*Pacific Timber Engineering Conference*
*Gold Coast Australia*
*July 11 - July 15, 1994.*

# STRENGTH PROPERTIES OF LOW MOISTURE CONTENT SOUTHERN PINE

**D. Kretschmann, D. Green, * USDA Forest Service, U.S.A.**

**SUMMARY**

Contemporary engineering design practices in the United States require information on the strength of lumber for moisture contents as low as 4 percent. Efficient design of experimental studies on lumber properties at low moisture contents requires a better understanding of the basic mechanisms controlling moisture-property relationships. Studies were conducted on the effect of moisture content on strength and stiffness in tension and compression parallel and perpendicular to grain, and centerpoint bending. The test specimens were cut from commercially dried lumber and sorted into matched groups based on specific gravity. One group was saturated with water and four groups were equilibrated to 4, 8, 12, and 18 percent moisture content prior to testing. The results show that strength and stiffness properties are a function of both moisture content and density. Although properties generally increased with a decrease in moisture content, tensile strength parallel and perpendicular to the grain reached a maximum at about 12 percent moisture content. Further drying caused significant loss in tensile strength. Empirical models are presented for predicting the effect of moisture content on tensile strength parallel and perpendicular to grain, bending, compression parallel and perpendicular to grain, and shear parallel to grain.

## INTRODUCTION

In the United States, lumber is used at 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 lumber used over 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 the grain, does not always increase with decreasing moisture content, and (2) limited, but persistent, failures have been reported in timber structures subjected to environmental conditons that lead to very low moisture contents.

Each year, for the past 15 years, the Forest Products Laboratory receives one to three telephone calls about failures in structural members subjected to ambient environmental conditions that result in member moisture contents in the range of 2 to 4 percent. A significant number of these calls are from consulting engineers experienced with wood. Some calls may be followed by written reports, including pictures, or callers may send samples of wood cut from failed members. Virtually all reports involve commercial buildings. Some failures occur at connections, but a surprising number also exhibit failure in the middle of the member far removed from a joint. In some instances, there is evidence of thermal

---

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.

degradation, and in others, no evidence of thermal degradation.

This evidence, coupled with the experimental evidence of a decrease in lumber tensile strength with drying below about 12 percent MC (Green and Evans 1989, Green et al. 1990) suggest the need for additional experimental studies on the effect of low MC on the UTS of structural lumber.

## BACKGROUND

Experimental studies on the effect of low MC on the UTS of structural lumber are very expensive and time-consuming. The need to obtain a more fundamental understanding of the effect of MC on properties was recognized by Dr. Green in the mid 1980s. Other priorities, and the 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).

Considerable data exist on the effect of MC on the mechanical properties of clear, straight-grained wood. In general, in any one study data are given for only a few properties and only a limited number of specimens were tested for a given property-moisture content combination. The number of researchers who have data on properties of clear wood at $\leq$6 percent MC is much more limited than those with data >6 percent MC. From the studies reported, modulus of elasticity in bending and compression strength, for both parallel and perpendicular to the grain, apparently increase linearly with drying below the fiber saturation point. Tensile strength parallel and perpendicular to the grain and shear strength parallel to the grain increase with decreasing moisture content from green to about 12 to 15 percent. A number of studies indicate that a significant decrease in these properties may occur with further drying (Green and Kretschmann, in preparation). These decreases in properties could explain part of the loss in the UTS of lumber at MC levels below 12 percent, as reported by Green and Evans (1989). However, given the limitations of the available data it is not possible to draw absolute conclusions. Therefore, a study was conducted to collect a set of moisture effect data for a number of clear wood properties at one time. The results reported in this paper are part of this study (Green and Kretschmann, in preparation). The objective of this paper is to summarize initial effects of MC change on the strength of clear Southern Pine.

## EXPERIMENTAL METHODS

Traditionally, clear specimens for MC-property studies have been cut from green logs and then dried to various target MC levels. However, the intended use of these data is to model tensile strength-MC relationships for commercial lumber. Commercial lumber is dried in a dry kiln using commerical schedules. After drying the lumber is used in a structure, at which time the effect of a change in property with a change in MC is needed. The degree to which kiln schedule, moisture hysteresis, and other practical considerations affect the tensile strength of commercial lumber is not precisely known. To more closely incorporate any potential effects into our study, we decided to cut clear samples from previously dried commercial lumber. We chose Southern Pine because it is a locally available, commercially important species for which there are no data on MC-tensile strength data for lumber. Specimen preparation, dimensions, and testing procedures will be described in detail in a future report (Green and Kretschmann, in preparation).

### Material Selection

Material for this study was cut from 150 3.7-m (12-ft) Southern Pine (either *Pinus echinata* or *P. taeda*) nominal 2- by 6-in. (standard 38-mm by 140-m) lumber (hereafter designated aS 2 by 6) obtained from local suppliers in Madison, Wisconsin. Care was taken to obtain flat-sawn lumber without pith. The lumber was either KD15 Dense Select Structural or No. 1 Dense visually graded lumber (SPIB 1977) from three mills.

The 1.50 2 by 6 boards were numbered sequentially. Specific gravities based on ovendry weight and volume were then obtained for each board. The boards were ranked according to specific gravity. To assign lumber to a specific moisture

content cell, five 2 by 6 boards with the highest specific gravity were randomly assigned to one of five moisture content levels. The next five boards were selected and assigned randomly to their respective groups. This procedure was followed until all the specimens were assigned to each moisture level cell. At least one, and possibly two, 1,320-mm (52-in.) sections with straight grain and free from noticeable defects was cut from each 2 by 6 board.

The small sections were placed into conditioning chambers with the appropriate temperature and relative humidity (RH) to bring the wood to equilibrium at target MC levels of 4 percent (32°C (90°F) and 20 percent RH), 8 percent (27°C (80°F). and 30 percent RH), 12 percent (26°C (78°F) and 65 percent RH), and 18 percent (27°C (80°F) and 90 percent RH). The saturated material was obtained by water soaking under a vacuum. To prevent excessive stain and the possibility of decay, the saturated material was stored in sealed bags in a cold room at 2°C (36°F) and 82 percent RH prior to testing.

**Specimen Preparation**

After equilibration, the small sections were planed to a thickness of 20 mm (0.787 in.). Seven specimen blanks were cut from the conditioned sections: tension parallel to the grain, tension perpendicular to the grain (two specimens, side by side), bending, compression parallel to the grain, compression perpendicular to the grain, and shear parallel to the grain. The specimens were cut in such a way as to keep them oriented with the straightest-grain section while being as close together as possible.

**Testing**

The tension parallel to grain, center-point bending, compression, and shear tests were conducted on scaled specimens that comformed to the shapes specified in ASTM D143 (ASTM 1993). The tests were conducted on a universal test machine in a test chamber with a climate controlled by a portable AMINCO conditioning unit.' The unit maintained the required temperature and MC levels (either 4, 8, 12, or 18 percent) for each MC group. The saturated specimens were tested under controlled temperature-humidity conditions of 26°C (78°F) and 65 percent RH. For all tests, information was gathered to determine MC and specific gravity at the time of test.

**RESULTS**

The average, coefficient of variation, minimum, and maximum specific gravity for MC are given in Tables 1 to 4. No specific gravity information was collected on the tension perpendicular to the grain tests. A summary of the average strength values for tension and compression parallel and perpendicular to the grain, bending, and shear is given in Table 5. Data points and boxplots are used to illustrate data trends (Figs. 1 to 6). The boxplots show the lowest datum point, the 25th percentile, the median, the 75th percentile, and the highest datum point. The boxplots were centered on the average MC for each moisture level. No correction was made for MC before the percentiles were calculated.

**Hatching**

The average specific gravity adjusted to 12 percent MC using equations given in ASTM D 2395 was 0.53 for all MC levels. This is slightly above the clear wood average of 0.51 for loblolly or shortleaf pine (USDA 1987). A good match is present between the specific gravities of the different MC groups. Note that all groups. also have similar ranges in specific gravity values.

**Conditioning**

A good separation between MC groups was obtained with little overlap in moisture levels. The control capability of the various conditioning chambers governed the scatter present in MC results. The 4- and 8-percent levels had much tighter controls than did the 12- and 18-percent

'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.

Table 1- Specific gravity values for tension and bending specimens at target moisture content (MC) levels[a]

| MC level (%) | Specific gravity | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Tension parallel to grain[b] | | | | Modulus of rupture | | | |
| | Avg | COV | Min | Max | Avg | COV | Min | Max |
| 4 | 0.52 | 11.5 | 0.39 | 0.63 | 0.53 | 9.4 | 0.42 | 0.63 |
| 7 | 0.53 | 9.4 | 0.43 | 0.61 | 0.54 | 9.3 | 0.44 | 0.64 |
| 12 | 0.53 | 7.5 | 0.43 | 0.65 | 0.54 | 9.3 | 0.43 | 0.68 |
| 18 | 0.52 | 9.6 | 0.42 | 0.61 | 0.52 | 9.6 | 0.41 | 0.65 |
| Saturated | 0.53 | 7.5 | 0.43 | 0.59 | 0.55 | 9.1 | 0.41 | 0.65 |

[a]Values adjusted to 12% MC. COV is coefficient of variation.
[b]No data for tension perpendicular to grain.

Table 2-Specific gravity values for compression and shear specimens at target MC levels

| MC level (%) | Specific gravity[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Compression parallel to grain | | | | Compression perpendicular to grain | | | | Shear parallel to grain | | | |
| | Avg | COV | Min | Max | Avg | COV | Min | Max | Avg | COV | Min | Max |
| 4 | 0.53 | 9.4 | 0.44 | 0.64 | 0.53 | 11.3 | 0.42 | 0.62 | 0.53 | 11.3 | 0.43 | 0.63 |
| 7 | 0.54 | 9.3 | 0.43 | 0.62 | 0.53 | 11.3 | 0.42 | 0.63 | 0.53 | 11.3 | 0.42 | 0.64 |
| 12 | 0.53 | 7.5 | 0.46 | 0.67 | 0.54 | 9.3 | 0.43 | 0.67 | 0.53 | 7.5 | 0.44 | 0.68 |
| 18 | 0.51 | 9.8 | 0.40 | 0.62 | 0.52 | 9.6 | 0.42 | 0.63 | 0.51 | 9.8 | 0.40 | 0.62 |
| Saturated | 0.54 | 9.3 | 0.43 | 0.63 | 0.53 | 9.4 | 0.42 | 0.60 | 0.53 | 9.4 | 0.42 | 0.62 |

[a]Values adjusted to 12% MC.

Table 3-Moisture content values for tension and bending specimens at target MC levels

| MC level (%) | Moisture content (%)[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tension parallel to grain | | | | Tension perpendicular to grain | | | | Shear parallel to grain | | | |
| | Avg | COV | Min | Max | Avg | COV | Min | Max | Avg | COV | Min | Max |
| 4 | 4.4 | 4.5 | 4.1 | 4.9 | 4.2 | 2.3 | 3.9 | 4.4 | 4.5 | 4.4 | 4.0 | 4.9 |
| 7 | 7.6 | 2.6 | 6.8 | 7.9 | 6.7 | 3.0 | 6.0 | 7.1 | 7.7 | 3.9 | 7.1 | 8.6 |
| 12 | 12.0 | 11.6 | 9.6 | 15.9 | 11.9 | 8.4 | 9.9 | 13.3 | 11.9 | 9.2 | 9.8 | 13.4 |
| 18 | 18.3 | 7.1 | 15.9 | 20.4 | 18.7 | 5.3 | 16.7 | 20.9 | 17.7 | 9.6 | 10.7 | 20.6 |
| Saturated | 106.9 | – | 43.6 | 147.1 | 104.9 | – | 62.7 | 149.9 | 115.9 | – | 50.3 | 189.3 |

[a]Values adjusted to 12% MC.

Table 4-Moisture content values for compression and shear specimens at target MC levels

| | Specific gravity[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Compression parallel to grain | | | | Compression perpendicular to grain | | | | Shear parallel to grain | | | |
| MC level (%) | Avg | COV | Min | Max | Avg | COV | Min | Max | Avg | COV | Min | Max |
| 4 | 4.4 | 2.3 | 4.0 | 4.6 | 4.1 | 7.3 | 3.4 | 4.9 | 4.0 | 10.0 | 3.1 | 4.9 |
| 7 | 7.1 | 4.2 | 6.4 | 8.2 | 6.9 | 8.7 | 6.0 | 9.9 | 6.5 | 6.1 | 5.7 | 7.3 |
| 12 | 12.3 | 9.8 | 9.1 | 13.8 | 11.9 | 10.9 | 8.7 | 13.5 | 12.2 | 10.6 | 9.3 | 13.7 |
| 18 | 18.4 | 6.5 | 16.8 | 20.7 | 18.2 | 6.0 | 16.6 | 20.8 | 18.6 | 5.9 | 16.6 | 20.8 |
| Saturated | 108.2 | – | 46.0 | 158.1 | 111.5 | – | 56.6 | 150.3 | 106.8 | – | 52.0 | 149.2 |

[a]Values adjusted to 12% MC.

Table 5-Average data for strength[a,b]

| | Strength property (lb/in$^2$) | | | | | |
|---|---|---|---|---|---|---|
| | Tension | | | Compression | | Shear |
| MC (%) | PARA | PERP | MOR | PARA | PERP | PARA |
| 4 | 17,260 | 570 | 18,720 | 11,120 | 2,150 | 2,890 |
| 7 | 19,740 | 620 | 17,530 | 9,690 | 1,890 | 2,790 |
| 12 | 21,190 | 650 | 15,550 | 7,550 | 1,450 | 2,430 |
| 18 | 19,360 | 490 | 10,970 | 4,800 | 1,050 | 1,960 |
| Saturated | 14,660 | 270 | 7,070 | 3,120 | 580 | 1,300 |

[a]PARA is parallel to grain, PERP perpendicular to grain, MOR modulus of rupture.
[b]1 lb/in$^2$ = 6.894 kPa.

Table 6-Equations for curves fit to strength MC data

| | $P = A(MC)^2 + B(MC) + C$ | | | |
|---|---|---|---|---|
| Property | $A(MC)^2$ | B(MC) | C | Peak MC |
| UTS parallel | -60.5 | 1,524 | 11,685 | 12.6 |
| UTS perpendicular | -2.3 | 48 | 409 | 10.2 |
| MOR | -13.4 | -274 | 20,371 | – |
| Compression parallel | 1.6 | -472 | 13,077 | – |
| Compression perpendicular[a] | – | -83 | 2,496 | – |
| Shear parallel | -3.3 | 8 | 2,881 | 1.2 |

[a]Linear fit used on data for compression perpendicular to the grain.

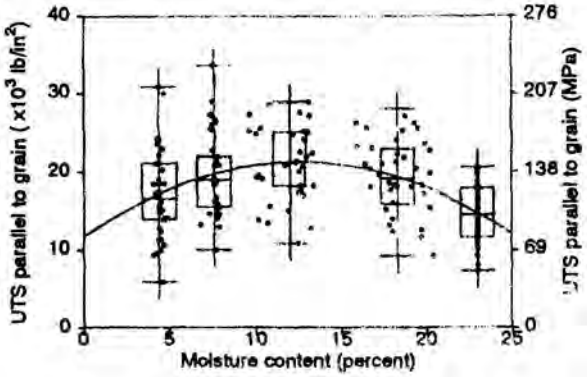


Figure 1-Relationship of ultimate tensile stress (UTS) parallel to the grain to moisture content.

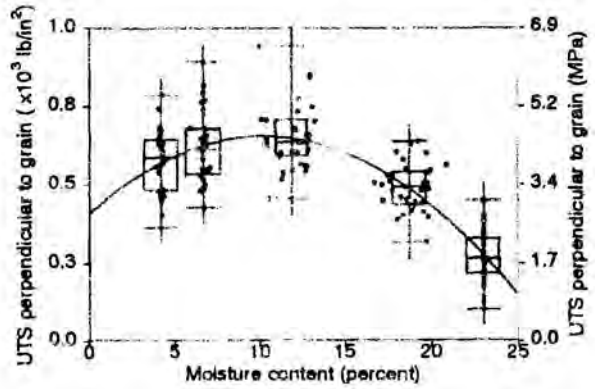


Figure 2 – Relationshipof UTS perpendicular to the grain to moisture content.

levels. The actual average MC levels for all the groups (4.3 7.2, l2.0, and 18.1 percent) were within 10 percent of the target MC levels (4, 8, 12, and 18 percent). All of the saturated pieces were well above the fiber saturation point.

The average MC at which wood properties exhibit noticeable change rarely coincides with the wood fiber saturation point. The term Mp refers to an "effertive" moisture content at which further drying has a significant effect or the properties but wetting has little or no noticeable effect. A procedure similar to the historic method (Wilson 1932) was used to establish the Mp values for our test material. For each property, the strength data were plotted for the four MC levels below the fiber saturation point. We decided that a quadratic curve provided a good fit because of the nonlinear nature of the data (with the exception of compression perpendicular to the grain). An intercept between the average for the saturated data and the quadratic curve for each property was then calculated. A liner fit was used in Mp calculations for compression perpendicular to the grain. From these results, we determind that 23 percent MC best represented an overall Mp value for this material (Green and Kretschmann, in preparation). The value of 23 percent compares favorably to the Mp values that Wilson (1932) calculated. Once the Mp value of 23 percent was determined, a quadratic curve was fit to all five MC groups. The results of these curve fits are tabulated in Table 6.

**Tension Parallel to Grain**

Results indicate that shear tensile parallel-to-grain stress increases with decreasing MC from green to about 7 to 12 percent. Upon further drying, the strength values decrease (Fig. 1). Relative to the value at 12 percent MC, the percentaye of change in average tensile parallel stress is about -31 percent when green, -9 percent at 18 percent MC, -7 percent at 8 percent MC, and -19 percent at 4 percent MC. The peak suggested by the curve fit equation would be located at 12.6 percent MC>

**Tension Perpendicular to Grain**

Results indicate that ut1tirnate tensile perpendicular-to-grain stress increases with decreasing MC from green to about 7 to 12 percent. Upon further drying, the strength values decrease (Fig. 2). Relative to the value at 12 percent MC, the percent-age of change in average tensile perpendicular stress is about -58 percent when green, -25 percent at 19 percent MC, -5 percent at 7 percent MC, and 12 percent at 4 percent MC. The peak suggested by the curve fit equation would be located st 10.2 percent MC.

**Bending**

Results indicate that modulus of rupture (MOR) increases with decreasing MC from green to 4 percent (Fig. 3). The relationship appears slightly nonlinear Relative to the value at 12 percent MC, the percentage of change in average MCR is about -55 percent when green,

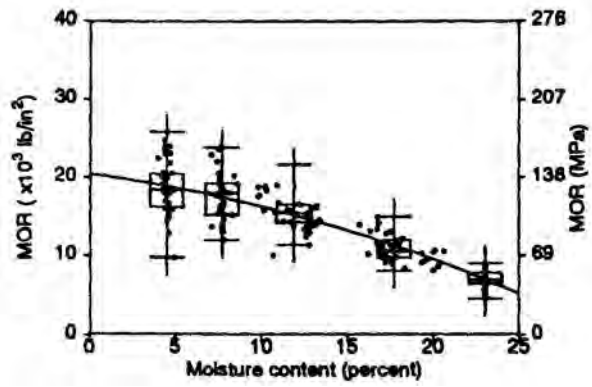


Figure 3-Relationship of modulus of rupture (MOR) to moisture content.

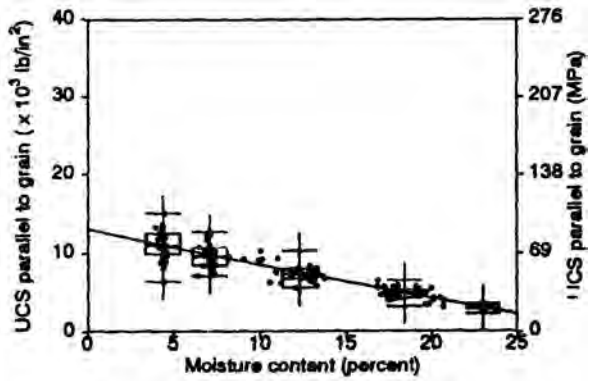


Figure 4-Relationship of ultimate compressive stress (UCS) parallel to the grain to moisture content.

-29 percent at 18 percent MC, 13 percent at 8 percent MC, and 20 percent at 4 percent MC.

**Compression Parallel to Grain**

Results indicate that compressive parallel-to-grain stress increases linearly with decreasing MC from green to 4 percent (Fig. 4). Relative to the value at 12 percent MC, the percentage of change in average compressive stress is 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**

Results indicate that compressive perpendicular-to-grain stress increases linearly with decreasing MC from green to 4 percent (Fig. 5). Relative to the value at 12 percent MC, the percentage of change in average compressive stress is about -60 percent when green, -28 percent at 18 percent MC, 30 percent at 7 percent MC, and 48 percent at 4 percent MC.

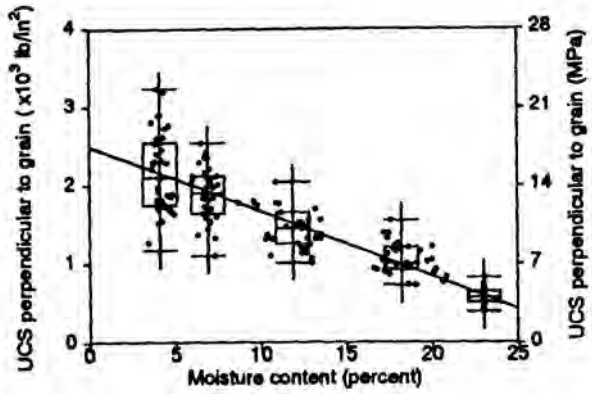


Figure 5-Relationship of UCS perpendicular to the grain to moisture content.

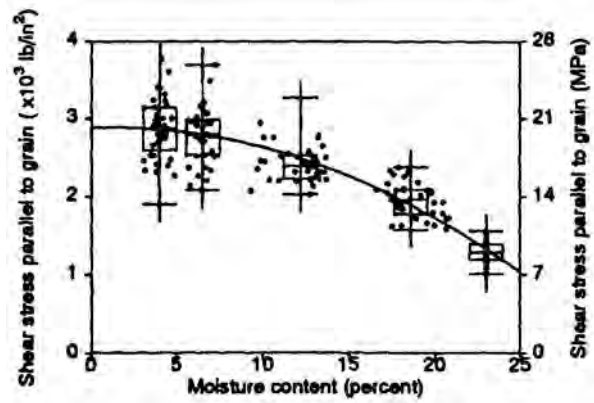


Figure 6-Relationship of ultimate shear stress parallel to the grain to moisture content.

**Shear Parallel to Grain**

Results indicate that shear parallel-to-grain stress increases with decreasing moisture content from green to 4 percent (Fig. 6). The relationship appears to be nonlinear. Relative to the value at 12 percent MC, the percentage of change in average shear stress is about -47 percent when green, -19 percent at 19 percent MC, 15 percent at 7 percent MC, and 19 percent at 4 percent MC. The peak for shear strength suggested by the curve fit equation would be at 1.2 percent MC.

**DISCUSSION**

The trends in the results presented for Southern Pine show that some fundamental mechanism, or combination of mechanisms, produces changes in strength properties at lower MC levels. Tensile strength parallel and perpendicular to the grain reaches a maximum value at about 12 percent MC and then decreases noticeably

with further drying. Some data reported in the literature suggest that strength loss may begin at even higher MC levels.

Shear strength parallel to grain increases from green to about 7 percent MC. With further drying, shear strength increases little, if at all. Compression parallel and perpendicular to grain appear 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 percept way be critical levels in understanding wood moisture-property reationships.

The basis for the significance of 6 percent MC may be explained ky molecular considerations. Several theories postulate that water molecules in the cell wall are held on preexisting internal surfaces (Caulfield 1990, Hartley and Kamke 1992, Skaax 1972). A theory by Brunauer, Emmel, and Teller (BET theory) postulates that, at room temperature, the MC corresponding to complete monomolecular sorption is about 6 percent. As the monolayer of water is driven off, the wood may start to degrade. Thus, it is not surprising that some properties beqin to decrease in strength at about 6 percent MC. A theory by Nessan indicates that 5 percent MC might be critical. He relates the reduction in elastic modulus with the increasing MC to a reduction in elastic bands available to maintain the saturated integrity of the cell wall.

## 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 (UTS) parallel and perpendicular to the grain increases as MC decreases, reaching a maximum in a range from 12.6 percent MC. The UTS values decrease with further drying.

- Shear strength parallel to grain increases from green to about 7 percent MC, then increases little, if at all, with further drying.

- Compression parallel and perpendicular to grain and bending appear to increase in an approximately linear fashion with drying from green to 4 percent MC.

The authors believe that critical levels of MC in the MC-property relationship occur at about 6 and 12 percent, depending upon property, and that these levels can be understood from consideration of molecular forces and wood macrostructure.

## FUTURE CONSIDERATIONS

A future paper will present empirical equations for predicting the mechanical properties of clear Southern Pine as a function of MC and density. These equations are being used to simulate the efferct of MC on the tensile strength of lumber.

## REFERENCES

ASTM. 1993, "Standard methods of testing small clear specimens of timber (D 143-83) Annual Rook of Standards," Volume 4.09, American Society for Testing and Materials Philadelphia, PA.

Caulfield, D. 1990. "Effect of Moisture Content and Temperature on the Mechanical Properties of Paper," in Solid Mechanics Advances in Paper Related Industries: Proceedings of Natural Science Foundation Workshop, 1986 Aug. 13-15, Syracuse, NY, Syracuse University, pp. 50-62.

Cramer, S.M. & McDonald, K.A. 1989, "Predicting Lumber Tensile Stiffness and Strength With Local Grain Angle Measurements and Failure Analysis, " Wood and Fiber Science, vol. 21, no. 4, pp, 393-410.

Green, David & Evans J.W. 1989, Moisture Content and the Mechanical Properties of Lumber: Decision for the Futrue," Proceedings: In-grade testing of structural lumber. 1988 June 25-29, Forest Products Laboratory, Madison, WI. Proceedings 47363. Forest Products Research Society. Madison, WI.

Green, D.W. & Kretschmann, D.E. "Moisture Content and the Properties of Clear Southern Pine," in preparation as a Research Paper, USDA Forest Service, Forest Products Laboratory, Madison, WI.

Green, D.W., Pellerin, R., Evans, J.W., & Kretschmann, D.E. 1990, "Moisture Content and Tensile Strength of Douglas Fir Dimension Lumber," Res. Pap. FPL-RP-497, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 33p.

Hartley, I.D. & Kamke, F.A. 1992, "Cluster Theory for Water Sorption in Wood," Wood Science and Technology, vol. 26, pp. 83-99.

Skaar, C. 1972, "Water in wood," Syracuse University Press, Syracuse, NY. 218 p.

SPIB. 1977, "Grading Rules," Southern Pine Inspection Bureau, Pensacola, FL.

USDA. 1987, "Wood Handbook: Wood as an Engineering Material," Agric. Handb. 72, Washington. DC: U.S. Department of Agriculture.

Wilson, T.R.C. 1932, "Strength-Moisture Relations for Wood," Tech. Bull. 282, Washington, DC: United States Department of Agriculture.

*In:* PTEC 94 Timber shaping the future: Proceedings of Pacific timber engineering conference; 1994 July 11–15, Gold Coast, Australia. Fortitude Valley MAC, Queensland, Australia: Timber Research Development and Advisory Council: 731–739. Vol. 2.

PRINTED WITH SOY INK on recycled paper