# Effects of Treatment, Incising, and Drying on Mechanical Properties of Timber

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## Abstract

The design demands of timber construction used in transportation structures, such as bridges, require extended durability and reliability. As such, preservative-treated timber, rather than naturally durable timber, is most often required by code. Design demands also require minimal strength loss during treatment or during the service life of the structure. This report critiques the literature on treatment effects and recommends treating procedures for controlling reductions in strength properties. Particular emphasis is given to the effects of pretreatment drying, incising, treatment processing factors, and post-treatment drying practices.

Keywords: Mechanical properties, preservative treatment, creosote, waterborne preservatives, air drying, kiln drying, timber, lumber, incising.

## Introduction

Wood in the standing tree has high moisture content, usually in excess of 75 percent. Green wood must be seasoned (i.e., dried) before it can be adequately treated with preservative. With dimension lumber, smaller timber, and Southern Pine poles, pretreatment drying is often achieved using standard air- or kiln-drying techniques commonly used in the lumber industry. With the largest timbers, refractory poles, and/or piles, pretreatment drying is often performed within the treating cylinder immediately prior to treatment. Several researchers have studied the magnitude and severity of these pretreatment drying practices.

Drying of green wood decreases warp in service by removing much of the moisture and reduces transportation costs by reducing total weight. In addition, strength generally increases as wood is dried from the green condition to moisture contents below the fiber saturation point. Yet, strength can also be negatively affected by the temperatures used in the drying process and by the introduction of other materials, such as chemical preservatives or fire retardants.

The strength and stiffness of wood decreases when heated and increases when cooled. This temperature effect is immediate and, for the most part, recoverable for short heating durations. If wood is exposed to elevated temperatures for an extended time, strength is permanently reduced because of degradation of the wood substance with a corresponding loss in woody material and weight. The magnitude of any permanent effects depends upon moisture content, heating medium, temperature, exposure period, and, to a lesser extent, species and specimen size.

The treatment of wood with waterborne preservatives results in a product with high moisture content, usually well in excess of the fiber saturation point. Accordingly, post-treatment drying is sometimes undertaken to increase the market value of the treated material by improving dimensional stability, assuring preservative fixation, and reducing shipping weight. Several researchers have shown that the severity of the post-treatment drying process is a significant co-contributor, along with the preservative chemical, to adversely affecting the mechanical properties of the treated and dried material.

This report critiques the literature on treatment effects and recommends treating procedures for controlling reductions in strength properties. Particular emphasis is given to the effects of pretreatment kiln drying and incising, treatment processing, and post-treatment drying practices.

## Seasoning Practices in Wood-Treating Industry

In the lumber industry, standard drying practices and the effects of these practices on the mechanical properties of wood are well documented (Forest Products Laboratory 1987, Koch 1985, Rietz and Page 1971, Simpson 1991). These reviews of the research have shown that the negative effects of the initial kiln drying process on strength are negligible at 71°C (160°F) or below. At higher temperatures, however, the effects of the initial kiln drying processes, especially at or above the boiling point of water, can be significant.

In addition to the standard air- and kiln-drying practices used by the timber industry, several other drying methods are practiced by the treating industry. Most notable are two artificial drying methods performed within the pressure-treating cylinder: Boultonizing and steam conditioning. In Boultonizing, green wood is boiled in oil under vacuum. In steam conditioning, green wood is steamed for several hours, followed by a vacuum. In each case, moisture is evaporated from the green wood by either increasing the kinetic energy or reducing the vapor pressure within the retort. These techniques are generally used to partially dry large members prior to treating with oil-type preservatives and were thoroughly described by Henry (1973) and MacLean (1952). Much of the general data on the effects of these accelerated drying methods were summarized by MacLean (1951, 1952, 1953) and Thompson (1980, 1982). Treatment standards were modified to preclude strength losses in treated timber resulting from excessive thermal treatment. The American Wood Preservers' Association (AWPA 1995) Standards have strict limitations for treatment processing for both temperature and duration of temperature. Third-party sanctioned adherence to AWPA Standards will negate any need for design adjustments for strength loss resulting from in-cylinder seasoning.

### Air Drying

Air drying and its analogs, such as controlled air-drying and tunnel drying, have been the primary methods used to dry large timbers and other large commodities prior to treatment. As such, air drying represents the standard to which most accelerated conditioning methods are compared. Air drying, if properly done with respect to snickering and stacking, is usually assumed to have no detrimental effects on wood properties.

### Kiln Drying

Kiln drying is the most common method for pretreatment drying of softwood dimension lumber, but it is used to a lesser extent with large commodities such as posts, poles, pilings, and timbers. The negative effects of kiln drying are generally observed when the drying temperature exceeds the boiling point of water, commonly known as high-temperature drying. The strength reductions associated with high-temperature drying presumably arise from the hydrolysis of the amorphous carbohydrates by acetic acid liberated from acetyl groups in the wood (Hillis 1975), resulting in depolymerization, which has been correlated to strength loss (Ifju 1964). Elevated temperature and moisture content have been shown to accelerate the production of acid (Hillis 1975) and increase the rate of strength loss (Thompson 1969).

Koch (1985) summarized much of the work on high-temperature drying of dimension lumber. High-temperature drying has only a minimal effect on mechanical properties; modulus of rupture (MOR) varies from +5 to –10 percent and modulus of elasticity (MOE) from +2 to -3 percent in the Southern Pines (Koch 1971, 1976, Yao and Taylor 1979). High-temperature drying has a more severe effect on other softwoods, notably Douglas Fir, Hem–Fir, and Spruce-Pine-Fir; MOR varies from –9 to –21 percent and MOE from +3 to –4 percent (Cech and Huffman 1974, Comstock 1976, Gerhards 1979, Kozlik 1968, Salamon 1963, 1969). The limited data available on the effect of high-temperature drying on the strength of hardwoods indicate similar minimal reductions in mechanical properties—MOR from +1 to –10 percent and MOE from +4 to –4 percent (Gerhards 1983, Laden 1956, MacKay 1976). However, it should be understood that most studies on the effects of kiln drying were conducted at a dry-bulb temperature ≤ 116°C ( ≤ 240ºF). Few, if any, recent studies have investigated initial kiln-drying temperatures from 116°C to 149°C (240°F to 300°F), which are sometimes used to kiln-dry lumber commercially.

### Other Drying Methods

Several new drying techniques have recently been applied to wood. These methods include steam drying at or above atmospheric pressure, dehumidification drying, solar drying, and vacuum drying. Of these methods, the first and last may have application in the treating industry. Southern Pine nominal 2 by 6 (standard 38 by 190 mm) lumber was dried in superheated steam at atmospheric pressure in less time than that required for high-temperature drying with equivalent results in terms of moisture contents and variation (Taylor 1985); no data on mechanical properties were presented. A subsequent study with Southern Pine landscape timbers showed no difference in the treatability of timbers dried using a conventional (82°C (180°F)), high-temperature (118°C (245°F)), or superheated (118°C (245°F)) steam schedule (Barnes and Taylor 1985). Again, no data on mechanical properties were presented.

Pressure steam drying of wood has been reported in a number of articles (McGinnis and Rosen 1984, Oswald and others 1984, Phelps and Cutter 1985, Rosen 1980, 1981, 1985, Rosen and others 1983). In this process, wood is dried in superheated steam above atmospheric pressure. Oswald and others (1984) studied the effects of pressure steam drying on the strength of yellow poplar dried at 116°C to 149°C (240°F to 300°F) for 1 to 30 h. Control samples were kiln dried using the continually rising temperature schedule T11–D4 (Simpson 1991) with a maximum dry bulb temperature of 82°C (180°F). No significant differences in bending properties, compression parallel to grain, or hardness were noted; toughness was slightly decreased.

Vacuum/radio frequency drying is a technique in which green wood is exposed to radio frequency energy while being held under vacuum. Radio frequency drying was found to have no deleterious effects upon mechanical properties (Harris and Taras 1985, Lee and Harris 1984).

## Oil-Type Preservative Treatment

Oil-type preservative treatments are generally recognized as imparting superior dimensional stability and weatherability to treated wood products when compared to waterborne preservative treatments because of the nonpolar nature and natural water-repellency of oilbome systems (Barnes and Winandy 1986). Oil-type preservative treatments are also generally recognized as having less effect on mechanical properties than do waterborne treatments because they do not react with the wood cell wall material. The effects of oil-type preservative treatments, such as creosote and creosote-coal tar mixtures, on mechanical properties were extensively studied in the early part of the 20th century (Gregory 1915, Harkom and others 1930, 1931, Hatt 1906, Thunell 1941, Wilson 1930). These studies generally concluded that the effects of treating softwood timbers with oil-type preservative treatments generally resulted in no appreciable loss in stiffness or strength. However, when evaluating the effects of a treatment on strength. it is important to note the moisture content at time of test. Luxford and MacLean (1951) noted that several early investigators tested matched lots of untreated green timbers and compared them to retort-conditioned and treated timbers. The treated, but conditioned, material often had an average moisture content of about 22 percent, with surface moisture content of 17 percent. Thus, it is feasible that these differences in moisture content could erroneously account for the early findings of virtually no difference between semi-dry treated timber and green untreated timber. More recent work involving comparably conditioned materials investigated the effects of creosote treatment on softwood timbers at terrestrial retentions ( $\leq$ 192 kg/m$^3$ ( $\leq$ 12 lb/ft$^3$)) (Luxford and MacLean 1951), softwood piles at very high marine retentions (320 kg/m$^3$ (20 lb/ft$^3$)) (Eaton and others 1978, Resch and Parker 1982, and hardwood laminated veneer lumber ( $\leq$ 192 kg/m$^3$ ( $\leq$ 12 lb/ft$^3$)) (Kimmel and others 1994). As a result of these studies, it is now recognized that the effects of treating hardwoods, softwoods, solid-sawn lumber, and laminated veneer lumber with oil-type preservative treatments generally results in small, but measurable, losses in stiffness or average strength of about 5 to 10 percent.

Any loss in strength from treatment with oil-type preservatives can be greatly exaggerated if certain allowable in-retort seasoning parameters are exceeded (for Boultonizing, steam conditioning, etc.) and/or if excessive temperatures or pressures are employed during the actual treating process. The impact of thermal exposure during oil-type preservative treatments was extensively studied (Hunt 1915, MacLean 1927, 1951, 1952, 1953). As a result, specific limitations were implemented in AWPA Standards to minimize these effects (Barnes and Winandy 1986). As long as the processing limitations in AWPA Standards are strictly adhered to, there should be no adverse effect of oil-type preservative treatment on mechanical properties and, thus, no need to adjust design stresses.

## Waterborne Preservative Treatment

Waterborne-preservative-treated wood represents a major segment of the forest products industry. In North America, the primary waterborne preservatives are chromated copper arsenate (CCA), ammoniacal copper systems, and amine copper systems.

The metallic oxides, commonly used in waterborne preservative formulations, physically react with the cell wall components by undergoing hydrolytic reduction upon contact with wood sugars. This process, known as fixation, oxidizes the wood cell wall components and may reduce wood strength. The CCA waterborne preservative formulations most commonly used today are sufficiently acidic to cause cell wall hydrolysis, and, as with any chemical reaction, the addition of heat exacerbates the potential for further strength reduction.

Overall, the post-treatment strength of treated wood is affected by many factors. For treated products, specific questions of when and how much strength is affected are relative to initial material quality and its processing history. The magnitude of treatment effects is related to the composition of the treatment chemicals and the temperature, temperature duration, and temperature–moisture content history of the treating process and kiln drying after treatment.

Currently, few modifications are required to allowable stress design values if material is treated with waterborne preservative within the processing limits of AWPA Standards (AWPA 1995). However, recent research showed that treated materials exposed to impact loads do not experience the same increase in strength as does untreated material (Winandy 1995c). In response, the engineering design community recently adopted a standard design procedure that prohibits the application of the load-duration adjustment ($C_D$ factor) of 2.0 to CCA-treated material exposed to impact loads ( $\leq$ 10 s) (AF&PA).

With the exception of this case, strength loss in waterborne-preservative-treated material is minimized or controlled because several AWPA Standards for treating lumber have instituted post-treatment redrying temperature limits to control strength effects. This section will review the technical literature on waterborne preservative treatment-redrying effects and thereby document the reasoning behind the AWPA post-treatment redrying temperature limits.

The overall effects of waterborne preservative treatment appear to be directly related to several key pretreatment, treatment, and post-treatment processing factors:

- redrying temperature
- grade and size of timber
- type of preservative and/or chemical
- preservative retention
- initial kiln-drying temperature

### Redrying Temperature

Redrying temperature appears to be the single most decisive processing factor that affects strength. Air drying after treatment and kiln drying at $\leq$ 71°C ( $\leq$ 160°F) have been shown to have little practical effect on allowable design stresses (Winandy 1989, Winandy and Boone 1988). Above that level, the higher the redrying temperature the greater the negative effect on mechanical properties (Barnes and Mitchell 1984, Winandy and Boone 1988). However, the magnitude of the effects of post-treatment kiln-drying also depends on the initial kiln-drying temperature and the grade, size, and species of the treated wood.

Kiln redrying does have some advantages over air redrying when the environmental aspects of using preservative-treated wood are critical, such as uses associated with sensitive streams or biotic communities. Controlled kiln redrying significantly decreases the amount and rate of preservative leaching into the soil when the treated wood is placed in service (Boone and others 1995).

### Grade and Size of Timber

Although little is known about timber-sized material, the higher grades of dimension lumber appear to be reduced in strength more than the lower grades. Barnes and Mitchell (1984) found that MOE and work to proportional limit were not affected. Average bending strength of the No. 1 and Better lumber was significantly reduced by 8 percent when the lumber was redried at 88°C (190°F) and by 12 percent at 116°C (240°F) when compared to untreated controls. Fifth percentile values were reduced more than the mean—14 percent when the lumber was redried at 88°C (190°F) and 19 percent at 116°C (240°F).

For lower grades (e.g., No. 2) of Southern Pine lumber, CCA treatment was found to significantly reduce average bending strength (Winandy 1989, Winandy and Boone 1988). However, unlike the results of earlier studies, few differences were found between untreated controls and CCA-treated groups in the lower tails of the bending strength distributions. The authors noted that higher redrying temperatures reduced strength over a broader range of the bending strength distribution than did lower redrying temperatures. The higher grades of treated lumber appeared to be reduced in strength more than the lower grade material. The authors concluded that the effect of CCA treatment and redrying on bending strength is related to both the grade and the quality level within that grade. Larger sizes are reduced in strength less than smaller sizes. This is probably related to the surface-to-volume ratio of each treated product. Recent technical reviews have shown that at comparable retentions, large timbers, poles, and piles are generally reduced in strength less than is dimension lumber, which, in turn, is reduced in strength less than are small specimens (Barnes and Winandy 1986; Winandy 1995a).

### Preservative Chemical

The relative impact of various waterborne preservative systems is directly related to the system's chemistry and the severity of its fixation/precipitation reaction. Amine– and ammoniacal–copper preservative systems were once considered to have less effect on strength than do acidic copper systems like CCA, but recent studies with ammoniacal–copper systems have shown strength loss comparable to that associated with CCA (Barnes and others 1993, Winandy and Lebow 1996).

The relative impact of various CCA formulations appears to be related to chromium content (Bendtsen and others 1983). Thus, waterborne preservatives are now generally classified by their effects on strength as follows:

(least effect) (most effect)
amine Cu < ammoniacal Cu = CCA-C < CCA–A

### Preservative Retention

For the most frequently used waterborne preservative retentions—0.25 to 0.60 lb/ft$^3$ (4.0 to 9.6 kg/m$^3$)—there appears to be little relative difference in their effect on strength when the lumber is redried at comparable temperatures (Winandy 1995a). However, the higher retention required for marine use (2.5 lb/ft$^3$ (40 kg/m$^3$)) does significantly reduce impact strength (Bendtsen and others 1983). This is why the newest design standards for wood construction (AF&PA 1996) will limit allowable design stresses for preservative-treated wood when the wood is exposed to impact loads (duration $\leq$ 1 s).

Recent work also showed that CCA-treated lumber mechanically tested at $\leq$ 15 percent moisture content experienced a greater loss in strength and experienced this loss over a greater range of the strength distribution than CCA-treated lumber tested at higher moisture content (Winandy 1995b). Although no action has yet been adopted by the standards- or code-writing communities, this result may have serious design implications for the use of CCA-treated materials in arid environments where wood moisture content might be low for long periods of the year.

### Initial Kiln-Drying Temperature

While initial kiln drying of Southern Pine lumber at high temperatures of 100°C to 116°C (212°F to 240”F) for short durations apparently has little effect on its structural properties (Koch 1976, Yao and Taylor 1979), high temperature drying does result in more degradation of the cell wall than does drying at lower-temperature kiln schedules. Subsequent treating and redrying of material initially dried at high temperatures cause additional hydrolytic degradation.

Initial kiln drying at 113°C (235°F) resulted in slightly greater reductions in strength throughout the entire bending and tensile strength distributions than did initial kiln drying at 91°C (196°F) when those two sets of lumber were subsequently treated with CCA preservative and redried (Barnes and others 1990, Winandy and others 1992). Because most Southern Pine lumber is initially kiln dried at high temperatures, the implications of these results are significant. If initial kiln-drying temperature and redrying temperatures were unlimited, a sizable reduction in allowable design values would be required. However, if initial kiln-drying were limited to 116°C (240°F) and redrying temperatures were limited to 91°C (196°F), then allowable design stresses for bending and tensile strength apparently would not require adjustment. Accordingly, in 1991, the AWPA lowered the redrying temperature limit for waterborne-preservative-treated material from 88°C (190°F) to 71°C (160°F) in the AWPA Standards to preclude the need to adjust allowable design stresses.

Further, a systematic investigation of post-treatment strength effects resulting from pretreatment high-temperature kiln-drying in the current commercial temperature range of 116°C to 149°C (240°F to 300°F) and their interaction with waterborne preservative treatment effects has not been done. This is a significant gap in our knowledge base.

## Incising

Regardless of whether waterborne- or oil-type preservative treatments are used, incising is required by AWPA Standards when treating difficult-to-treat species. Incising is a pretreatment mechanical process in which steel knives are used to make longitudinal incisions into the four sawn faces of lumber or timber. The incisions range in depth from 5 mm (0.2 in.) (for dimension lumber) to 25 mm (1 in.) for large timbers. Incising is also required for treating difficult-to-treat round materials, such as poles and piles. Poles may be incised to a depth of 64 mm (2.5 in.), or even through-bored in some cases. Although incising dramatically improves preservative penetration and distribution, it also reduces strength (Kass 1974, Lam and Morris 1991, Perrin 1978). However, it is generally agreed that this strength loss is beneficial in the long run because the increase in treatability provides a substantial increase in service life when compared to that of unincised, but treated, refractory material. For example, incised nominal 2 by 4 (standard 38 by 89 mm) lumber may be reduced in strength by 10 to 20 percent when compared to unincised and treated lumber of this size. However, if the two pieces of wood are placed in a decay-prone environment, the incised product will substantially outperform the unincised product. The strength of large timbers tends to be less affected by incising (Perrin 1978). The limited technical literature supports a 10- to 20-percent reduction in allowable design stresses for nominal 2-in.- (standard 38-mm- ) thick lumber and a 0- to 10-percent reduction for thicker material (Kass 1974, Lam and Morris 1991, Perrin 1978). Additional cooperative research on incised dimension lumber is currently underway at the Forest Products Laboratory and Oregon State University.

## Recommendations

In summary, oil-type preservative treatments have little effect on design stresses, if thermal-processing limitations in AWPA Treating Standards are strictly followed. Waterborne preservative treatments generally reduce the mechanical properties of wood more than do oil-type preservative treatments because waterborne preservative chemicals physically react with the wood cell wall material. This effect is exaggerated when wood treated with waterborne preservative is processed at high temperatures either before, during, or after treatment (e.g., initial kiln-drying, in-treatment drying, post-treatment redrying). Similar to the history of creosote treatments in the early 1950s, these facts about waterborne preservative treatments were recently used to justify temperature limitations in AWPA Treating Standards for pretreatment, treatment, and post-treatment processing to avoid large reductions in strength. As a result, allowable stress design values do not need to be modified for waterborne-preservative-treated material because current AWPA Standards limit treating and redrying temperatures. Only two exceptions exist: for incised material and treated material exposed to impact loads.

## References


AF&PA. 1996. National design specification for wood construction. Washington, DC: American Forest and Paper Association (in press).

AWPA. 1995. Annual book of standards. Woodstock, MD: American Wood Preservers' Association.

Barnes, H.M.; Mitchell P.H. 1984. Effects of post-treatment drying schedule on the strength of CCA-treated Southern Pine dimension lumber. Forest Products Journal. 34(6): 29–33.

Barnes, H.M.; Taylor, F.W. 1985. The effect of drying schedule on treatability and check formation of Southern Pine landscape timbers. Forest Products Journal. 35(1): 57–60.

Barnes, H.M.; Winandy, J.E. 1986. The effect of drying and preservatives on the properties of treated wood. In: Proceedings, American Wood Preservers' Association: 82: 95–105.

Barnes, H.M.; Winandy, J.E.; Mitchell, P.H. 1990. The effect of initial and post-treatment drying temperature on the bending strength of CCA-treated Southern Pine. Journal of Institute of Wood Science. 11(6): 222–230.

Barnes, H.M.; Lyons, D.E.; Zahora, A.R.; Muisu, F. 1993. Strength properties of ACQ-treated Southern Pine lumber. Woodstock, MD: American Wood Preservers' Association: 89: 51–60.

Bendtsen, B.A.; Gjovik, L.R.; Verrill, S. 1983. The mechanical properties of salt-treated longleaf pine. Res. Pap. FPL–434. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Boone, R.S.; Winandy, J.E.; Fuller, J.J. 1995. Effects of redrying schedule on preservative fixation and strength of CCA-treated lumber. Forest Products Journal. 45(9): 65–73.

Cech, M.Y.; Huffman, D.R. 1974. High-temperature drying for mixed spruce, jack pine, and balsam fir. Pub. 1337. Ottawa, Ontario: Canadian Forest Service, Eastern Forest Products Laboratory. 15 p.

Comstock, G.L. 1976. Comparison of mechanical properties of Douglas-fir and Southern Pine lumber dried by CRT, high temperature, and conventional schedules. In: Gerhards, C.C.; McMillan, J.M., eds. Proceedings, Conference on high temperature drying effects on mechanical properties of softwood lumber. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Eaton, M.L.; Drelicharz, J.A.; Roe, T. Jr. 1978. Mechanical properties of preservative-treated marine piles—Results of limited full scale testing. Tech. Note N–1535. Port Hueneme, CA: Civil Engineering Laboratory, Naval Construction Battalion Center. 38 p.

Forest Products Laboratory. 1987. Wood Handbook: Wood as an engineering material, Agric. Handbook 72. (Rev.) Washington, DC: U.S. Department of Agriculture. 466 p.

Gerhards, C.C. 1979. Effect of high-temperature drying on tensile strength of Douglas-fir 2 × 4's. Forest Products Journal 29(3): 39–46.

Gerhards, C.C. 1983. Effect of high-temperature drying on the bending strength of yellow-poplar 2 × 4's. Forest Products Journal. 33(2): 61–67.

Gregory, D.S. 1915. Strength tests of structural timber treated with commercial preservatives. Bull. 186. Washington, DC: U.S. Department of Agriculture.

Harkom, J.F.; Alexander, J.B. 1931. Strength tests of creosoted Douglas-fir railway ties. Circ. 29. Ottawa, Ontario, Canada: Department of Interior, Forest Service.

Harkom, J.F.; Rochester, G.H. 1930. Strength tests of creosoted Douglas-fir railway beams. Circ. No. 28. Ottawa, Ontario, Canada: Department of Interior, Forest Service.

Harris, R.A.; Taras, M.A. 1985. A summary of research findings in radio-frequency/vacuum drying of wood. In: P. Mitchell, H,, ed. Proceedings, North American drying symposium. State College, Mississippi: Mississippi Forest Products Utilization Laboratory, Mississippi State University: 201–211.

Hatt, W.K. 1906. Experiments on the strength of treated timber. Circ. 39. Washington, DC: U.S. Department of Agriculture, Forest Service.

Henry, W.T. 1973. Treating processes and equipment. In: Nicholas, D.D., ed. Wood deterioration and its prevention by preservative treatments. Vol. Il. Preservatives and preservative systems. Syracuse, NY: Syracuse University Press: 279–298.

Hillis, W.E. 1975. The role of wood characteristics in high-temperature drying. Journal Institute of Wood Science. 7(2): 60–67.

Hunt, G.M. 1915. Temperature changes in wood under treatment. Woodstock, MD: America Wood Preservers' Association. 11: 85–89.

Ifju, G. 1964. Tensile strength behavior as a Function of cellulose in wood. Forest Products Journal. 14(8): 366–372.

Kass, A.J. 1974. Effect of incising on bending properties of redwood dimension lumber. Res. Pap. FPL–259. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Kimmel, J.D.; Janowiak, J.J.; Baileys, R.T.; Merrick, P. 1994. Characteristics of creosote-treated LVL materials. Forest Products Journal. 44(5): 49–53.

Koch, P. 1971. Process for straightening and drying Southern Pine 2 by 4's in 24 hours. Forest Products Journal. 21(5): 17–24.

Koch, P. 1976. Strength of Southern Pine lumber dried at high temperatures. In: Proceedings, Research conference on high-temperature drying effects on mechanical properties of softwood lumber; 1976 February 25–26; Madison, WI. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: p. 38–49.

Koch, P. 1985. Drying Southern Pine at high temperature—a summary of research at Pineville, LA. from 1963–1982. In: Proceedings, North American drying symposium, Mitchell, P.H., ed. State College, Mississippi: Mississippi Forest Products Utilization Laboratory, Mississippi State University: 1–38.

Kozlik, C.T. 1968. Effect of kiln-drying temperatures on strength of Douglas-fir and hemlock dimension lumber. Corvallis, OR: Forest Research Laboratory, Oregon State University.

Ladell, J.L. 1956. High-temperature drying of yellow birch. Forest Products Journal. 6(11): 470–475.

Lam, F.; Morris, P.I. 1991. Effect of double-density incising on bending strength of lumber. Forest Products Journal. 41(9): 43–47.

Lee, A.W.C. and Harris, R.A. 1984. Properties of red oak lumber dried by radio-frequency/vacuum process and dehumidification process. Forest Products Journal. 34(5): 56–58.

Luxford, R.F.; MacLean, J.D. 1951. Effect of pressure treatment with coal-tar creosote on the strength of Douglas-fir structural timbers. Rep. D179. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

MacKay, J.G.G. 1976. Effect of high temperature kiln-drying on lumber properties. In: Proceedings, Research conference on high temperature drying effects on mechanical properties of softwood lumber. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 73–78.

MacLean, J.D. 1927. Steam treatments: Report to Committee 8-1. Woodstock, MD: American Wood Preservers' Association 23: 189–195.

MacLean, J.D. 1951. Rate of disintegration of wood under different heating conditions. Woodstock, MD: American Wood Preservers' Association 47: 155–168.

MacLean, J.D. 1952. Preservative treatment of wood by pressure methods. Agric. Handb. 40. Madison WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 160 p.

MacLean, J.D. 1953. Effects of steaming on the strength of wood. In: Proceedings, American Wood Preservers' Association . Woodstock, MD: American Wood Preservers' Association. 49: 88–112.

McGinnes, E.A., Jr.; Rosen, H.N. 1984. Macroscopic and microscopic analyses of color changes of wood steam-dried above atmospheric pressure. Wood and Fiber Science. 16(1): 48–56.

Oswald, K.T., Rosen, H.N.; Wengert, E.M. 1984. Pressure steam drying affects the mechanical properties of yellow-poplar. In: Proceedings, 38th annual meeting. St. Louis, MO: Forest Products Research Society.

Perrin, P.W. 1978. Review of incising and its effects on strength and preservative treatment of wood. Forest Products Journal. 28(9): 27–33.

Resch, H.; Parker, R. 1982. Strength and stiffness of preservative-treated marine piles. Wood and Fiber. 14(4): 310–319.

Rietz, R.C.; and Page, R.H.. 1971. Air drying lumber: a guide to industry practice. Agric. Handb. 402. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Rosen, H.N. 1980. Drying lumber above atmospheric pressure—development of a prototype dryer. In: Proceedings of the wood drying working party, IUFRO Division V conference, Oxford, England: 45–58.

Rosen, H.N. 1981. Drying of lumber in superheated steam above atmospheric pressure. American Institute of Chemical Engineers symposium series 77(207): 32–37.

Rosen, H.N. 1985. Theoretical developments in high-temperature drying of wood. In: Mitchell, P.H., ed. Proceedings, North American drying symposium. State College, Mississippi: Mississippi Forest Products Utilization Laboratory, Mississippi State University: 58–71.

Rosen, H.N.; Bodkin, R.E.; Gaddis, K.D. 1983. Pressure steam drying of lumber. Forest Products Journal. 33(1): 17–24.

Salamon, M. 1963. Quality and strength properties of Douglas-fir dried at high temperatures. Forest Products Journal. 13(8): 339–344.

Salamon, M. 1969. High temperature drying and its effect on wood properties. Forest Products Journal. 19(3): 27–34.

Simpson, W.T. 1991. Dry kiln operator's manual. Agric. Handb. 188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 274 p.

Taylor, F.W. 1985. Superheated steam drying in an experimental chamber. In: Mitchell, P.H., ed. Proceedings, North American drying symposium. State College, Mississippi: Mississippi Forest Products Utilization Laboratory, Mississippi State University: 97–101.

Thompson, W.S. 1969. Effect of drying method on the strength properties of Southern Pine poles. Part I. Mechanical effects. Forest Products Journal. 19(1): 21–28.

Thompson, W.S. 1980. Effect of preservative treatments and exposure conditions on the mechanical properties and performance of wood. In: Lyon, D.E.; Galligan, W.L., co-chairmen. Proceedings, Workshop on how the environment affects lumber design: assessments and recommendations. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Thompson, W.S. 1982. Adverse environments and related design considerations-chemical effects. In: Meyer, R.W.; Kellogg, R.M., eds. Proceedings, Structural use of wood in adverse environments. New York, NY: Society of Wood Science and Technology. Van Nostrand Reinhold Company: 117–130.

Thunell, B. 1941. Statens Provoningsanstalt. Stockholm (In Swedish). Trans. by H. Becker. 1966. Seifen–Ole–Fette–Wachse (Soaps Oils Fats Waxes). 92(26): 991–1009.

Wilson, T.R.C. 1930. The effect of creosote on strength of fir timbers. Timberman. 31(8): 50–56.

Winandy, J.E. 1989. The effects of CCA preservative treatment and redrying on the bending properties of 2 × 4 Southern Pine lumber. Forest Products Journal. 39(9): 14–21.

Winandy, J.E. 1995a. Effects of waterborne preservative treatment on mechanical properties: A review. In Proceedings. Woodstock, MD: American Wood Preservers' Association. 91: 17–33.

Winandy, J.E. 1995b. Effects of moisture content on strength of CCA-treated lumber. Wood and Fiber Science. 27(2): 168–177.

Winandy, J.E. 1995c. The Influence of time-to-failure on the strength of CCA-treated lumber. Forest Products Journal. 45(2): 82–85.

Winandy, J.E.; Boone, R.S. 1988. The effects of CCA preservative treatment and redrying on the bending properties of 2 × 6 Southern Pine lumber. Wood and Fiber Science 20(3): 50–64.

Winandy, J.E.; Lebow, S.T. 1996. Effects of ammoniacal copper citrate-preservative treatment and redrying on the flexural properties of two grades of Southern Pine 2 by 4's. Wood Science and Technology (submitted).

Winandy, J.E.; Barnes, H.M.; Mitchell, P.H. 1992. The effect of initial and post-treatment drying temperature on the tensile strength of CCA-treated Southern Pine. Journal of Materials in Civil Engineering. 4(3): 240–251.

Yao, J.; Taylor, F. 1979. Effect of high-temperature drying on the strength of Southern Pine dimension lumber. Forest Products Journal. 29(8): 49–51.

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