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Moisture Content and the Properties of Clear Southern Pine

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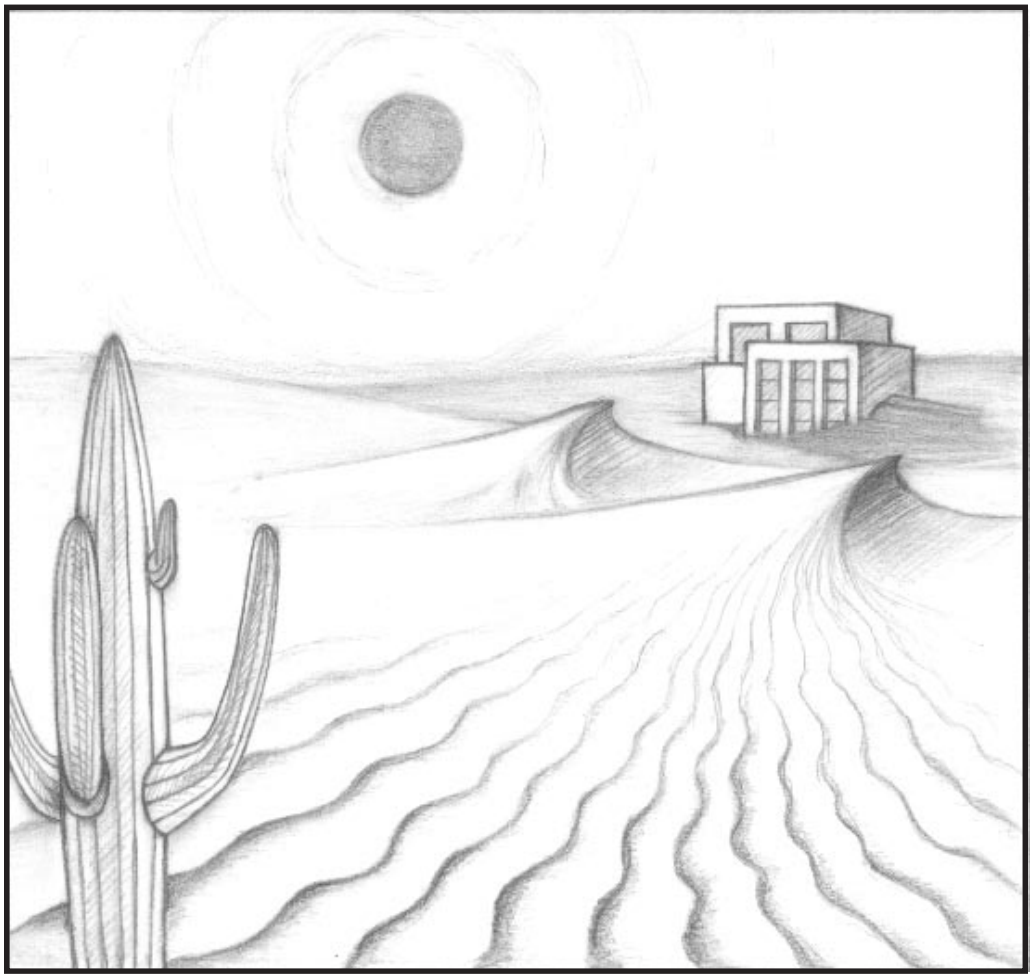

Abstract

Studies were conducted on the effect of moisture content (MC) on the mechanical properties of clear Southern Pine stressed in tension and compression parallel and perpendicular to grain, shear parallel to grain, three-point bending, and mode I (opening) and mode II (forward shear) stress intensity factors K_{IcTL} and K_{IIcTL}. The effects of MC on Poisson's ratios in the longitudinal–radial and longitudinal–tangential plane were also determined. The test specimens were cut from 150 commercially dried 2- by 6-in. lumber. Specimens were sorted into five matched groups of approximately 40 specimens each based on specific gravity. One group of specimens was saturated with water, and four groups were equilibrated to MC levels of 4, 8, 12, and 18 percent prior to testing. The MC level above which properties cease to be affected by MC was determined to be 23 percent. Results indicate that tensile stress parallel and perpendicular to grain and both mode I and mode II stress intensity factors increase with decreasing MC from green to a peak between 7 and 13 percent MC. Upon further drying, these properties decrease. Maximum fiber stress in bending, compression parallel and perpendicular to grain, and shear parallel to grain and all elastic modulii increase with decreasing MC from green to 4 percent MC. For some of these properties, the increase is not linear at lower MC levels.

Keywords: Moisture content, specific gravity, clear wood, tension, bending, compression, shear, stress intensity factor, Poisson's ratio, Southern Pine

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Research Highlights

Contemporary engineering design practices in the United States require information on the strength of lumber for moisture content levels as low as 2 to 4 percent. This study is part of a program to gain a fundamental understanding of the effect of moisture content (MC) on the mechanical properties of wood. The program was initiated because (1) previous research indicated that lumber strength, especially ultimate tensile stress (UTS) parallel to grain, does not always increase with decreasing MC and (2) limited but persistent failures were reported on timber structures subjected to environmental conditons that lead to very low MC levels.

To efficiently design future experimental studies on lumber properties at low MC levels, it is desirable to obtain a better understanding of the basic mechanisms controlling moisture–property relationships. The results of this study will be used to develop empirical equations for predicting the mechanical properties of clear Southern Pine as a function of MC and/or density. These equations will then be used to simulate the effect of MC on the tensile strength of lumber. This information is also useful for computer modeling of moisture effects on other engineering properties, such as fastener strength.

The objective of this study was to establish a database for the mechanical properties of clear Southern Pine stressed in tension and compression parallel and perpendicular to grain, shear parallel to grain, three-point bending, and mode I (opening) and mode II (forward shear) stress intensity factors K_{IcTL} and K_{IIcTL}. The effects of MC on Poisson's ratios in the longitudinal–radial and longitudinal–tangential plane were also determined. Test specimens were cut from 150 commercially dried 2- by 6-in. lumber. Specimens were sorted into five matched groups of approximately 40 specimens per group based on specific gravity. One group of specimens was saturated with water and four groups were equilibrated to MC levels of 4, 8, 12, and 18 percent prior to testing.

The results of this study indicate the following:

- Ultimate tensile stress parallel and perpendicular to grain and the critical stress intensity factor K_{IIcTL} increase as MC decreases, reaching a maximum in the range from 7 to 13 percent MC. These properties then decrease with further drying. The K_{IcTL} factor peaks at about 6 percent MC and decreases with further drying.
- Modulus of elasticity (MOE) in tension parallel and perpendicular to grain, MOE in compression parallel to grain, and shear strength parallel to grain increase linearly with drying from green to about 6 percent MC. With further drying, these properties increase at a slower rate or remain constant.
- Modulus of elasticity in bending and in compression perpendicular to grain increase linearly with drying from green to 4 percent MC.
- The MC above which properties cease to decrease with increasing MC, M_p, is remarkably constant across properties and averages 23 percent.
- All properties are positively correlated with specific gravity. However, the slope of the property–specific gravity relationship is a function of MC.
- Critical levels of MC in the MC–property relationship occur at about 6 and 12 percent, depending upon property. The behavior can be understood from consideration of molecular forces and wood macrostructure.

Moisture Content and the Properties of Clear Southern Pine

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Introduction

In the United States, lumber is used with a wide range of moisture content (MC) levels. For example, lumber installed green in timber bridges may remain at, or near, the fiber saturation point for several years after bridge installation. In contrast, lumber used in attics in the dry southwestern parts of the country or above heat sources in commercial buildings may be reduced to moisture levels as low as 2 to 4 percent within a year of installation. This study is part of a program to gain a fundamental understanding of the effect of MC on the mechanical properties of wood. The program was initiated because (1) previous research indicated that lumber strength, especially ultimate tensile stress (UTS) parallel to grain, does not always increase with decreasing MC and (2) limited, but persistent, failures have been reported in timber structures subjected to environmental conditions that lead to very low MC levels.

In the past few years, several studies have been conducted on the effect of MC on the bending strength and tensile and compressive strength parallel to grain of nominal 2-in.-thick commercial lumber (Green and Evans 1989) (see Table 1 for metric conversions). This work refutes traditional assumptions that bending and tensile strength always increase with decreasing MC. This is especially true for tensile strength (Fig. 1). The traditional model of ASTM Standards D245–D2915 (1993) assumes that tensile strength increases linearly with decreasing MC within the range from green (assumed to be 22 percent MC in D2915) and 0 percent MC. However, this model is not based on experimental evidence. Rather, the tensile–MC model is based on the assumption that the effect of MC on tensile strength is identical to the model (also erroneous) given in standards relating bending strength to MC (Green 1980). However, experimental evidence for lumber indicates that UTS at most percentile levels first increases with decreasing MC below the fiber saturation point and then decreases as MC falls below about 10 to 15 percent (Green and others 1990). Based on this work, new empirical models were derived to describe the effect of MC on tensile properties (Green and Evans 1989) and simplified models derived for general design use (ASTM 1993, D1990). The experimental design of this new research was driven by the needs of the U.S. In-Grade Testing Program (Green 1983). Because only a small amount of commercial lumber is intentionally dried to less than about 10 percent MC, this level was the lowest MC for which UTS data were obtained.

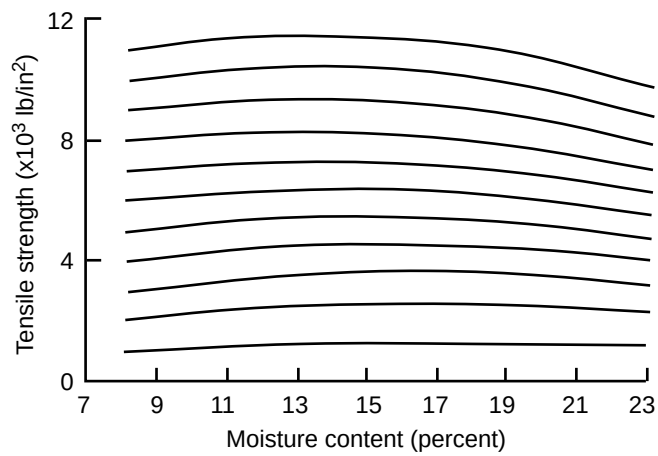

Figure 1—Moisture effects on dimension lumber in tension (Green and others 1990).

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
°F	(°F – 32)/1.8	°C
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
pound (lb)	0.4535	kilogram (kg)
pound per cubic foot (lb/ft^3)	1.60	kilogram per cubic meter (kg/m^3)
lb/in^2	6.895	kilopascal (kPa)

Each year for the past 15 years, the USDA Forest Service, Forest Products Laboratory (FPL), has received one to three calls about failures in structural members subjected to ambient environmental conditions that have member MC levels ranging from 2 to 4 percent. A significant number of these calls have been from consulting engineers. Some calls have been followed by written reports, including photographs. We have also received samples of wood cut from failed members. Virtually all reports have involved commercial buildings. Some failures have occurred at connections, but a surprising number have also exhibited failure in the middle of the member far removed from a joint. In some instances, there has been evidence of thermal degradation.

When looking for evidence of thermal degradation, we first look for darkening of the surface. In some instances, we may detect degradation of the cell structure as a result of prolonged heating. It is also possible to look for changes in chemical composition. The following examples received by Dr. David W. Green illustrate the scope of the potential problem:

> Every couple of years, engineers in Phoenix, Arizona, have called to discuss periodic failures of individual members in the tension cords of bowstring trusses. The members had been in the roofs of several commercial buildings with no known interior heat source. The MC levels of the members were extremely low (less than 6 percent by moisture meter). Failures near joints and away from joints were reported, and temperatures in the attic area were reported to be more than 100°F for significant periods. The trusses had been in use since the 1950s.
>
> A call was received about a failure in truss members over a drying oven for painted metal surfaces in Michigan. A sample of the wood sent to the FPL indicated significant thermal degradation and an ovendry MC of about 2 percent.
>
> Several telephone calls and a follow-up written report, with color photographs, were received about failures in wooden members in several buildings used for glass factories in New England. The buildings had been in use for 20 to 75 years. A very low MC level and thermal degradation were indicated.
>
> A noted consulting engineer reported on some member failures in a commercial building in California he had inspected. The failures were primarily in lower chord truss members and at locations removed from the joint. He judged that temperatures in the roof area sometimes exceeded 100°F and the MC of the members was very low.

Suddarth (1990) reported on bolted connection tests that were conducted as a result of a heavy-timber roof collapse. For specimens having three-bolt connections and tested at MC levels of 7 to 8 percent, 8 of the 11 joints failed to carry their design loads. Suddarth felt the interaction between having a low MC and large rigid bolts might be contributing to high splitting forces and causing failures at much lower loads than expected. Surprised by the experimental results, Suddarth (1990) said, “It is clear that the use of large bolts, and possibly shear plates, should be suspended until the problem indicated by these few tests is better understood.”

Thus, considerable anecdotal information exists indicating that, although very low moisture conditions are not common for wooden structures, when these conditions do occur, there are limited, but persistent, reports of failure. This evidence, coupled with the experimental evidence of a decrease in lumber tensile strength with drying to less than about 12 percent MC, suggests the need for additional experimental studies on the effect of low MC levels on the UTS of structural lumber. However, such studies are expensive and time consuming.

The need to obtain a more fundamental understanding of the effect of MC on lumber properties was recognized by Dr. Green in the mid-1980s. However, other priorities and a lack of an adequate analytical model for predicting the strength of lumber using fundamental mechanisms prevented such a study. Such a model is now available (Cramer and McDonald 1989). Thus, the remaining research needed to better understand the effect of low MC levels on the properties of both solid lumber and bolted joints is a study of the effect of MC on clear wood properties.

The objective of this study was to determine the effect of MC on a wide range of clear wood properties. Empirical models fit to this data will serve as input to a comparison study using the Cramer–McDonald model.

Background

An extensive amount of work has been done on the effect of MC on several clear wood properties. General discussions of the effect of MC on clear wood mechanical properties can be found in Panshin and DeZeeuw (1980) or the *Wood Handbook* (Foest Products Laboratory 1987). These discussions indicate that clear wood strength for a number of mechanical properties increases with decreasing MC (Fig. 2). A thorough

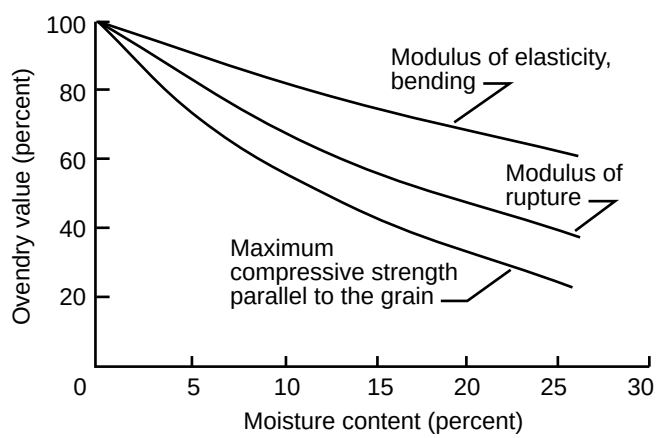

Figure 2—Increasing properties with decreasing moisture content (Panshin and DeZeeuw 1980).

review of research findings involving moisture and temperature effects on clear wood was compiled by Gerhards (1982). In the following section, we review and supplement the information compiled by Gerhards. Table 2 summarizes the clear wood literature discussed in this section. Most clear wood data sets cited in these publications contain only a few mechanical properties and perhaps a limited range in MC levels. We know of no data set containing information on all the properties required for input into Cramer's finite element model.

Modulus of Elasticity

Data for modulus of elasticity (MOE) have been collected by a number of researchers on compression, tension, bending parallel to grain, and tension and compression perpendicular to grain (Table 2). Figure 3 shows Gerhards's (1982) data of parallel to grain MOE with Ostman's (1985) work overlaid. For the data reviewed, Schneider's (1971) bending curve and Ostman's tension curve for MOE parallel to grain show a flattening in the slope with decreasing MC levels less than about 6 percent. However, Conners and Medvecz's (1992) results for yellow poplar show a loss in MOE parallel to the grain at less than 12 percent MC (Fig. 4). The MOE perpendicular to grain cited by Kadita and others (1961) also seems to show flattening of the curve at low MC levels (Fig. 5).

Tensile Strength

Work investigating tensile strength parallel to grain in clear wood was been done by Kollmann (1956), Kufner (1978), Ostman (1985), Curry (1952), and Leont'ev (1962). Kollmann's work with spruce shows a peak in strength at about 6-percent MC (Fig. 6). Kufner's work with beech, bongossi, fir, oak, poplar, and zpatero shows a definite indication of peaking between 4.5 and 8.0 percent, with the combined curve having a peak at 5 percent MC. Curry's (1952) work with Sitka spruce shows a definite peak in tensile strength as the wood dries at around 14 to 18 percent MC (Fig. 7). Like Curry's work, Ostman's data on spruce indicate a peak in tensile strength being reached at about 14 percent MC. Leont'ev's model for *Pinus silvestris*, larch, and fir tension parallel to grain also indicates a leveling of strength with decreasing MC (Fig. 8). The curve for fir appears to reach a maximum at about 7 percent MC, with pine and larch peaking at lower MC levels.

For tensile strength perpendicular to grain, there is also evidence of a leveling or falling in strength with decreasing moisture. Kollmann fitted an increasing curve to his tensile data (Fig. 9). However, data (Fig. 9) seem to show a flattening of tensile strength with decreasing MC at about 12 percent MC. Leont'ev's formulas for alder, aspen, and pine indicate a peaking of strength between 8 and 12 percent MC (Fig. 10). Schniewind's (1962) work with California black oak shows a nonlinear curve with a decreasing slope as lower MC levels are approached (Fig. 11). Siimes's (1967) work with *Pinus silvestris* at room temperature shows a decrease in tensile strength perpendicular to grain occurring at less than 10 percent MC for the two upper specific gravity levels and suggests a flattening of tensile strength for all specific gravity levels starting at 13 percent MC (Fig. 12). Finally, Youngs's (1957) work with red oak at room temperature shows a flattening at 12 percent MC (Fig. 13). One exception found to these trends of flattening or decreasing strength with decreased moisture is work conducted by Greenhill (1936). Greenhill's work with beech shows an increase in strength perpendicular to grain as the material dried. A probable explanation is that Greenhill's data were limited and only went down to 7 percent MC.

It appears from the data reviewed that many studies found that tensile strength, both parallel and perpendicular, first increases with decreasing MC until it reaches an MC ranging from 10 to 15 percent, and then flattens, or in some instances decreases, with decreasing MC. However, some studies do not show this trend. Therefore, tensile strength, perpendicular and parallel, may have an important role in explaining the change in tensile strength of lumber with change in MC (Fig. 1).

Bending Strength

Gerhards reported on five studies (Drow 1945, James 1964, Leont'ev 1960, Sulzberger 1953, Wilson 1932) that looked at the effect of MC on bending strength (Fig. 14). Figure 14 suggests that a decrease in MC results in an increase in bending strength. Only Sulzberger's results suggest a flattening in the bending–MC relationship at lower MC levels.

Compressive Strength

A large amount of data on compressive parallel to grain is available. Data were collected by Wilson (1932), Drow (1945), Matejek and Starecka (1971), Ishida (1954), and Schneider (1971). In addition, Leont'eiv (1960) proposed a series of equations of the form

$$\mathrm{Str} = A \cdot M^2 + B \cdot M + C$$

where M is MC and A, B, and C are constants, to describe moisture effects on compression strength. Values for compression strength parallel to grain tended to increase linearly with decreasing MC (Fig. 15). Flattening in the relationship at low MC was not indicated.

Available data for compressive strength tangential to grain are limited. Extensive studies were conducted by Kunesh (1968), Siimes (1967), Okohira (1955), Ellwood (1954), Wilson (1932), and Youngs (1957). Again, flattening in the relationship at low MC was not indicated (Fig. 16).

Compressive data both parallel and perpendicular to grain indicate that as MC decreases, compressive strength increases. This trend is to be expected because compression will close strength-reducing voids within the cell wall created by drying stresses. However, the magnitude of the increase is dependent on species.

Table 2—Summary of references on clear wood moisture content

Reference	Properties tested	Species	Moisture content (percent)	Sample size per MC group
Conners and Medvecz 1992	MOE compression parallel, MOE tension parallel	Yellow-poplar	6, 12, 18, green	15
Curry 1952	Tension parallel	Sitka spruce	9, 12, 15, 20, green	50 to 200
DeBaise and others 1966	Strain energy release rate G_{Ic} TL and RL	White pine	0.5, 9, 18, green	5 to 10
Drow 1945	Compression parallel, shear parallel, bending	Douglas-fir, Sitka spruce	2, 7, 10, 14, 19, 22	10
Drow and McBurney 1954	Poisson's ratio	Sitka spruce	7, 13, 16, 22	14
Ellwood 1954	Compression perpendicular, tension parallel	Beech	6, 12, 18, green	
Ewing and Williams 1979	K_{Ic} fracture	Scotts pine	Ovendry, 7, 11, 14, 20	8 to 10
Fonselius and Riipola 1992	K_{IIc} fracture	Spruce, pine	10, 12, 16	30
Greenhill 1936	MOE tension perpendicular, tension perpendicular	Beech	7, 14, 20, green	30 to 35
Ishida 1954	Compression parallel	Jezo-spruce	Ovendry, 15, green	
James1964	Bending, MOE bending, MOE compression parallel, compression parallel	Douglas-fir	2, 12, 15, 21, 28	20
Kollman 1956	Tension parallel, tension perpendicular	Fir	Ovendry to 28	40 total
Kufner 1978	MOE tension parallel, MOE vibration, tension parallel	Beech, bongossi, Douglas-fir, fir, oak, poplar, zpatero	0, 3, 6, 9, 12, 15, 20, 25, 30	10
Kunesh 1968	MOE compresion perpendicular, compression perpendicular	Douglas-fir, western hemlock	6, 12, green	240
Leont'ev 1960	Compression parallel, compression perpendicular, tension parallel, tension perpendicular	Beech, hornbeam, oak, basswood, larch, alder, aspen, fir, pine, poplar, ash	5 to 30	Various
Logemann and Schelling 1992	K_{Ic} fracture	Swedish spruce	8, 12, 16, green	12
Matejek and Starecka 1971	Compression parallel	Beech, oak, pine	Ovendry, 7, 10, 20, green	
McBurney and Drow 1956	Poisson's ratio	Douglas-fir	7, 13, 20	4
Okohira 1955	Compression perpendicular	Sugi	5 to green	
Ostman 1985	MOE tension parallel , tension parallel	Spruce	0 to 30	10 total
Petterson and others 1981	K_{Ic} fracture, MOE bending , MOE tension perpendicular	Loblolly pine, lodgepole pine , shortleaf pine, Douglas-fir, redwood, western larch, Engelmann spruce, ponderosa pine, western hemlock, western redcedar	5 to green	30 per species

Table 2—Summary of references on clear wood moisture content—con.

Reference	Properties tested	Species	Moisture content (percent)
Porter 1964	Strain energy release rate G_{IC} TL and RL	White pine	0.5, 9, 16, green
Schneider 1971	MOE vibration	Beech pine	0, 7, 12, 24
Schniewind 1962	MOE tension perpendicular, tension perpendicular	California black oak	6, 12, 20, green
Schniewind and others 1982	K_{Ic} fracture	White pine	0.5, 9, 16, green
Siimes 1967	MOE tension perpendicular, MOE compression perpendicular, tension perpendicular, compression radial tangential	Birch, pine, spruce	4, 8, 12, 16, 20, green
Sulzberger 1953	MOE bending, compression parallel, bending	Bollywood, coachwood, hoop pine, mountain ash, silver quandong, Sitka spruce	0, 8, 12, 20, green
Wilson 1932	MOE bending, MOE compression parallel, compression parallel, compression perpendicular, shear parallel, bending	Chestnut, Douglas-fir , greenheart, loblolly pine, longleaf pine, Norway pine, red spruce, Sitka spruce, tamarack, western hemlock , western larch, white ash, yellow birch	3, 5, 8, 10, 12, 15, 20, 25, green
Wright 1986	K_{Ic} fracture	Pine, spruce, spruce laminated veneer lumber	10, 12, 16 9 to 22
Youngs 1957	MOE tension perpendicular, MOE compression perpendicular, compression perpendicular, tension perpendicular	Red oak	6, 12, 18, green

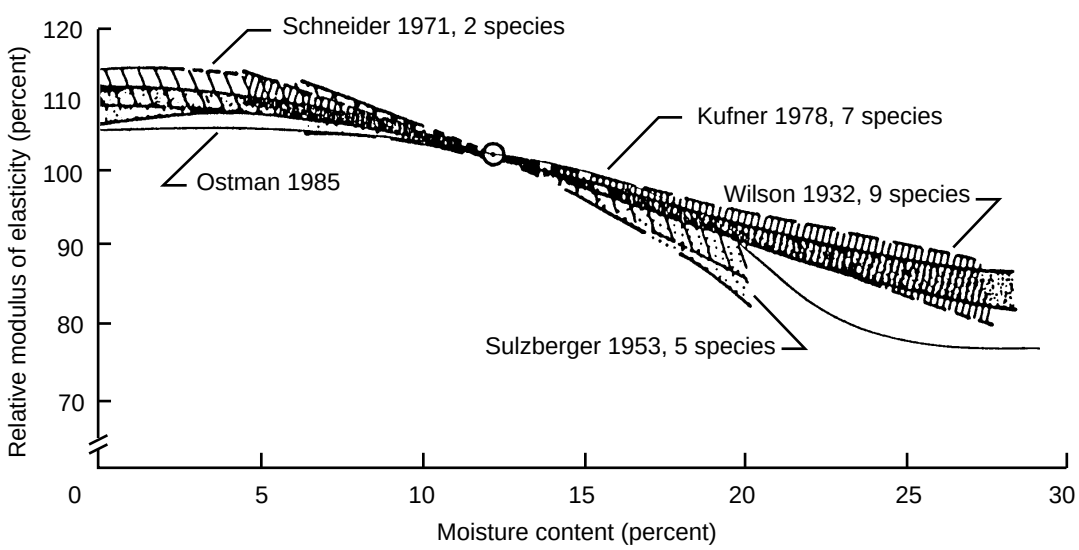

Figure 3—Relationship between modulus of elasticity parallel to grain and moisture content (Gerhards 1982).

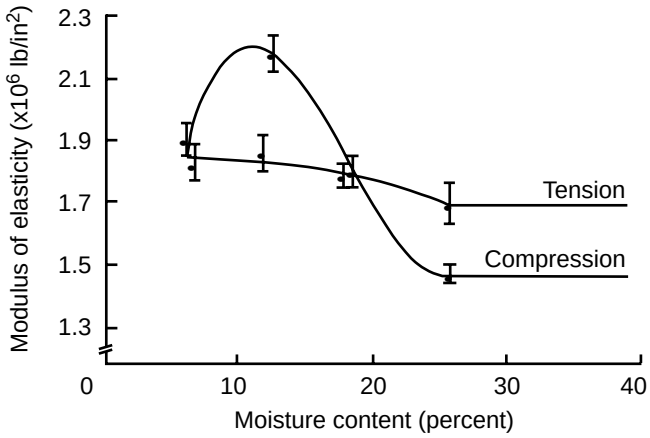

Figure 4—Relationship between modulus of elasticity parallel to grain in compression and tension for yellow poplar (Conners and Medvecz 1992).

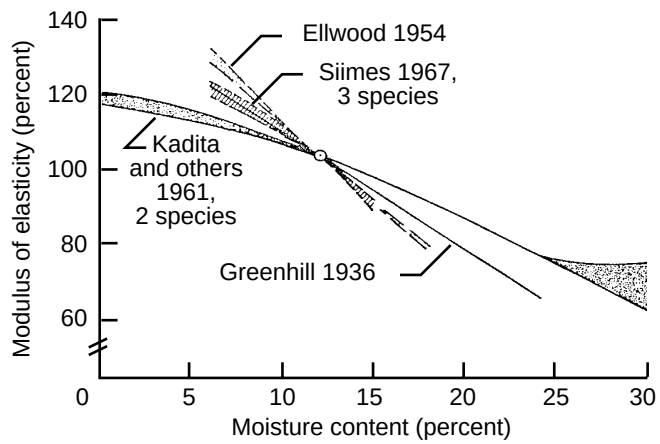

Figure 5—Relationship between relative modulus of elasticity perpendicular to grain and moisture content (Gerhards 1982).

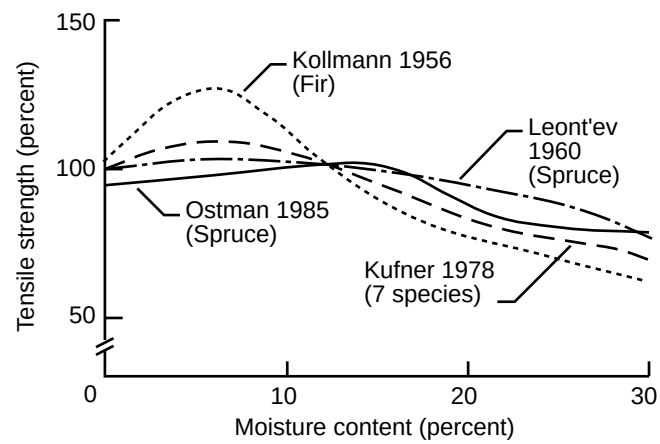

Figure 6—Relationship between relative tensile strength parallel to grain and moisture content.

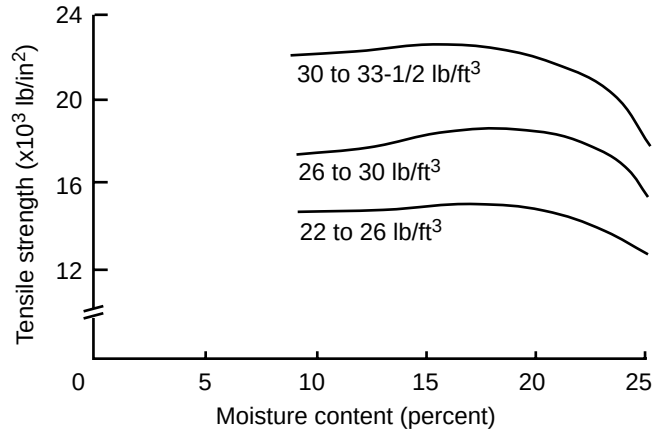

Figure 7—Relationship between average tensile strength parallel to grain and moisture content for Sitka spruce (Curry 1952).

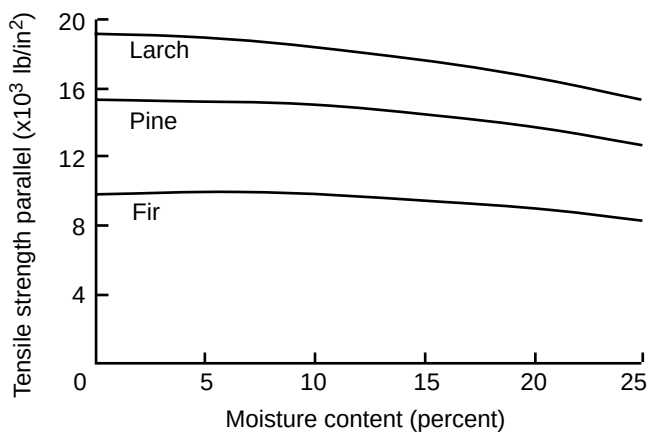

Figure 8—Relationship between tensile strength parallel to grain and moisture content (Leont'ev 1960).

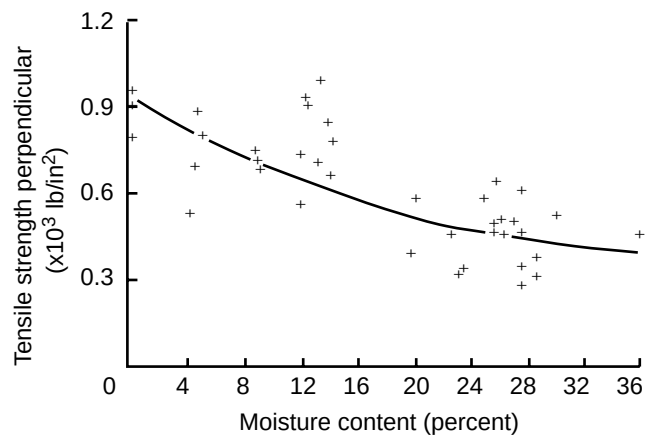

Figure 9—Relationship between tensile strength perpendicular to grain and moisture content (Kollman 1956).

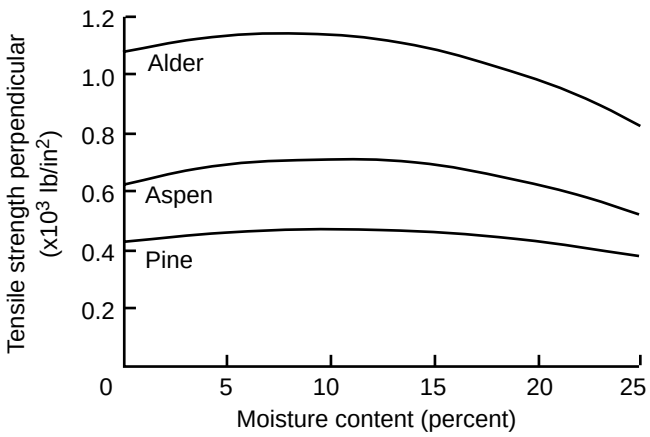

Figure 10—Relationship between tensile strength perpendicular to grain and moisture content (Leont'ev 1960).

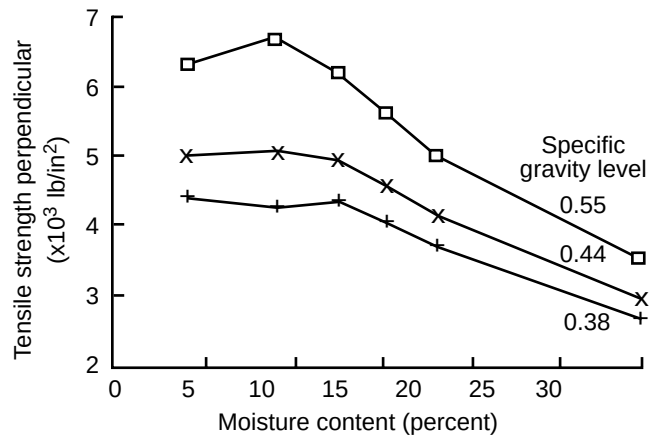

Figure 12—Relationship between tensile strength perpendicular to grain and moisture content for *Pinus silvestris* (Siimes 1967).

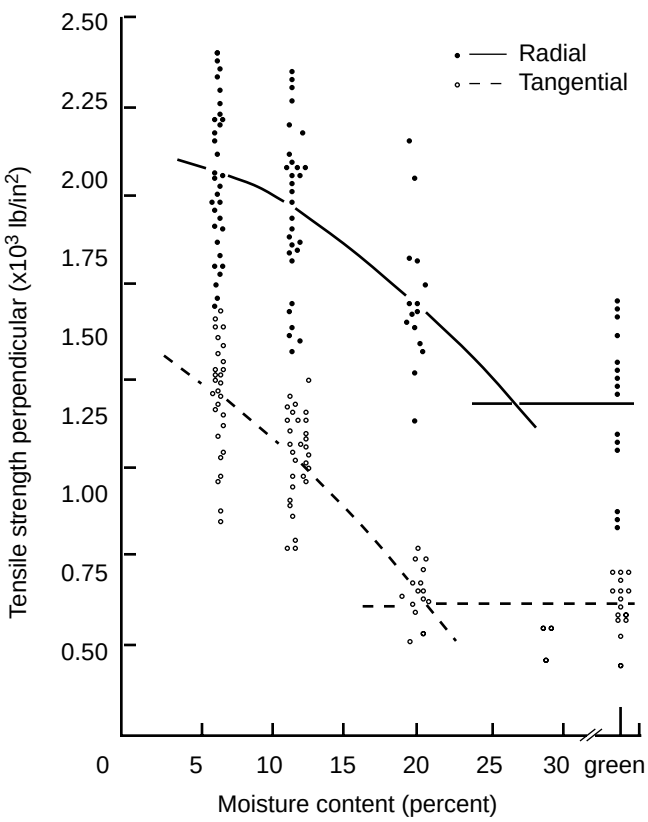

Figure 11—Relationship between maximum tensile strength perpendicular to grain and moisture content for black oak (Schniewind 1962).

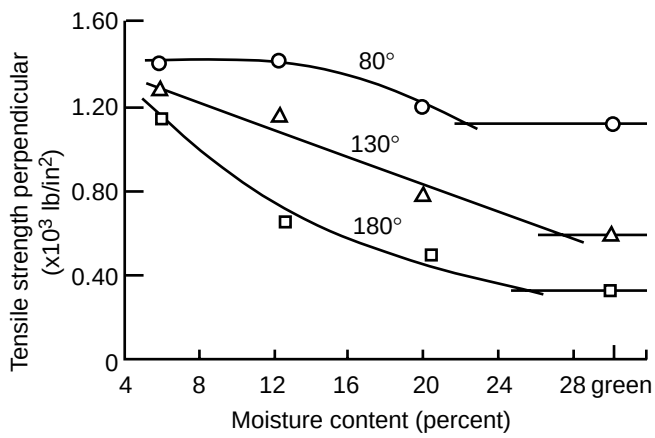

Figure 13—Relationship between tensile strength perpendicular to grain and moisture content for red oak (Youngs 1957).

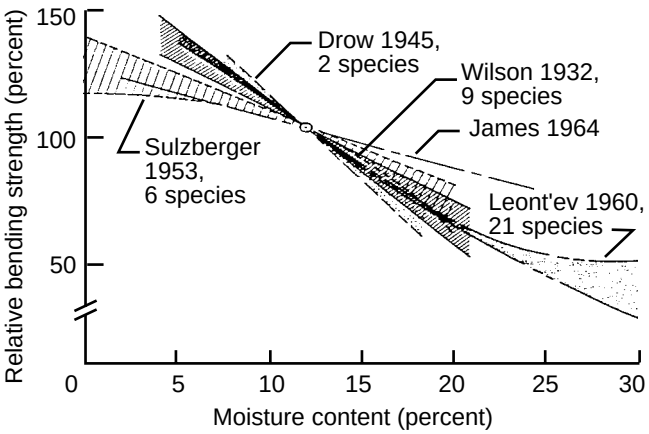

Figure 14—Moisture content effects on bending strength (Gerhards 1982).

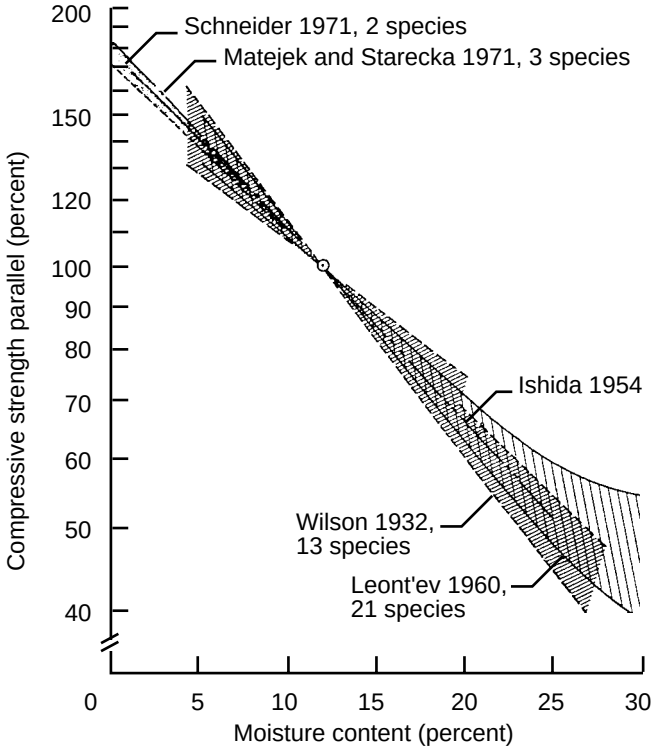

Figure 15—Relationship between relative compressive strength parallel to grain and moisture content (Gerhards 1982).

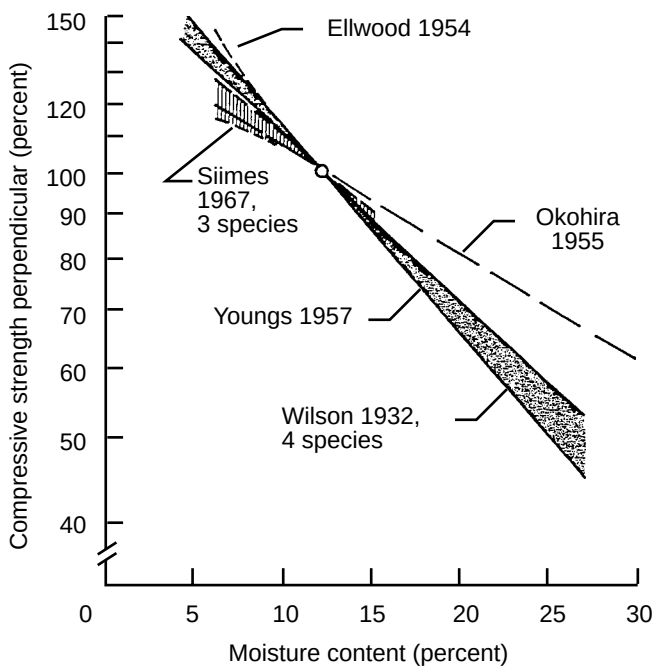

Figure 16—Relationship between relative compressive strength perpendicular to grain and moisture content (Gerhards 1982).

Shear Strength Parallel to Grain

If shear data collected by Wilson (1932) on Sitka spruce and Douglas-fir were reexamined, an indication of decreasing shear strength with decreasing MC would be observed at 10 to 12 percent MC (Fig. 17). Drow's (1945) work with Douglas-fir and Sitka spruce, however, does not indicate a flattening or decline in shear strength at lower MC levels (Fig. 18). Drow's data only go down to 7 percent MC. If confirmed, the data of Wilson would indicate that shear strength may be an important contributing factor to strength loss in lumber, as shown in Figure 1.

Mode I and II Fracture Toughness

A recent summary of fracture toughness testing on wood was compiled by RILEM (Valentine and others 1990). Fracture theory is based on the assumption of the existence of critical flaws that initiate failure in materials. Three types of stress fields and associated stress intensity factors can be defined at a crack tip: opening mode (I), forward shear mode (II), and transverse shear mode (III) (Fig. 19a). Wood exhibits distinct properties in each of its three principal orthogonal directions: longitudinal (L), radial (R), and tangential (T). A crack may lie in one of the three planes and may propagate in one of two directions in each plane. This gives rise to six crack propagation systems: RL, TL, RT, TR, LR, LT (Fig. 19b). The first letter indicates the axis perpendicular to the crack plane, and the second indicates the direction of crack propagation. Of these six propagation systems, four systems are of practical importance: RL, TR, RT, and TL. These four systems allow for propagation of the crack along the low strength path parallel to grain (Barrett 1976). The TL and RL orientations in wood (where T or R is direction of load and L is direction of crack propagation) will predominate as a result of the low strength and stiffness of wood perpendicular to grain (Patton–Mallory and Cramer 1987). Therefore, one of these two orientations is most often tested. In the study reported here, we looked at mode I critical stress intensity factor, K_{IcTL}, and mode II critical stress intensity factor, K_{IIcTL}, in the TL orientation.

The effect of MC on mode I fracture toughness was investigated by Ewing and Williams (1979), Petterson and others (1981), Schniewind and others (1982), Wright (1986), Kretschmann and others (1990), and Logemann and Schelling (1992). The existing mode I fracture–moisture data suggest that fracture toughness peaks in value before reaching low MC levels.

In Ewing and Williams's work with Scotch pine, the K_{IcTL} value increases to a maximum at about 6 percent MC (Fig. 20). However, the lowest MC level was obtained by ovendrying the specimens at 221°F. Thus, thermal degradation could have biased this conclusion. A peak fracture toughness at about 10 percent MC was also indicated by

some species in the work by Petterson and others (1981). In these tests, a wide range of MC levels was used, with a total sample size of approximately 30 pieces. Half the specimens were tested in the green condition, and the remainder of the data points were distributed throughout a range of MC levels ranging from about 8 percent to green. Schniewind and others (1982) reviewed prior work on the effect of MC on fracture toughness. They concluded that "The most comprehensive investigations of the effect of MC and temperature were made very early by Porter (1964) and DeBaise and others (1966)." Schniewind converted the strain energy density values (G_{Ic}) to critical stress intensity factor (K_{IcTL}) values and compared them with MC (Fig. 21). Porter's work averaged seven western white pine specimens in each of four moisture levels (0.5, 9.0, 16.0 percent, and green) and five temperature conditions (–319°F, 68°F, 104°F, 122°F, 176°F). Debaise's work looked at an average of 5 to 10 white pine RL fracture specimens at the same four MC levels and seven temperatures (–22°F, –4°F, –14°F, 32°F, 50°F, 68°F, 86°F). Data showed a definite maximum occurring between green and ovendry. For DeBaise, the room temperature peak occurred at about 7 percent MC. For Porter, the room temperature peak occurred at about 16 percent MC. Wright looked at five moisture levels (ovendry, 4 to 6, 10, 12, 16 percent). Only the ovendried specimens showed lowered measured fracture toughness values.

Much less information exists for moisture effects on mode II fracture toughness. Work was conducted by Kretschmann and others (1991) and Fonselius and Riipola (1992). The work by Kretschmann and others will be discussed later in this paper. Mikael Fonselius and Krista Wright–Riipola of the Technical Research Centre of Finland examined 1,200 specimens equally divided between pine, spruce, and spruce laminated veneer lumber and mode I and mode II testing. For the mode II work, three moisture levels were investigated (10, 14, 18 percent). These results indicated an insensitivity of mode II fracture toughness to changes in moisture content when pine and spruce were dried.

Poisson's Ratio

Moisture effects on Poisson's ratio of Sitka spruce and Douglas-fir were reported by Drow and McBurney (1954) and McBurney and Drow (1956). All six possible orientations were investigated (LT, LR, TL, TR, RL, RT). The Sitka spruce study had 14 specimens at each of four moisture levels; the Douglas-fir study was limited, having four specimens at each of three moisture levels. Poisson's ratios LR, TR, and RT seem to be rather insensitive to changes in moisture content. Poisson's ratio for LT may have decreased with decreasing MC, and RL and TL seemed to increase with decreasing MC to a peak between 10 and 15 percent and then decrease. The results for RL are shown in Figure 22.

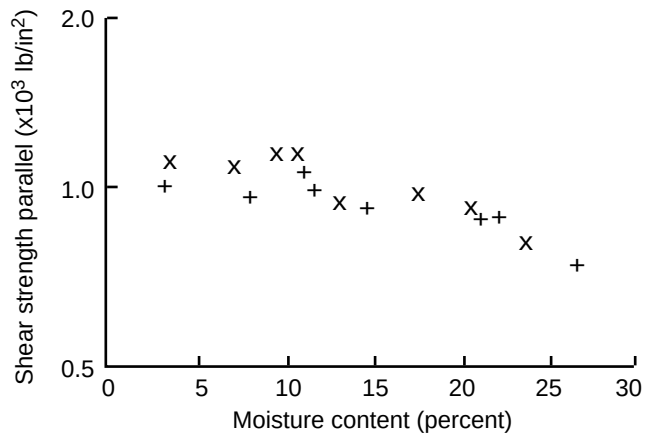

Figure 17—Relationship between shear strength parallel to grain and moisture content (Wilson 1932).

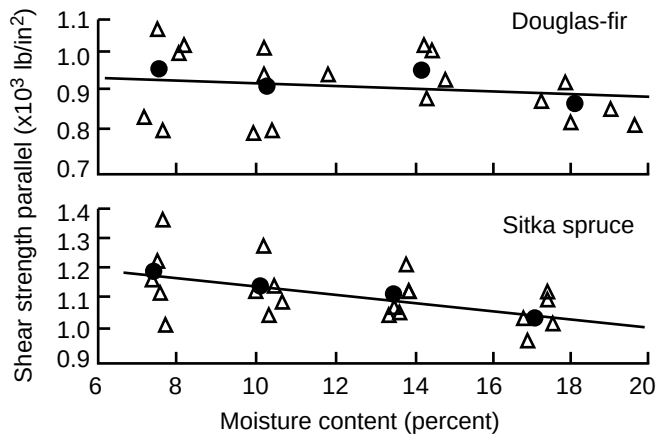

Figure 18—Relationship between shear strength parallel to grain and moisture content (Drow 1945).

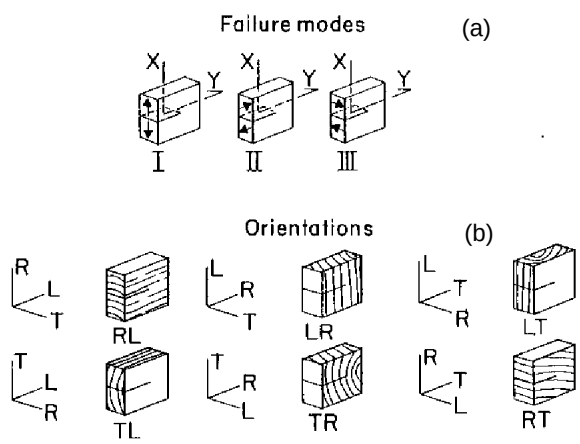

Figure 19—Possible crack propagation systems for wood: (a) failure modes, (b) orientations.

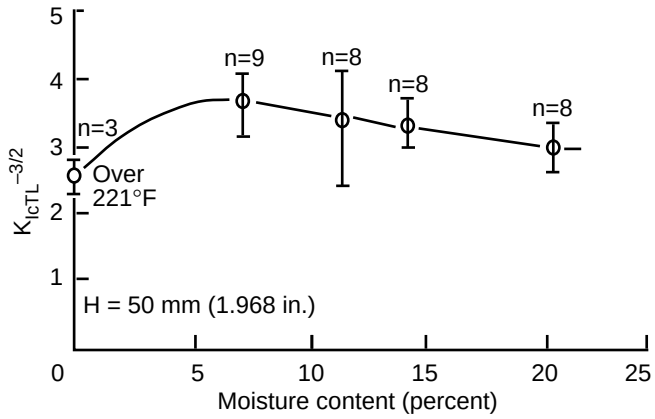

Figure 20—Relationship between K_{IcTL} stress intensity factor and moisture content (Ewing and Williams 1979).

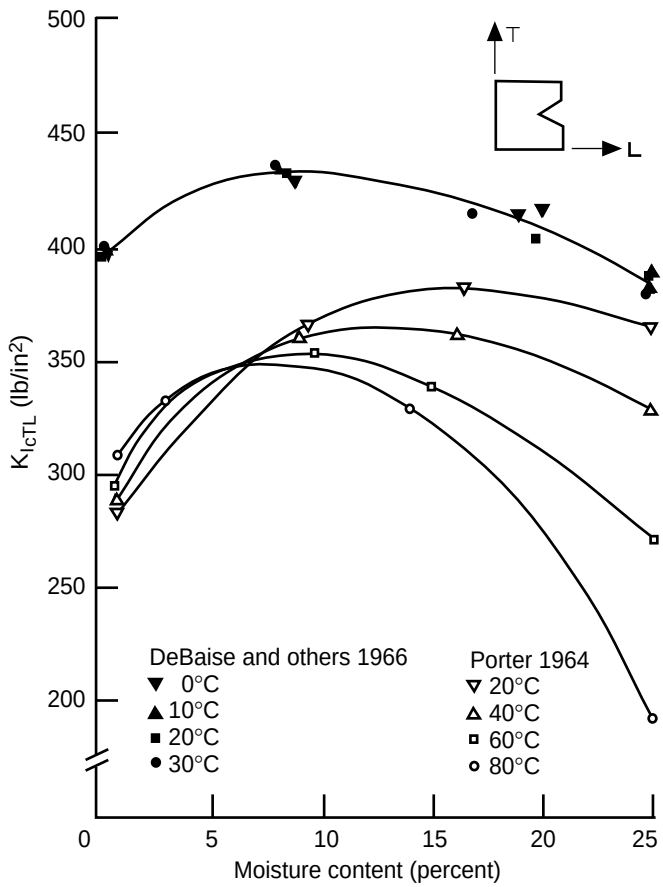

Figure 21—Relationship between K_{IcTL} stress intensity factor and moisture content (Schniewind 1982).

Summary

Considerable data exist on the effect of MC on the mechanical properties of clear, straight-grained wood. In general, the data reported in any one study were for only a few properties, and limited specimens were often used for a given property–MC combination. Much more limited data have been reported for ≤6 percent MC than for >6 percent MC.

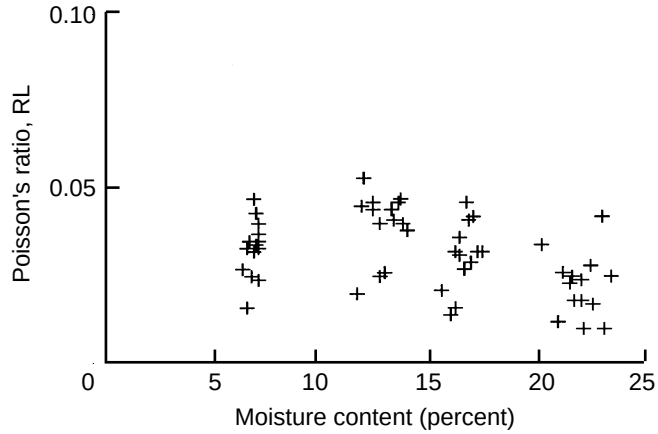

Figure 22—Relationship between Poisson's ratio radial–longitudinal (RL) and moisture content for Sitka spruce (Drow and McBurney 1954).

From the studies reported, it appears that MOE in bending and compressive strength parallel and perpendicular to grain increase linearly with drying below the fiber saturation point. There is some indication that the MOE parallel and perpendicular to grain–MC curves flatten for MC levels less than about 6 percent. Tensile strength parallel and perpendicular to grain, shear strength parallel to grain, and mode I and II fracture toughness also increase with decreasing MC from green to about 12 to 15 percent. Several studies indicated that a significant decrease in these property values may occur with further drying. These property value decreases could explain the loss in the UTS of lumber at MC levels less than 12 percent (Fig. 1). However, given the limitations of the available data, it is not possible to draw absolute conclusions.

Experimental Methods

Material Selection and Preparation

Traditionally, clear specimens for MC–property studies have been cut from green logs and then dried to various target moisture levels. However, the intended use of these data is to model tensile strength–MC relationships from commercial lumber. It is after drying that the lumber is used in a structure; at this time, knowledge of the affect of a change in property with a change in MC is needed. The extent to which kiln schedule, moisture hysteresis, and other practical considerations affect the tensile strength of commercial lumber is not known. Therefore, to more closely incorporate any potential effects into our study, we cut clear samples from previously dried commercial lumber. We chose Southern Pine because it is a locally available, commercially important species for which data are not available on MC–tensile strength. However, the properties of Southern Pine are not as sensitive to a kiln schedule as those of Douglas-fir.

Material Selection

Material for this study was cut from 150 12-ft Southern Pine (*Pinus echinata* or *P. taeda*) 2- by 6-in. (2 by 6) lumber obtained from local suppliers in Madison, Wisconsin. Care was taken to obtain flat-sawn lumber that did not contain pith. The lumber was either KD15 Dense Select Structural or No. 1 Dense visually graded lumber (SPIB 1977) from three different mills.

The 150 2 by 6's were numbered sequentially. Then, specific gravity values based on ovendry weight and volume were obtained for each piece, and the pieces were ranked according to specific gravity (ASTM D2395). To assign lumber to a specific target moisture content group, the five 2 by 6's with the highest specific gravity were randomly assigned to one of five MC levels. The next five pieces were selected and assigned randomly to their respective groups. This procedure was followed until all specimens were assigned to each MC group. From each 2 by 6, at least one, and possibly two, 52-in. sections having straight grain and free from noticeable defects were cut.

The 52-in. sections were placed into conditioning chambers with the appropriate temperature and relative humidity (RH) to bring the sections to equilibrium at a target MC of 4 percent (90°F and 20 percent RH), 7 percent (80°F and 30 percent RH), 12 percent (78°F and 65 percent RH), and 18 percent (80°F and 90 percent RH). The saturated material was obtained by water soaking under vacuum. To prevent excessive stain and the possibility of decay, the saturated material was stored in sealed bags at a cold room temperature of 36°F and 82 percent RH. Prior to testing, the specimens were removed from the cold room and placed in the conditioning chamber set at 12 percent MC (78°F and 65 percent RH).

Specimen Preparation and Testing

After the 52-in. sections had equilibrated, they were planed to a thickness of 0.787 in. Eight specimen blanks were cut from the conditioned 52-in. sections: tension parallel to grain, two side-by-side tension perpendicular to grain, bending, compression parallel to grain, compression perpendicular to grain, shear parallel to grain, mode I and II fracture. The cutting pattern is shown in Figure 23. The specimens were arranged to keep the material from the straightest grain section as close together as possible. When cut, each specimen was marked with an identification code that specified stick number, moisture content, piece number, and test mode. The dimensions for the individual pieces are shown in Figure 24.

Testing was conducted in the Engineering Mechanics Laboratory at the FPL. Tests were conducted on a universal test machine in a test chamber (Fig. 25), which was

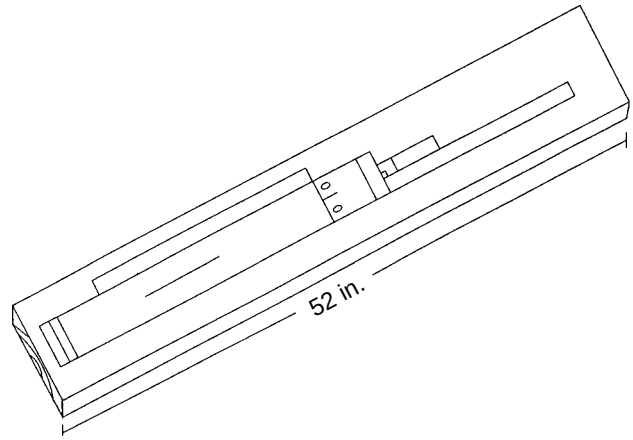

Figure 23—Specimen cutting pattern.

controlled by a portable AMINCO[1] conditioning unit that maintained the required temperature and MC levels (4 , 7, 12, 18 percent) for each group. The saturated specimens were tested under controlled temperature–humidity conditions of 78°F and 65 percent RH. For all tests, information was gathered to determine MC and specific gravity at the time of test.

The following explains the dimensions and procedures for the individual tests.

Tension Parallel to Grain

The tension-parallel-to-grain specimen required a number of machining steps to produce its characteristic dog-bone shape. The machined portion of the specimen conformed with the shape specified in ASTM standard D143. The original blank was 0.787 by 1 by 18 in. The necked-down section had a cross section of 0.375 by 0.188 in. Testing was conducted in accordance with ASTM D143 with a head speed of 0.05 in/min. Information was gathered on UTS, MOE, and cross-sectional area. A load–deflection plot was obtained based on a 2-in. gauge length for each specimen.

Tension Perpendicular to Grain

The amount of material available mandated the use of a thin, wafer-type specimen for establishing tension perpendicular strength. The dimension of the wafer specimen was 0.5 by 0.787 by 5 in. Two matched wafers were tested in the chamber at a crosshead speed of 0.024 in/min. The distance between grips was 1 in. The test setup is shown in Figure 26. Information was collected on UTS and cross-sectional area. A load–deflection plot was maintained for the second half of the test specimen pair.

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[1]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.

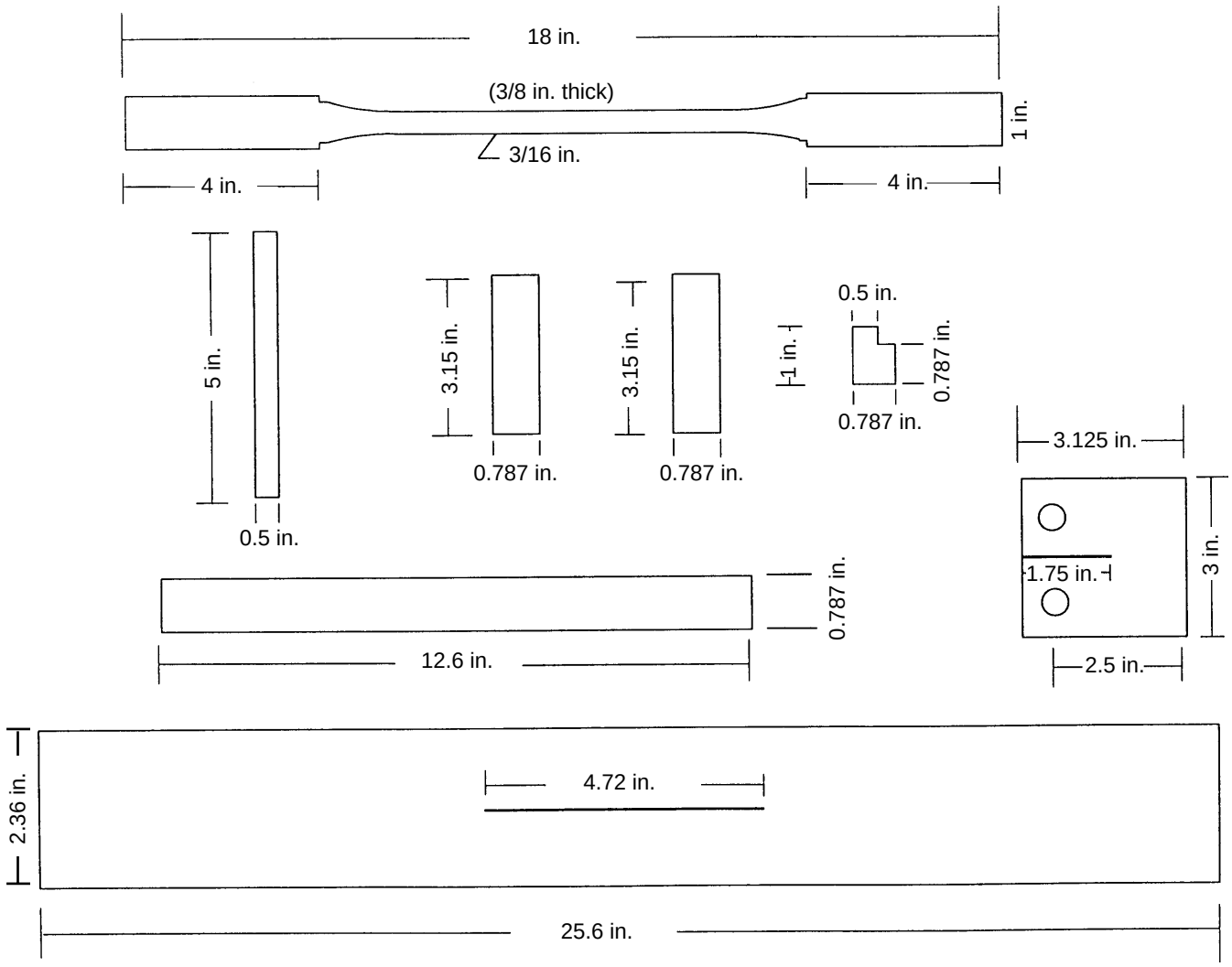

Figure 24—Dimensions of test specimens.

Bending

The static bending test specimens had a dimension of 0.787 by 0.787 by 12.6 in. The testing was conducted in a conditioning room at a crosshead speed of 0.05 in/min. The test span for a center-point load was 11 in. Load and deflection information were collected; bending MOE and MOR were calculated.

Compression Parallel to Grain

The compression-parallel-to-grain specimens were 0.787 by 0.787 by 3.15 in. The compression parallel test setup is shown in Figure 27. Tests were conducted at a crosshead speed of 0.024 in/min. Information was gathered on ultimate compressive stress, MOE, cross-sectional area, load–deflection plots, and Poisson's ratio LR. With the exception of the specimen dimensions, testing was conducted in accordance with ASTM D143.

Compression Perpendicular to Grain

The compression-parallel-to-grain specimens were 0.787 by 0.787 by 3.15 in. The compression-perpendicular-to-grain setup was the same as that for the compression parallel to grain. The crosshead speed for the test was 0.024 in/min. Data were collected on crushing strength, MOE perpendicular to the grain, cross-sectional area, load–deflection plots, and Poisson's ratio LT. With the exception of specimen size, the testing was conducted in accordance with ASTM D143.

Shear Parallel to Grain

Because of the small amount of material, a reduced version of the standard shear block was used. The block dimensions were 0.787 by 0.787 by 0.98 in. The testing was done in the ASTM D143-83 standard test jig (ASTM 1993). The crosshead speed was 0.024 in/min. The maximum shearing stress, weight, and dimensions, wet and dry, were recorded for each specimen.

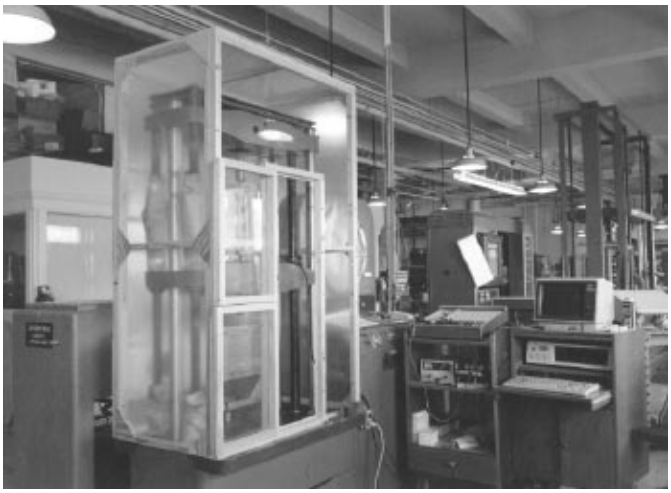

Figure 25—Conditioning test setup (M90 0212-5).

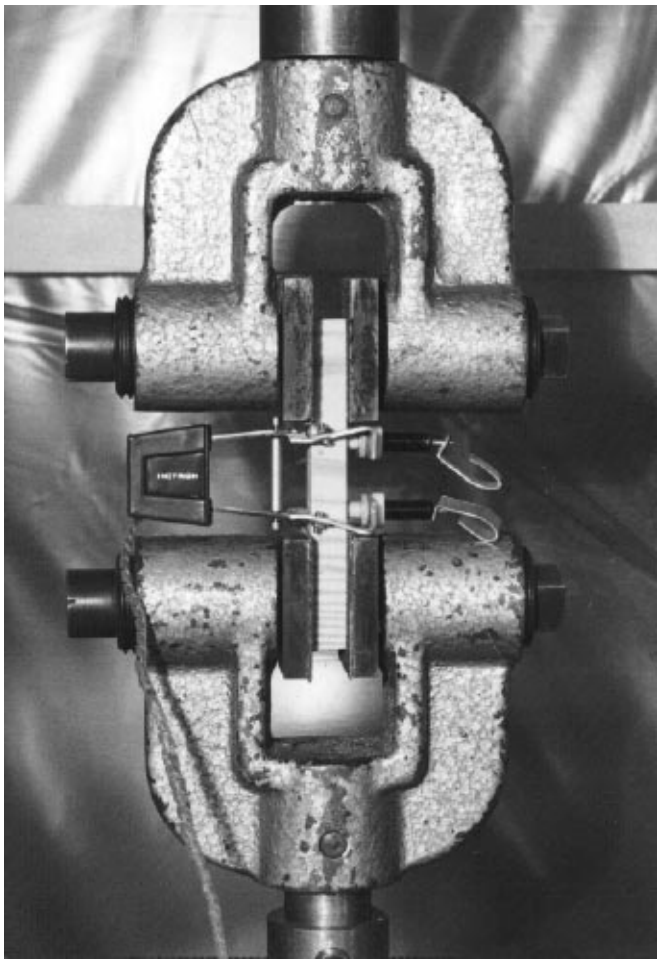

Figure 26—Tension perpendicular to grain test setup (M91 0142-2).

Mode I and II Fracture Toughness

The preparation of the 3.0 by 3.25 by 0.787 in. compact–tension specimens (CTS) and the 25.6 by 2.36 by 0.787 in. center-split beams (CSB) is described in Kretschmann and others (1990, 1991). The CTS testing was conducted in the test chamber at a crosshead speed of 0.05 in/min. This rate of crosshead movement resulted in a time to failure of 1.5 to 3.0 min. Loads were recorded with a 5,000-lb load cell. A clip-crack opening displacement gauge was used to track crack opening motion. The CSB testing was conducted in the test chamber at a crosshead speed of 0.01 in/min. This rate of crosshead movement resulted in a time-to-failure of 1.5 to 3.0 min. Loads were recorded with a 5,000-lb load cell. Horizontal displacements were measured for all specimens and vertical displacements were measured for the 4, 8, 18, and saturated MC groups using linear variable displacement tranducers. Displacements and load were recorded simultaneously on an *X–Y* plotter and an interfaced microcomputer. Recordings were stopped after the crack propagated explosively. After testing, one end of the CSB was removed and ovendried to determine MC and specific gravity. The CTS and CSB testing are described in detail in Kretschmann and others (1990, 1991).

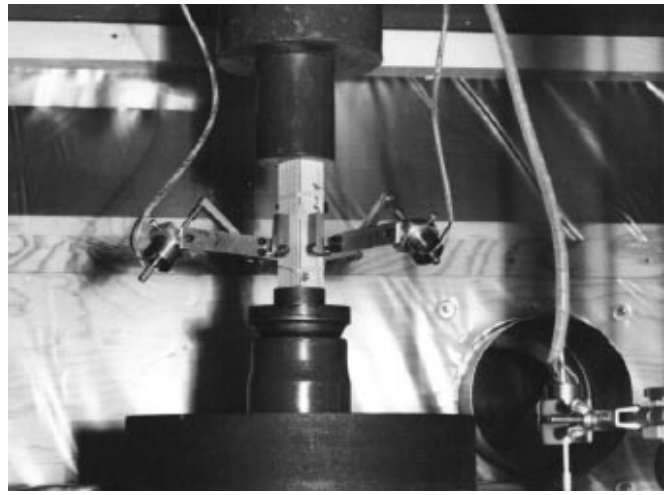

Figure 27—Compression parallel to grain test setup (M90 0230-3).

M_p Calculation

The fiber saturation point (fsp) is the MC level at which all liquid water has been removed from the cell cavities but the woody cell walls are still saturated with water. For practical purposes, it is generally assumed that most property values do not change as MC changes above the fsp. As wood dries below the fsp, it is usually assumed that properties do change (FPL 1987). Although a useful concept for understanding and describing wood properties, the fsp is only a convenient modeling tool. In fact, it has long been known that different "apparent" fsp values are obtained if different properties are studied (Wilson 1932) and that extractives, prolonged heating, and other factors affect the fsp (Stamm 1964). For mechanical properties, Wilson (1932) named the "apparent fsp" the intersection MC, M_p.

Wilson's method of calculating M_p is illustrated in Figure 28. A log transformation of the dry data was made,

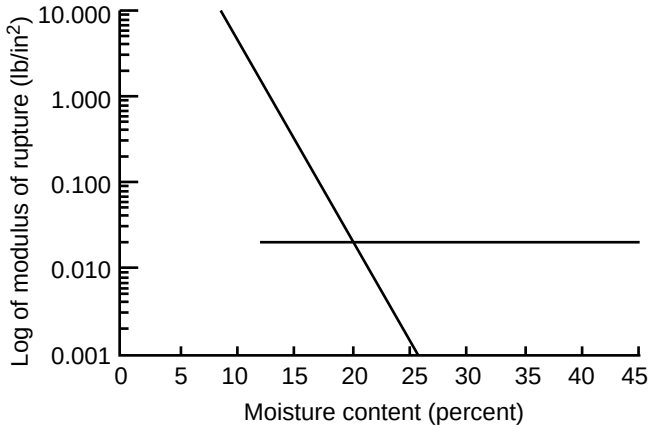

Figure 28— Historic method for determining the M_p value in clear wood.

and a linear curve fit to the transformed data. Then, the intersection between the dry property curve and the average for the saturated property data was determined to establish the M_p value for the property. For Southern Pine, Wilson found the M_p = 21 percent. Note that Wilson's data usually contained property measurements at MC levels as low as 4 to 6 percent. For many properties, the data at these low MC levels fall below the linear relationship between property and MC that he modeled for higher MC levels (e.g., Fig. 17). Wilson clearly stated that he ignored these low data points when deriving his model to obtain a simple model for practical application at common MC levels

Results

The average, standard deviation, maximum and minimum MC, and specific gravity data for the five moisture groups and eight test modes are summarized in Tables 3 and 4. The average test results for all strength properties and K_{IcTL} and K_{IIcTL} fracture toughness are given in Table 5. The average test results for all elastic moduli are given in Table 6. Poisson's ratio data are summarized in Table 7. Detailed distributional information for strength and elastic moduli are given in Tables 10 to 12 in the Appendix.

Effectiveness of Grouping and Conditioning

Specific Gravity

The average, coefficient of variation (COV), minimum, and maximum specific gravity values for seven of the eight test modes are listed in Table 3. Specific gravity information was not collected on the tension-perpendicular-to-grain tests. When adjusted to 12 percent MC using equations given in ASTM D2395, the average specific gravity for all MC groups was 0.53 for all levels. This is slightly greater than the clear wood average of 0.51 for *Pinus echinata* or *P. taeda* (FPL 1987). The specific gravity values of the different moisture groups matched well. Note that all groups have a similar specific gravity range.

Moisture Content

A good separation between MC groups was obtained, with little overlap in moisture levels (Table 4). The control capability of the various conditioning chambers governed the scatter in MC results. The 4- and 8-percent levels had much tighter controls than did the 12- and 18-percent levels. The actual average moisture levels for all groups were 4.3, 7.2, 12.0, and 18.1 percent MC. All saturated pieces were well above the fsp.

M_p Calculation

A procedure similar to the historic method was used to establish the M_p values for our test material. For each property, the 4-, 8-, 12-, and 18-percent MC level data were plotted. For these data, with the exception of compression perpendicular to grain, a quadratic curve provided the best fit. A linear fit was used in M_p calculations for compression perpendicular to grain. A quadratic curve was fit to the four dry MC levels. An intercept between the average of saturated data and the quadratic curve for each property was then calculated (Fig. 29). Table 8 gives the curve fits and the resulting individual M_p values. From these results, it was determined that 23 percent MC best represented an overall M_p value for this material. The value of 23 percent compares favorably to the M_p values that Wilson (1932) calculated (Table 9).

Moisture Content Effects on Strength

Tension Parallel to Grain

Ultimate tensile stress parallel to grain increased with decreasing MC from green to about 7 to 12 percent. Upon further drying, the strength values decreased (Fig. 30). Relative to the value at 12 percent MC, the change in average tension parallel stress was about –31 percent when green, –9 percent at 18 percent MC, –7 percent at 7 percent MC, and –19 percent at 4 percent MC.

Tension Perpendicular to Grain

Tension-perpendicular-to-grain stress increased with decreasing MC from green to about 7 to 12 percent. Upon further drying, the strength values decreased (Fig. 31). Relative to the value at 12 percent MC, the change in average tension perpendicular to grain was about –59 percent when green, –25 percent at 19 percent MC, –5 percent at 7 percent MC, and –10 percent at 4 percent MC.

Bending

Modulus of rupture increased with decreasing MC from green to 4 percent (Fig. 32). The relationship appeared slightly nonlinear. Relative to the value at 12 percent MC, the change in average MOR was about –55 percent when green, –29 percent at 18 percent MC, 13 percent at 7 percent MC, and 20 percent at 4 percent MC.

Table 3—Mean, coefficient of variation (COV), minimum, and maximum data for specific gravity adjusted to 12 percent moisture content[a]

Moisture content (%)	Specific Gravity Mean	COV	Minimum	Maximum	Moisture content (%)	Specific Gravity Mean	COV	Minimum	Maximum	Moisture content (%)	Specific Gravity Mean	COV	Minimum	Maximum
Tension parallel					Tension perpendicular					Modulus of rupture				
4	0.52	11.5	0.39	0.63	4	—	—	—	—	4	0.53	9.4	0.42	0.63
7	0.53	9.4	0.43	0.61	7	—	—	—	—	7	0.54	9.3	0.44	0.64
12	0.53	7.5	0.43	0.65	12	—	—	—	—	12	0.54	9.3	0.43	0.68
18	0.52	9.6	0.42	0.61	18	—	—	—	—	18	0.52	9.6	0.41	0.65
Saturated	0.53	7.5	0.43	0.59	Saturated	—	—	—	—	Saturated	0.55	9.1	0.41	0.65
Compression parallel					Compression perpendicular					Shear parallel				
4	0.53	9.4	0.44	0.64	4	0.53	11.3	0.42	0.62	4	0.53	11.3	0.43	0.63
7	0.54	9.3	0.43	0.62	7	0.53	11.3	0.42	0.63	7	0.53	11.3	0.42	0.64
12	0.53	7.5	0.46	0.67	12	0.54	9.3	0.43	0.67	12	0.53	7.5	0.44	0.68
18	0.51	9.8	0.40	0.62	18	0.52	9.6	0.42	0.63	18	0.51	9.8	0.40	0.62
Saturated	0.54	9.3	0.43	0.63	Saturated	0.53	9.4	0.42	0.60	Saturated	0.53	9.4	0.42	0.62
K_{Ic}					K_{IIc}									
4	0.53	9.4	0.43	0.62	4	0.52	9.6	0.41	0.62					
7	0.54	9.3	0.42	0.62	7	0.53	11.3	0.41	0.64					
12	0.53	7.5	0.45	0.61	12	0.54	9.3	0.47	0.65					
18	0.52	9.6	0.42	0.62	18	0.52	11.5	0.41	0.63					
Saturated	0.54	9.3	0.41	0.62	Saturated	0.53	9.4	0.42	0.62					

[a]—, no data.

Table 4—Mean, coefficient of variation (COV), minimum, and maximum data for moisture content

Moisture content (%)	Moisture content (%) Mean	COV	Minimum	Maximum	Moisture content (%)	Moisture content (%) Mean	COV	Minimum	Maximum	Moisture content (%)	Moisture content (%) Mean	COV	Minimum	Maximum
Tension parallel					Tension perpendicular					Modulus of rupture				
4	4.4	4.5	4.1	4.9	4	4.2	2.3	3.9	4.4	4	4.5	4.4	4.0	4.9
7	7.6	2.6	6.8	7.9	7	6.7	3.0	6.0	7.1	7	7.7	3.9	7.1	8.6
12	12.0	11.6	9.6	15.9	12	11.9	8.4	9.9	13.3	12	11.9	9.2	9.8	13.4
18	18.3	7.1	15.9	20.4	18	18.7	5.3	16.7	20.9	18	17.7	9.6	10.7	20.6
Saturated	106.9	23.9	43.6	147.1	Saturated	104.9	20.6	62.7	149.9	Saturated	115.9	24.4	50.3	189.3
Compression parallel					Compression perpendicular					Shear parallel				
4	4.4	2.3	4.0	4.1	4	4.1	7.3	3.4	4.9	4	4.0	10.0	3.1	4.9
7	7.1	4.2	6.4	6.9	7	6.9	8.7	6.0	9.9	7	6.5	6.1	5.7	7.3
12	12.3	9.8	9.1	11.9	12	11.9	10.9	8.7	13.5	12	12.2	10.6	9.3	13.7
18	18.4	6.5	16.8	18.2	18	18.2	6.0	16.6	20.8	18	18.6	5.9	16.6	20.8
Saturated	108.2	28.1	46.0	111.5	Saturated	111.5	23.4	56.5	150.3	Saturated	106.8	24.8	52.0	149.2
K_{Ic}					K_{IIc}									
4	4.4	4.5	3.8	4.6	4	4.4	2.3	4.1	4.6					
7	7.4	2.7	6.6	7.7	7	7.4	2.7	6.7	7.9					
12	12.1	10.7	9.7	13.6	12	12.0	10.0	9.7	13.3					
18	17.5	7.4	15.7	19.8	18	17.5	7.4	15.2	20.4					
Saturated	109.9	23.0	51.5	147.1	Saturated	107.7	27.3	43.3	150.9					

Table 5—Average data for strength

Moisture content (%)	Tension parallel (lb/in^2)	Tension perpendicular (lb/in^2)	Modulus of rupture (lb/in^2)	Compression parallel (lb/in^2)	Compression perpendicular (lb/in^2)	Shear (lb/in^2)	K_{Ic} (lb•in$^{-3/2}$)	K_{IIc} (lb•in$^{-3/2}$)
4	17,260	574	18,723	11,120	2,153	2,890	427	1,687
7	19,740	617	17,533	9,686	1,889	2,789	458	1,857
12	21,191	652	15,552	7,547	1,452	2,431	424	1,879
18	19,365	490	10,973	4,802	1,054	1,955	350	1,673
Saturated	14,663	269	7,069	3,122	575	1,297	259	1,247

Table 6—Average data for modulus of elasticity[a]

Moisture content (%)	Modulus of elasticity ($\times 10^6$ lb/in^2)				
	Tension parallel	Tension perpendicular	Modulus of rupture	Compression parallel	Compression perpendicular
4	2.388	0.139	1.998	2.660	0.123
7	2.256	0.145	1.898	2.533	0.111
12	2.248	—	1.882	2.403	0.086
18	1.868	0.080	1.564	1.695	0.060
Saturated	1.636	0.043	1.181	1.154	0.032

[a]—, no data.

Table 7—Moisture content effects on Poisson's Ratio[a]

Moisture content (%)	Sample size	Poisson's ratio							
		Mean		COV (%)		Minimum		Maximum	
		LT	LR	LT	LR	LT	LR	LT	LR
4	41	0.291	0.158	23.4	32.9	0.165	0.075	0.538	0.312
8	39	0.270	0.133	28.9	37.6	0.170	0.019	0.482	0.243
12	38	0.260	0.126	23.1	51.6	0.162	0.004	0.387	0.236
18	38	0.183	0.078	33.3	73.1	0.052	0.008	0.320	0.239
Saturated	40	0.162	0.038	32.1	94.7	0.060	0.000	0.277	0.147

[a]L, longitudinal; T, tangential; R, radial. The first letter indicates the axis perpendicular to the crack plane, the second indicates the direction of crack propagation.

Table 8—Equations fit to 4-day moisture content levels to determine M_p[a]

P	$P = A(\mathrm{MC})^2 + B(\mathrm{MC}) + C$			M_p
	A	B	C	
UTS parallel (lb/in^2)	–55.45	1,418.7	12,122.5	23.7
UTS perpendicular (lb/in^2)	–1.970	40.106	440.93	24.0
MOR (lb/in^2)	–18.03	–177.19	19,968.4	22.3
UCS parallel (lb/in^2)	2.891	–510.60	13,268.7	22.1
UCS perpendicular[a] (lb/in^2)	1.962	–123.05	2,636.27	23.8
Shear parallel (lb/in^2)	–1.694	24.891	3,009.15	25.3
K_{Ic} TL (lb•in$^{-3/2}$)	–4.348	94.71	1,369.70	21.5
K_{IIc} TL (lb•in$^{-3/2}$)	–0.999	15.71	383.93	23.0
MOE tension parallel ($\times 10^6$ lb/in^2)	–0.00124	–0.0058	2.428	22.4
MOE tension perpendicular ($\times 10^6$ lb/in^2)	–0.000357	0.0041	1.2305	—
MOE bending ($\times 10^6$ lb/in^2)	–0.00181	0.0065	2.0343	22.4
MOE compression parallel ($\times 10^6$ lb/in^2)	–0.00614	0.0767	2.390	21.7
MOE compression perpendicular[b] ($\times 10^6$ lb/in^2)	0.0000352	–0.00536	0.1456	23.8

[a]Overall average M_p = 23.0; —, no data.
[b]Linear fit used for compression perpendicular.

Table 9—Intersection moisture content values for selected species (Wilson 1932)

Species	Moisture content (%)
Ash, white	24
Birch, yellow	27
Chestnut, American	24
Douglas-fir	24
Hemlock, western	28
Larch, western	28
Pine, loblolly	21
Pine, longleaf	21
Pine, red	24
Redwood, ovendry	21
Spruce, red	27
Spruce, sitka	27
Tamarack	24

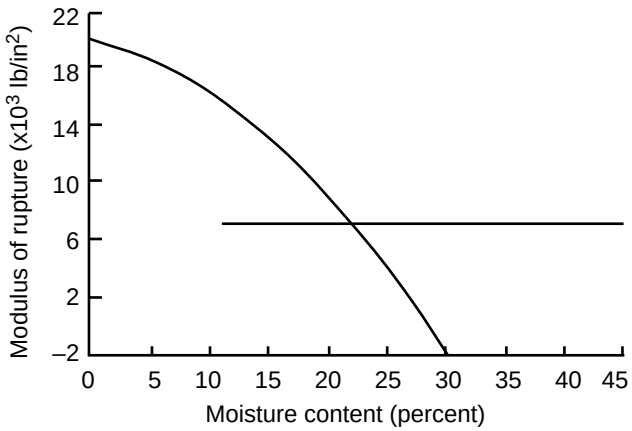

Figure 29—Example of determining M_p from test data.

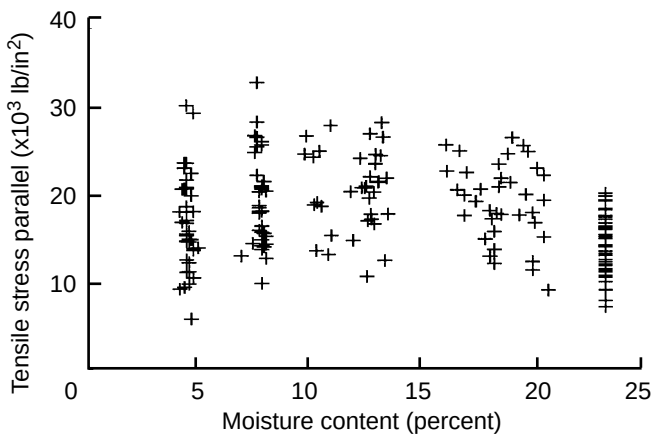

Figure 30—Relationship of ultimate tensile stress parallel to grain to moisture content.

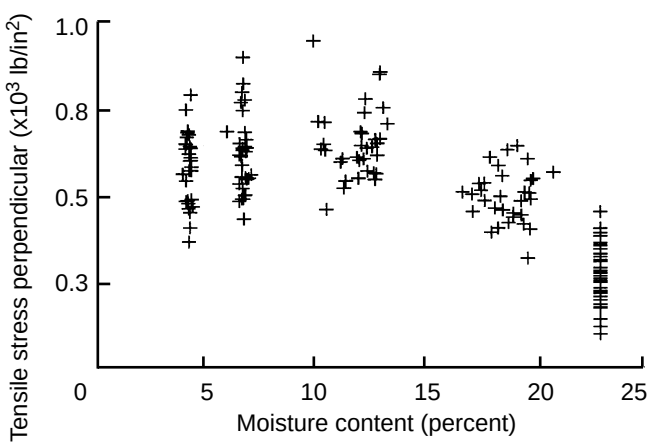

Figure 31—Relationship of ultimate tensile stress perpendicular to grain to moisture content.

Compression Parallel to Grain

Compression-parallel-to-grain stress increased linearly with decreasing MC from green to 4 percent MC (Fig. 33). Relative to the value at 12 percent MC, the change in average compressive stress was about –59 percent when green, –36 percent at 18 percent MC, 28 percent at 7 percent MC, and 47 percent at 4 percent MC.

Compression Perpendicular to Grain

Compression-perpendicular-to-grain stress increased linearly with decreasing MC from green to 4 percent (Fig. 34). Relative to the value at 12 percent MC, the change in average compressive stress was about –60 percent when green, –27 percent at 18 percent MC, 30 percent at 7 percent MC, and 48 percent at 4 percent MC.

Shear Parallel to Grain

Although the bending, compression, and shear specimens were smaller than standard specimens (ASTM 1993), any volume effect adjustment for bending and compression would be expected to be relatively small. Work by Foschi and Barrett (1976) indicated that the shear results reported here should be multiplied by a factor of 0.70 to be compatible with results for standard-size specimens. However, the change in shear strength with change in moisture content would not be expected to be affected by specimen size.

Shear-parallel-to-grain stress increased with decreasing MC from green to 4 percent (Fig. 35). The relationship appeared to be nonlinear. Relative to the value at 12 percent MC, the change in average shear stress was about –47 percent when green, –20 percent at 19 percent MC, 15 percent at 7 percent MC, and 19 percent at 4 percent MC.

Mode I

Figure 36 shows a definite trend toward an increase in mode I stress intensity factor (K_{IcTL}) as MC decreased until a peak was reached at about 7 percent. With continued drying below 7 percent, MC decreased. Relative to the value at 12 percent MC, the change in average K_{IcTL} was –39 percent when green, –18 percent at 18 percent MC, 9 percent at 7 percent MC, and about the same at 4 percent MC.

Mode II

Like the mode I results, the mode II shows a definite trend toward an increase in K_{IIcTL} as MC decreased, until a peak is reached between 12 and 7 percent (Fig. 37). Below 7 percent, the stress intensity factor declined. Relative to the values at 12 percent MC, the change in K_{IIcTL} values was about –30 percent when green, –10 percent at 18 percent MC, equal at 7 percent MC, and –10 percent at 4 percent MC.

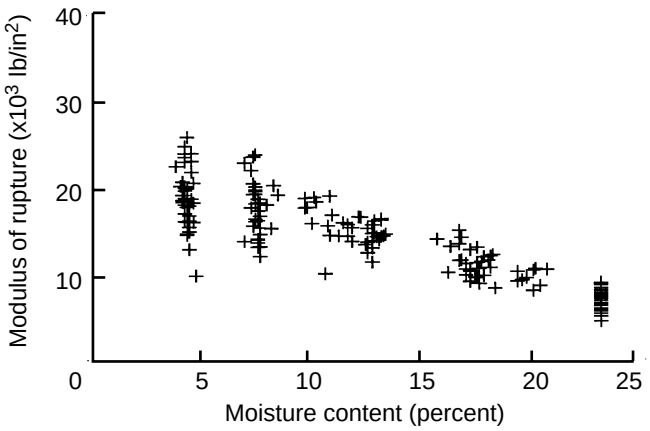

Figure 32—Relationship of modulus of rupture to moisture content.

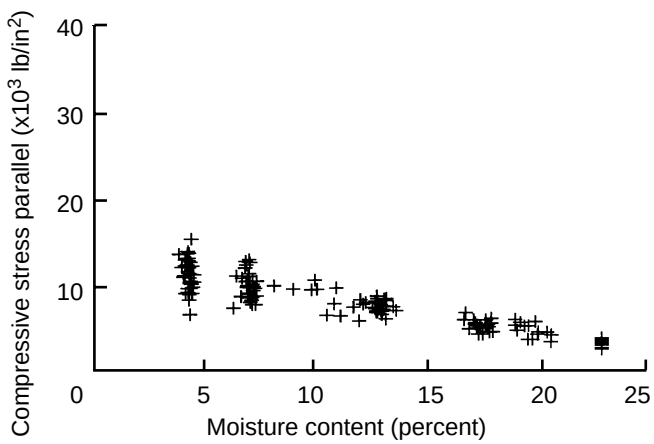

Figure 33—Relationship of ultimate compressive stress parallel to grain to moisture content.

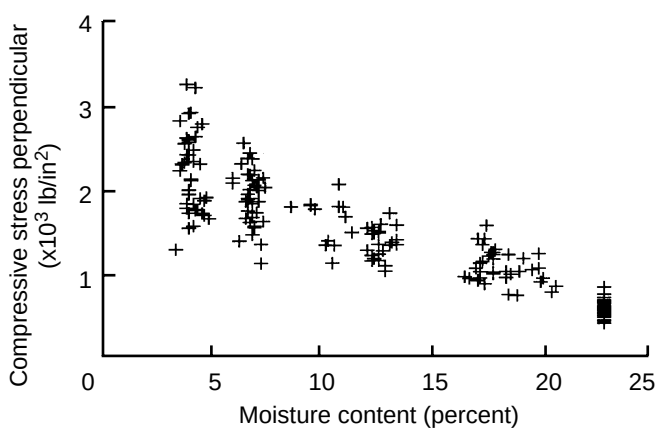

Figure 34—Relationship of compressive stress perpendicular to grain to moisture content.

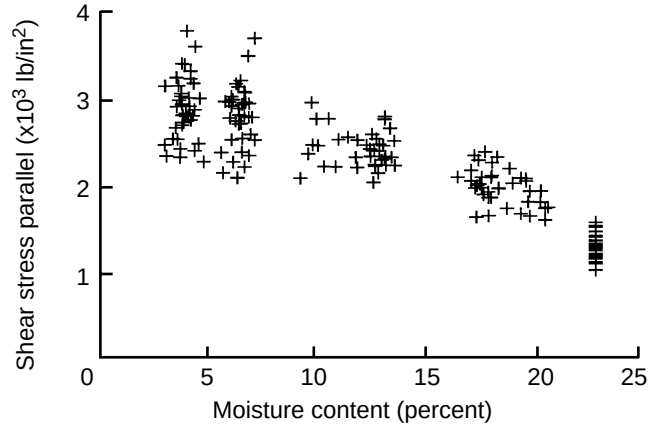

Figure 35—Relationship of ultimate shear stress parallel to grain to moisture content.

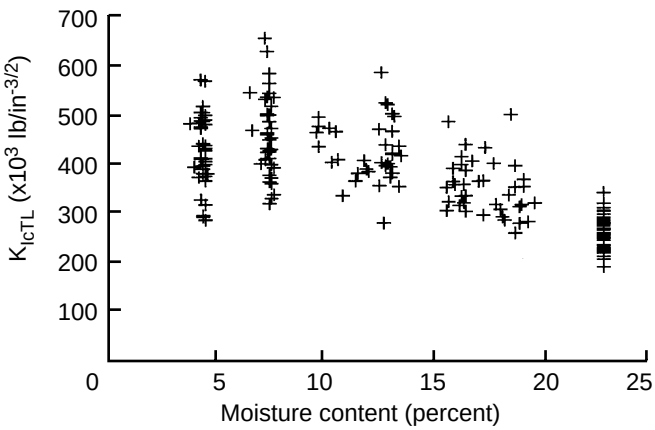

Figure 36—Relationship of K_{IcTL} stress intensity factor to moisture content.

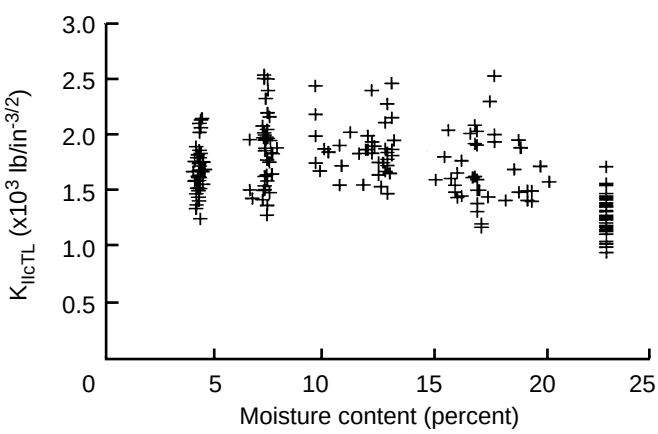

Figure 37—Relationship of K_{IIcTL} stress intensity factor to moisture content.

Moisture Content Effects on Modulus of Elasticity

Tension Parallel to Grain

Modulus of elasticity parallel to grain increased with decreasing MC from green to 4 percent (Fig. 38). However, the relationship appeared to be nonlinear. Relative to the value at 12 percent MC, the change in average tensile stress was about –27 percent when green, –17 percent at 18 percent MC, no change at 7 percent MC, and 6 percent at 4 percent MC.

Tension Perpendicular to Grain

Modulus of elasticity perpendicular to grain increased with decreasing MC from green to 7 percent (Fig. 39). However, the relationship appeared to be nonlinear. Because the data at 12 percent MC were lost, comparisons were not possible.

Bending

Bending MOE increased with decreasing MC from green to 4 percent MC (Fig. 40). Again, the relationship appeared nonlinear. Relative to the value at 12 percent MC, the change in average bending stress was about –37 percent when green, –17 percent at 18 percent MC, 1 percent at 7 percent MC, and 6 percent at 4 percent MC.

Compression Parallel to Grain

Compression parallel to grain MOE increased with decreasing MC from green to 4 percent MC (Fig. 41). The relationship appeared to be nonlinear. Relative to the value at 12 percent MC, the change in average compressive stress was about –52 percent when green, –30 percent at 18 percent MC, 5 percent at 7 percent MC, and 8 percent at 4 percent MC.

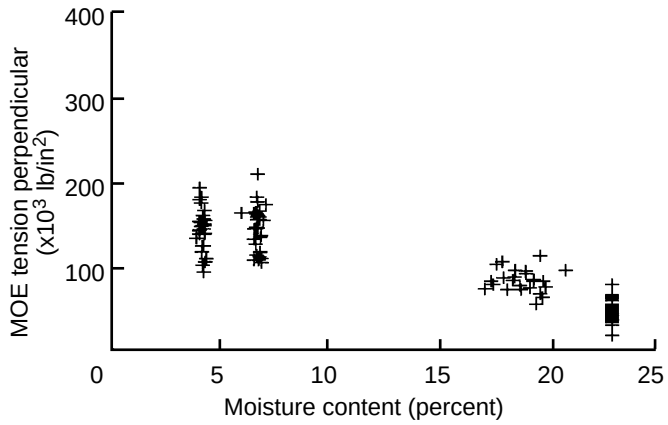

Figure 39—Relationship of modulus of elasticity (MOE) in tension perpendicular to grain to moisture content.

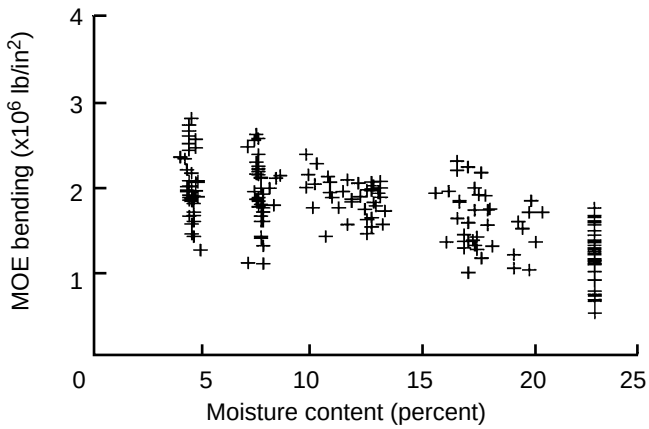

Figure 40—Relationship of modulus of elasticity (MOE) in bending to moisture content.

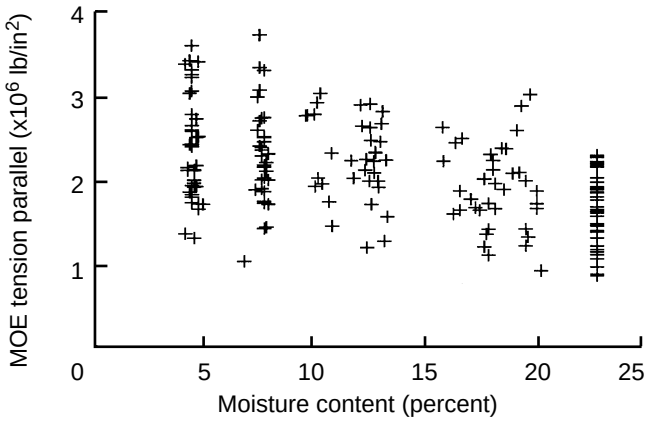

Figure 38—Relationship of modulus of elasticity (MOE) in tension parallel to grain to moisture content.

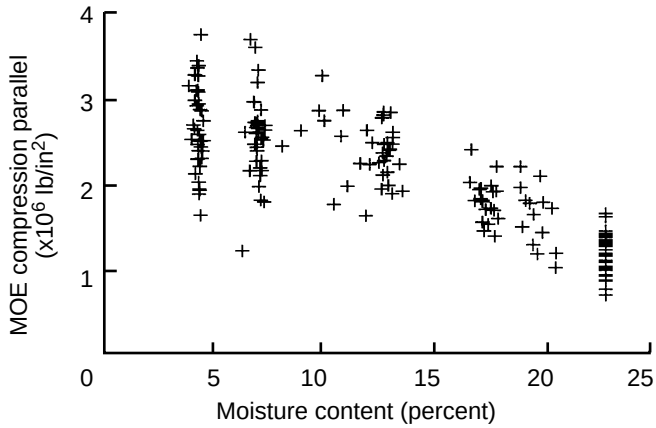

Figure 41—Relationship of modulus of elasticity (MOE) in compression parallel to grain to moisture content.

Compression Perpendicular to Grain

Compression parallel to grain MOE increased linearly with decreasing MC from green to 4 percent MC (Fig. 42). Relative to the value at 12 percent MC, the change in average compressive stress was about –52 percent when green, –30 percent at 18 percent MC, 5 percent at 7 percent MC, and 8 percent at 4 percent MC.

Moisture Content Effects on Poisson's Ratio

Both LT and LR Poisson's ratio increased with increasing MC (Figs. 43, 44). For this material, the average LT and LR Poisson's ratios were 0.26 and 0.13, respectively. Relative to the value at 12 percent MC, the change in average LT Poisson's ratio was about –38 percent when green, –30 percent at 18 percent MC, 4 percent at 7 percent MC, and 12 percent at 4 percent MC. Relative to the value at 12 percent MC, the change in average LR Poisson's ratio was about –70 percent when green, –38 percent at 18 percent MC, 6 percent at 7 percent MC, and 25 percent at 4 percent MC. For 4, 7, 12, and 18 percent MC, LR was consistently about half the value for LT.

Specific Gravity Relationships

Linear regressions for properties tested at each moisture level are given in the Appendix, Table 13. All properties investigated, except Poisson's ratio, were positively correlated to specific gravity. The r^2 values for the regressions ranged from a low of 0.10 to a high of 0.71. Both LR and LT Poisson's ratios were insensitive to changes in specific gravity.

Strength

The slopes of the tension parallel to grain, bending, K_{IcTL}, and K_{IIcTL} relationships behaved similarly and were most sensitive to changes in specific gravity at the 7-percent MC level. Our results also indicated that for these properties, the slope of the stress intensity factor–specific gravity relationship was a function of MC level. The slopes increased with drying to a maximum value at the 8 percent MC, then decreased with further drying. Compression parallel and perpendicular to grain, MOR, and shear had the strongest overall correlation. Tension parallel to grain results had the weakest correlation to specific gravity.

Modulus of Elasticity

Modulus of elasticity was most sensitive to changes in specific gravity, as indicated by the steep slopes, at the lowest moisture level. Modulus of elasticity for compression perpendicular to grain had the strongest correlation to specific gravity. Modulus of elasticity for compression parallel to grain had the weakest correlation.

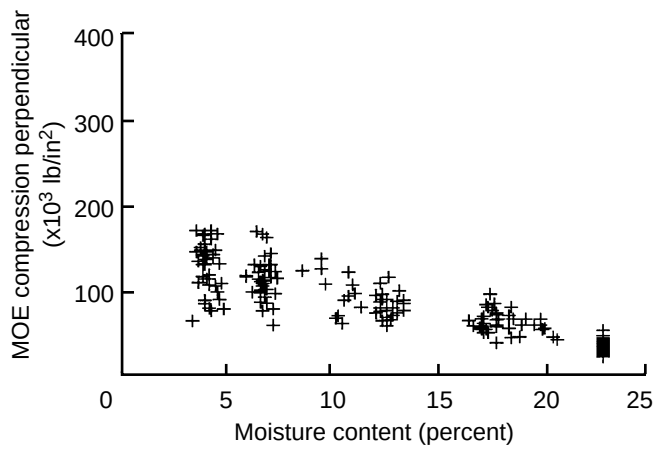

Figure 42—Relationship of modulus of elasticity (MOE) in compression perpendicular to the grain to moisture content.

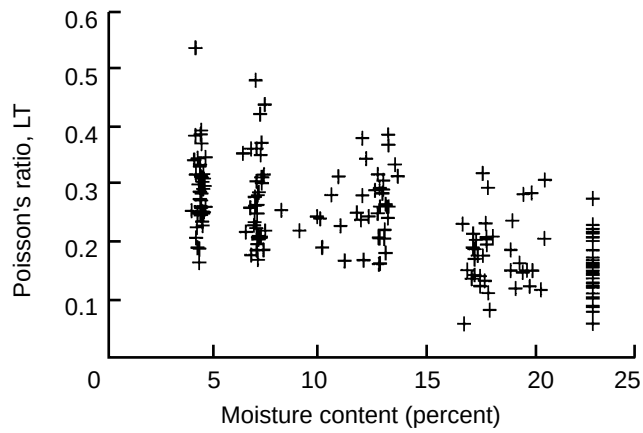

Figure 43—Relationship of Poisson's ratio in the longitudinal–tangential (LT) direction.

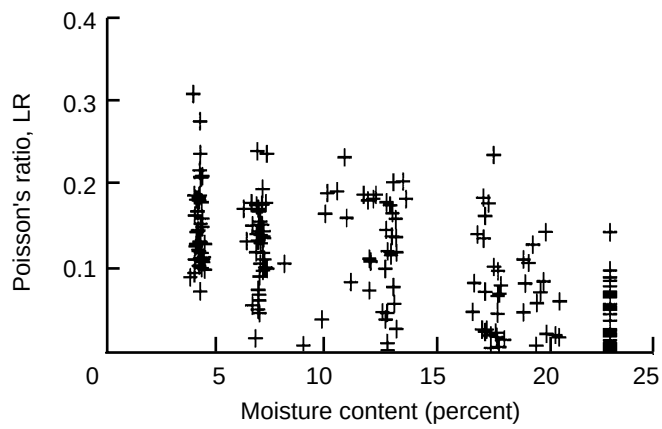

Figure 44—Relationship of Poisson's ratio in the longitudinal–radial (LR) direction.

Discussion

From trends in the results presented for Southern Pine, it is obvious that some fundamental degradation mechanism, or combination of mechanisms, is involved when properties are evaluated at lower MC levels. Tensile strength parallel and perpendicular to grain reached a maximum value at about 12 percent MC and then decreased noticeably with further drying. Some data reported in the literature suggest degradation may begin at even higher MC levels. The mode II critical stress intensity factor K_{IIcTL} also reached a maximum value at about 12 percent MC and then decreased noticeably with further drying.

Other properties seemed to reach a maximum value at about 6 percent MC. K_{IcTL} reached a maximum value at about 6 percent MC and then decreased noticeably. Other properties appeared to increase more or less linearly from green to about 6 percent MC. With further drying, these properties increased little, if at all. Properties in this group included shear strength and MOE in tension parallel and perpendicular to grain. Modulus of elasticity in compression parallel to grain was also in this group. All other properties appeared to increase in an approximately linear fashion with drying from green to 4 percent MC. Thus, it would appear that MC levels of about 6 and 12 percent may be critical to understanding wood moisture–property relationships and the fundamental relationships controlling the tensile strength of lumber containing knots.

Molecular Considerations

Several theories postulate that water molecules in the cell wall are held on preexisting internal surfaces (Skaar 1972, Hartley and Kamke 1992). The most popular of these theories is that of Brunauer, Emmel, and Teller (the BET theory). The BET theory considers that this sorbed water exists in one to several layers. The first, or primary layer, is water that is an inherent part of wood. At room temperature, the MC corresponding to complete monomolecular sorption is about 6 percent. As the monolayer of water is driven off, the wood begins to degrade. Thus, it was not surprising that some properties began to degrade at about 6 percent MC.

Research on the effect of MC on the mechanical properties of paper provides additional insight into fundamental property–moisture content mechanisms. A theory developed by Nessan relates the reduction in elastic modulus with increasing MC to a reduction in the effective number of hydrogen bonds available to maintain the saturated integrity of the cell wall (Caulfield 1990):

$$\frac{d(\ell\mathrm{n}(\mathrm{MOE}))}{d(\mathrm{MC})} = -K$$

The predicted value of K at less than about 5 percent MC is much different than at greater than 5 percent MC. Thus, Nessan's theory would identify 5 percent as a critical MC level. Caulfield also notes that the tensile strength of paper reaches a maximum at a relative humidity from 30 to 50 percent. Thus, the tensile strength of paper would be maximum at 6 to 9 percent MC.

Failure Initiation in the Cell Wall

A thorough discussion of failure mechanisms at the microscopic level in softwood species is given by Richard Mark (1967) in *Cell Wall Mechanics of Tracheids.* Mark documents that initial failure in the cell wall is most likely to occur in the S_1 layer or at the S_1/S_2 interface. Further, he hypothesizes that interlaminar shear stresses are the most likely cause of failure. Following this initial failure, he calculates a redistribution of stresses with final failure in the S_2 layer. We note that K_{IIcTL}, which characterizes resistance to the formation of cracks as a result of shearing stresses, is maximum at about 12 percent MC. We hypothesized that shearing stresses at the microscopic level could help to account for the maximum value of tensile strength parallel to grain observed at about 12 percent MC.

From the previous discussion, it would appear that there is a theoretical basis for expecting 6 and 12 percent to be critical MC levels with respect to wood properties. These expectations are generally confirmed by the results of our study.

Conclusions

From the results of our study on the effect of moisture content (MC) on clear wood properties in Southern Pine, we conclude the following:

- Ultimate tensile stress parallel and perpendicular to grain and the critical stress intensity factor K_{IIcTL} increase as MC decreases, reaching a maximum in a range from 7 to 13 percent MC. These properties then decrease with further drying; K_{IcTL} peaks at about 6 percent MC and decreases with further drying.
- Modulus of elasticity in tension parallel and perpendicular to grain, MOE compression parallel to grain, and shear strength parallel to grain increase linearly with drying from green to about 6 percent MC. With further drying, these properties increase at a slower rate or remain constant.
- Moduli of elasticity in bending and in compression perpendicular to grain increase linearly with drying from green to 4 percent MC.
- The MC above which properties cease to decrease with increasing MC, M_{p}, is remarkably constant across properties and averages 23 percent.

- All properties are positively correlated to specific gravity. However, the slope of the property–specific gravity relationship is a function of MC.
- The critical levels of MC in the MC–property relationship occur at about 6 and 12 percent, depending upon property. The behavior can be understood from consideration of molecular forces and wood macrostructure.

Future Considerations

Future papers will present empirical equations for predicting the mechanical properties of clear Southern Pine as a function of MC and/or density. These equations are being used to simulate the effect of MC on the tensile strength of lumber.

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Appendix—Strength, Modulus of Elasticity, and Linear Regression Data

Tables 10 to 12 contain nonparametric distribution of information for strength and MOE. Table 13 contains linear regressions for all properties tested at five moisture levels.

Table 10—Southern Pine nonparametric distributional information for strength

		Strength (lb/in^2)							
Moisture content (%)	Sample size	Mean	COV	Minimum	5th percentile	25th percentile	50th percentile	75th percentile	Maximum
Tension parallel									
4	44	17,260	31.0	5,920	9,450	113,980	16,650	21,150	30,910
7	39	19,740	26.0	10,070	13,000	15,590	18,930	22,000	33,580
12	39	21,190	21.8	10,890	12,720	18,140	21,260	25,000	28,880
18	40	19,370	24.6	9,280	11,650	15,900	19,090	22,940	28,040
Saturated	43	14,660	24.2	7,330	8,310	11,640	14,570	17,830	20,620
Tension perpendicular									
4	30	570	17.4	360	390	480	590	600	780
7	35	620	18.3	430	470	530	610	680	890
12	35	650	15.8	460	500	590	630	710	940
18	34	490	15.3	320	360	440	490	540	640
Saturated	40	270	29.6	100	120	220	270	330	450
Bending									
4	44	18,720	17.7	9,740	13,230	16,260	18,430	20,410	25,790
7	39	17,530	16.9	12,010	13,080	15,230	17,980	19,200	23,790
12	38	15,550	13.1	11,360	12,370	14,310	15,450	16,550	21,590
18	41	10,970	15.8	8,090	8,380	9,710	10,570	12,010	15,010
Saturated	43	7,070	15.4	4,550	5,200	6,450	6,940	7,850	9,020
Compression parallel									
4	41	11,120	16.5	6,350	8,080	9,880	10,980	12,490	15,070
7	39	9,690	14.9	7,080	7,470	8,430	9,670	10,740	12,710
12	38	7,550	15.1	5,570	5,770	6,720	7,369	8,090	10,310
18	38	4,800	16.1	3,160	2,430	4,280	4,940	5,360	6,520
Saturated	40	3,120	11.2	2,340	2,360	2,940	3,140	3,440	3,600
Compression perpendicular									
4	44	2,150	23.1	1,170	1,330	1,750	2,100	2,540	3,240
7	40	1,890	16.8	1,100	1,330	1,640	1,900	2,110	2,540
12	39	1,450	17.5	1,010	1,070	1,260	1,450	1,660	2,040
18	42	1,050	19.0	720	740	920	1,010	1,210	1,550
Saturated	43	580	17.7	400	400	510	570	650	820
Shear parallel									
4	41	2,890	14.7	1,900	2,270	2,600	2,870	3,140	4,100
7	39	2,790	12.5	2,080	2,140	2,530	2,790	2,980	3,690
12	39	2,430	10.2	2,030	2,070	2,230	2,390	2,530	3,270
18	42	1,960	11.0	1,580	1,600	1,780	1,960	2,090	2,380
Saturated	41	1,300	10.1	1,010	1,020	1,200	1,290	1390	1,560

Table 11—Southern Pine nonparametric distributional information for stress intensity factors

Moisture content (%)	Sample size	Stress (lb•in.$^{-3/2}$) Mean	COV	Minimum	5th percentile	25th percentile	50th percentile	75th percentile	Maximum
K_{Ic}									
4	40	430	16.5	380	290	380	430	480	570
7	38	460	17.6	320	330	400	450	520	650
12	37	420	14.2	280	330	339	420	470	580
18	40	350	15.7	260	280	310	340	390	500
Saturated	42	260	13.8	190	210	230	260	290	340
K_{IIc}									
4	41	1,690	12.5	1,240	1,340	1,570	1,670	1,800	2,150
7	40	1,860	17.5	1,280	1,370	1,590	1,870	2,010	2,540
12	38	1,880	12.9	1,470	1,530	1,720	1,800	1,990	2,460
18	40	1,670	17.7	1,170	1,200	1,460	1,600	1,920	2,530
Saturated	40	1,250	13.7	940	990	1,130	1,200	1,380	1,710

Table 12—Southern Pine nonparametric distributional information for modulus of elasticity[a]

Moisture content (%)	Sample size	Modulus of elasticity ($\times 10^6$ lb/in^2) Mean	COV	Minimum	5th percentile	25th percentile	50th percentile	75th percentile	Maximum
Tension parallel									
4	44	2.390	24.9	1.285	1.411	1.903	2.379	2.779	3.580
7	39	2.260	24.5	1.007	1.400	1.871	2.185	2.571	3.703
12	38	2.250	21.5	1.172	1.245	1.956	2.220	2.671	3.058
18	40	1.870	26.4	0.901	1.089	1.583	1.848	2.201	2.998
Saturated	43	1.636	25.8	0.844	0.853	1.358	1.658	1.920	2.274
Tension perpendicular									
4	30	0.139	17.9	0.090	0.094	0.121	0.141	0.152	0.190
7	35	0.145	19.6	0.101	0.103	0.123	0.151	0.160	0.226
12	39	—	—	—	—	—	—	—	—
18	26	0.080	18.1	0.052	0.055	0.070	0.079	0.091	0.109
Saturated	36	0.043	28.1	0.015	0.024	0.034	0.044	0.050	0.075
Bending									
4	44	2.027	17.7	1.280	1.377	1.822	1.981	2.287	2.787
7	39	1.952	19.6	1.059	1.111	1.772	1.922	2.221	2.563
12	38	1.893	12.9	1.403	1.538	1.729	1.898	2.016	2.704
18	41	1.565	20.0	1.018	1.067	1.313	1.553	1.795	2.294
Saturated	43	1.275	24.0	0.546	0.676	1.125	1.275	1.465	1.817
Compression parallel									
4	41	2.660	18.3	1.605	1.862	2.365	2.609	3.068	3.734
7	39	2.533	19.9	1.187	1.766	2.165	2.572	2.703	3.678
12	38	2.403	15.9	1.599	1.727	2.183	2.414	2.636	3.252
18	38	1.695	18.6	0.989	1.143	1.480	1.734	1.912	2.378
Saturated	40	1.540	18.5	0.670	0.742	0.996	1.155	1.312	1.626
Compression perpendicular									
4	44	0.123	24.1	0.062	0.068	0.103	0.129	0.145	0.168
7	40	0.111	21.4	0.057	0.074	0.097	0.110	0.125	0.167
12	39	0.086	23.5	0.056	0.059	0.071	0.084	0.097	0.135
18	42	0.060	21.2	0.036	0.040	0.052	0.057	0.067	0.093
Saturated	43	0.032	22.6	0.020	0.021	0.026	0.032	0.036	0.051

[a]—, no data.

Table 13—Linear regression relationship between property and specific gravity[a]

Moisture content (%)	Intercept	Slope	r^2	Intercept	Slope	r^2
Tension parallel (lb/in^2)				MOE tension parallel ($\times 10^6$ lb/in^2)		
4	–14,970	61,750	0.43	–1.61	7.61	0.53
7	–18,430	71,980	0.41	–1.44	6.98	0.33
12	–6,350	51,850	0.17	–0.64	5.43	0.16
18	–340	38,030	0.13	–1.75	6.96	0.42
Saturated	–3,650	34,510	0.12	–0.63	4.28	0.13
MOR (lb/in^2)				MOE bending ($\times 10^6$ lb/in^2)		
4	–3,930	42,670	0.44	–0.74	5.12	0.54
7	–7,180	45,970	0.69	–0.87	5.14	0.53
12	–660	30,080	0.50	0.81	1.97	0.14
18	–2,030	24,820	0.58	–0.71	4.33	0.40
Saturated	–1,150	14,910	0.43	–0.05	2.22	0.11
Compression parallel (lb/in^2)				MOE compression parallel ($\times 10^6$ lb/in^2)		
4	–3,000	26,640	0.58	–0.68	6.31	0.43
7	610	19,250	0.52	0.55	3.69	0.16
12	–3,530	20,720	0.45	–1.06	6.47	0.38
18	–1,640	12,550	0.67	–0.64	4.54	0.52
Saturated	390	5,030	0.52	0.25	1.66	0.13
Compression perpendicular (lb/in^2)				MOE compression perpendicular ($\times 10^6$ lb/in^2)		
4	–1,220	6,440	0.57	–0.07	0.37	0.52
7	–390	4,300	0.59	–0.05	0.30	0.53
12	–570	3,770	0.40	–0.03	0.22	0.20
18	–630	3,250	0.71	–0.04	0.18	0.52
Saturated	–340	1,710	0.60	–0.01	0.08	0.23
Shear (lb/in^2)				K_{IIc} (lb•in.$^{-3/2}$)		
4	–300	6,080	0.70	660	1,200	0.24
7	–1240	5,450	0.47	–680	4,780	0.70
12	330	3,940	0.47	–40	3,540	0.44
18	200	3,430	0.61	–200	3,630	0.40
Saturated	230	2,400	0.66	–180	2,670	0.51
K_{Ic} (lb•in.$^{-3/2}$)						
4	1670	490	0.10			
7	–130	1,090	0.48			
12	–60	910	0.39			
18	–340	750	0.47			
Saturated	20	440	0.36			

[a]Property = intercept + slope (specific gravity at 12 percent MC).