Wood Properties Affecting Finish Service Life

R. Sam Williams—USDA Forest Service*
Charles Jourdain—California Redwood Association**
George I. Daisey—Rohm and Haas Co.†
Robert W. Springate—Tru-Test Manufacturing Co.††

Wood is a biological material that has widely different properties depending on species, geographic area where the tree grew, the growth conditions, size of the tree at harvest, sawing, and other manufacturing processes. Some of the more important wood properties as they relate to wood finishing are discussed, e.g., growth rate, density, knots, extractives, juvenile wood, grain orientation, and weathering characteristics.

Current knowledge on wood properties has accumulated through decades of research in laboratories located in many parts of the world and is contained in a number of publications.[1–7] Much of this knowledge, particularly information on North American wood species, is summarized in the *Wood Handbook: Wood as an Engineering Material*.[8] Detailed information on wood properties that relate to wood finishing is given in Chapter 15 of that publication, in *Finishes for Exterior Wood*,[9] and in a monograph by Feist.[10] The benchmark research conducted by Browne[11] during the 1950s and 1960s is still valid and stands out as the authoritative work documenting the effect of wood properties on finish performance, particularly oil-based film-forming finishes. Detailed information on wood properties is contained in these publications. This paper covers wood properties that have the greatest effect on finish performance and particularly the properties of lumber available from today's forests.

Although dramatic changes have occurred to both the country's timber base[12] and to exterior wood finish formulations since the 1950s and 1960s, the relationships between finish performance and wood properties have not changed. Although wood properties themselves have not changed, finishing practices need to accommodate changes in species mix, the dependence on small, fast-grown second and third growth timber, and more widespread use of wood composites to meet lumber demands. Flat-grained lumber produced from small-diameter, rapidly grown trees contains a higher percentage of knots, wider growth rings, and possibly juvenile wood. The ways that these properties affect finishing practices are discussed elsewhere.[13] This paper is an overview of wood properties. Wood that has been chemically treated (by preservatives, fire retardants, or bulking agents) and wood composites (plywood, flakeboard, and fiberboard) do not usually have the same properties as the original wood. The properties of these wood-based materials will be the subject of an additional publication.

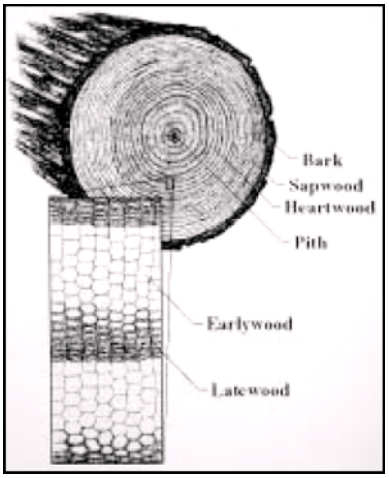

Figure 1—Cross section of log showing heartwood, sapwood, earlywood, latewood, and pith.

Natural Characteristics

Growth Rate

In temperate climates, tree species add one growth increment, or ring, to their diameter each year (*Figure* 1). This ring shows two distinct periods of growth and therefore two bands, called earlywood (springwood) and latewood (summerwood). Latewood is denser, harder, smoother, and darker than earlywood, and its cells have thicker walls and smaller cavities. The proportion of earlywood to latewood, the density differences, and the transition from the less dense earlywood to the more dense latewood during the growing season can vary, depending on species and growing conditions. Many species have a rather gradual change in density during the growing season. Some species have

*Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705-2398.
**405 Enfrente Dr., Ste. 200, Novato, CA 94949.
†727 Norristown Rd., Spring House, PA 19477-0904.
††823 W. Blackhawk, Chicago, IL 60622.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 2—Paint failure over wide latewood bands on plywood.

rather narrow latewood bands; others have wide latewood bands. For some species, the density differences are not very large; others have large differences in density between the latewood and earlywood. However, for all temperate species, the change in density from the end of one growing season to the beginning of the next is always abrupt. If the difference is large, the stresses imposed on a coating system can be quite large when dimensional changes occur at this transition zone. This abrupt transition in wood density also causes differences in properties for the pith side and bark side of flat-grained lumber.

The dimensional changes at the latewood–earlywood interface can cause cracks in film-forming finishes at this zone. Paint failure on latewood often begins with these cracks. If the bands of latewood are narrow enough, as in slow growth trees, the stresses are decreased and there is less tendency for paint to crack or peel than on the wide latewood bands. Wide latewood bands are normally absent from edge-grained cedar and redwood, improving the paintability of these species. It is well established that wide latewood bands on softwoods give a surface that is difficult to finish (*Figure* 2). They are prominent in southern yellow pine and Douglas-fir, two of the most common species used for general construction and for the production of plywood. Coarse grain (i.e., wide annual growth rings of alternating earlywood and latewood) is a natural result of the rapid growth rate of young-growth forests under the optimal growing conditions of intensive silviculture. On the other hand, growth rate does not seem to significantly affect the ability of hardwoods to retain a film-forming finish. They are generally more difficult to finish than softwoods (*Table* 1).

Paint performance on hardwoods, such as oak, is more a function of density and the size and location of vessels rather than distinctions between earlywood and latewood (*Figure* 3). These vessels are common to hardwoods only and are sometimes much larger than the surrounding wood cells. They give added texture to the wood and sometimes make it more difficult to finish these species.

Density

The density of wood is one of the most important factors that affect finishing characteristics. Density varies tremendously from species to species (*Table* 1), and this is important because high density woods shrink and swell more than do low density woods. This dimensional change occurs as wood, particularly in exterior applications, gains or loses moisture with changes in the relative humidity and from periodic wetting caused by rain and dew. Excessive dimensional change in wood stresses film-forming finishes and may cause cracking or flaking, or both.

The amount of warping and checking that occurs as wood changes dimension and during the natural weathering process is also directly related to wood density. Cupping is probably the most common form of warp for siding. Cupping is the distortion of a board that causes a deviation from flatness across the width of the piece. Wide boards cup more than narrow boards, and flat-grained boards cup more than vertical-grained boards. Boards may also bow, crook, or twist from one end to the other. Warping is generally caused by uneven shrinking or swelling within the board. Furthermore, checks or small cracks along the grain may develop from stress that developed during the initial drying (shrinking) or from stresses caused by the alternate shrinking and swelling during service. High density (heavy) woods such as southern pine, Douglas fir, and oak tend to warp and check more than do the low density (light) woods such as redwood and western redcedar (*Table* 1).

Knots

A knot is the portion of a branch that has become incorporated in the stem of a tree (*Figure* 4). The influence of knots on the finishing properties of lumber depends on their size, location, shape, and soundness. When sawing lumber from a log, a nearly round shaped knot results when a branch is sawn through at right angles to its length as in flat-grained lumber. Vertical-grained lumber may have spike knots, which result from sawing a branch radially (*Figure* 5). Oval knots will result from sawing a branch diagonally as in lumber that is intermediate between flat grain and vertical grain. Knots are further classified as intergrown or encased. Intergrown or tight knots result from the growth of the stemwood around a living branch (*Figure* 4). After a branch dies, additional growth on the stem encloses the dead limb. This results in an encased knot where the fibers of the stem are not continuous with the fibers of the branch. Because shrinkage is greater across the knot than in the surrounding wood, encased knots may loosen and fall out causing a knothole. Encased knots often have bark surrounding the knot, which may cause additional discoloration problems with light-colored finishes.[14]

Knots are usually considered defects in wood for a number of reasons. The wood of the knot itself is different in density (usually higher), and its grain orientation is more or less perpendicular to the surrounding wood. Grain orientation around the knot is often distorted, which makes it difficult to achieve an acceptable machined finish on the surface of the wood. For structural lumber, the size and location of knots are two of the factors that determine grade and thus the design values of the lumber. Knots also affect the appearance grades of lumber, which include siding and trim. Although knots are usually considered defects, a number of species and grades that exhibit knots with some degree of regularity such as knotty pine, select tight knot (STK) cedar, and rustic grades of redwood have been successfully marketed to feature their knots.

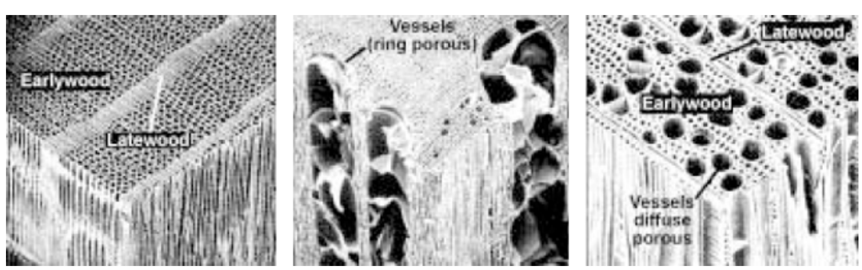

Figure 3—Wood anatomy affects the durability of paint. Left, a nonporous wood (softwood or conifer such as southern pine); center, a ring-porous wood (white oak) showing the large open vessels characteristic of this species; and right, a diffuse-porous wood (yellow-poplar).

Table 1—Characteristics of Selected Solid Woods for Painting and Finishing

Wood	Specific Gravity ovendry[a]	Paint-Holding Characteristic (I Best, V; Worst)[b]	Resistance to Cupping (1, Most; 4, Least)	Conspicuousness of Checking (1, Least; 2, Most)	Color of heartwood	Degree of Figure on Flat-Grained Surface
Softwood						
Western redcedar	0.32	I	1	1	Brown	Distinct
Cypress	0.46	I	1	1	Light brown	Strong
Redwood	0.40	I	1	1	Dark brown	Distinct
Eastern white pine	0.35	II	2	2	Cream	Faint
Ponderosa pine	0.42	III	2	2	Cream	Distinct
White fir	0.39	III	2	2	White	Faint
Western hemlock	0.45	III	2	2	Pale brown	Faint
Spruce	0.35	III	2	2	White	Faint
Douglas fir	0.48	IV	2	3	Pale red	Strong
Southern yellow pine	0.51	IV	2	2	Light brown	Strong
Hardwood						
Eastern cottonwood	0.40	III	4	2	White	Faint
Magnolia	0.48	III	2	—	Pale brown	Faint
Yellow poplar	0.42	III	2	1	Pale brown	Faint
Lauan (plywood)	—[c]	IV	2	2	Brown	Faint
Yellow birch	0.62	IV	4	2	Light brown	Faint
Gum	0.52	IV	4	2	Brown	Faint
Sycamore	0.59	IV	—	—	Pale brown	Faint
American elm	0.50	V or III	4	2	Brown	Distinct
White oak	0.64	V or IV	4	2	Brown	Distinct
Northern red oak	0.63	V or IV	4	2	Brown	Distinct

(a) Specific gravity based on ovendry weight and volume.
(b) Woods ranked in group V are hardwoods with large pores, which require wood filler for durable painting. If all the pores are properly filled before painting, the wood could be classified in group II.
(c) The specific gravity of different species varies from 0.33 to 0.55.

From the standpoint of finishing, knotty grades of siding are better suited for natural finishes such as water-repellent preservatives and semitransparent stains than for paint systems. Paint adhesion is poor over dense knots, and resin bleeding of knots can discolor most paints unless they are sealed with shellac or a similar product prior to priming.

Moisture Content

The moisture content of wood is the amount of water contained in the wood. Moisture content includes both water absorbed into the wood cell wall and free water within the hollow center of the cell (and within the vessels for hardwoods), and it is expressed as a weight percentage.

$$MC\ (\%) = \frac{\text{Mass (undried)} - \text{Mass (oven dried)} \times 100}{\text{Mass (oven dried)}}$$

The amount of water that wood can absorb (i.e., that can be bound in the cell wall) depends on the wood species. Most species can absorb about 30% of their weight in water. When the wood reaches this limit to the amount of water that can be bound in its wood cell walls, it is at the fiber saturation point. Wood can reach the fiber saturation point by absorbing either liquid water or water vapor.

The amount of water vapor that can be absorbed depends primarily on the relative humidity (RH) of the surrounding air. If wood is stored at 0% RH, the moisture content will eventually reach 0%. If wood is stored at 100% RH, it will eventually reach fiber saturation (about 30% water). Of course, if it is kept at a constant RH between these two extremes, the wood will reach a moisture content between 0 and 30%. The moisture content is controlled by the RH, and when the moisture content is in balance with the RH, the wood is at its equilibrium moisture content. This rarely happens because as the RH changes, so does the moisture content of the wood, and an atmospheric RH is almost always changing. It varies through daily and seasonal cycles, thus driving the moisture content of wood through daily and seasonal cycles. Equilibrium moisture content of wood *cannot* be changed by the application of finishes. Finishes affect only the rate at which absorption occurs. Finishes can decrease daily and seasonal moisture absorption and desorption, but they do not change the equilibrium moisture content.

Wood exposed outdoors cycles around a moisture content of about 12% in most areas of the United States. In the Southeast, average moisture content can be slightly higher, and, in the Southwest, the average can be lower (9%). Daily and annual moisture content will vary from these average values. Even in very humid areas, the RH is rarely high enough or long enough to bring the moisture content of wood above 20%. Wood that is warmed by the sun experiences a virtual RH far below the ambient RH. Wood will dry faster and become drier than expected given the ambient RH. This is why checking often occurs on

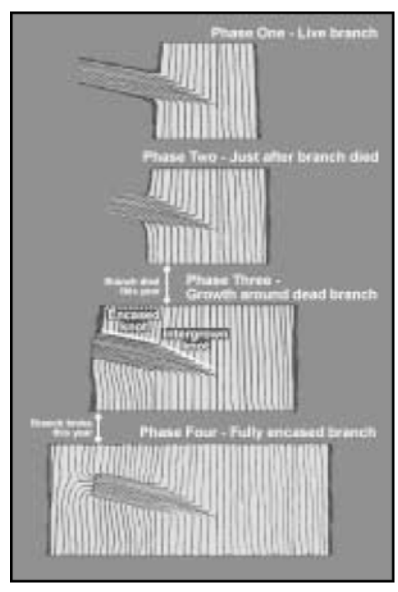

Figure 4—Formation of knots in the stem.

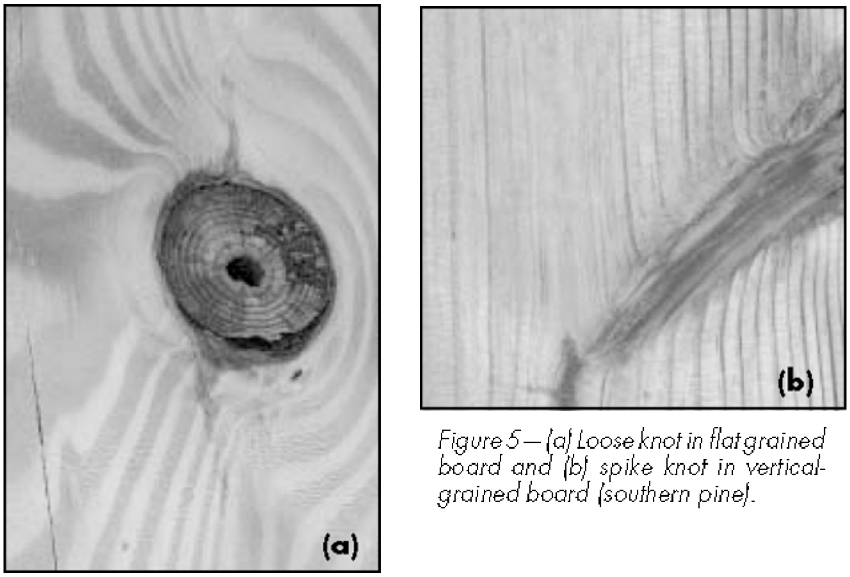

Figure 5—(a) Loose knot in flat grained board and (b) spike knot in vertical-grained board (southern pine).

decking boards; the surface is much drier than the rest of the board. The dryness causes shrinkage of the top of the board, which goes beyond the elastic limit of the wood at the surface, and checks form parallel to the grain.

As mentioned, fiber saturation is the greatest amount of water that can be absorbed by wood via water vapor absorption. This absorption is rather slow compared with the moisture changes that can occur through absorption of liquid water. Liquid water can quickly cause the wood to reach fiber saturation, and it is the only way to bring the moisture content of wood above fiber saturation. As wood continues to absorb water above its fiber saturation point, the water is stored in the hollow center of the wood cell; when all the air in the hollow center has been replaced by water, the wood is waterlogged and moisture content can be as high as 200%. The sources and ways by which wood can get wet sometimes seem endless. The result is always the same — poor performance, both of the wood and the finish.

Water also causes peeling of paint. Even if other factors are involved, water accelerates paint degradation. If the moisture content of the wood exceeds 20% when the wood is painted, the risk of blistering and peeling is increased. Moreover, dark water-soluble extractives in woods like redwood and western redcedar may discolor paint shortly after it is applied. Fortunately, the moisture content of lumber can be controlled. But all too often this critical factor is neglected during the construction and finishing processes. It is best to paint wood when its average moisture content is about that expected to prevail during its service life. The moisture content and thus the dimensions of the piece will still fluctuate somewhat, depending on the cyclic changes in atmospheric RH, but the dimensional change will not be excessive. Therefore, film-forming finishes (such as paints) will not be stressed unnecessarily, and service life should be better.

Plywood, particleboard, hardboard, and other wood composites undergo a significant change in moisture content during manufacture. Frequently, the moisture content of these materials is not known and may vary depending on the manufacturing process. To improve the service life of the finish, wood composites should also be conditioned prior to finishing.

Water-Soluble Extractives

In addition to the physical structure and moisture content of wood, wood chemical composition affects the performance of paints and finishes. Old growth timber is characterized by a high percentage of heartwood. Heartwood contains extraneous compounds such as tannins and other polyphenolics. These compounds, called extractives, impart natural decay and insect resistance to heartwood of several species of wood, such as redwood and the cedars. The presence of water-soluble extractives can discolor the surface of paints and finishes and is often referred to as extractive bleeding.[15] Although these extractives can cause problems with discoloration of finishes if not sealed with a stain blocking primer, the decay resistance that some of them impart to wood greatly outweighs disadvantages caused by discoloration. The amount of extractives within the heartwood depends on the age of the tree, thus the heartwood of younger trees will naturally have a lower extractive content than that from older trees. Although lumber from younger trees is less durable than lumber from old growth trees, extractive bleeding through finishes is less problematic. For clear grades of wood, extractive bleeding can be eliminated with proper priming, good building design, and conscientious construction practices.

Water-Insoluble Extractives

Water-insoluble extractives, such as pitch and resin, may also interfere with the appearance of a painted surface. In some species, small amounts of pitch form in the wood. In other species, the pitch can form in large deposits called pitch pockets. If the wood is kiln-dried at high temperature, the pitch can be hardened or set in the wood. Specific kiln schedules have been developed for many wood species to accomplish this. Unfortunately, some of these schedules can discolor the surface of the wood. If pitch is not set, it can become fluid enough during periods of warm weather to flow to the surface of the wood. If the wood has been painted, the pitch tends to soften and discolor the paint. Young growth knotty siding products that have been air-dried rather than kiln-dried may be more prone to pitch bleeding. Young growth products will typically have smaller pitch pockets than those found in old growth. Additionally, knots of many softwood species contain an abundance of resin that can sometimes cause paint to turn yellow-brown over the knots. Primers formulated to block wa-

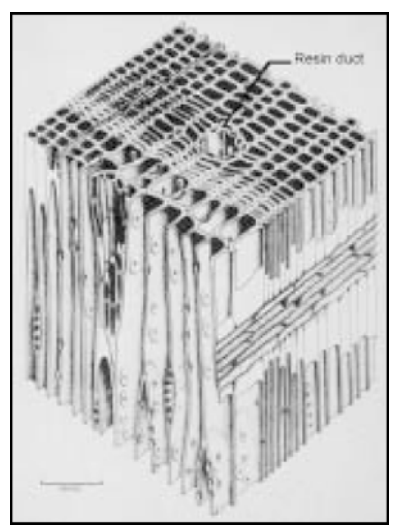

Figure 6—Microscopic view of softwood with a resin duct.

ter-soluble extractives will not block these resins.

The resins in some softwoods can occur in small ducts (*Figure 6*). Depending on the grain orientation, a large number of these ducts can intersect the surface of the lumber. Paint on these surfaces may be more prone to discolor. If various cuts of lumber (i.e., grain orientation) are used to make finger-jointed moldings, the discoloration of the various pieces of wood in a particular piece of molding can cause a checkerboard pattern of discoloration. This can also occur with water-soluble extractives, particularly with finger-jointed western redcedar or redwood.

Weathering

Weathering is the general term used to describe the degradation of materials exposed outdoors. This degradation occurs on the surface of all organic materials, including wood, as well as finishes used on wood, such as paints and stains. The process occurs through photooxidation of the surface catalyzed by ultraviolet (UV) radiation in sunlight, and it is augmented by other processes such as washing by rain, changes in temperature, abrasion by windblown particles, and changes in moisture content. Although the weathering process can take many forms depending on the exposed material, in general, the process begins with a color change, followed by slow erosion (loss of material) from the surface. The surface initially develops slight checking. With some materials, deep cracks may ultimately develop. Weathering is dependent on the chemical makeup of the affected material. Because the surface of a material may be composed of many different chemicals, not all materials on the surface may erode at the same rate.

The surface of wood consists of four types of organic materials: cellulose, hemicellulose, lignin, and extractives. Each of these materials is affected by the weathering process in a different way. The extractives undergo changes upon exposure to sunlight and lighten or darken in color. With some wood species, this color change can take place within minutes of exposure. Changes in the color of the surface are accompanied by other changes that affect the wettability and surface chemistry of the wood. The mechanism of these early changes is not very well understood, but these changes can have a drastic effect on the surface chemistry of wood and thus the wood's interaction with other chemicals such as paint and other finishes and adhesives.

Lignin comprises 20 to 30% of the wood surface. It is a polymeric substance that glues the celluloses together. Because lignin is affected by photodegradation more than are celluloses, lignin degrades and cellulose fibers remain loosely attached to the wood surface. Further weathering causes fibers to be lost from the surface (a process called erosion), but this process is so slow that on average only about 6 mm (1/4 in.) of wood is lost in a century (*Figure 7*). This erosion rate is slower for most hardwoods.

Biological attack of a wood surface by microorganisms is recognized as a contributing factor to color change or graying of wood. This biological attack, commonly called mildew, does not cause erosion of the surface, but it may cause initial graying or an unsightly dark gray and blotchy appearance. The microorganisms primarily responsible for gray discoloration of wood are commonly found on weathered wood.

Paint Adhesion to Weathered Wood

Although the erosion of the wood surface through weathering is a slow process, the chemical changes that occur within a few weeks of outdoor exposure can drastically decrease the adhesion of paints subsequently applied to the weathered surface. It is fairly obvious that a badly weathered, powdery wood surface cannot hold paint very well. This fact is not so obvious for wood that has weathered for only two to three weeks. The wood appears sound and much the same as unexposed wood. However, when smooth-planed boards that had been preweathered for 1, 2, 4, 8, or 16 weeks were painted, the paint had a drastic loss in adhesive strength after four weeks of preweathering.[16] Similar results are reported in other publications.[17–28] In subsequent studies using similarly preweathered boards, the time until the paint started to peel was directly related to the preweathering time.[29] Additional weathering of these panels showed that, for panels preweathered 16 weeks, the paint started to peel within three years. For panels preweathered for only one week, the paint started to peel after 13 years (Williams, unpublished data). Panels that were not preweathered showed no sign of peeling after 13 years. The paint system was a commercial oil-alkyd primer with two acrylic latex topcoats over planed all-heartwood vertical-grained western redcedar.

The best remedy for restoring a weathered wood surface is to sand it with 50 to 80 grit sandpaper. Even if the wood has not been weathered, scuff sanding provides a much better surface for painting.

Juvenile Wood

The presence of juvenile wood, which is often characterized by lower density and higher longitudinal shrinkage, is responsible for much of the decrease in strength of young growth timber. Juvenile wood is produced during the early growth and development stages of trees; therefore, it is located around the pith of the tree. Much of the warp, crook, and bow in lumber containing the pith or sawn close to the pith is caused by the presence of juvenile wood. Cross-grained cracking of lumber is often a sign of juvenile wood (*Figure 8*). Because of the younger age and smaller diameter of trees harvested from young growth forests, a higher proportion of the volume in a log consists of juvenile wood. Juvenile wood is particularly problematic in the short rotation (harvested at 20 to 30 years), plantation grown softwoods.

Manufacturing Characteristics

Grain Orientation

Several properties of flat-grained lumber differ from vertical-grained lumber.

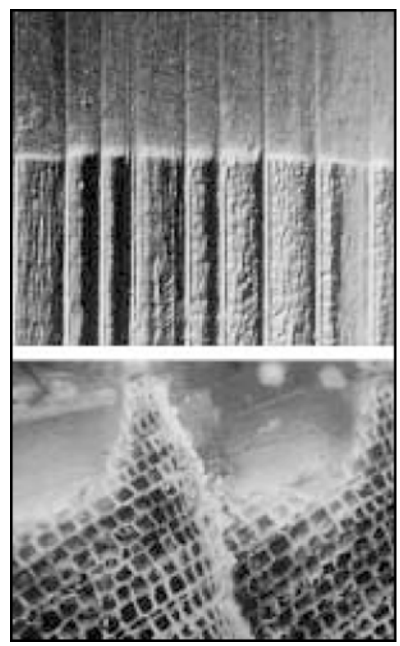

Figure 7—Western cedar exposed to weather for eight years. Top, weathered specimen with top half protected by a metal strip. Bottom, side view micrograph of weathered surface.

Figure 8—Warping (top) and excessive surface degradation (bottom) resulting from juvenile wood.

These include appearance or figure, dimensional stability, potential for grain raising and grain separation, and ability to hold film-forming finishes. The broad alternating bands of earlywood and latewood that make up the annual growth rings are highly visible on the surface of flat-grained lumber. This grain figure is valued for applications such as indoor paneling where maximum natural grain pattern of the wood is desired. As previously mentioned, in flat-grained lumber, knots will appear round or oval rather than spiked as in vertical-grained lumber. Since tangential shrinkage is about twice the rate of radial shrinkage, flat-grained lumber can be expected to shrink across its face much more than vertical-grained lumber.

Perhaps the greatest difficulty associated with the use of flat-grained lumber is the increased potential for grain raising and grain separation (*Figures* 9a and 9b). Raised grain, which results in a corrugated appearance on the surface of flat-grained lumber, usually occurs when the harder latewood portion of each annual growth ring is projected above the level of the softer earlywood. This usually occurs when dry flat-grained lumber is allowed to pick up moisture. When the interface between the latewood and earlywood becomes loosened, the result is separated grain, also known as loosened grain, shelling, feathering, or lifting of the grain. Raised or separated grain is much more pronounced on the pith side than on the bark side of flat-grained lumber. The primary method of preventing problems with grain separation is to orient the bark side rather than the pith side of the product to the weather. Since grain raising and grain separation can be exacerbated by poor manufacturing practices, closer attention to machine set up and more frequent sharpening of knives and greater attention to quality control procedures are required when surfacing flat-grained lumber.

Surface Texture

Surface quality and texture play an important role in finish performance, and the variables that influence the surface characteristics of the wood are numerous. Rough sawn, sanded, saw-textured, and smooth-planed surfaces all influence finishes differently.

Generally speaking, rough sawn and saw-textured surfaces require more finish than smooth-planed surfaces, and they provide longer lasting performance because more finish must be applied. Rougher surfaces provide more tooth for finish adhesion and actually have much more surface area. Rough surfaces also have far less of a problem with grain raising than does flat-grained lumber because of less grain compression caused by planing processes. As the timber resource changes from an old growth to a young growth supply, the ratio of flat grain to vertical grain is increasing dramatically. For this reason, rough sawn and saw-textured surfaces are being used more frequently in an effort to decrease grain raising and improve finish performance on flat-grained wood products.

The bark side of flat-grained products weathers differently than the pith side; therefore, lumber patterns that have an obvious exposed face can be manufactured to leave the bark side exposed. This is referred to as "graining the piece." Some patterns are reversible and in these cases it is up to the installer to grain the piece and apply the product with the bark side exposed. In cases where the customer knows which face of a pattern will be exposed to weathering, the manufacturer should be notified prior to manufacturing so that the pattern can be grained and manufactured properly. Graining solid sawn lumber is a common practice that can be done by an experienced planer or molder operator. This practice, however, is not always practical when manufacturing finger-jointed lumber, and the chances of encountering grain raising and the associated finish problems may be higher for these products. For this reason, the use of saw-textured patterns is especially important with finger-jointed wood substrates.

Recent studies have shown that sanding surfaces may improve finish performance and durability. Sanding with 50 to 80 grit sandpaper not only cleans the surface by removing dirt, oil, and other contaminants, but it also roughens the surface slightly and removes raised grain. The abrasion of the surface is particularly important on the latewood portion of the growth rings where the wood is more dense, and it is more difficult to attain finish adhesion. Sanding helps prepare this portion of the wood. Under magnification, sanded surfaces emulate characteristics similar to saw-textured surfaces but to a lesser degree. More surface area is exposed in the sanding process, creating better conditions for finish adhesion.

Moisture Content and Drying

Significant regional geographic differences exist in lumber drying practices resulting from species mix, building practices, and climate throughout North America. Wood products are available green (unseasoned), S-Dry (Surfaced-Dry, 19% or less moisture content), or kiln-dried (typically 10 to 15% moisture content). Only dimension and finish lumber two inches and thinner in nominal thickness (standard 38 mm) may be available S-Dry or kiln-dried. Larger dimensions of solid sawn lumber should be assumed to be green. Higher grades of lumber such as those used for architectural finish are normally kiln-dried.

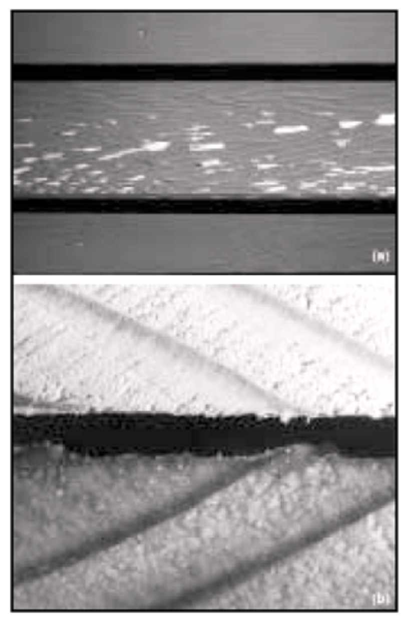

Figure 9—(a) Paint failure caused by raised grain; (b) Raised grain on book-matched specimens of planed lumber. The cross sections of a planed board illustrate grain raise caused by water. Top, surface immediately following planing but not wetted; bottom, the same planed surface but wetted.

Common grades of lumber are usually available S-Dry and are less frequently kiln-dried.

Wood moisture content is one of the most critical factors governing the performance of paints and other film-forming finishes. Typically, paints and other surface coatings cannot be successfully applied to wood that has a surface moisture content in excess of approximately 20%. If the moisture content is too high, continued movement of this moisture out of the wood may result in extractive bleeding and blistering and peeling of film-forming finishes. For best results the wood should be at a moisture content typical of what it will have during its service. For most areas of the United States and Canada, this is about 12%. Penetrating finishes such as water-repellent preservatives and semitransparent stains may be applied to products that have a dry surface but which still may contain a high enough internal or core moisture content to be considered green. Since penetrating finishes do not block moisture movement, they allow the wood to dry but do not blister or peel.

Lumber manufacturing can also have an effect on the overall performance of a coating on wood. As previously discussed, proper drying plays an important role in producing a wood product that will be dimensionally stable and have a durable finish. Proper kiln drying provides the best situation for wood because it creates a balanced piece of lumber that has an even moisture content throughout the piece. Kiln-dried lumber has less tendency to shrink or warp, but the most important characteristic from the standpoint of finishing is that kiln-dried lumber develops less surface checking. Paint applications are especially susceptible to performance failures when surface checking of the wood substrate occurs. These checks initiate cracking and peeling of the coating. Kiln-drying dramatically decreases this condition.

The finish applied to air-seasoned or S-Dry lumber is more durable than that applied to green lumber. However, these partially dried products will probably not give the same quality of finish performance as kiln-dried lumber. While some of the moisture has been removed in S-Dry and air-seasoned lumber, a percentage of excess moisture is still present in the wood and this can be detrimental to film-forming finishes such as paint. Partially dried products offer dried surfaces that are satisfactory for applying penetrating finishes such as water repellents and semitransparent stains.

Green lumber is generally not suitable for immediate finishing with paint or other film-forming finishes. Green lumber can be used in situations where penetrating stains and finishes will be applied, but the wood surface must first be allowed to dry sufficiently to accept the finish. This can usually be accomplished during a few days of dry weather. As described previously, longer exposure times lead to surface degradation and should be avoided. Other problems associated with the use of green lumber products include the natural shrinkage that occurs as these products acclimate to ambient conditions. Checks, splits, and warping may occur from rapid, uneven shrinkage of lumber. These characteristics can be minimized by using higher grades of lumber.

Performance Expectations

Unlike building materials such as steel and masonry, wood is a biological product. As such, individual pieces vary more in appearance, properties, and performance. The life expectancy of a lumber product is related to a number of direct and indirect factors. Direct factors include the properties of a particular species, the characteristics of the grade, and the quality of manufacture. Indirect factors include how the product is used after it has left the manufacturing facility. These indirect factors include handling, storage, installation, and maintenance. Siding is but a single component of a building. Its performance depends on many critical factors including climate, the design of the structure, the skill of the person doing the installation, and the interaction with other materials such as fasteners, flashing, sheathing, and house-wrap or felt.

Under ideal conditions, wood can have an almost indefinite service life. As a rule of thumb, most low-rise residential structures are designed and built with an intended service life of 100 years. It is assumed that after 50 years, the structure will require extensive renovation that will include the replacement of the exterior cladding. A service life for exterior wood siding on the order of 50 to 100 years is therefore generally considered acceptable. The National Association of Home Builders (NAHB)[30] gives a life expectancy for wood siding of only 10 years if constantly moistened but up to 100 years if properly maintained. Keeping wood and wood products dry is essential for long-term service life. A service life of 100 years is easily obtained if the wood is kept dry and maintained with a finish. There are many examples of wood siding lasting more than 200 years; for example, the siding on Mount Vernon and numerous other historic structures throughout the East Coast of the United States.

Wood buildings that are properly designed to shed exterior water and to avoid trapping moisture from interior sources routinely give service lives of much longer than 100 years. This is particularly true if the wood is maintained with a paint finish. The roof of the building protects the wood from most of the water. The finish stops the weathering of the wood's surface because the pigments in the paint completely block the UV radiation in sunlight, which catalyzes the degradation of the wood. The paint itself undergoes UV degradation, and a paint system comprised of a primer and two topcoats lasts about 10 years in full sunlight. During this time, the topcoats erode and when the primer begins to show, the surface should be repainted. By keeping an intact paint film on wood, the wood's surface can be protected indefinitely.

Wood used in exterior landscaping projects such as decks and fences is generally considered to have a much shorter expected service life. There are a number of reasons for this. Decks and fences are often in direct ground contact or in very close proximity to the ground. This results in a higher risk for termite and wood decay fungus infestations. The horizontal exposure of decks results in a much higher degree of weathering from UV radiation, precipitation, and other elements. Decks are also directly exposed to the wear from foot traffic. For preservative-treated wood, the service life is often determined by the weathering of the decking boards. The NAHB estimates the life expectancy of wood decks and fences to be 15 years and 12 years, respectively.[30] We consider these life expectancies to be conservative. There are many examples of decks and fences lasting much longer when properly designed, constructed, and maintained. We believe that a reasonable expectation of service life for these and other types of wood landscaping structures is 20 to 25 years.

Summary and Conclusions

Of the vast array of wood properties that affect the performance of finishes for wood, several stand out as having a major effect on the long-term service life of finishes. The growth rate and the grain pattern that results from the growth rate, particularly the relative width and densities of the earlywood and latewood, affect the dimensional stability and thus the amount of stress at the wood–coating interface. Coating systems lacking sufficient flexibility can crack as a result of these stresses. The grain orientation of lumber is affected by the way it is cut from a log. Flat-grained surfaces are much more difficult to finish than are vertical-grained surfaces. The high density and latewood in some species have rather poor paint adhesion properties. The extremely large amount of longitudinal dimensional changes of juvenile wood can often cause cross-grained cracking of wood with resulting cracking of film-forming finishes. Water-soluble extractives and water-insoluble resins must be blocked by a primer or suitable sealer to avoid discoloration. Knots often contain large concentrations of both water-soluble and water-insoluble compounds and therefore must be sealed.

Through understanding the properties of wood and using finish systems compatible with these properties on well-designed and well-constructed buildings, painted wood can last for centuries.

References

(1) Browning, B.L., "The Wood–Water Relationship," in *The Chemistry of Wood*, Browning, B.L. (Ed.), InterScience, London, 1964.

(2) Kollmann, F.F.P. and Côté, W.A. *Principles of Wood Science and Technology, Vol. 1, Solid Wood*, Springer-Verlag, New York, 1968.

(3) Chudnoff, M., *Tropical Timbers of the World*, Ag. Handbk. 607, USDA Forest Service, Washington, D.C., 1984.

(4) Siau, J.F., *Transport Processes in Wood*, Springer-Verlag, New York, 1984.

(5) Siau, J.F., *Flow in Wood*, Syracuse University Press, Syracuse, NY, 1971.

(6) Skaar, C., *Water in Wood*, Chapter 3, Syracuse University Press, Syracuse, NY, 1972.

(7) Stamm, A.J., *Wood and Cellulose Science*, Ronald Press, New York, 1964.

(8) Forest Products Laboratory, "Wood Handbook: Wood as an Engineering Material," Gen. Tech. Rep. FPL–GTR–113, USDA Forest Service, Forest Products Laboratory, Madison, WI, 1999.

(9) Williams, R.S., Knaebe, M.T., and Feist, W.C., *Finishes for Exterior Wood*, Forest Products Society, Madison, WI, 1996.

(10) Feist, W.C., "Finishing Exterior Wood," *Federation Series on Coatings Technology*, Federation of Societies for Coatings Technology, Blue Bell, PA, 1996.

(11) Browne, F.L., "Wood Properties that Affect Paint Performance," FPL Report R1053, USDA Forest Service, Forest Products Laboratory, Madison, WI, 1951.

(12) MacCleery, D.W., "American Forests: A History of Resiliency and Recovery," USDA Forest Service, Report FS-540, USDA Forest Service, Washington, D.C., and Forest History Society, Durham, NC, 1992.

(13) Jourdain, C.J., Dwyer, J., Kersell, K., Mall, D., McClelland, K., Springate, R., and Williams, S., "Changing Nature of Wood Products–What Does it Mean for Coatings and Finish Performance," JOURNAL OF COATINGS TECHNOLOGY, *71*, No. 890, 61 (1999).

(14) Levitin, N., "Extractives of Red and White Pine and Their Effect on Painted Lumber," *Timber of Canada*, June, 66 (1962).

(15) Donegan, V., et al. "A Headache Called Extractive Discoloration: Pointing to the Problem and Specifying Solutions," *Am. Paint. Contractor*, June 1992.

(16) Williams, R.S., Winandy, J.E., and Feist, W.C., "Paint Adhesion to Weathered Wood," JOURNAL OF COATINGS TECHNOLOGY, *59*, No. 749, 43 (1987).

(17) Williams, R.S., Plantinga, P.L. and Feist, W.C., "Photodegradation of Wood Affects Paint Adhesion," *Forest Prod. J.*, *40*, No. 1, 45 (1990).

(18) Arnold, A., Feist, W.C., and Williams, R.S., "Effect of Weathering of New Wood on the Subsequent Performance of Semitransparent Stains," *Forest Prod. J.*, *42*, No. 3, 10 (1992).

(19) Williams, R.S. and Feist, W.C., "Effect of Preweathering, Surface Roughness, and Wood Species on the Performance of Paint and Stains," JOURNAL OF COATINGS TECHNOLOGY, *66*, No. 828, 109 (1994).

(20) Evans, P.D., Thay, P.D., and Schmalzl, K.J., "Degradation of Wood Surfaces During Natural Weathering. Effects on Lignin and Cellulose and on the Adhesion of Acrylic Primers," *Wood Sci. Technol.*, *30*, No. 6, 411 (1996).

(21) Underhaug, Å., Lund, T.J., and Kleive, K., "Wood Protection—The Interaction Between Substrate and the Influence on Durability," *J. Oil & Colour Chemists' Assoc.*, *66*, No. 11, 345 (1983).

(22) Miller, E.R., "Chemical Aspects of External Coatings for Softwoods," Symposium on Chem. Aspects of Wood Tech., Swedish Forest Prod. Res. Lab., Södergarn, Stockholm, 1981.

(23) Bravery, A.F. and Miller, E.R., "The Role of Pre-treatment in the Finishing of Exterior Softwood," *Proc. of the Ann. Conv. of the British Wood Pres. Assoc.*, p. 14-23 (1980).

(24) Boxall, J., "Painting Weathered Timber," Information Sheet 20/77, Building Research Establishment, Princes Risborough Laboratory, Alyesbury, Bucks, England, 1977.

(25) Shurr, G.G., "Proper Coatings for Wood Exteriors," *Am. Paint. Contractor*, *12*, 18 (1969).

(26) Desai, R.L., "Coating Adhesion to Weathered Wood," Eastern Forest Products Laboratory, Ottawa, Canada, *Bi-Monthly Research Notes*, *23*, No. 5, 36 (1967).

(27) Kleive, K., "Weathered Wooden Surfaces—Their Influence on the Durability of Coating Systems," JOURNAL OF COATINGS TECHNOLOGY, *58*, No. 740, 39 (1986).

(28) Richter, K., Feist, W.C., and Knaebe, M.T., "The Effect of Surface Roughness on the Performance of Finishes. Part 1. Roughness Characterization and Stain Performance," *Forest Prod. J.*, *45*, No. 7/8, 91 (1995).

(29) Williams, R.S. and Feist, W.C., "Durability of Paint or Solid-Color Stain Applied to Preweathered Wood," *Forest Prod. J.*, *43*, No. 1, 8 (1993).

(30) National Association of Home Builders, *Housing Facts, Figures and Trends*, NAHB, Washington, D.C., 1997.