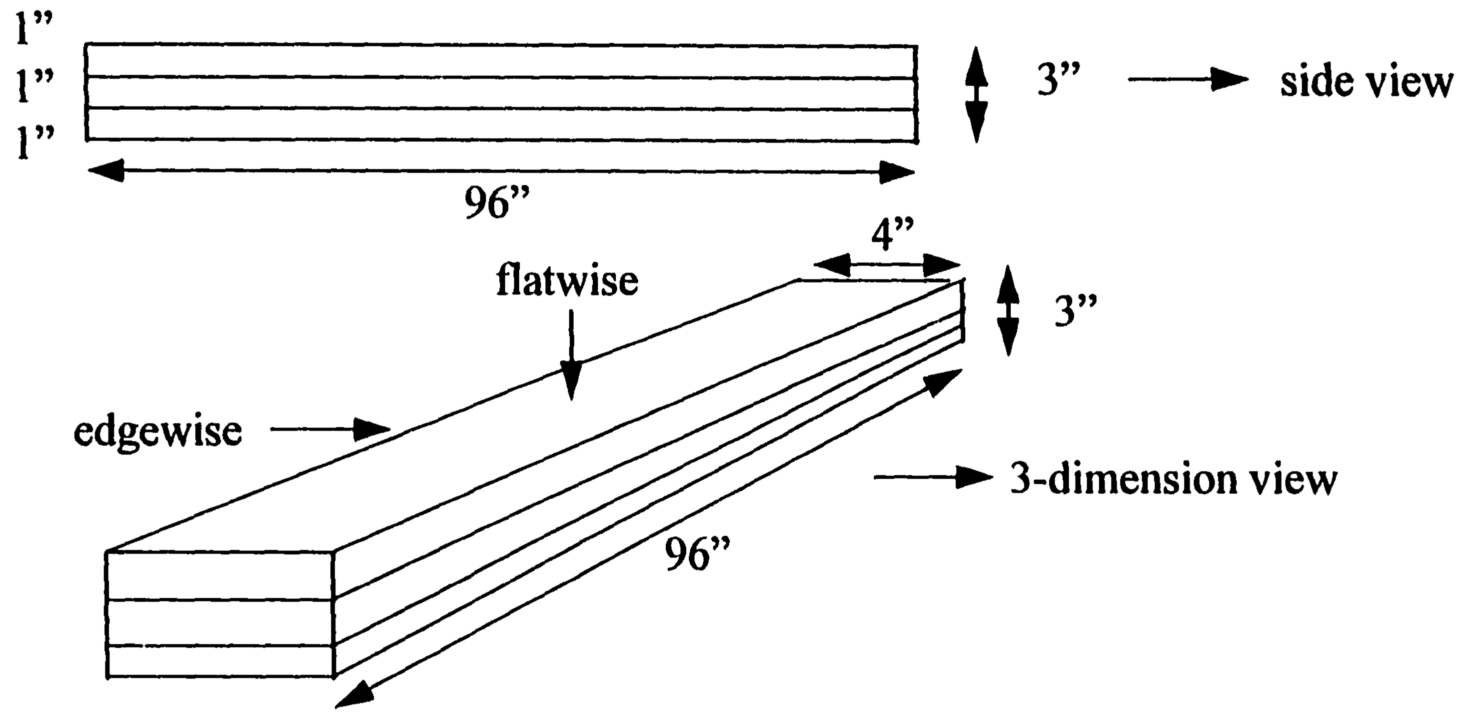

Figure 5.5. Three-ply laminated beams without end-to-end gluing (unjointed)

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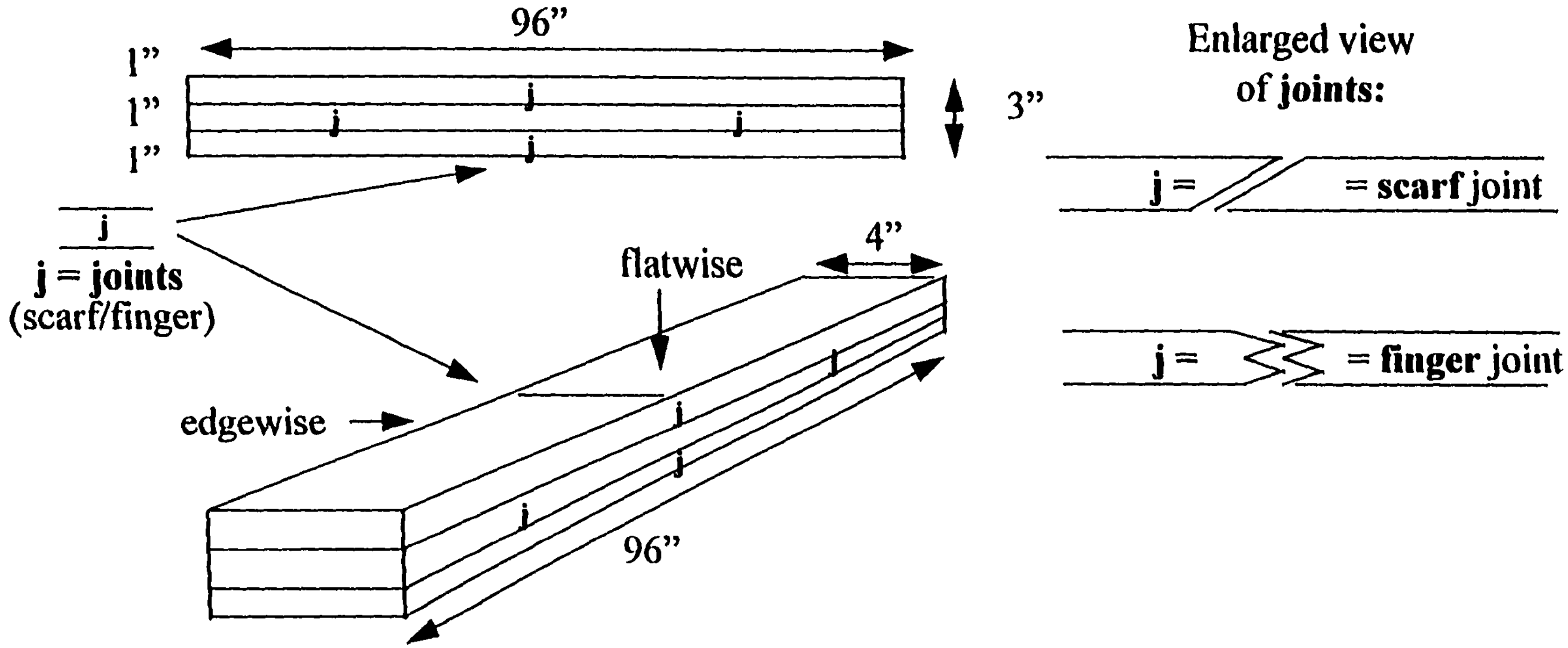

Figure 5.6. Three-ply laminated beams with two types of end-to-end gluing
(scarf or finger joints)

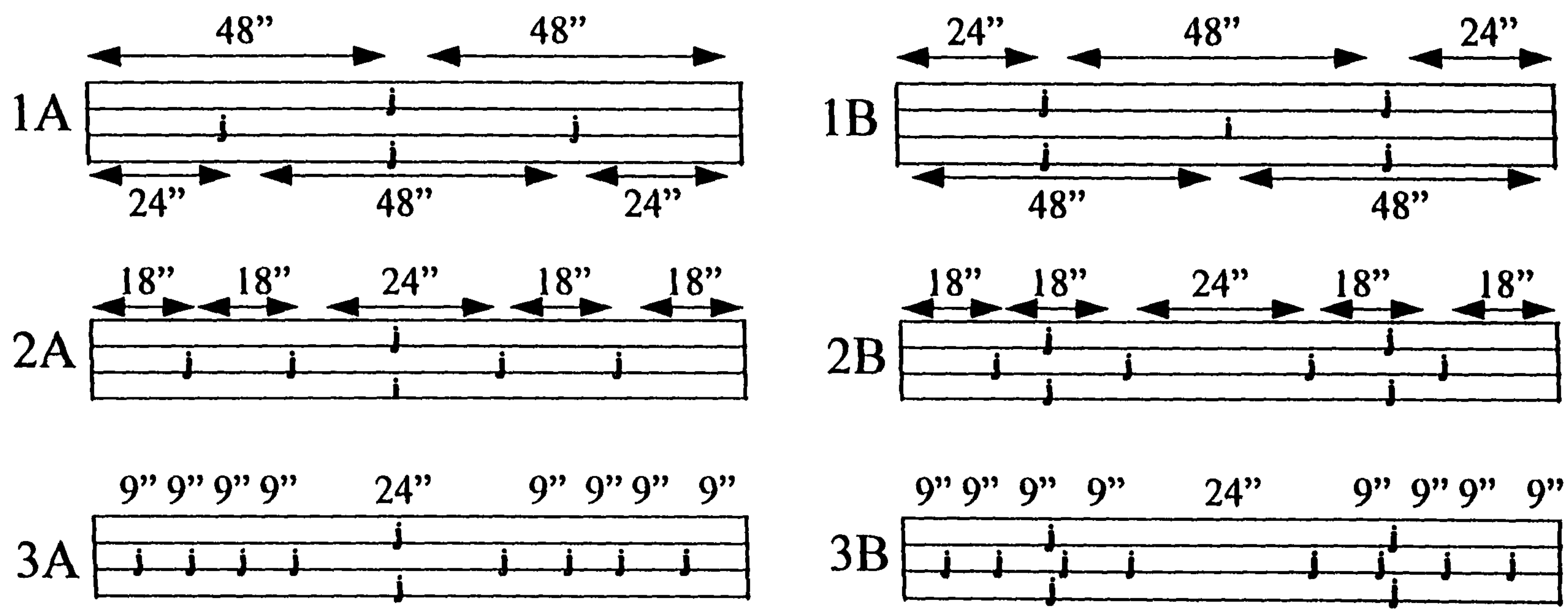

Figure 5.7. Three-ply laminated beams with six configurations (1A, 1B, 2A, 2B, 3A, and 3B showing end-to-end gluing locations (j) for scarf or finger joints

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Table 5.2. Design specifications of end-to-end gluing (scarf or finger joints) in 3-ply beams

Configuration[1]	Design A[1]			Design B[1]		
	E[2]	I[2]	T[2]	E	I	T
1	2 (4)[3]	2 (3)[3]	4 (7)[3]	4 (6)	1 (2)	5 (8)
2	2 (4)	4 (5)	6 (9)	4 (6)	4 (5)	8 (11)
3	2 (4)	8 (9)	10 (13)	4 (6)	8 (9)	13 (15)

[1]For further details, refer to Figure 5.7
[2]E, and I denote number of joints in exterior and interior beam, respectively; and T is total number of joints in the beam
[3]Figures in parenthesis means number of laminae in exterior (E), interior (I), and whole beam (T), respectively

The adhesive used was an RPF type with the same glue spread and pressure as in the 2-ply lamination. Testing in flexure bending was also the same. Analysis of adjusted variance with factorial design was used in the analysis of data with variables as sources of variation: numbers of glued laminae, types of glued laminae (untreated and treated), beams with and without end-to-end gluing, types of end-gluing (scarf and finger joints), joint design (A vs. B), and flexure direction (flatwise vs. edgewise). LW percentage and AGR (Figure 5.8) were also included in the analysis as covariates.

Results and Discussion

Stress wave time (SWT)

Data of SWT and LW percentage of defect-free untreated SYP lumber are presented in Appendix E.1. Regression analysis (Table 5.3) shows significant linear relationship between LW percentage and second power of longitudinal stress wave speed (Figure 5.9), indicating that strength of wood parallel to grain is linearly affected by specific gravity. Specific gravity, in turn, is linearly related to LW percentage (Walker et al. 1993). The positive relationship between LW percentage and second power of stress wave speed is understandable (Gerhard 1975). Higher LW percentage indicates that the wood is more dense and contains less air space. The speed of sound in air is less than in wood in the longitudinal direction (Tsoumi 1991); thus, it is dependent on wood density. Furthermore, the variation in SWT in different SYP lumbers due to variation in LW percentage suggests that LW should be considered in fabricating 2- and 3-ply beams.

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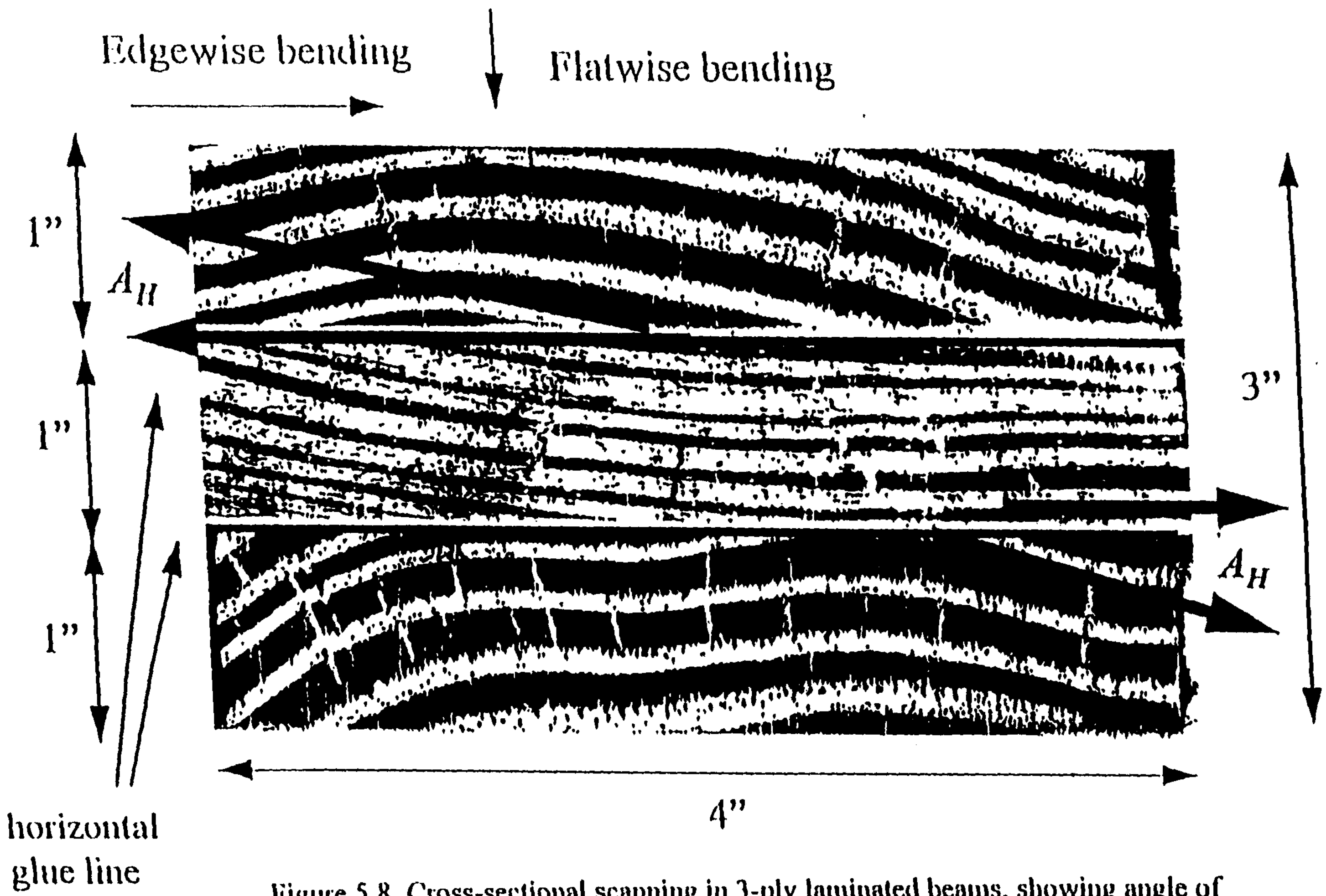

Figure 5.8. Cross-sectional scanning in 3-ply laminated beams, showing angle of growth rings to the horizontal glue line (A_H) in flatwise bending

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Table 5.3. Regression analysis of stress wave time

Source of variation	DF	F-values	F-tables	
			$\alpha = 0.05$	0.01
Regression (LW percentage)	1	103.845**	1.74	1.17
Error	197	Y= 132.02444[1]	CV= 4.932[2]	

[1]Overall average of second power of stress wave speed (10^6 ft^2/sec^2)
[2]Coeff. of variation (%)
**denotes significance at 0.01 level

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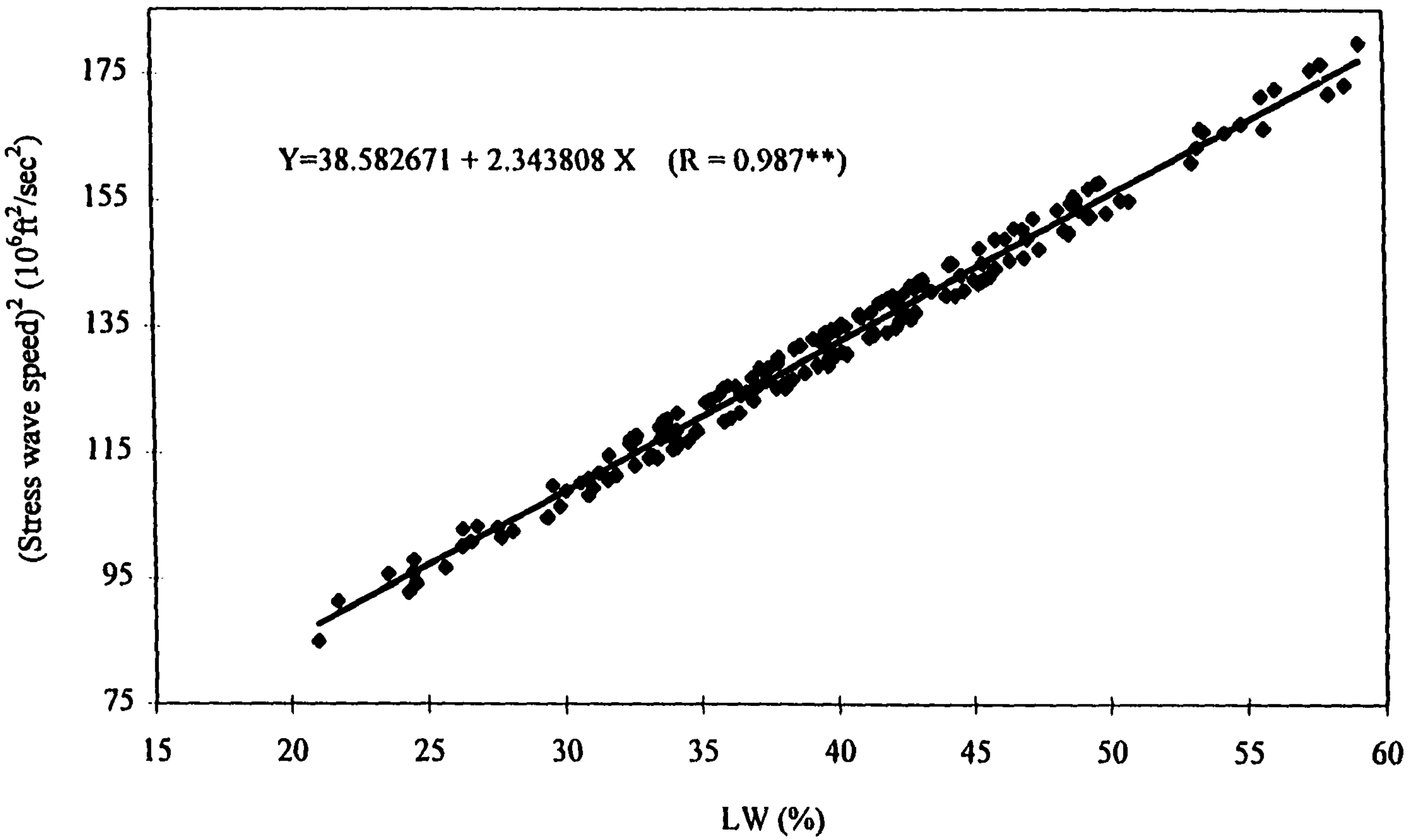

Figure 5.9. Relationship between latewood (LW) percentage and stress wave speed

Table 5.4. Stress wave time (SWT) and LW percentage in untreated SYP laminae for 2-ply beam

Laminae		SWT values (T)[1]		LW	
Size	Number	Average	S.D.[2]	Average	S.D.[2]
		------------- µs ------------		--------------- % --------------	
1- by 4- inches	24	683.04	41.79	38.85	3.58
1- by 2-inches	84	671.92	35.82	40.75	3.95
1- by 1.33-inches	60	710.75	45.09	35.08	5.98
1- by 1-inches	24	707.19	37.21	36.12	4.57
1- by 0.66-inches	24	679.14	42.52	39.86	4.71

[1]Time required, in microsesonds (µs) to travel along 96-inch length of SYP laminae
[2]Standard deviation

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Table 5.5. Analysis of variance of stress wave time of laminae for 2-ply beams

Source of variation	DF	F-values	F-tables	
			$\alpha = 0.05$	0.01
Sizes of laminae (S)	4	1.14	2.41	3.41
LW percentage (L)	1	14.32**	3.89	6.76
Interaction (L*W)	4	1.31	2.41	3.41
Error	206	Y=694.09[1]	X=38.31[2]	
CV=7.13[3]				

[1]Overall average of time (in microseconds) required to travel along 96-inch length of each laminae
[2]Overall average of LW (%)
[3]Coeff. of variation (%)
**denotes significant at 0.01 level

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Two-ply laminated beams

Data of SWT and LW percentage of the laminae with various sizes for 2-ply beams are presented in Table 5.4. The analysis of variance (Table 5.5) shows that different laminae sizes (width) did not affect the SWT; however, SWT was affected by variation in LW content since SWT tended to decrease with higher LW (Table 5.4). This suggests that laminae with width ranging from 0.66- to 4.00-inches (Figure 5.3) could be reasonably fabricated for 2-ply beams, but their LW content should be considered.

Strength properties of the fabricated 2-ply beams with various gluing models, LW percentage, and AGR are presented in Appendix E.2. The analysis of adjusted variance (Table 5.6), which considered the LW percentage and AGR to the glue line, shows the effect of gluing model, bending direction, and types of laminae (untreated vs. treated) on beam strengths. The interaction of these three variables was significant with respect to the strengths. The significant interaction was further indicated by the variable values of the intercepts of both MOR and MOE for each treatment combination, as shown in the multiple regression analysis (Tables 5.7). The Tukey's test confirms the variability in strengths (Table 5.8), which reveals that increasing the number of glued laminae caused a consistent reduction in MOR (Figure 5.10) and MOE (Figure 5.11). However, for the beams from untreated SYP, with models I to IV or numbers of glued laminae 2 to 7 (Figure 5.3), their flatwise and edgewise strengths were higher than those of defect-free SYP lumber. This means that 2-ply beams of satisfactory strengths can be fabricated by utilizing

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Table 5.6. Analysis of adjusted variance of MOR and MOE in 2ply beams from treated poles and untreated SYP

Source of variation	DF	F-values		F-tables	
		MOR	MOE	$\alpha = 0.05$	0.01
<u>Main factor</u>					
Gluing model (C)	3	71.10**	9.95**	2.81	4.24
Bending direction (B)	1	27.42**	6.54*	4.05	7.21
Untreated vs. treated laminae (T)	1	57.84**	25.63**	4.05	7.21
Interactions:					
C*B	3	24.44**	3.58*	2.81	4.24
C*T	3	57.84**	18.91**	2.81	4.24
B*T	1	16.94**	18.62**	4.08	7.21
C*B*T	3	7.35**	9.52**	2.81	4.24
<u>Covariates</u>					
LW percentage (X1)	1	59.99**	41.07**	4.05	7.21
A_H[1] (X2)	1	25.74**	21.78**	4.05	7.21
A_V[2] (X3)	1	7.39**	6.40*	4.05	7.21
Error	45				
X1[3]		35.91			
X2[4]		36.97			
X3[5]		36.65			
Y[6]		1.4094	1.5997		
CV[7]		5.05	7.19		

[1]Angle of growth rings to the horizontal glue line
[2]Angle of growth rings to the vertical glue line
[3]Average of LW percentage
[4]Average of A_H
[5]Average of A_V
[6]Average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[7]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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Table 5.7. Multiple regression analysis on MOR and MOE in 2-ply beams from treated poles and untreated SYP ($Y = bo + b1X1 + b2X2 + b3X3$)

Source of variation	DF	MOR			MOE		
		bi[1]	F-values	R_p^2	bi	F-values	R_p
Intercept[3], bo	1	0.98106	-		1.15370	-	
LW percentage (X1), b1	1	0.01649	59.99**	+0.863**	0.01714	41.07**	+0.789**
Angle of growth rings to the horizontal glue line (X2), b2	1	-0.00205	25.74**	-0.746**	-0.00202	21.78**	-0.725**
Angle of growth rings to the vertical glue line (X3), b3	1	-0.00045	7.39**	-0.702**	-0.00059	6.40*	-0.691**
Error	45						
Y[4]			1.4094			1.5997	
CV[5]			5.05			7.19	
(R^2)[6]			0.832			0.803	

[1] Regression coefficient (slope); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2]Coeff. of partial correlation
[3]Overall average of intercept; for specific values of intercepts of each treatment combination, refer to Table 5.8.
[4]Overall average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[5]Coeff. of variation (%)
[6]Coeff. of determination
** and *Denotes significance at 0.01 and 0.05 levels, respectively

Table 5.8. Deviation (Δ)[1] of intercept, and comparison (d) of average MOR and MOE by Tukey's test for significant difference

Number of glued laminae (treatment combination)	MOR -- Δ -- (10^4 psi)	MOR -- d --	MOE -- Δ -- (10^6 psi)	MOE -- d --
Untreated SYP				
Flatwise				
2 (T1)	0.0719	A[2]	0.0701	A
4 (T2)	0.0639	A	0.0654	A
5 (T3)	0.0540	B	0.0586	AB
7 (T4)	0.0415	BC	0.0579	AB
Edgewise				
2 (T1)	0.0624	AB	0.0670	A
4 (T2)	0.0601	B	0.0545	AB
5 (T3)	0.0490	B	0.0480	B
7 (T4)	0.0343	C	0.0479	B
Treated poles				
Flatwise				
2 (T1)	-0.0528	G	-0.0639	G
4 (T2)	-0.0614	H	-0.0687	G
5 (T3)	-0.0709	H	-0.0713	GH
7 (T4)	-0.0834	HI	-0.0749	H
Edgewise				
2 (T1)	0.0474	BC	0.0538	AB
4 (T2)	-0.0647	H	-0.0773	H
5 (T3)	-0.0760	HI	-0.0826	H
7 (T4)	-0.0910	J	-0.0865	HI
Overall average of intercept[3]	0.9811		1.1537	

[1] For specific values of intercept for each treatment combination: add Δ to the overall average of intercept

[2] Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H>I>J)

[3] Refers to Table 5.7

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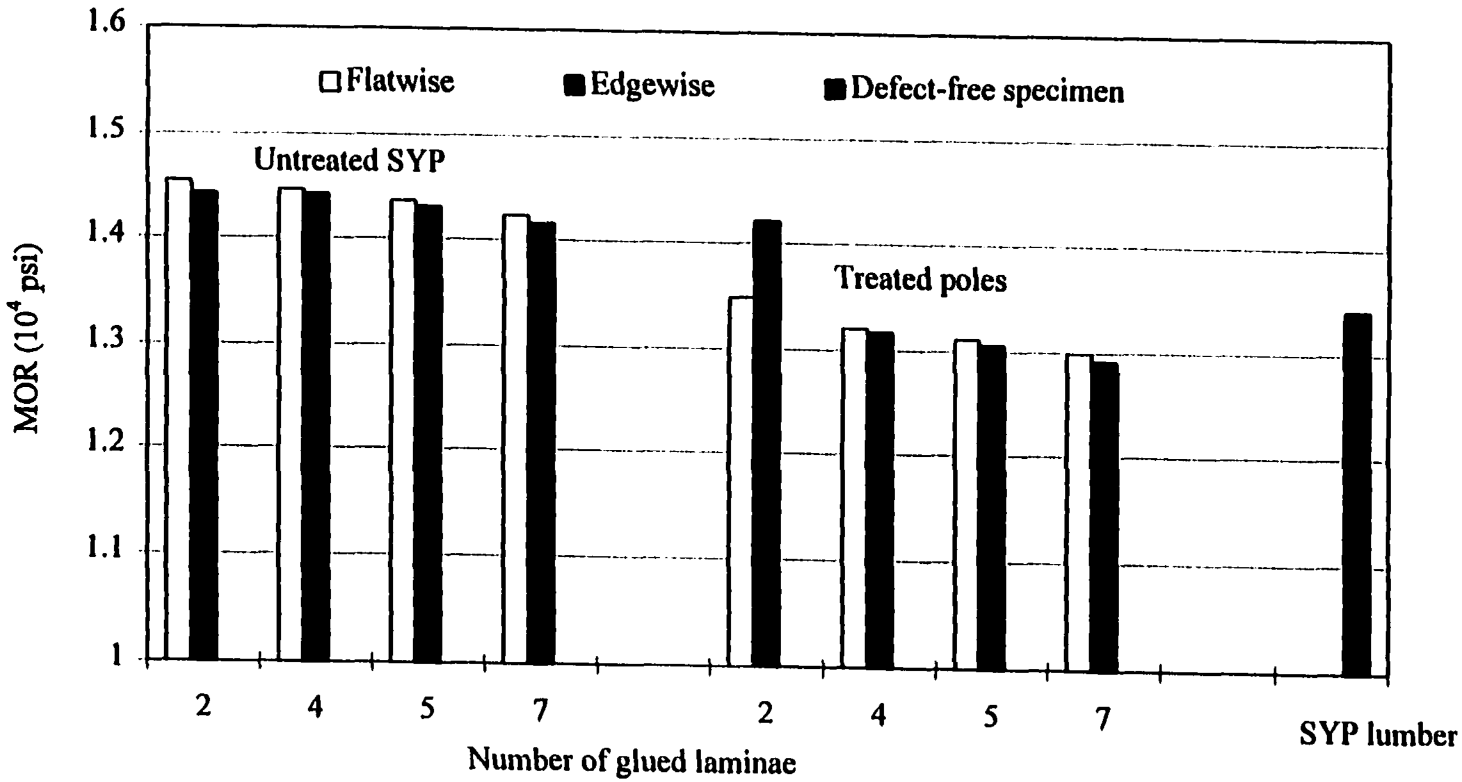

Figure 5.10. MOR of 2-ply laminated beams (LW=35.91%, angle of growth rings to the horizontal glue lines (A_H) = 36.97 and to the vertical (A_V) glue lines = 36.65).

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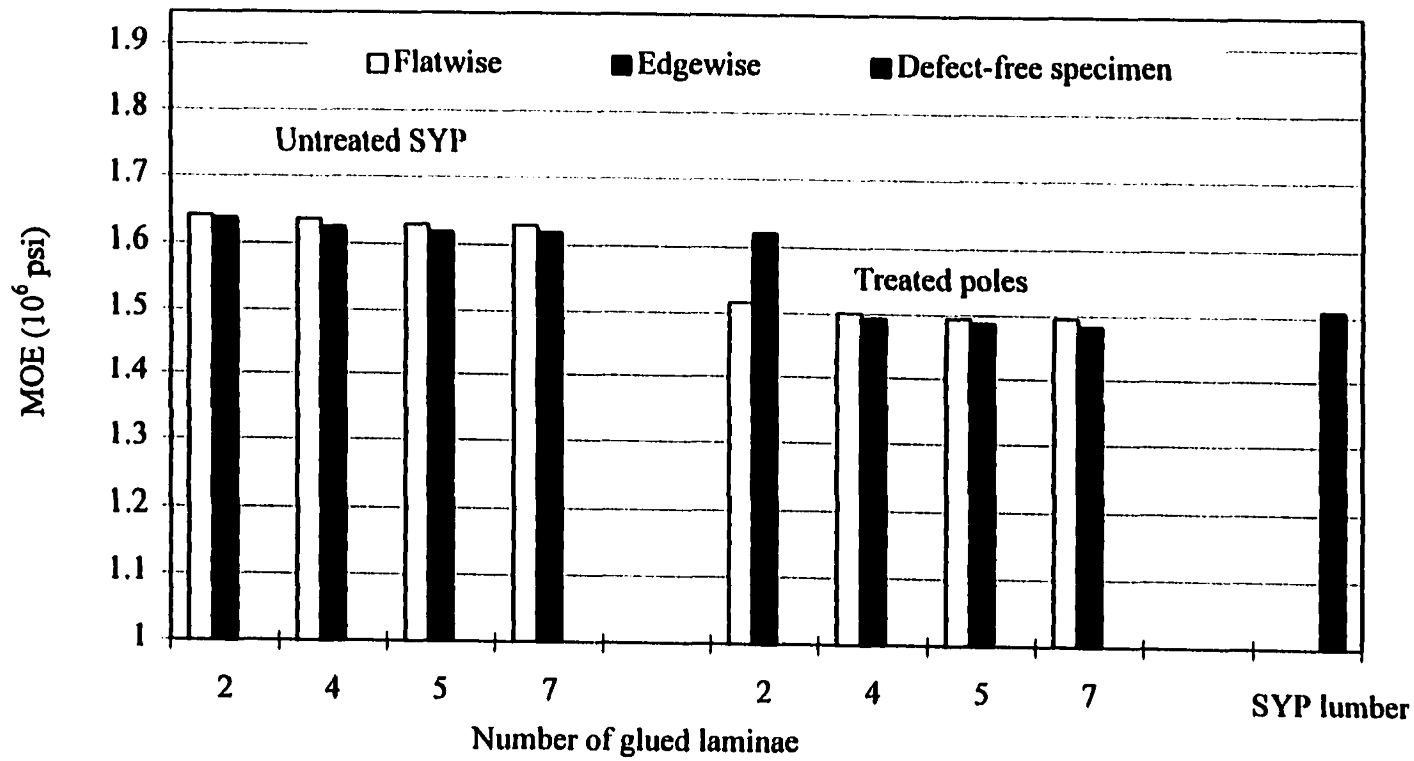

Figure 5.11. MOE of 2-ply laminated beams (LW = 35.91%; A_H=36.97; and A_V=36.65).

laminae with small sizes (1- by 1.33-inch and 1-by 0.66-inch) and with total glue-line area up to 864 sq. in. (Table 5.1). Using small size laminae utilizes wood more efficiently, but a larger glue-line area consumes a greater amount of adhesive.

For beams from untreated SYP, the strengths in the flatwise direction were somewhat higher than in the edgewise directions. The edgewise beams have greater depth than the flatwise beams if viewed in the vertical direction (4- vs. 2-inches); but both underwent simultaneous compression, tension, and shear stresses in bending. As reported by Hoadley (1980) and Walker, et al. (1993), increasing the depth causes second or third power increase in compression and tensile stresses, accompanied by a linear increase in shear stress. Consequently, the contribution of those three stress factors (compression, tensile, shear) at the same unit of beam depth is lower as the depth increases. Furthermore, Freas (1954) also reported that solid wood with high or deep beams gave lower strengths than shallow beams. The flatwise 2-ply beams had horizontal glue-line area of 384 sq. in. for models I, II, III, and IV; whereas the edgewise 2-ply beams had horizontal glue-line areas of 0, 192, 288, 480 sq. in. for models I, II, III, and IV, respectively (Table 5.1). However, MOR (Figure 5.10) and MOE (Figure 5.11) of the 2-ply flatwise beams in untreated SYP were also consistently higher than those of the 2-ply edgewise beams for each model. The horizontal glue-line area was used since the glued-area could undergo significant shear stress in bending. The phenomena in solid-wood products also occurred in glued-wood products, indicating that if gluing is done properly, the glued products have strength properties similar like solid wood (Koch 1975)

Increasing the number of glued laminae also caused a consistent reduction in strengths of 2-ply beams in treated poles. Most of the strengths of these beams were

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lower than those for untreated SYP, as shown in Table 5.8 and in Figure 5.10 for MOR and Figure 5.11 for MOE. The lower strengths of flatwise beams in treated poles, as compared to flatwise untreated SYP beams, was due to the interference of residual creosote on the horizontal glue bond causing some relief of internal shear stress when the beams underwent bending test. For configuration model I (Figure 5.3), the strengths of 2-ply beams in the flatwise direction were lower than in the edgewise direction, which was the opposite of beams of the same model in untreated SYP (Table 5.1). On the other hand, comparable strengths in edgewise beams of model I between those in untreated SYP and in treated poles indicates that, without a horizontal glue line, interference of residual creosote on the 384 sq. in. vertical glue line could be regarded negligible. This is understandable since the vertical glue line, unlike the horizontal glue line, was not significantly affected by internal shear stress in bending.

For the beams from treated poles with models II-IV (Figure 5.3), strengths in the flatwise direction were somewhat higher than in the edgewise direction. Increased number of laminae resulted in reduction in strengths, consistent with beams in untreated SYP in the same models (II-IV). It is interesting to note that the introduction of the horizontal glue line (192 sq. in. area) in edgewise beams from treated poles in model II (Table 5.1) resulted in significantly lower strength than with the edgewise beams in model I. This confirms again that horizontal glue area could relieve internal shear stress that occurred in model I. Furthermore, the consistently different patterns between strengths of flatwise and edgewise beams in models II-IV

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of untreated SYP as well as treated poles (Table 5.8 and Figures 5.10 and 5.11) reveals that the introduction of the vertical glue line (192-480 sq. in.) on the surface of both untreated SYP and treated pole had negligible effect on strengths. The significant effect was again from the horizontal glue line in creosote-treated wood surface; consequently, the strengths of models II, III, and IV beams in treated poles were lower than in untreated SYP, in both flatwise (384 sq. in. horizontal glue-line area) and edgewise (192-480 sq. in. horizontal glue area) directions.

MOR of the 2-ply beams from treated poles (Figure 5.10) with the number of glued laminae up to 5 (model III) was comparable to the defect-free solid SYP lumber. However, for MOE (Figure 5.11), number of glued laminae up to 7 (model IV) was still comparable to the defect-free SYP lumber. This means that small size laminae from weathered poles, 96-inch length and 1- by 2-inch with 576 sq. in. glue-line area (Figure 5.3; Table 5.1) and residual creosote content of 8-11 percent, can be fabricated for 2-ply beams in model II with satisfactory results. This is encouraging considering that the lumber recovery factor values of weathered poles, described in Chapter 2, were satisfactory.

Analysis of adjusted variance (Table 5.6) also confirms that LW percentage and AGR affected strength significantly. Further evaluation using multiple regression analysis (Table 5.7) indicates that both MOR and MOE were correlated positively with LW percentage ($R_p = 0.863^{**}$ for MOR, and 0.789^{**} for MOE), and negatively with AGR ($R_p = -0.746^{**}$ for MOR, and -0.725^{**} for MOE to the horizontal glue line; and -0.702^{**} for MOR, and -0.691^{**} for MOE to the

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horizontal and vertical glue lines). The F-values show that the effect of AGR upon horizontal glue line was greater than upon the vertical glue line (F=25.74** vs. 7.39** for MOR; and F=21.78** vs. 6.40* for MOE). Again, this demonstrates that the horizontal glue line of the flatwise beam was subjected to greater shear in bending than was the vertical glue line of the edgewise beam (Figure 5.3).

Three-ply laminated beams from untreated SYP

A summary of strength properties of these beams is presented in Appendix E.3. The analysis of adjusted variance (Table 5.9) shows that joint types (scarf vs. finger joints), gluing configuration, joint design (A vs. B), bending direction, and interaction of these four variables significantly affected beam strengths. The significance of the interaction, as shown by the variability of the intercepts value for MOR and MOE, was explained by multiple regression analysis (Table 5.10) and by the Tukey's test (Table 5.11). The test demonstrates that strengths of flatwise beams were somewhat higher than those of edgewise beams, as shown in Figure 5.12 for MOR and Figure 5.13 for MOE, since the depth of 3-ply edgewise beams (4 inches) was greater than flatwise beams (3 inches).

The Tukey's test also reveals that strengths of end-to-end gluing, either scarf or finger joint, were significantly lower than the strengths of unjointed beams, as shown in Figure 5.12 for MOR and Figure 5.13 for MOE. The stresses that could develop in the glue line or in the wood during bending, either in flatwise or edgewise direction, are tension, compression, and shear (Hoadley 1980) with face-to-face gluing and without joints (Figure 5.5). The introduction of end-to-end gluing

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Table 5.9. Analysis of adjusted variance of MOR and MOE in 3-ply beams from untreated SYP

Source of variation	DF	F-values		F-tables	
		MOR	MOE	α = 0.05	0.01
Main factor					
Joint type (T)	1	22.69**	34.07**	3.94	6.90
Joint configuration (C)	3	31.58**	53.89**	2.46	3.51
A vs. B design (V)	1	3.37	4.10*	3.94	6.90
Bending direction (B)	1	3.68	3.01	3.94	6.90
Interactions:					
T*C	3	17.63**	16.40**	2.46	3.51
T*V	1	0.01	0.29	3.94	6.90
T* B	1	0.46	0.52	3.94	6.90
C*V	3	1.10	1.38	2.46	3.51
C*B	3	0.80	0.45	2.46	3.51
V*B	1	1.02	1.98	3.94	6.90
T*C*V	3	1.19	1.82	2.46	3.51
T*C *B	3	0.27	0.19	2.46	3.51
C*V*B	3	3.33*	3.67**	2.46	3.51
T *V*B	1	1.17	1.01	3.94	6.90
T*C*V*B	3	2.59*	2.70*	2.46	3.51

** and *denote significance at 0.01 and 0.05 levels, respectively

(table cont'd)

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Source of variation	DF	F-values		F-tables	
		MOR	MOE	$\alpha = 0.05$	0.01
Covariates					
LW percentage (X1)	1	19.77**	17.23**	3.94	6.90
A_H[1] (X2)	1	4.22*	5.72*	3.94	6.90
A_V[2] (X3)	1	3.79	3.60	3.94	6.90
Error	93				
X1[3]		40.60			
X2[4]		9.60			
X3[5]		9.15			
Y[6]		1.4683	1.6434		
CV[7]		7.58	9.67		

[1]Angle of growth rings to the horizontal glue line
[2]Angle of growth rings to the vertical glue line
[3]Average of LW percentage
[4]Average of A_H
[5]Average of A_V
[6]Average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[7]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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Table 5.10. Multiple regression analysis of MOR and MOE in 3-ply beams from untreated SYP
($Y = bo + b1X1 + b2X2 + b3X3$)

Source of variation	DF	MOR			MOE		
		bi[1]	F-values	R_p[2]	bi	F-values	R_p
Intercept[3], bo	1	0.80569	-		1.08108	-	
LW percentage (X1), b1	1	0.01648	19.77**	+0.872**	0.01160	17.23**	+0.852**
Angle of growth rings to the horizontal glue line (X2), b2	1	-0.00207	4.22*	-0. 804**	-0.00281	5.72**	-0.797**
Angle of growth rings to the vertical glue line (X3), b3	1	-0.00043	3.79*	-0.759**	-0.00167	3.60*	-0.765**
Error	93						
Y[4]			1.4683			1.6463	
CV[5]			7.58			9.67	
(R^2)[6]			0.829			0.817	

[1] Regression coefficient (slope); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2]Coeff. of partial correlation
[3]Overall average of intercept; for specific values of intercepts of each treatment combination, refer to Table 5.11.
[4]Overall average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[5]Coeff. of variation (%)
[6]Coeff. of determination
** and *denotes significance at 0.01 and 0.05 levels, respectively

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Table 5.11. Deviation (Δ)[1] of intercept, and comparison (d) of average MOR and MOE by Tukey's test for significant difference

Treatment combination[2]	MOR		MOE	
	-- Δ -- (10^4 psi)	-- d --	-- Δ -- (10^6 psi)	-- d --
Unjointed beams				
Flatwise (F)	0.3095	A[3]	0.3818	A
Edgewise (E)	0.2740	AB	0.3623	B
Finger-jointed beams				
- Configuration number:				
1A-F	-0.0779	I	-0.0059	I
1A-E	-0.0861	I	-0.0263	IJ
1B-F	-0.0664	HI	-0.1230	HI
1B-E	-0.0778	I	-0.0157	I
2A-F	-0.1620	JK	-0.1774	LM
2A-E	-0.1747	K	-0.1999	M
2B-F	-0.1499	J	-0.1620	L
2B-E	-0.1673	JK	-0.1859	L/M
3A-F	-0.2328	L	-0.2707	N
3A-E	-0.2604	LH	-0.2837	NO
3B-F	-0.2301	KL	-0.2483	O
3B-E	-0.2408	L	-0.2592	P

(table cont'd)

[1] For specific values of intercept for each treatment combination: add Δ to the overall average of intercept

[2] Refer to Appendix E.3. for the meaning of each treatment combination

[3] Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H>I>J)

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Treatment combination[2]	MOR		MOE	
	–Δ– (10^4 psi)	–d–	–Δ– (10^6 psi)	–d–
Scarf-jointed beams				
- Configuration number:				
1A-F	0.2164	C[3]	0.1948	E
1A-E	0.1840	D	0.1762	EF
1B-F	0.2295	BC	0.2309	D
1B-E	0.1949	CD	0.1863	E
2A-F	0.1201	E	0.0858	G
2A-E	0.0817	F	0.0664	GH
2B-F	0.1310	E	0.0859	G
2B-E	0.0966	EF	0.0721	G
3A-F	0.0303	G	0.0080	HI
3A-E	0.0100	G	-0.0280	J
3B-F	0.0370	FG	0.0095	H
3B-E	0.0187	G	0.0079	HI
Overall average of intercept[4]	0.9811		1.1537	

[1]For specific values of intercept for each treatment combination: add Δ to the overall average of intercept

[2]Refer to Appendix E.3. for the meaning of each treatment combination

[3]Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H>I>J)

[4]Refers to Table 5.10

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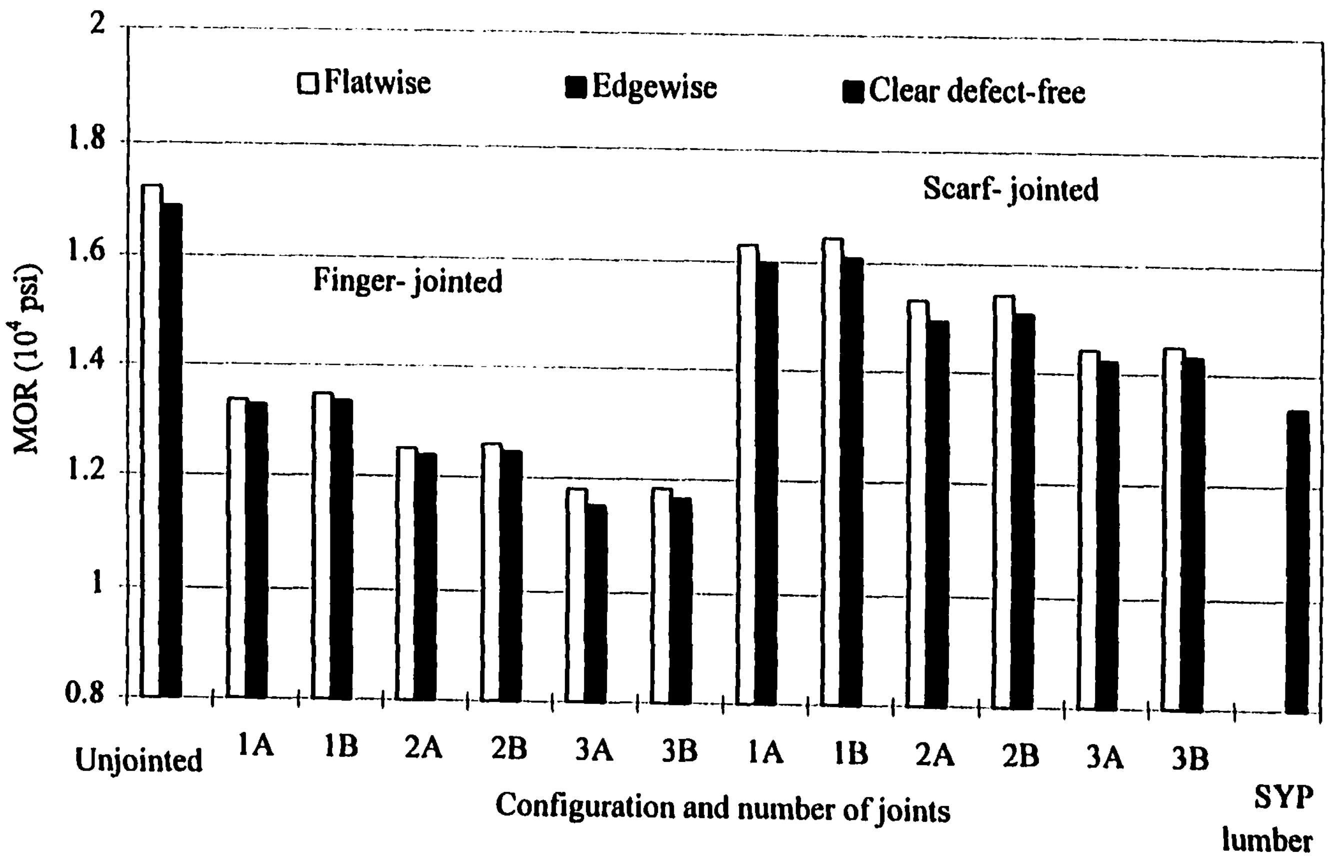

Figure 5.12. MOR of 3-ply laminated beams (LW=40.60%; A_{II}=9.63; and A_V=9.16).

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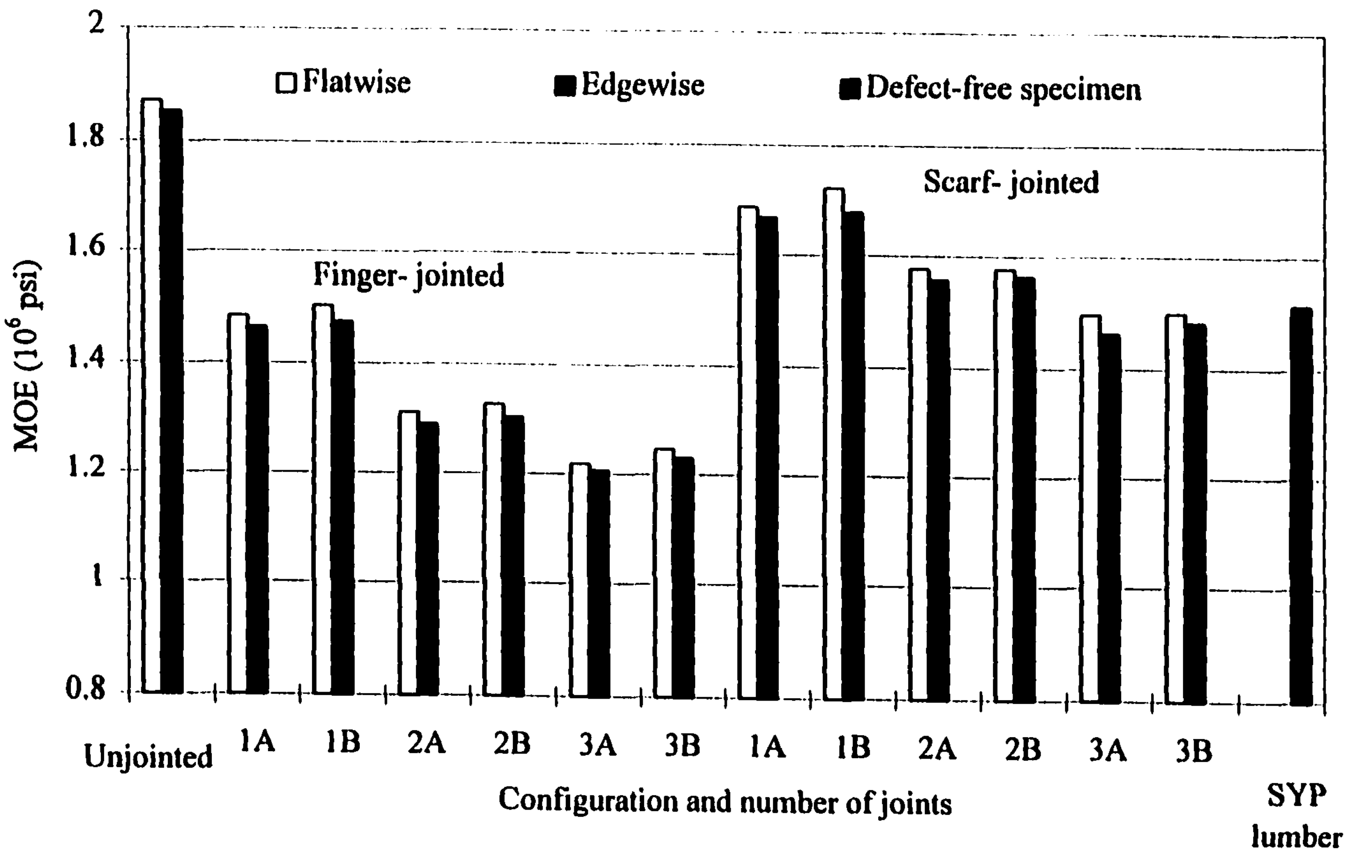

Figure 5.13. MOE of 3-ply laminated beams (LW=40.60%; A_{II}=9.63; and A_V=9.16).

created more weakness area in the beams and therefore might affect negatively the three types of stresses in bending.

Further evaluation by Tukey's test (Table 5.11) demonstrates that increasing the number of scarf and finger joints caused a steady reduction in strengths in both flatwise and edgewise directions. As shown in Table 5.2, the number of joints (finger or scarf) in the exterior part of the beam are constant (2 for design A; or 4 for design B), regardless of different configurations; whereas the number of joints in the interior part varies from 2 to 8 in design A, and 1 to 8 in design B. Therefore, increasing the number of joints in the interior could negatively affect the capability of the internal stresses that develop in the beam, to resist flatwise or edgewise bending.

The application of scarf joints with configurations 3A (10 joints) and 3B (12 joints) reduced the strengths about 13 percent in MOR (Figure 5.12) and 19 percent in MOE (Figure 5.13), as compared with the unjointed beams, in both flatwise and edgewise directions. However, the MOR of these scarf jointed beams was higher than defect-free SYP lumber, whereas MOE was comparable to defect-free SYP. This means that beams with many scarf joints, i.e., 13 laminae in design A and 15 laminae in design B (Table 5.2), could still have satisfactory strengths. In configurations 3A and 3B, the Tukey's test (Table 5.11) indicates no significant difference in MOR between design A and design B, and between flatwise and edgewise directions; however, the MOE in flatwise direction and in design B was greater than in edgewise direction and in design A, respectively. In the scarf-jointed beams with configurations 3A and 3B, design B used more joints (12) and more

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laminae (15) than design A (10 and 13, respectively). The lower MOE in configuration 3A was due to the location of the two joints in the midspan of the beam; while in configuration 3B, there was no joint in the midspan (Figure 5.7). Therefore, in design A the beams have more weak area for internal stresses to develop in either flatwise or edwise bending than in design B.

The introduction of finger joints with configurations 1A and 1B in the 3-plý beams (Figure 5.7) reduced the strength of about 20 percent in both MOR (Figure 5.12) and MOE (Figure 5.13) as compared with the unjointed 3-ply beams. However, MOR and MOE of these finger-jointed beams were still comparable to those of the defect-free SYP lumber. In this case, both MOR and MOE show no significant difference between configuration 1A and configuration 1B, and between flatwise and edgewise directions, as shown by the Tukey's test (Table 5.11). In configuration 1A, the beams have two finger joints located in the exterior midspan, whereas in configuration 1B the beams have only one finger joint in the interior midspan (Figure 5.7). Theoretically, the former could be expected to be weaker than the later; however, no significant difference occurred in strengths between configuration 1A and configuration 1B in either flatwise or edgewise bending. This means that 3-ply beams can achieve satisfactory strengths with 4 finger joints and 7 laminae in configuration 1A or 5 finger joints and 8 laminae in configuration 1B. The Tukey's test (Table 5.11), however, indicates that overall MOR (Figure 5.12) and MOE (Figure 5.13) of finger-jointed beams were significantly lower than scarf-jointed beams. Gillepsie, at al. (1978) stated that such reduced strengths were due to the smaller effective bond area of finger joints (18.0 sq. in.), as compared with scarf joints (24.2 sq. in.)

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Analysis of adjusted variance (Table 5.9) and multiple regression analysis (Table 5.10) shows that strengths were affected positively by LW percentage (R_p = 0.872** for MOR, and 0.852** for MOE) and negatively by AGR (R_p = -0.804** for MOR, and -0.797** for MOE to the horizontal glue line; and R_p = -0.759** for MOR, and -0.765** for MOE to the vertical glue line), whereby the F-values of AGR to horizontal glue line were greater than to vertical glue line (4.22* vs. 3.79 for MOR, and 5.72* vs. 3.60 for MOE).

Comparison between three-ply beams made of treated poles and of untreated SYP

Because of the satisfactory performance of scarf-jointed beams from untreated SYP with configurations 3A and 3B (Figures 5.12 and 5.13), fabrication of scarf-jointed beams from treated poles was made with the same configurations. Strength values and other details of the fabricated 3-ply beams from treated poles, in comparison with untreated SYP, are presented in Appendix E.4. The analysis of adjusted variance (Table 5.12) indicates that strengths were significantly affected by scarf-joint configurations, joint designs (A vs. B), and by the interaction between bending direction and types of laminae (untreated vs. treated). The significant effect of these variables was further described by multiple regression analysis (Table 5.13) as shown by the differences in intercepts for MOR and MOE. The Tukey's test (Table 5.14) confirms that the differences were significant, whereby MOR (Figure 5.14) and MOE (Figure 5.15) of beams from treated poles were lower than from untreated SYP. The Tukey's test also shows that strengths of the beams from untreated SYP in the flatwise direction was significantly greater than in the edgewise direction, which was the opposite for beams from treated poles. In addition, the test

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Table 5.12. Analysis of adjusted variance of MOR and MOE in 3-ply beams from untreated SYP and treated poles

Source of variation	DF	F-values		F-tables	
		MOR	MOE	α = 0.05	0.01
<u>Main factor</u>					
Joint configuration (C)	1	41.17**	17.25**	4.18	7.60
A vs. B design (T)	1	5.44*	6.60*	4.18	7.60
Bending direction (B)	1	0.12	0.09	4.18	7.60
Treated vs. untreated laminae (U)	1	11.25**	14.52**	4.18	7.60
Interactions:					
C*T	1	0.48	0.65	4.18	7.60
C*B	1	0.04	0.53	4.18	7.60
C*U	1	0.13	0.13	4.18	7.60
T*B	1	0.11	0.17	4.18	7.60
T*U	1	1.32	0.47	4.18	7.60
B*U	1	8.08**	12.34**	4.18	7.60
C*T*B	1	0.20	0.14	4.18	7.60
C*T*U	1	0.96	0.17	4.18	7.60
C*B*U	1	0.27	0.32	4.18	7.60
T*B*U	1	0.31	0.36	4.18	7.60
C*T*B*U	1	0.67	1.13	4.18	7.60

(table cont'd)

** and *denote significance at 0.01 and 0.05 levels, respectively

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Source of variation	DF	F-values		F-tables	
		MOR	MOE	$\alpha = 0.05$	0.01
Covariates					
LW percentage (X1)	1	12.75**	22.48**	4.18	7.60
A_H[1] (X2)	1	5.63*	6.67*	4.18	7.60
A_V[2] (X3)	1	4.46*	4.52*	4.18	7.60
Error	29				
X1[3]		—— 41.69 ——			
X2[4]		—— 10.08 ——			
X3[5]		—— 9.53 ——			
Y[6]		1.5587	1.6586		
CV[7]		8.63	9.38		

[1]Angle of growth rings to the horizontal glue line
[2]Angle of growth rings to the vertical glue line
[3]Average of LW percentage
[4]Average of A_H
[5]Average of A_V
[6]Average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[7]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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Table 5.13. Multiple regression analysis of MOR and MOE in 3-ply beams from untreated SYP and treated poles (Y= bo + b1X1 + b2X2 + b3X3)

Source of variation	DF	MOR			MOE		
		bi[1]	F-values	R_p[2]	bi	F-values	R_p
Intercept[3], bo	1	0.99773	-		1.11261	-	
LW percentage (X1), b1	1	0.01492	12.75**	0.923**	0.01207	22.48**	0.917**
Angle of growth rings to the horizontal glue line (X2), b2	1	-0.00216	5.63*	-0.836**	-0.00291	6.67**	-0.853**
Angle of growth rings to the vertical glue line (X3), b3	1	-0.00107	4.46*	-0.817**	-0.00174	4.52*	-0.825**
Error	93						
Y[4]			1.5587			1.6586	
CV[5]			8.63			9.38	
(R^2)[6]			0.816			0.794	

[1] Regression coefficient (slope); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2] Coeff. of partial correlation
[3] Overall average of intercept; for specific values of intercepts of each treatment combination, refer to Table 5.14.
[4] Overall average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[5] Coeff. of variation (%)
[6] Coeff. of determination
** and *denotes significance at 0.01 and 0.05 levels, respectively

Table 5.14. Deviation (Δ)[1] of intercept, and comparison (d) of average MOR and MOE by Tukey's test for significant difference

Treatment combination[2]	MOR		MOE	
	-- Δ -- (10^4 psi)	-- d --	-- Δ -- (10^6 psi)	-- d --
Untreated SYP				
Unjointed beams				
Flatwise (F)	0.2547	A[3]	0.3246	A
Edgewise (E)	0.2033	AB	0.2636	B
Scarf-jointed beams				
- Configuration number				
3A-F	-0.0472	E	-0.0828	FG
3A-E	- 0.0638	F	-0.1057	G
3B-F	- 0.0190	D	-0.0476	F
3B-E	- 0.0481	E	-0.0929	FG
Treated poles				
Unjointed beams				
F	0.1283	C	0.1931	CD
E	0.1814	B	0.2436	B
Scarf-jointed beams				
- Configuration number				
3A-F	- 0.1751	G	-0.2159	I
3A-E	- 0.1465	FG	-0.1615	G
3B-F	- 0.1521	FG	-0.1917	HI
3B-E	- 0.1141	EF	-0.1263	FG
Overall average of intercept[4]	0.9977		1.1126	

[1]For specific values of intercept for each treatment combination: add Δ to the overall average of intercept
[2]Refer to Appendix E.4, for the meaning of each treatment configuration
[3]Similar letters indicate no significant difference exists (A>B>C>D>E>F>G>H>I)
[4]Refer to Table 5.13

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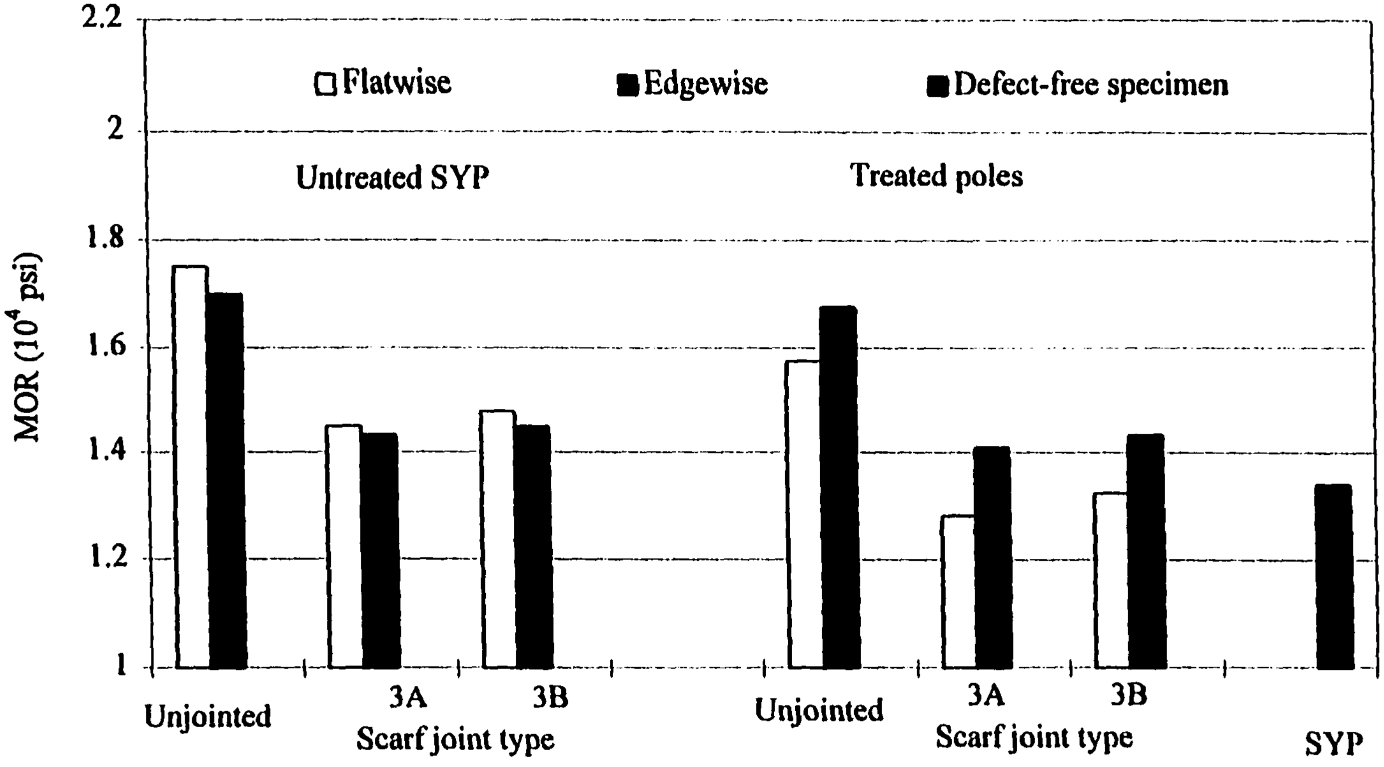

Figure 5.14. MOR of unjointed and scarf-jointed 3-ply beams
(LW=41.69 %; A_H=10.02; and A_V=9.53)

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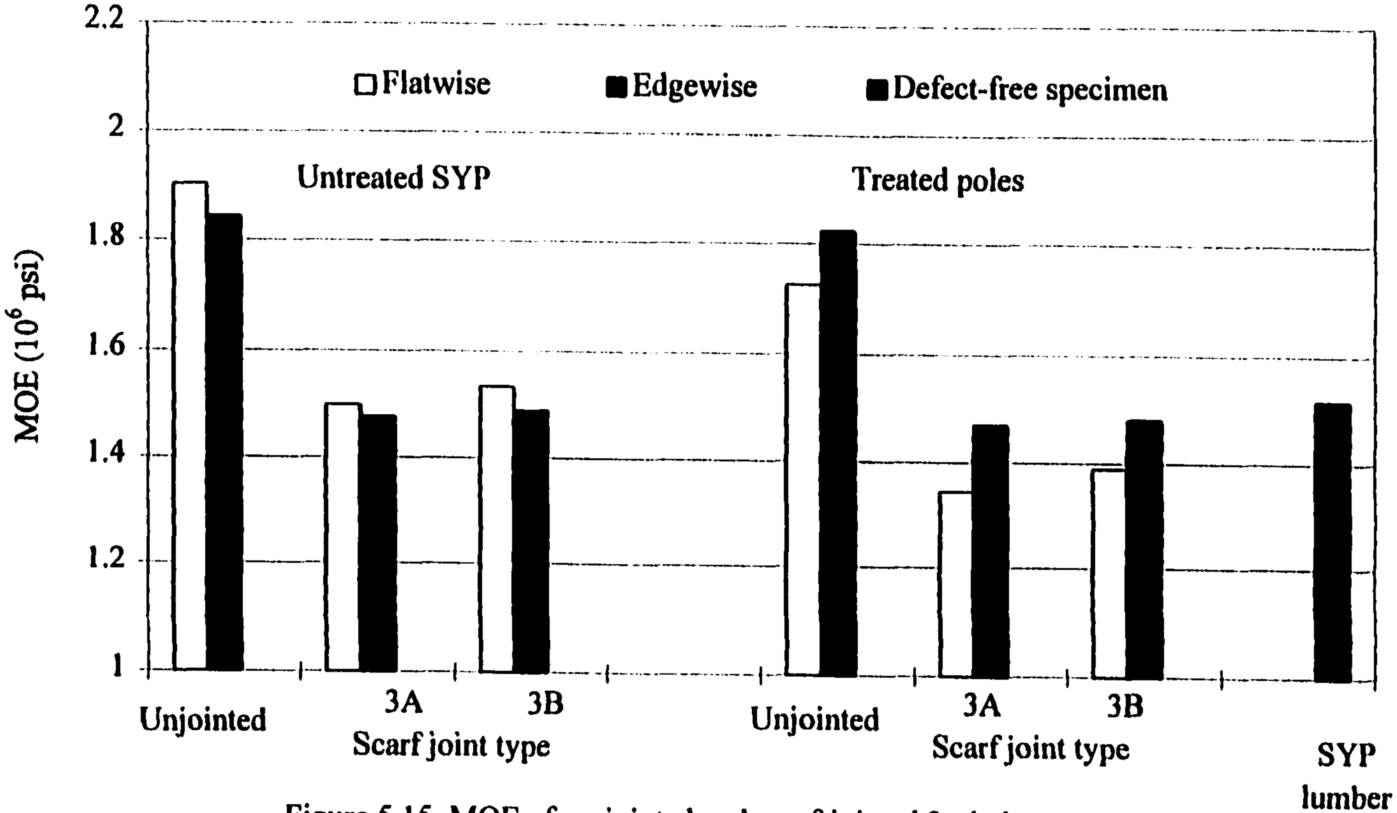

Figure 5.15. MOE of un-jointed and scarf-jointed 3-ply beams
(LW=41.69 %; A_{II}=10.02; and A_V=9.53)

confirms that beams in design B tended to be significantly greater in strengths than design A.

Overall values of MOR and MOE for unjointed beams from treated poles were about 93 percent of those from untreated poles. The Tukey's test (Table 5.14) shows that this difference is not significant for unjointed beams in the edgewise direction, but significant for unjointed beams in the flatwise direction. The latter again indicates that residual creosote on the horizontal glue-line area in treated beams interfered with bonding, thereby relieving some internal shear stress during flatwise bending. On the contrary, gluing on the vertical surface of untreated SYP or treated pole gave no significant difference in the edgewise strengths of these unjointed 3-ply laminated products.

The introduction of scarf joints in beams with configurations 3A and 3B in treated poles caused a significant 19-20 percent reduction in both MOR (Figure 5.14) and MOE (Figure 5.15) as compared with unjointed treated beams. However, the Tukey's test (Table 5.14) indicates that MOR and MOE of these scarf-jointed beams in treated poles in the edgewise direction were not significantly different from the same beams in untreated SYP in the same direction. Also, no significant difference in MOR and MOE occurred between configurations 3A and 3B in the edgewise direction of treated beams. Moreover, MOR and MOE values of these scarf-jointed beams were still comparable to those of defect-free SYP lumber. This means that the application of scarf joints with configurations 3A and 3B for 3-ply beams from treated poles and from untreated SYP could result in similar edgewise strengths. Therefore, in fabricating 3-ply scarf-jointed beams with 96-inch length and 3-inch

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depth, satisfactory strengths in the edgewise direction could be achieved using as many as 10 joints and 13 laminae in configuration 3A, and 12 joints and 15 laminae in configuration 3B (Figure 5.7; Table 5.2) from treated wood poles having residual creosote contents of 8-11 percent. On the other hand, MOR (Figure 5.14) and MOE (Figure 5.15) of scarf-jointed beams in treated poles with configurations 3A and 3B in flatwise direction was significantly lower than in edgewise direction. Again, this was due to interference of residual creosote on gluing in the horizontal glue-line area which resulted in some relief of internal shear stress during bending. In addition, MOR and MOE of these scarf-jointed treated beams in flatwise direction were lower than defect-free SYP lumber.

As with the 3-ply beams in untreated SYP, strengths in treated poles are also correlated positively with LW percentage (R_p = 0.923** for MOR, 0.917** for MOE), and negatively with AGR to horizontal glue line (R_p = -0.836** for MOR, and -0.853** for MOE) and to vertical glue line (R_p = -0.817** for MOR, and -0.825** for MOE), as shown by multiple regression analysis (Table 5.13).

Comparison between unjointed two- and three-ply laminated beams

Strengths of both unjointed 2- and 3-ply beams in untreated SYP and treated poles are shown in Appendix E.5. Analysis of adjusted variance (Table 5.15) indicates the significant effect of interaction between types of laminae (untreated vs. treated), number of unjointed glued laminae (2 vs. 3), and bending direction on strengths. The significant interaction was given by variability in the intercepts value for both MOR and MOE from the multiple regression analysis (Table 5.16). The Tukey's test (Table 5.17) explained the variability, which shows that MOR (Figure

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Table 5.15. Analysis of adjusted variance of MOR and MOE in unjointed 2- and 3-ply beams from untreated SYP and treated poles

Source of variation	DF	F-values		F-tables	
		MOR	MOE	α = 0.05	0.01
Main factor					
Untreated vs treated laminae (T)	1	24.28**	31.37**	4.45	8.40
2- vs 3-ply (P)	1	0.22	1.30	4.45	8.40
Bending direction (B)	1	13.01**	19.94**	4.45	8.40
Interactions:					
T*P	1	0.31	1.01	4.45	8.40
T*B	1	28.08	45.98	4.45	8.40
P*B	1	0.29	1.45	4.45	8.40
T*P*B	1	6.04*	5.62*	4.45	8.40
Covariates					
LW percentage (X1)	1	19.11**	28.79**	4.45	8.40
A_H[1] (X2)	1	12.89**	8.94**	4.45	8.40
A_V[2] (X3)	1	4.59*	3.12	4.45	8.40
Error	17				
X1[3]		------ 39.64 -------			
X2[4]		------ 10.80 -------			
X3[5]		------ 11.00 -------			
Y[6]		1.5939	1.7845		
CV[7]		6.06	8.27		

[1]Angle of growth rings to the horizontal glue line
[2]Angle of growth rings to the vertical glue line
[3]Average of LW percentage
[4]Average of A_H
[5]Average of A_V
[6]Average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[7]Coeff. of variation (%)
** and *denote significance at 0.01 and 0.05 levels, respectively

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Table 5.16. Multiple regression analysis of MOR and MOE in unjointed 2- and 3-ply beams from untreated SYP and treated poles ($Y = bo + b1X1 + b2X2 + b3X3$)

Source of variation	DF	MOR			MOE		
		bi[1]	F-values	R_p[2]	bi	F-values	R_p
Intercept[3], bo	1	1.01129	-		1.19468	-	
LW percentage (X1), b1	1	0.01744	19.155**	+0.923**	0.01679	28.79**	+0.936**
Angle of growth rings to the horizontal glue line (X2), b2	1	-0.00186	12.89**	-0.864**	-0.00153	8.94**	-0.847**
Angle of growth rings to the vertical glue line (X3), b3	1	-0.00046	4.39*	-0.812**	-0.00050	3.12*	-0.791**
Error	29						
Y[4]			1.5939			1.7845	
CV[5]			6.06			8.27	
(R^2)[6]			0.837			0.809	

[1]Regression coefficient (slope); i = 1 (bo), 1 (b1), 2 (b2), 3 (b3)
[2]Coeff. of partial correlation
[3]Overall average of intercept; for specific values of intercepts of each treatment combination, refer to Table 5.17.
[4]Overall average of MOR (10^4 psi) and MOE (10^6 psi), respectively
[5]Coeff. of variation (%)
[6]Coeff. of determination
** and *denotes significance at 0.01 and 0.05 levels, respectively

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Table 5.17. Deviation (Δ)[1] of intercept, and comparison (d) of average MOR and MOE by Tukey's test for significant difference

Treatment combination[2]	MOR		MOE	
	-- Δ -- (10^4 psi)	-- d --	-- Δ -- (10^6 psi)	-- d --
Untreated SYP[1]				
2-ply flatwise[3]	0.0375	A[3]	0.0346	A
2-ply edgewise	0.0298	AB	0.0270	AB
3-ply flatwise[3]	0.0368	A	0.0403	A
3-ply edgewise	0.0320	A	0.0374	A
Treated poles[2]				
2-ply flatwise	-0.0915	F	-0.0865	G
2-ply edgewise	0.0262	B	0.0231	B
3-ply flatwise	-0.0988	FG	-0.1063	GH
3-ply edgewise	0.0279	AB	0.0302	AB
Overall average of intercept[4]	1.0113		1.1947	

[1]For specific values of intercept for each treatment combination: add Δ to the overall average of intercept
[2]Refer to Appendix E.5, for the meaning of each treatment configuration
[3]Similar letters indicate that no significant difference exists (A>B>C>D>E>F>G>H)
[4]Refer to Table 5.16

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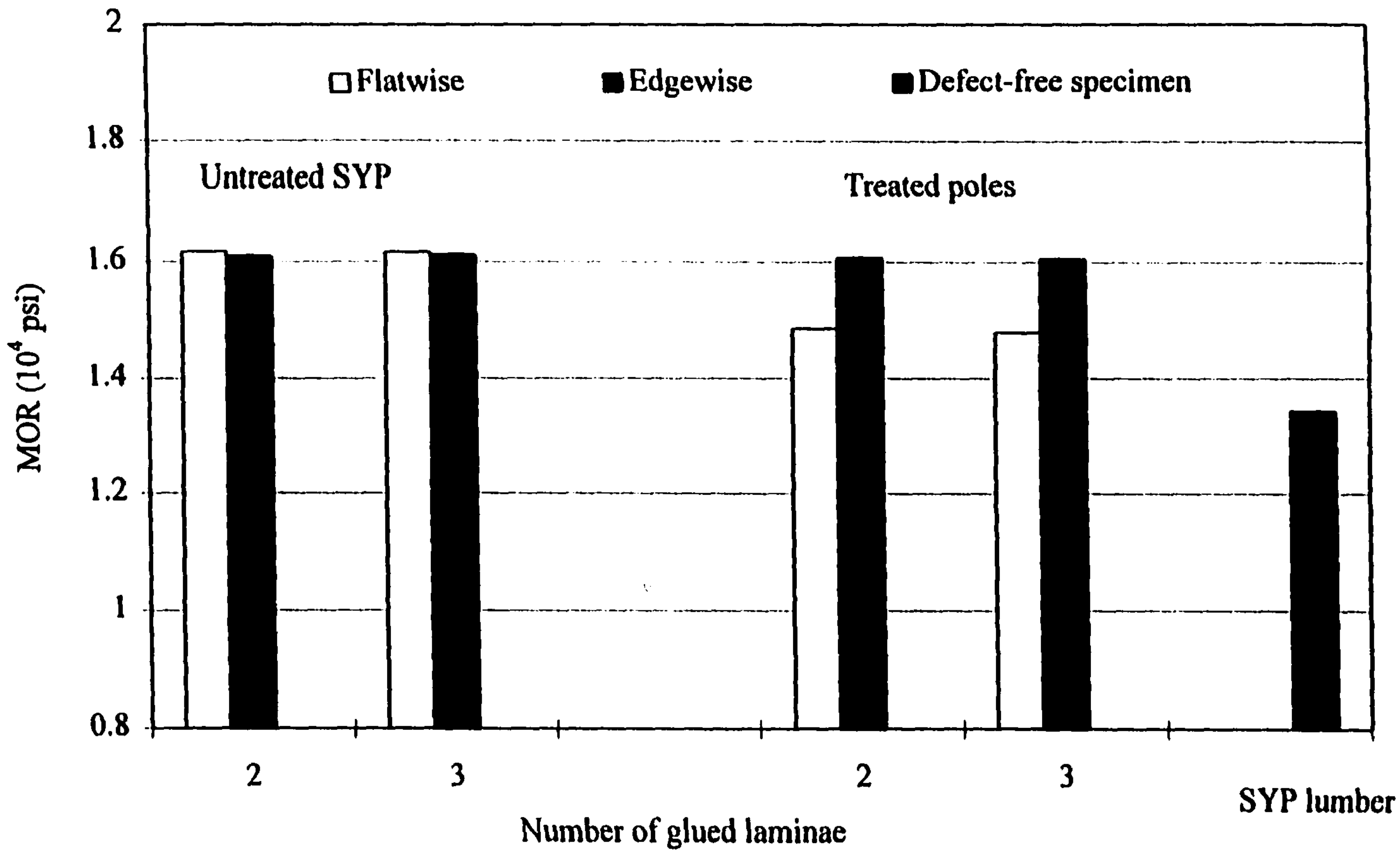

Figure 5.16. MOR of unjointed 2- and 3-ply beams
(LW=39.64 %; A_{II}=10.80; and A_V=11.01)

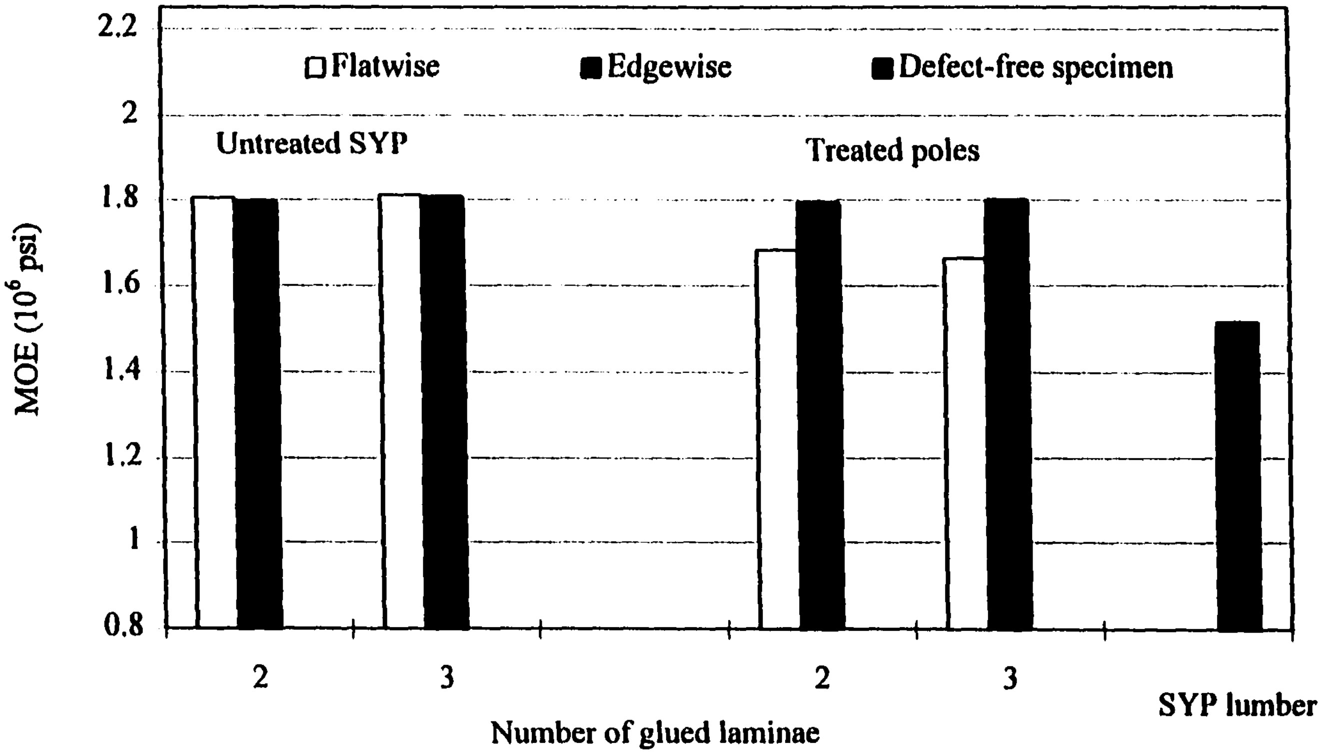

Figure 5.17. MOE of unjointed 2- and 3-ply beams ($LW=39.64\%; A_{II}=10.80$; and $A_V=11.01$).

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5.16) and MOE (Figure 5.17) of these beams from treated poles were lower than those from untreated SYP. Also, strengths of flatwise beams from treated poles were lower than those of edgewise beams. The result was the opposite of untreated SYP, due to bonding interference by residual creosote on the horizontal glue line.

The Tukey's test (Table 5.17) further indicates no significant difference of MOR and MOE in either flatwise or edgewise direction, with respect to untreated SYP, for 2-and 3-ply beams. But with respect to treated poles, strengths of 3-ply beams were somewhat lower than those of 2-ply beams, in flatwise direction. The reason is that the 2-ply beams had only one layer of glue line, whereas the 3-ply beams had two layers, thereby doubling the opportunity for bonding interference by the residual creosote. MOR and MOE from treated poles, in the flatwise direction were about 90 and 93 percent, respectively for 2-ply, and 87 and 90 percent, respectively for 3-ply beams, as compared to 2- and 3-ply beams from untreated SYP. On the other hand, in the edgewise direction, MOR and MOE were not significantly different between treated poles and untreated SYP, and between 2-ply and 3-ply beams. The overall strengths of unjointed 2- and 3-ply beams in untreated SYP or in treated poles were still satisfactory, as compared with those of defect-free SYP lumber (Figure 5.16 for MOR, and Figure 5.17 for MOE).

Conclusions

Fabricating 2- and 3-ply laminated beams from untreated SYP and treated pole laminae by edge-to-edge gluing variations, bonding models or bonding configurations (number of glued laminae), and bending direction (flatwise and edgewise) resulted in diverse strength properties. Two-ply beams from treated poles

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were lower in strengths than untreated SYP. Also, strengths decreased progressively with increase in the number of laminae.

In untreated SYP, the strengths of 3-ply laminated beams with end-to-end gluing decreased consistently with increase in the number of joints. The effect is less with scarf joints than with finger joints. Beams with joint design B in flatwise and edgewise directions resulted in slightly higher strengths than with joint design A in the same directions, respectively.

In treated poles, the strengths of unjointed and scarf-jointed 3-ply laminated beams were lower than those in untreated SYP of the same gluing configuration, especially in flatwise bending. In unjointed 2- and 3-ply beams, the strengths in the flatwise direction were lower than in the edgewise direction for treated poles, and the opposite for untreated SYP.

In all beams, whether treated or untreated, strengths were greater for higher LW percentage, and were lower with greater angle of growth rings to the glue line. The effect of angle to the horizontal glue line was more pronounced than the angle to the vertical line.

Strength properties of 2-ply beams with edge-to-edge gluing and 3-ply beams with end-to-end gluing in untreated SYP and in treated poles compared well with those of defect-free SYP lumber. This encouraging result suggests that out-of-service poles can be utilized for manufacture of engineered wood products with satisfactory results. High performance laminated beams can be fabricated by placing laminae with high strength and high creosote content on the surface, and low

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strength and low creosote content in the inside, with little or no additional preservative treatment

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SUMMARY AND CONCLUSIONS

This study on the recycling potential of out-of-service utility poles for value-added products involved (1) basic properties of waste poles and (2) development of useful engineered wood products from these poles. Basic properties of treated wood poles investigated were residual creosote content, strengths, dimensional stability related to exposure to moisture (swelling), lumber recovery, and decay resistance. In engineered wood products, investigation included gluability of poles and performance of glued-laminated beams.

Residual creosote contents were determined with the standard toluene extraction method. Long-term weathering caused the distribution of residual creosote in the poles to follow a specific pattern. Creosote contents were found to be higher in the bottom and inner portions of used poles than in the upper and outer portions. Poles in service 5 years had higher creosote content than those in service 25 years, but both contained much lower creosote than in poles which had been freshly treated.

In an effort to find a better and quicker procedure than the time-consuming toluene extraction method, the electronic spectrometry method was also used for creosote content determination. The results were still compatible. Slight differences in results between spectrometry, especially in 5- and 25-year poles, and toluene extraction were attributed to long-term weathering which resulted in an increase in maximum-absorbance wavelength of residual creosote in old poles, indicating that the creosote contained greater proportion of high-boiling compounds due to the more

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evaporation of low-boiling fractions compared to that in freshly treated poles. The difference in this proportion affected the readings of the spectrometry instrument, which relied upon the wavelength.

Steaming was applied to the weathered poles in an effort to learn its effectiveness in removing or eliminating the residual creosote. Regardless of initial contents of creosote, steaming reduced it to about 1.5 percent, which was less effective than solvent extraction since it can remove the creosote leaving practically zero percent. Also, removal by steaming was more difficult for poles with longer service duration and for poles from the inner portions. Steaming, however, is an efficient and cheap method of reducing the creosote content in treated poles.

Strength properties were determined for modulus of rupture, modulus of elasticity, and solid-wood shear on the defect-free parts of treated poles and untreated southern pine lumber. Poles after 25 years in service still maintained all strength properties which were comparable to those of freshly treated poles and untreated southern pine. However, the strengths of all treated poles decreased consistently from the outer surface to the pith, and from the bottom to top. The variations in strengths was found to be due to variation in latewood percentage in the poles. Dimensional stability decreased proportionately with latewood percentage. However, for a given latewood percentage, dimensional stability improved with greater creosote contents. Swelling was least in freshly treated poles, and greatest in 25-year old poles and in untreated southern pine. The loss of creosote with pole aging was further followed by reduction in the relative recovery of defect-free lumber from the poles. However, the lumber recovery factors of weathered poles

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were still comparable to the recovery of lumber produced from log-sawing operations.

Variations in decay resistance were directly related to creosote contents in treated poles. Those with creosote contents above 14 percent level still had an effective decay resistance, while the resistance of those below that level decreased substantially. As a result, reduction in decay resistance was greatest in weathered 25-year poles, much less in 5-year poles, and negligible in freshly treated poles. In the outer portions of 25-year poles, the decay resistance was very low, approaching to that of untreated southern pine lumber. Decay resistance was also higher at the bottom of treated poles, and least in the top. These results indicate that many parts of used poles, especially those with only 5-year service, are still effective in their decay resistance; therefore, used poles can be beneficial for reutilization and their conversion into useful wood products.

Gluability evaluated the strength of glue-to-wood bond in weathered poles, with three types adhesives (resorcinol-phenol formaldehyde, polyvinyl acetate, and casein glue), using glue-line shear and percent wood failure. The bond strength was related to the creosote content. The lower the creosote, the better the gluability. Wood poles with low creosote contents, such as in 25-year poles, had gluing properties comparable to untreated southern pine. In all the adhesives used, glue bonds were also affected positively by latewood percentage, and negatively by angle of growth rings to the glue line. From the gluing of untreated SYP, the best gluability was provided with resorcinol-phenol formaldehyde, and the least with casein glue.

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Performance of glue-laminated beams included fabrication of 2- and 3-ply beams from treated poles as well as untreated southern pine. The 2-ply beams were assembled in four edge-to-edge gluing models consisting of 2, 4, 5, and 7 laminae, such that the beams had horizontal and vertical glue lines. The beams with two glued laminae were also called unjointed 2-ply beams. The results indicate that increasing the number of glued laminae caused a consistent reduction in beam strengths. In treated poles, the strengths of beams were lower than those in untreated southern pine due to interference of residual creosote on the horizontal glue line. The vertical glue line had negligible effect on strengths of flatwise and edgewise beams.

Fabrication of 3-ply beams involved those with and without end-to-end gluings (unjointed). Fabrication with end-to-end gluing was arranged such that the numbers of glued laminae and joints were variable; and also two joint designs (A and B) were introduced, whereby the former had two joints located in the midspan of beams and the later had only one joint or none in the midspan. In untreated southern pine with end-to-end gluing, the strengths of both scarf-and finger-jointed beams were lower than those of unjointed beams. Furthermore, these beams decreased in strengths consistently with increasing numbers of joints. The effect was less with scarf joints than with finger joints. Beams with joint design B (5, 8, or 12 joints) in flatwise and edgewise directions had higher strengths than with joint design A (4, 6, or 10 joints) in the same directions, respectively.

In treated poles, the strengths of unjointed and scarf-jointed 3-ply laminated beams were lower than those in untreated southern pine of the same gluing configuration, especially in flatwise bending. In unjointed 2- and 3-ply beams for

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treated poles, the strengths in the flatwise direction were lower than in edgewise direction, and were the opposite for untreated southern pine. The edgewise strengths of the unjointed 2- and 3-ply beams were not affected by gluing on the vertical surface of treated poles as well as untreated southern pine.

In all beams, whether treated or untreated, strengths were greater for higher latewood percentage, and were lower with greater angle of growth rings to the glue line. The effect of angle to the horizontal glue line was more pronounced than angle to the vertical glue line.

Strength properties of 2-ply beams with edge-to-edge gluing and 3-ply beams with end-to-end gluing in untreated southern pine as well as in treated poles compared well with those of defect-free southern pine lumber

All these encouraging results suggest that high performance laminated products from out-of-service poles can be obtained if all the factors affecting strengths, such as level of creosote content, number of glued laminae, gluing arrangement, bending direction, latewood percentage, and angle of growth rings to the glue line are taken into consideration.

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Appendix A.1. Averages of initial creosote content (C_i), final creosote content (C_f), and approximate steaming duration (t) required to reach C_f[1]

Service duration	Sample location						
	Vertical location	Horizontal distance from pole surface (in.)					
		0.5			3.5		
		C_i (%)	C_f (%)	t (hours)	C_i (%)	C_f (%)	t (hours)
Freshly treated	Top	33.12	1.21	2.194	22.68	1.31	1.448
	Middle	34.17	1.32	2.167	24.11	1.39	1.548
	Bottom	32.22	1.26	2.031	23.64	1.28	1.515
5 years	Top	8.49	1.41	0.607	13.79	1.27	1.055
	Middle	10.98	1.39	0.779	14.21	1.32	1.084
	Bottom	11.65	1.28	0.826	14.48	1.31	1.103
25 years	Top	2.67	1.31	0.310	11.41	1.28	0.998
	Middle	3.65	1.29	0.378	12.72	1.25	1.089
	Bottom	3.76	1.43	0.381	12.85	1.27	1.098

[1]Overall averages of effective final creosote content (C_f=1.31%)

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Appendix B.1. Averages of LW percentage and strength properties (MOR, MOE, and shear) of treated poles and untreated SYP

Wood types	Sample codes	LW (%)	MOR (10^4 psi)	MOE (10^6 psi)	Shear (10^3 psi)
Treated poles[1]					
Fresh	v1 h1[2]	39.20	1.308	1.456	1.184
	v1 h2	30.83	1.187	1.432	1.093
	v1 h3	28.11	1.130	1.302	1.024
	v2 h1	45.41	1.392	1.586	1.388
	v2 h2	42.91	1.301	1.510	1.341
	v2 h3	33.24	1.250	1.427	1.242
	v3 h1	56.04	1.683	1.866	1.738
	v3 h2	48.89	1.539	1.723	1.595
	v3 h3	42.32	1.376	1.645	1.409
5 years	v1 h1	39.74	1.292	1.466	1.191
	v1 h2	33.78	1.236	1.427	1.101
	v1 h3	27.85	1.121	1.309	0.989
	v2 h1	47.61	1.402	1.594	1.390
	v2 h2	46.91	1.312	1.530	1.354
	v2 h3	38.61	1.223	1.423	1.199
	v3 h1	56.98	1.707	1.877	1.717
	v3 h2	49.91	1.590	1.691	1.621
	v3 h3	41.63	1.400	1.631	1.421
25 years	v1 h1	40.75	1.281	1.468	1.177
	v1 h2	30.48	1.210	1.520	1.086
	v1 h3	26.06	1.101	1.431	0.987
	v2 h1	44.92	1.399	1.588	1.377
	v2 h2	39.89	1.293	1.520	1.361
	v2 h3	39.33	1.255	1.431	1.231
	v3 h1	55.40	1.691	1.897	1.746
	v3 h2	48.24	1.607	1.716	1.615
	v3 h3	44.10	1.389	1.617	1.431

[1]Average of 5 poles (table cont'd)

[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, and h3 denotes 0.5-, 1.5-. and 2.5-inch distance from pole surface, respectively

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Wood types	Sample codes	LW (%)	MOR (10^4 psi)	MOE (10^6 psi)	Shear (10^3 psi)
Untreated SYP[3]	A	53.84	1.593	1.769	1.676
	B	27.32	1.178	1.358	0.984
	C	25.95	1.151	1.237	0.949
	D	28.98	1.110	1.241	1.027
	E	41.12	1.346	1.597	1.321
	G	31.75	1.163	1.335	1.119
	H	54.12	1.599	1.802	1.709
	I	53.32	1.533	1.728	1.615

[3]Average of 5 specimens for each of sample code

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Appendix B.2. Average of LW percentage, creosote content, and volumetric swelling of treated poles and untreated SYP

Wood types	Sample codes	LW (%)	Creosote content (%)	Volumetric swelling (%)
Treated poles[1]				
Fresh	v1 h1[2]	39.20	33.12	3.019
	v1 h2	30.83	26.82	2.670
	v1 h3	28.11	25.66	2.521
	v2 h1	45.41	34.17	3.662
	v2 h2	42.91	26.99	3.240
	v2 h3	33.24	25.99	2.898
	v3 h1	56.04	32.22	3.721
	v3 h2	43.89	27.89	3.592
	v3 h3	42.32	25.09	2.853
5 years	v1 h1	39.74	8.49	5.030
	v1 h2	33.78	11.48	4.698
	v1 h3	27.85	13.07	3.289
	v2 h1	47.61	10.98	5.771
	v2 h2	46.91	12.91	5.249
	v2 h3	38.61	13.77	4.513
	v3 h1	56.98	11.65	6.380
	v3 h2	45.91	13.04	5.808
	v3 h3	41.63	13.97	4.779
25 years	v1 h1	40.75	2.67	5.883
	v1 h2	30.48	3.65	5.719
	v1 h3	26.06	4.09	5.354
	v2 h1	44.92	3.65	6.772
	v2 h2	39.89	3.70	6.469
	v2 h3	39.33	6.06	5.402
	v3 h1	55.40	3.76	7.861
	v3 h2	44.24	3.83	6.832
	v3 h3	44.10	5.69	6.130

[1]Average of 5 poles (table cont'd)

[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, and h3 denotes 0.5-, 1.5-. and 2.5-in. distance from pole surface, respectively

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Wood types	Sample codes	LW (%)	Creosote content (%)	Volumetric swelling (%)
Untreated SYP[3]	A	53.84	0	8.612
	B	27.32	0	6.579
	C	25.95	0	6.456
	D	28.98	0	6.683
	E	41.12	0	7.874
	G	31.75	0	6.755
	H	54.12	0	8.831
	I	53.32	0	8.871

[3] Average of 5 specimens for each sample code

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Appendix B.3. Averages of dimensions and lumber recovery factor (LRF) of treated poles

Service duration	Vertical location	Length (in)	Midspan circumference (in)	Diameter of bolt (in)	Volume of bolt (in^3)	Total volume of deferct-free lumber (in^3)	LRF
Freshly treated	Top	106	30.16	9.62	7672.54	5560.18	8.69
	Middle	114	31.04	9.89	8740.02	6398.72	8.89
	Bottom	105	35.19	11.21	10347.21	8509.51	9.89
5 years	Top	98	31.10	9.91	7543.75	5260.94	8.48
	Middle	104	32.67	10.40	8834.68	6317.23	8.55
	Bottom	108	33.62	10.69	9711.41	6913.55	8.52
25 years	Top	102	28.43	9.04	6563.29	4047.23	7.40
	Middle	97	31.26	9.96	7542.73	4969.47	7.92
	Bottom	98	32.86	10.46	8422.76	5763.50	8.20

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Appendix C.1. Averages of LW percentage, creosote content, and weight loss of treated poles and untreated SYP

Wood types	Sample codes	LW (%)	Creosote content (%)	Weight loss (%)
Treated poles[1]				
Fresh	v1 h1[2]	36.20	33.12	0.631
	v1 h2	30.94	26.82	0.652
	v1 h3	29.14	25.66	0.671
	v1 h4	28.98	23.68	1.275
	v2 h1	45.81	34.37	0.619
	v2 h2	42.00	26.99	0.592
	v2 h3	33.18	25.99	0.613
	v2 h4	33.03	24.11	1.262
	v3 h1	55.98	32.22	0.595
	v3 h2	44.01	27.89	0.613
	v3 h3	42.52	25.09	0.955
	v3 h4	42.27	23.64	1.276
5 years	v1 h1	38.98	8.49	9.045
	v1 h2	33.65	11.48	4.857
	v1 h3	27.90	13.07	3.108
	v1 h4	27.68	13.79	2.311
	v2 h1	48.02	10.98	5.422
	v2 h2	47.03	12.91	3.283
	v2 h3	38.32	13.77	2.333
	v2 h4	37.94	14.21	1.846
	v3 h1	56.32	11.65	4.680
	v3 h2	44.85	13.04	3.141
	v3 h3	43.07	13.97	2.112
	v3 h4	42.85	14.48	1.598

[1]Average of 5 poles (table cont'd)

[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, h3, and h4 denotes 0.5-, 1.5-. 2.5-, and 3.5-inch distance from pole surface, respectively

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Wood types	Sample codes	LW (%)	Creosote content (%)	Weight loss (%)
Treated poles[1]				
25 years	v1 h1	41.13	2.67	34.829
	v1 h2	30.29	3.65	25.958
	v1 h3	27.95	4.09	22.845
	v1 h4	27.14	11.41	4.945
	v2 h1	44.92	3.65	32.909
	v2 h2	39.89	3.70	25.409
	v2 h3	39.33	6.06	15.771
	v2 h4	38.12	12.72	3.495
	v3 h1	55.40	3.76	31.902
	v3 h2	44.24	3.83	24.220
	v3 h3	44.24	3.83	17.068
	v3 h4	43.61	12.85	3.374
Untreated SYP[3]	L1	32.20	0	44.37
	L2	36.53	0	43.14
	H1	42.52	0	40.98
	H2	50.32	0	38.95

[1]Average of 5 poles
[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, h3, and h4 denotes 0.5-, 1.5-. 2.5-, and 3.5-inch distance from pole surface, respectively
[3] Average of 5 specimens for each sample code

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Appendix D.1. Averages of LW percentage, creosote content, angle of growth rings to the glue line, glue-line shear strength, and wood failure of treated poles and untreated SYP with RPF adhesive

Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3 psi)	Wood failure (%)
Treated poles[1]						
Fresh	v1 h1[2]	39.20	33.72	15	0.7108	57.9
	v1 h2	30.83	26.82	22	0.7493	58.4
	v1 h3	28.11	25.66	27	0.7655	58.9
	v2 h1	45.41	34.17	17	0.7200	58.3
	v2 h2	42.91	26.99	24	0.7623	58.9
	v2 h3	33.24	25.98	26	0.7678	59.4
	v3 h1	56.04	33.82	19	0.7291	58.8
	v3 h2	48.89	27.89	23	0.7638	59.3
	v3 h3	42.32	25.09	25	0.7290	59.7
5 years	v1 h1	39.74	8.49	13	1.1698	76.1
	v1 h2	33.78	11.49	21	0.9445	77.9
	v1 h3	27.85	13.07	25	0.8339	80.2
	v2 h1	47.61	10.98	14	1.4272	74.8
	v2 h2	46.91	12.91	21	1.1310	78.1
	v2 h3	38.61	13.77	23	0.9002	79.0
	v3 h1	56.98	11.65	17	1.5884	73.9
	v3 h2	49.91	13.07	20	1.5200	77.2
	v3 h3	41.63	13.97	24	1.1300	78.0
25 years	v1 h1	40.75	2.67	10	1.4769	80.0
	v1 h2	30.48	3.64	17	1.3825	82.9
	v1 h3	26.06	4.09	18	0.8867	86.1
	v2 h1	44.92	3.65	12	1.5369	77.9
	v2 h2	39.89	3.70	18	1.4136	81.2
	v2 h3	39.93	6.06	20	1.1917	81.1
	v3 h1	55.40	3.76	15	1.7457	78.1.
	v3 h2	48.24	3.83	18	1.6145	79.0
	v3 h3	44.10	5.69	22	1.2508	79.9

(table cont'd)

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Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3 psi)	Wood failure (%)
Untreated SYP[3]	A	28.71	0	14	1.3174	87.3
	B	39.88	0	14	1.5970	83.7
	C	34.97	0	30	1.2966	85.3
	D	26.14	0	11	1.2981	88.2
	E	38.76	0	36	1.2770	84.0
	G	39.30	0	24	1.3890	83.9
	H	54.06	0	30	1.8055	79.0
	I	30.26	0	23	1.3454	86.8

[1] Average of 5 poles
[2] v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, and h3 denotes 0.5-, 1.5-. and 2.5-inch distances from pole surface, respectively
[3] Average of 5 specimens for each of sample code

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Appendix D.2. Averages of LW percentage, creosote content, angle of growth rings to the glue line, glue-line shear strength, and wood failure of treated poles and untreated SYP with PVA adhesive

Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3psi)	Wood failure (%)
Treated poles[1]						
Fresh	v1 h1[2]	39.71	33.72	15	0.6765	56.7
	v1 h2	30.42	26.82	23	0.7221	54.4
	v1 h3	28.34	25.66	26	0.7407	58.0
	v2 h1	45.16	34.17	17	0.6799	57.4
	v2 h2	42.88	26.99	24	0.7245	56.9
	v2 h3	33.42	25.98	27	0.7385	57.8
	v3 h1	55.97	33.82	19	0.6797	57.6
	v3 h2	48.79	27.89	25	0.7206	57.7
	v3 h3	42.12	25.09	25	0.6917	58.4
5 years	v1 h1	39.87	8.49	13	1.1339	73.1
	v1 h2	33.68	11.49	21	0.9148	75.6
	v1 h3	27.90	13.07	25	0.8094	78.0
	v2 h1	47.33	10.98	14	1.3853	71.6
	v2 h2	47.01	12.91	22	1.0896	74.6
	v2 h3	38.45	13.77	23	0.8662	76.2
	v3 h1	57.03	11.65	17	1.5382	72.2
	v3 h2	49.73	13.07	19	1.4760	75.4
	v3 h3	41.83	13.97	24	1.0933	76.7
25 years	v1 h1	40.97	2.67	10	1.4410	78.7
	v1 h2	30.38	3.64	17	1.3557	82.0
	v1 h3	26.16	4.09	19	0.8638	85.2
	v2 h1	45.04	3.65	12	1.4973	77.6
	v2 h2	39.85	3.70	18	1.3785	79.7
	v2 h3	39.29	6.06	20	1.1570	79.8
	v3 h1	55.45	3.76	14	1.6969	76.2.
	v3 h2	48.23	3.83	18	1.5720	77.5
	v3 h3	44.21	5.69	23	1.2119	78.6

(table cont'd)

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Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3psi)	Wood failure (%)
Untreated SYP[3]	A	28.81	0	15	1.2921	86.4
	B	39.78	0	14	1.5619	82.4
	C	34.87	0	30	1.2658	84.7
	D	26.07	0	11	1.2751	87.3
	E	38.87	0	35	1.2429	82.8
	G	39.21	0	24	1.3544	82.6
	H	53.99	0	31	1.7579	77.3
	I	30.13	0	24	1.3187	85.9

[1]Average of 5 poles
[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, and h3 denotes 0.5-, 1.5-. and 2.5-inch distances from pole surface, respectively
[3]Average of 5 specimens for each of sample code

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Appendix D.3. Averages of LW percentage, creosote content, angle of growth rings to the glue line, glue-line shear strength, and wood failure of treated poles and untreated SYP with casein glue

Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3 psi)	Wood failure (%)
Treated poles[1]						
Fresh	v1 h1[2]	39.10	33.72	15	0.6683	55.1
	v1 h2	30.91	26.82	23	0.7159	53.2
	v1 h3	28.07	25.66	24	0.7350	56.8
	v2 h1	45.47	34.17	17	0.6707	55.6
	v2 h2	42.99	26.99	24	0.7158	55.2
	v2 h3	33.31	25.98	27	0.7318	56.5
	v3 h1	56.00	33.82	20	0.6684	55.4
	v3 h2	48.91	27.89	25	0.7107	55.8
	v3 h3	42.29	25.09	25	0.6832	56.6
5 years	v1 h1	39.64	8.49	12	1.1258	73.1
	v1 h2	33.88	11.49	21	0.9080	75.6
	v1 h3	27.75	13.07	26	0.8038	78.0
	v2 h1	47.59	10.98	14	1.3757	71.6
	v2 h2	47.86	12.91	22	1.0801	74.6
	v2 h3	38.66	13.77	24	0.8584	76.2
	v3 h1	56.91	11.65	17	1.5267	69.9
	v3 h2	49.81	13.07	19	1.4659	73.4
	v3 h3	41.59	13.97	24	1.0849	75.0
25 years	v1 h1	40.91	2.67	9	1.4327	77.1
	v1 h2	30.42	3.64	17	1.3495	80.8
	v1 h3	26.01	4.09	19	0.8585	84.1
	v2 h1	44.83	3.65	13	1.4882	75.8
	v2 h2	39.94	3.70	19	1.3704	78.1
	v2 h3	39.23	6.06	20	1.1491	78.2
	v3 h1	55.34	3.76	14	1.6857	74.0.
	v3 h2	48.19	3.83	18	1.5623	75.5
	v3 h3	44.20	5.69	24	1.2030	76.8

(table cont'd)

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Wood types	Sample codes	LW (%)	Creosote content (%)	Angle of growth rings	Shear strength (10^3 psi)	Wood failure (%)
Untreated SYP[3]	A	28.77	0	16	1.2863	82.2
	B	39.78	0	13	1.5584	80.8
	C	34.89	0	30	1.2587	83.3
	D	26.21	0	12	1.2698	86.3
	E	38.81	0	35	1.2350	81.2
	G	39.22	0	23	1.3465	81.0
	H	54.00	0	31	1.7470	75.1
	I	30.30	0	24	1.3126	84.6

[1]Average of 5 poles
[2]v1,v2,v3 denotes top, middle, and bottom portions, respectively, and h1, h2, and h3 denotes 0.5-, 1.5-. and 2.5-inch distances from pole surface, respectively
[3]Average of 5 specimens for each of sample code

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Appendix E.1. LW percentage and data of stress wave time (T, 1/T, and $(1/T)^2$);
T = time in microsecond which was required for the longitudinal wave stress to travel from one end to the other end of SYP lumber with the distance (L) = 97.75 inches

Percent LW	T (microsec)	1/T (10^3ft/sec)	$(1/T)^2$ (10^6ft^2/sec^2)
45.282	670.9658	82.3692	147.3908
33.617	743.4538	91.26798	120.0503
57.358	614.5487	75.44332	175.6946
47.059	667.6018	81.95623	148.8799
37.173	718.9168	88.25577	128.3848
43.188	682.4239	83.77582	142.4829
32.627	750.7445	92.163	117.7299
49.306	650.4766	79.8539	156.8223
48.975	657.7552	80.74745	153.3707
39.823	702.1333	86.19539	134.5959
41.674	691.0838	84.83894	138.9343
44.221	676.6987	83.07298	144.904
49.694	648.5987	79.62337	157.7317
39.626	710.4628	87.21794	131.4584
42.727	685.0262	84.09529	141.4024
49.599	649.057	79.67963	157.509
45.867	667.8665	81.98872	148.7619
39.13	706.4085	86.72023	132.9717
33.533	752.5116	92.37995	117.1776
34.135	739.7227	90.80995	121.2644
57.745	612.9685	75.24932	176.6017
59.135	607.3916	74.56469	179.8596
43.07	683.0872	83.85725	142.2063
37.863	714.4311	87.7051	130.0021
36	726.7403	89.2162	125.6356
48.764	653.1273	80.17931	155.5519
46.586	664.1155	81.52824	150.4471
38.67	709.2899	87.07395	131.8935
54.258	632.7102	77.67286	165.753
38.448	710.6931	87.24622	131.3732
41.91	689.7122	84.67056	139.4875
44.159	677.0382	83.11467	144.7587

(table cont'd)

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56.077	619.8679	76.09632	172.6922
40.823	696.0986	85.45456	136.9397
47.281	660.5491	81.09043	152.0761
55.579	621.9734	76.3548	171.525
26.261	803.3772	98.62431	102.8092
44.268	676.4416	83.04142	145.0142
37.057	727.3147	89.28671	125.4372
40.172	700.0094	85.93465	135.4139
53.353	631.6542	77.54323	166.3077
32.398	752.4617	92.37381	117.1932
41.577	691.65	84.90844	138.707
38.6	709.7315	87.12816	131.7295
42.07	688.787	84.55697	139.8625
33.745	742.5265	91.15415	120.3503
35.84	727.8273	89.34965	125.2605
39.567	703.7035	86.38816	133.9959
30.573	775.8292	95.24246	110.2399
42.034	690.8567	84.81105	139.0257
41.266	695.3731	85.36549	137.2257
35.345	733.4483	90.03969	123.348
53.509	632.39	77.63355	165.9209
54.852	630.0697	77.3487	167.1452
48.63	655.3778	80.45559	154.4855
48.847	654.3016	80.32347	154.9941
39.695	704.8945	86.53436	133.5435
36.879	722.987	88.75544	126.9434
30.049	780.1871	95.77744	109.0118
37.508	718.8251	88.24451	128.4176
42.224	689.7529	84.67555	139.471
32.544	753.782	92.5359	116.783
33.474	746.8444	91.68422	118.9627
32.3858	754.9815	92.68316	116.4122
43.147	684.465	84.02639	141.6344
29.556	777.4538	95.4419	109.7797
33.687	745.2822	91.49245	119.4619
37.829	716.7286	87.98714	129.17
44.594	680.945	83.59428	143.1024
46.233	667.6299	81.95968	148.8673
39.328	707.1757	86.8144	132.6834
32.403	754.8508	92.66711	116.4525
32.575	753.5477	92.50713	116.8556

(table cont'd)

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36.268	727.0999	89.26035	125.5113
24.434	832.0254	102.1412	95.85128
37.318	720.0747	88.39791	127.9723
42.218	689.7877	84.67982	139.457
42.89	685.9251	84.20564	141.032
26.554	811.2635	99.59246	100.8201
23.545	832.7217	102.2267	95.69103
35.311	733.6854	90.06879	123.2683
40.914	697.4729	85.62327	136.4006
37.838	716.6701	87.97996	129.1911
40.038	702.7823	86.27506	134.3475
42.032	690.8684	84.81248	139.021
42.424	688.5967	84.53361	139.9398
42.453	688.4295	84.51309	140.0078
21.717	852.0143	104.5951	91.40655
43.524	686.9912	84.33652	140.5946
35.186	734.5588	90.17602	122.9753
35.437	732.8081	89.96109	123.5636
35.655	731.2976	89.77567	124.0745
46.886	664.2242	81.54159	150.3979
48.167	657.6918	80.73966	153.4003
31.609	760.9556	93.41655	114.5915
40.319	701.066	86.06436	135.0061
24.478	823.3669	101.0783	97.8778
26.778	801.5885	98.40472	103.2686
53.245	637.291	78.23522	163.3787
26.223	814.403	99.97786	100.0443
34.85	748.8036	91.92474	118.341
31.056	778.6288	95.58615	109.4486
49.305	660.2351	81.05188	152.2207
42.643	696.9477	85.5588	136.6063
24.568	839.0994	103.0096	94.24195
39.711	715.1683	87.79559	129.7342
46.416	675.4286	82.91707	145.4495
37.797	727.8633	89.35406	125.2482
34.103	754.6528	92.6428	116.5136
34.865	748.6924	91.91109	118.3761
27.678	808.4176	99.24309	101.5312
29.802	789.2989	96.89602	106.5094
31.593	774.1901	95.04124	110.7072
38.386	723.8848	88.86566	126.6287

(table cont'd)

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37.795	727.8769	89.35573	125.2435
34.788	749.2638	91.98123	118.1957
39.947	713.6485	87.60902	130.2874
38.824	720.9683	88.50761	127.6553
36.485	731.233	89.76773	124.0965
50.468	654.4019	80.33578	154.9466
42.366	698.6098	85.76284	135.957
41.347	704.828	86.5262	133.5687
38.238	724.8784	88.98762	126.2818
39.293	717.884	88.12898	128.7545
45.84	678.5852	83.30458	144.0994
32.564	766.3531	94.07915	112.983
33.213	761.2457	93.45216	114.5042
45.077	682.8356	83.82636	142.3111
27.533	802.1863	98.47811	103.1147
41.411	704.4326	86.47766	133.7187
45.87	678.4197	83.28426	144.1697
39.761	714.8455	87.75597	129.8514
28.083	804.6649	98.78239	102.4804
36.941	733.7639	90.07844	123.2419
25.613	828.4036	101.6966	96.69123
49.37	659.905	81.01135	152.3731
41.191	705.7947	86.64488	133.2031
40.171	712.215	87.43304	130.8124
36.701	729.7458	89.58517	124.6028
44.047	688.702	84.54654	139.897
42.916	695.3212	85.35912	137.2461
33.117	761.9948	93.54412	114.2792
33.082	762.2684	93.57771	114.1971
34.169	753.9051	92.55101	116.7448
38.075	725.9773	89.12254	125.8998
48.418	664.7904	81.6111	150.1418
53.043	642.0177	78.81548	160.9819
31.892	771.7512	94.74184	111.408
33.732	751.0185	92.19664	117.644
34.53	753.6027	92.51388	116.8386
48.588	665.5754	81.70747	149.7878
50.762	654.5356	80.3522	154.8833
33.374	762.4955	93.60559	114.1291
40.374	712.9692	87.52563	130.5358
35.855	743.7827	91.30836	119.9441

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Appendix E.2. Latewood (LW) percentage, angle of growth rings to horizontal (A_H) and vertical (A_V) glue lines, MOR and MOE of 2-ply beams fabricated from untreated SYP and treated poles

Gluing models (Number of glued laminae)[1]	LW (%)	A_H	A_V	MOR (10^4 psi)	MOE (10^6 psi)
Untreated SYP[2]					
Flatwise					
T1 (2)	32.28	23.42	-	1.5371	1.7294
T2 (4)	35.80	24.04	69.92	1.3915	1.5739
T3 (5)	35.60	25.60	67.97	1.4267	1.6140
T4 (7)	37.19	20.76	70.21	1.3961	1.5937
Edgewise					
T1 (2)	35.98	-	24.88	1.4984	1.6591
T2 (4)	37.82	68.97	19.91	1.3537	1.5378
T3 (5)	39.96	67.81	21.23	1.3756	1.5655
T4 (7)	38.27	67.87	22.09	1.3323	1.5323
Treated poles[3]					
Flatwise					
T1 (2)	39.90	31.10	-	1.5223	1.7108
T2 (4)	34.66	28.46	50.23	1.4152	1.5919
T3 (5)	33.08	18.28	71.25	1.4059	1.5704
T4 (7)	31.56	24.01	67.67	1.3708	1.5314
Edgewise					
T1 (2)	30.45	-	25.00	1.5013	1.6830
T2 (4)	35.55	69.00	27.19	1.3622	1.5299
T3 (5)	39.56	59.42	33.36	1.4451	1.6092
T4 (7)	36.90	63.46	21.26	1.3982	1.5586
Defect-free specimen of SYP lumber[4]	36.39 (±7.3578)			1.3340 (±0.1771)	1.5084 (±0.2018)

[1]For more details, refer to Figure 5.3
[2]Average of 6 replicates
[3]Average of 2 replicates
[4]Tested according to the ASTM Standard D 143-86 (1994)

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Appendix E.3. Latewood (LW) percentage, angle of growth rings to horizontal (A_H) and vertical (A_V) glue lines, MOR and MOE of 3-ply beams fabricated from untreated SYP[1]

Treatment combination	LW (%)	A_H	A_V	MOR (10^4 psi)	MOE (10^6 psi)
1	2	3	4	5	6
Unjointed beams					
Flatwise (F)	43.91	19.47	-	1.7420	1.9377
Edgewise (E)	41.09	-	17.00	1.7250	1.8377
Finger-jointed beams					
- Configuration:					
1A-F[2]	39.55	17.40	-	1.2927	1.4844
1A-E	42.00	-	15.67	1.3737	1.4857
1B-F	39.25	18.61	-	1.2968	1.4896
1B-E	43.20	-	18.79	1.4070	1.5021
2A-F	37.17	19.41	-	1.1677	1.2799
2A-E	40.48	-	18.44	1.2684	1.2829
2B-F	37.30	18.56	-	1.1838	1.2969
2B-E	37.92	-	19.63	1.2394	1.2465
3A-F	43.41	21.88	-	1.1844	1.3932
3A-E	39.01	-	20.21	1.1619	1.1508
3B-F	38.30	20.73	-	1.1139	1.2199
3B-E	40.88	-	19.62	1.1902	1.1907

(table cont'd)

[1]Average of 4 replicates
[2]Meaning with: configuration number 1- design A - flatwise direction, and configuration number 1 - design A - edgewise; respectively (refer to Figures 5.6 and 5.7 for further details)

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1	2	3	4	5	6
Scarf-jointed beams					
- Configuration:					
1A-F	39.52	21.72	-	1.5766	1.6793
1A-E	40.21	-	18.36	1.6227	1.6880
1B-F	39.88	16.47	-	1.6060	1.7100
1B-E	39.21	-	19.47	1.6196	1.6269
2A-F	42.11	19.73	-	1.5246	1.6224
2A-E	39.06	-	19.72	1.5042	1.5039
2B-F	39.38	17.94	-	1.4978	1.5938
2B-E	39.46	-	19.79	1.5255	1.5240
3A-F	40.43	18.90	-	1.3993	1.4904
3A-E	41.69	-	18.31	1.4506	1.4508
3B-F	43.49	18.92	-	1.4644	1.5635
3B-E	40.60	-	16.99	1.4455	1.4550
Defect-free specimen of SYP lumber[3]	36.39 (±7.3578)			1.3340 (±0.1771)	1.5084 (±0.2018)

[3]Tested according to the ASTM Standard D 143-86 (1994)

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Appendix E.4. Latewood (LW) percentage, angle of growth rings to horizontal (A_H) and vertical (A_V) glue lines, MOR and MOE of 3-ply beams from untreated SYP and treated poles

Treatment combination	LW (%)	A_H	A_V	MOR (10^4 psi)	MOE (10^6 psi)
Untreated SYP[1]					
Unjointed beams					
Flatwise (F)	43.91	19.47	-	1.7420	1.9377
Edgewise (E)	41.09	-	17.00	1.7250	1.8377
Scarf-jointed beams					
- Configuration:					
3A-F[2]	40.43	18.90	-	1.3993	1.4904
3A-E	41.69	-	18.31	1.4506	1.4508
3B-F	43.49	18.92	-	1.4644	1.5635
3B-E	40.60	-	16.99	1.4455	1.4550
Treated poles[3]					
Unjointed beams					
F	43.63	22.19	-	1.6068	1.7990
E	41.91	-	22.52	1.7210	1.8098
Scarf-jointed beams					
- Configuration:					
3A-F[2]	39.83	23.05	-	1.2561	1.3413
3A-E	41.55	-	26.72	1.3976	1.3900
3B-F	41.69	19.09	-	1.3092	1.3491
3B-E	40.48	-	18.41	1.4025	1.4355
Defect-free specimen of SYP lumber[4]	36.39 (±7.3578)			1.3340 (±0.1771)	1.5084 (±0.2018)

[1]Average of 4 replicates
[2]Refer to Figures 5.6 and 5.7 for further details)
[3]Average of 2 replicates
[4]Tested according to the ASTM Standard D 143-86 (1994)

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Appendix E.5. Latewood (LW) percentage, angle of growth rings to horizontal (A_H) and vertical (A_V) glue lines, MOR and MOE of unjointed 2- and 3-ply beams from untreated SYP and treated poles

Treatment combination	LW (%)	A_H	A_V	MOR (10^4 psi)	MOE (10^6 psi)
Untreated SYP[1]					
2-ply flatwise[3]	32.28	23.42	-	1.5371	1.7294
2-ply edgewise	35.98	-	24.88	1.4984	1.6591
3-ply flatwise[3]	43.91	19.47	-	1.7420	1.9397
3-ply edgewise	41.09	-	17.00	1.7250	1.8397
Treated poles[2]					
2-ply flatwise	39.90	31.00	-	1.5223	1.7108
2-ply edgewise	38.45	-	25.00	1.5013	1.6830
3-ply flatwise	43.63	22.19	-	1.6068	1.7990
3-ply edgewise	41.91	-	22.52	1.7210	1.8098
Defect-free specimen of SYP lumber[4]	36.39 (±7.3578)			1.3340 (±0.1771)	1.5084 (±0.2018)

[1]Average of 6 and 4 replicates for 2- and 3-ply beams, respectively
[2]Average of 2 replicates for both 2- and 3-ply beams
[3]Refer to Figures 5.3 and 5.5 for further details
[4]Tested according to the ASTM Standard D 143-86 (1994)

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VITA

The author was born in Madiun (eastern part of Java island), Indonesia. He received a Bachelor of Science degree in Forestry from Bogor Agricultural University in Indonesia in 1974. He is employed as a research scientist at the Forest Products Research and Development Center, Ministry of Forestry in Bogor, Indonesia. He received a Master of Science degree in Wood and Paper Sciences from the University of Washington in 1992. He is presently a candidate for the Doctor of Philosophy degree in Forestry, majoring in Wood Science and Technology.

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DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Han Roliadi

Major Field: Forestry

Title of Dissertation: The Recycling Potential of Out-of-Service Utility Poles for Engineered Wood Products

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

May 1, 1997

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