In: Gopu, Vijaya K.A., ed. Proceedings of the
international wood engineering conference; 1996 October
28-31; New Orleans, LA. Baton Rouge, LA: Louisiana
State University: Vol. 2: 536-542

Moisture Content–Specific Gravity Relationships for Clear Southern Pine

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Abstract

U.S. engineering design practices require information about the strength of lumber, even if the lumber has a moisture content level as low as 4 percent. To efficiently design experimental studies on lumber properties at low levels of moisture content, it is desirable to obtain a better understanding of the basic mechanisms controlling moisture-property relationships. As part of a larger study on the effect of moisture content on the tensile strength of lumber, studies were conducted on the effect of moisture content on eight mechanical properties of clear Southern Pine (tension parallel to the grain, tension perpendicular to the grain, bending, compression parallel to the grain, compression perpendicular to the grain, mode I fracture, mode II fracture, and shear parallel to the grain). Specimens were cut from commercially dried standard 38- by 140-mm (nominal 2- by 6-in.) lumber and sorted into five matched moisture groups of approximately 40 specimens each, based on density. This paper presents (1) empirical equations relating clear wood properties to moisture content and specific gravity and (2) graphical surface plots of these equations.

Keywords: Moisture content, specfic gravity, clear wood, tension, bending, compression, shear, stress intensity factor, Southern Pine, empirical models, dimension lumber, drying

Introduction

In the United States, lumber is used at a wide range of moisture content (MC) levels. Persistent reports of structural failures at low MC levels, coupled with the experimental evidence of a decrease in wood strength at lower MC levels, suggest the need for a better understanding of the effect of MC on the mechanical properties of wood, especially ultimate tensile stress (UTS) at low MC levels. The objective of this study was to determine the effect of MC and density on a wide range of clear wood properties. This study is part of a program to gain a fundamental understanding of the effect of MC on the mechanical properties of wood.

Background

Experimental studies on the effect of low MC on the UTS of structural lumber are expensive and time consuming. The need to obtain a more fundamental understanding of the effect of MC on properties was recognized by Dr. David Green in the mid- 1980s. The lack of an adequate analytical model for predicting the strength of lumber using fundamental mechanisms hindered developing an understanding of this effect.

Considerable literature exists on the effect of MC on the mechanical properties of clear, straight-grained wood. A detailed discussion of this literature is found in Green and Kretschmann (1994). In general, individual studies have collected data for only a few properties and only a limited number of specimens have been tested for a given property-moisture content combination.

In the literature, data on properties of clear wood at less than 6 percent MC are much more limited than are those with data greater than 6 percent MC. 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

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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 have indicated that a significant decrease in these property values may occur with additional drying (Green and Kretschmann 1994). These property value decreases could explain the loss in the UTS of lumber at MC levels less than 12 percent.

This paper summarizes previously published research and presents (1) empirical equations relating clear wood properties to moisture content and specific gravity and (2) graphical surface plots of these equations, ten of which were previously not reported. Experimental techniques are explained in detail in Green and Kretschmann (1994). Theoretical approaches to moisture absorption that may explain experimental results are discussed in Kretschmann and Green (1996).

Experimental Methods

Traditionally, clear specimens for MC property studies have been cut from green logs and then slowly dried to various target MC levels (Eskelson and others 1993, Hui Zhou and Smith 1991, Wilson 1932). But in reality, lumber is not treated so simply in service. It is subjected to a range of variables. The majority of commercial lumber is kiln dried first. Then, when the lumber is used, it is under a wide range of environmental conditions with varying MC. Thus, the traditional MC property studies may not be true representations of the lumber tensile strength-MC relationship, because those relationships do not reflect the degee to which kiln schedule, moisture hysteresis, and other practical considerations affect the tensile strength of commercial lumber. Therefore, to account for kiln schedule, hysteresis, and other factors, we cut clear samples from previously kiln-dried commercial lumber. We chose Southern Pine because it is locally available and a commercially important lumber species for which data on MC tensile strength does not exist. The lumber was grade stamped at mills that used conventional (<82°C (180°F)), not high temperature (> 110°C (230°F)) drying schedules. Details of specimen preparation, dimensions, and testing procedures are described in Green and Kretschmann (1994) and Kretschmann and Green (1996).

Material Selection

Material for this study was cut from 3.7-m (12-ft) Southern Pine (either *Pinus echinata* or *P. taeda)* standard 38- by 140-mm lumber (nominal 2- by 6-in., hereafter designated as 2 by 6) that was obtained from local suppliers in Madison, Wisconsin. One hundred fifty 2 by 6 boards were numbered sequentially and equilibrated in a 25°C (78°F) and 65 percent relative humidity conditioning room. The boards were ranked and sorted into five groups with equivalent specific gravity distributions. Four of the five groups 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 fifth group of material was to be saturated. The saturated material was obtained by water soaking under a vacuum, To prevent excessive staining 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.). Nine 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, mode I fracture, mode II fracture, and shear parallel to the grain. The specimens were arranged to keep the material from the straightest grain section as close together as possible.

Testing

The tension parallel to grain, center-point bending, compression, and shear tests were conducted on scaled specimens that conformed 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 temperature and MC levels at which the MC groups were conditioned. 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

Matching

The average density at 12 percent MC was 590 kg/m^3 (specific gravity at 12 percent = 0.53). This is slightly greater than the clear wood average of 570 kg/m^3 (specific gravity at 12 percent MC = 0.51) (Forest Products Laboratory 1987). The average densities of the different MC groups as well as the range of density values were similar.

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 levels. The actual average MC levels for all the groups (4.3, 7.2, 12.0, and 18.1 percent) were close to the target MC levels (4, 8, 12, and 18 percent). All the saturated pieces were well above the fiber saturation point.

Determination of M_p

The term M_p refers to an “effective” moisture content at which additional drying would have’ a significant effect on properties but wetting has little or no noticeable effect. In our study, a procedure similar to the historic method (Wilson 1932) was used to establish the M_p values. For each property, strength data were plotted for the four dry MC levels. Inspection of the data suggested that a quadratic curve provided a good fit because of its nonlinear nature. An intercept between a horizontal line drawn through the average for the saturated data and the quadratic curve fit to the four dry MC data sets for each property was then calculated. A linear fit was used in M_p calculations for compression perpendicular to the grain. From these results, we determined that 23 percent MC best represented an overall M_p value for this material (Green and Kretschmann 1994). The value of 23 percent compares favorably to the 21 percent M_p value that Wilson (1932) calculated. If Wilson had included his 4 percent data when determining M_p, his value for M_p would have been greater.

Moisture Content/Density-Property Relationships

Because density is known to have a significant effect on clear wood properties, empirical models were obtained using both MC and density. Table 1 shows the equations fit to the data for surface models of the form:

$$\text{Property} = \text{Int} + a(\text{MC}) + b(\text{MC})^2 + c(\text{DN}) + d(\text{DN})^2 + e(\text{MC})(\text{DN})$$

where

Int	is	the intercept,
MC		the moisture content as a percentage,
DN		density at 12 percent MC, and
a,b,c,d,e are		modeled coefficients.

After consultation with a statistician, this model form was chosen because it allows for interaction between MC and density and fit the observed trends in the data.

Discussion

Moisture Content-Density Interactions

The interaction between density and changes in MC explain a large portion of the observed variability in properties. The r^2 values of the curve fits range from a low of 0.37 to a high of 0.95. The response surfaces for the properties tested are shown in Figures (1-15). The dots on the response surfaces represent the density and moisture content location of individual data points.

Strength *Properties* — The tension parallel and perpendicular to grain, mode I stress intensity, and mode II stress intensity surfaces indicated a consistent peak at all levels of density distribution (Fig. 1,2,7,8). For tensile stress parallel and perpendicular to grain and mode II stress intensity factor, this peak was between 10 and 12 percent MC. For mode I, this peak was reached around 5 to 7 percent MC. The compression parallel and perpendicular to grain and shear surfaces indicated that higher density specimens are more sensitive to changes in moisture content than are low density specimens (Figs. 4-6). The shear surface also appears to level off between 6 and 9 percent MC. As expected, the MOR surface is a combination of the tension and compression surfaces (Fig. 3).

Elastic Properties — All modulus of elasticity (MOE) levels were quite sensitive to density. The tension perpendicular to grain and compression parallel and perpendicular to grain MOE surfaces indicated that higher density specimens are more sensitive to changes in moisture content than are low density specimens (Figs. 10,12, 13). Modulus of elasticity in tension perpendicular to grain and MOE compression parallel to grain increased from green to about 6 percent MC, then increased little with additional drying The tension parallel to grain and bending MOE surface responded the same to decreasing MC at all levels of density (Fig. 9). As expected, the MOE bending surface was a combination of the tension and compression surfaces (Fig. 11). Poisson’s ratios are not very sensitive to specific gravity or MC (Figs. 14,15).

From observations of the failure process and trends in the results presented for Southern Pine, it appears that some fundamental degradation mechanism, or combination of mechanisms, is involved when properties are evaluated at lower MC levels. Molecular considerations and micromechanical failure mechanisms in the cell wall may offer a possible explanation of these mechanisms (Kretschmann and Green 1996).

Table 1—Equations for curves fit to strength moisture content and density data[a,b]

	Property = Int + a(MC) + b(MC)^2 + c(DN) + d(DN)^2 + e(MC) (DN) (Property = Int + a(MC) + b(MC)^2 + c(SG) + d(SG)^2 + e(MC) (SG))						
	Int	a	b	c	d	e	r^2
UTS parallel	–16.16 (–2.344)	17.364 (2.5184)	–0.422 (–0.06127)	–0.158 (–25.595)	0.000539 (98.009)	–0.01129 (–1.833)	0.47
UTS perpendicular	–4.785 (–0.694)	0.462 (0.067)	–0.0155 (–0.00224)	0.01663 (2.7011)	–0.00000583 (–1.0611)	–0.000262 (–0.0425)	0.80
MOR	1.4717 (0.2134)	4.4049 (0.63886)	–0.1013 (–0.01469)	0.14216 (23.092)	0.000145 (26.384)	–0.010108 (–1.642)	0.90
UCS parallel	–4.0422 (–0.5862)	0.3801 (0.05512)	0.02191 (0.00318)	0.1383 (22.458)	0.0000377 (6.8676)	–0.00661 (–1.074)	0.95
UCS perpendicular[b]	–17.456 (–2.532)	0.2393 (0.0347)	0.001599 (0.000232)	0.07598 (12.341)	–0.0000296 (–5.3852)	–0.001407 (–0.2285)	0.91
Shear parallel	3.0033 (0.4356)	0.8299 (0.12036)	–0.02232 (–0.003238)	0.013746 (2.2329)	0.0000242 (4.4097)	–0.001295 (–0.2104)	0.93
K_{Ic} TL	284.8 (259.2)	21.20 (19.30)	–0.918 (–0.836)	–0.395 (–403.1)	0.00106 (1,210.0)	–0.0113 (–11.52)	0.72
K_{IIc} TL	870.9 (792.6)	110.5 (100.6)	–4.494 (–4.081)	–1.290 (–1,315.1)	0.00408 (4,662.3)	–0.0251 (–25.60)	0.70
MOE tension parallel	9,164.9 (1,329.2)	499.0 (72.37)	–8.723 (–1.265)	–25.256 (–4,102.4)	0.064 (11,647)	–0.9012 (–146.4)	0.52
MOE tension perpendicular	-503.1 (–72.0)	54.7 (7.83)	–1.834 (–0.263)	2.718 (435.8)	–0.000287 (–51.63)	–0.0734 (–11.77)	0.89
MOE bending	–3,790.6 (550)	703.17 (102.0)	–16.554 (–2.401)	–3.183 (–517.1)	0.03139 (5,710.5)	–0.9146 (–148.6)	0.68
MOE compression parallel	–1,444.0 (–209.4)	862.5 (125.1)	–28.047 (–4.068)	24.024 (3,902)	0.014 (22,550)	–1.1011 (–178.9)	0.80
MOE compression perpendicular	–458.01 (–66.4)	25.132 (3.64)	–0.1588 (–0.023)	2.2448 (364.6)	0.000249 (45.32)	–0.08988 (–14.60)	0.87
Poisson's ratio LT	–0.355 (–0.355)	–0.0082 (–0.0082)	–0.000131 (–0.000131)	0.002336 (2.617)	–0.000002037 (–2.556)	0.000008034 (0.0090)	0.37
Poisson's ratio LR	0.284 (0.284)	–0.0056 (–0.0056)	–0.000217 (–0.000217)	–0.00355 (–0.398)	0.000000233 (0.293)	0.000009135 (0.0102)	0.41

[a] Int is the intercept; MC is the moisture content as a percentage; DN is density in kg/m^3 at 12% MC; a,b,c,d,e are modeled coefficients; units for P for K_I and K_{II} are KN•m$^{-3/2}$; Poisson's ratio is unitless; values remaining are in MPa.

[b] For the parenthetical term, Int is the intercept; MC is the moisture content as a percentage; SG is the specific gravity based on ovendry weight and volume at 12% MC; a,b,c,d,e are modeled coefficients; units for P for K_I and K_{II} are lb•in$^{-3/2}$; Poisson's ratio is unitless; values remaining are in (×10^3 lb/in^2).

Concluding Remarks

From the moisture content–density surfaces determined for clear Southern Pine in this study, we conclude the following:

- Ultimate tensile stress parallel and perpendicular to grain and mode II stress intensity factor increases as MC decreases, reaching a maximum between 10 and 12 percent MC for all levels of density. Mode I stress intensity factor increases as MC decreases, reaching a maximum between 7 and 9 percent MC for all levels of density. The strength values decrease with additional drying.
- Modulus of elasticity in tension perpendicular to grain, MOE compression parallel to grain, and shear strength parallel to grain increase from green to about 6 percent MC, then increase little with additional drying.
- Compression strength parallel and perpendicular to grain, shear parallel to grain, MOE tension perpendicular to grain, and MOE compression parallel and perpendicular to grain appear to be more sensitive to changes in moisture content when the density level is high.
- The MC above which properties cease to decrease with increasing MC (M_p) averages 23 percent.

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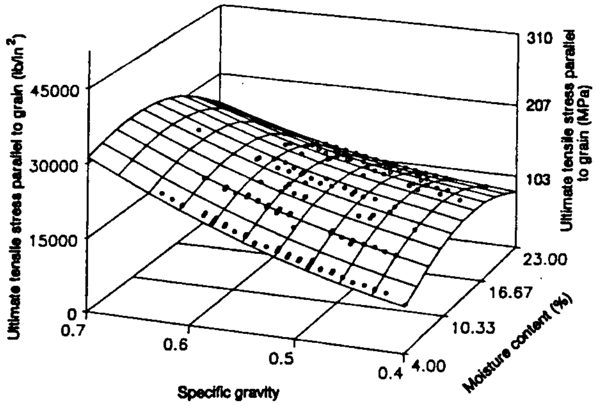

Figure 1—Response surface for tension parallel to grain stress. Dots on surface represent x-y location of test data on surface.

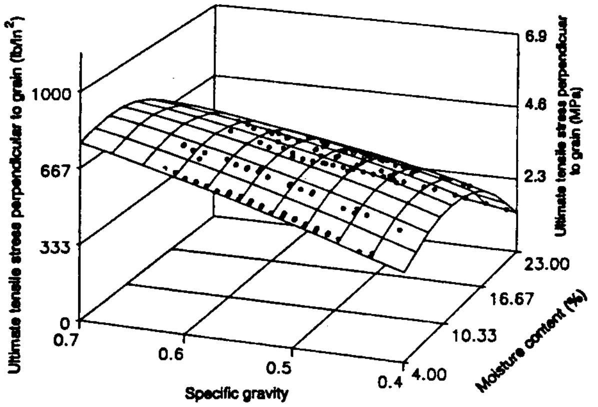

Figure 2—Response surface for tension perpendicular to grain stress. Dots on surface represent x-y location of test data on surface.

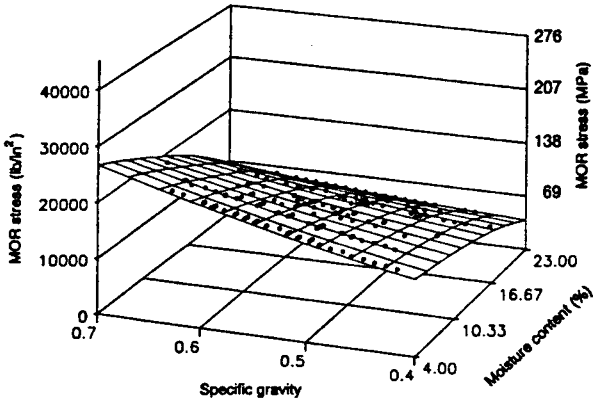

Figure 3—Response surface for modulus of rupture (MOR). Dots on surface represent x-y location of test data on surface.

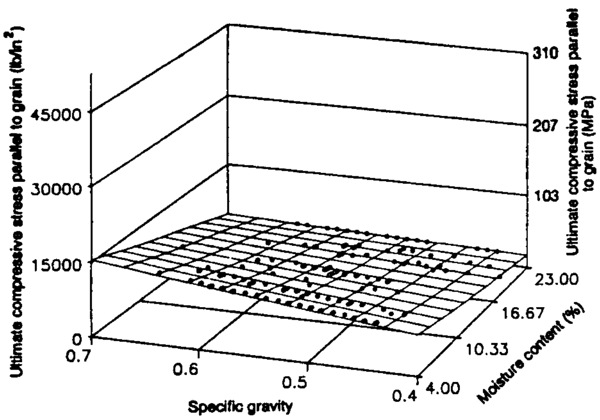

Figure 4—Response surface for compression parallel to grain stress. Dots on surface represent x-y location of test data on surface.

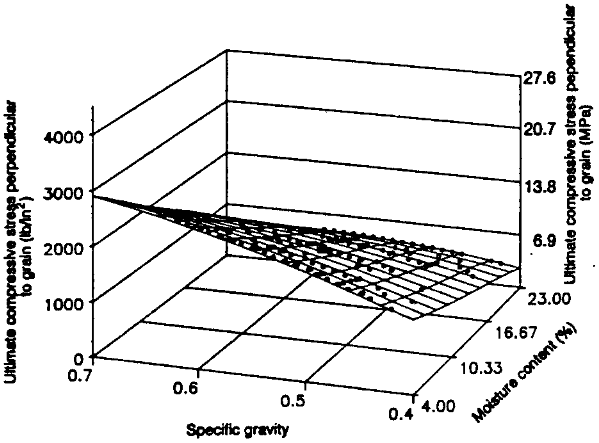

Figure 5—Response surface for compression perpendicular to grain stress. Dots on surface represent x-y location of test data on surface.

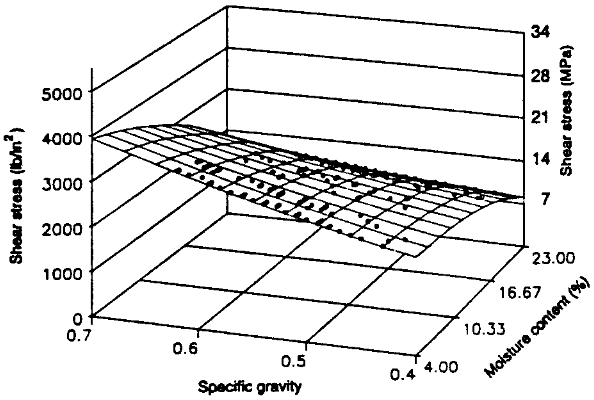

Figure 6—Response surface for shear parallel to grain stress. Dots on surface represent x-y location of test data on surface.

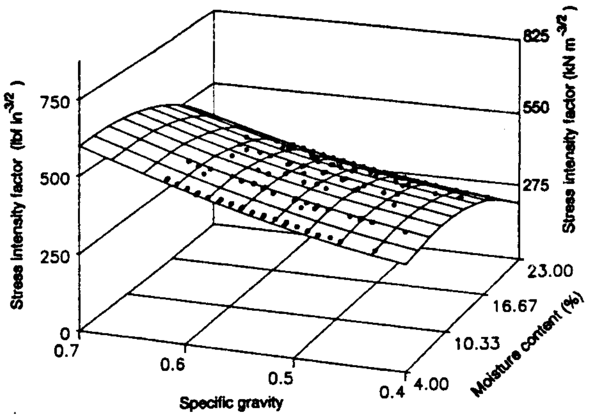

Figure 7—Response surface for mode I stress intensity factor. Dots on surface represent x-y location of test data on surface.

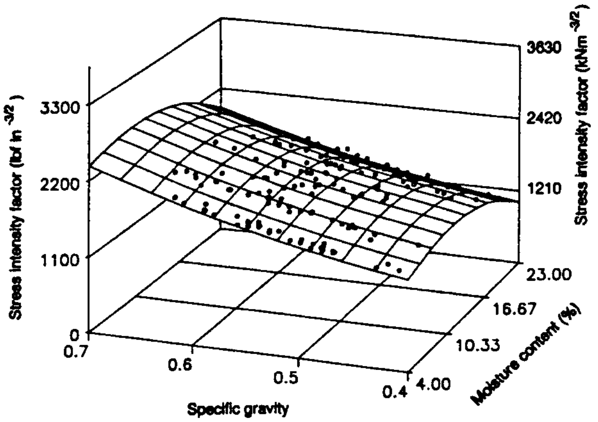

Figure 8—Response surface for mode II stress intensity factor. Dots on surface represent x-y location of test data on surface.

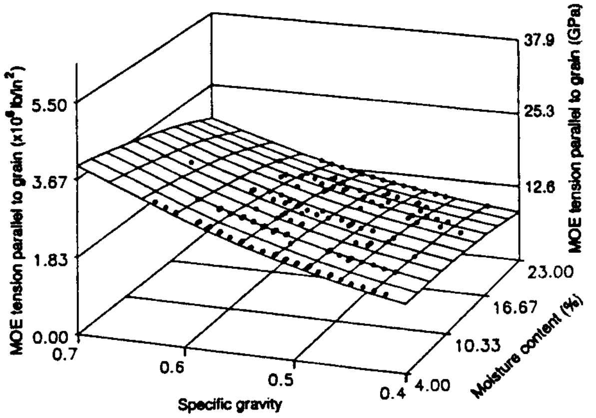

Figure 9—Response surface for tension parallel to grain modulus of elasticity (MOE). Dots on surface represent x-y location of test data on surface.

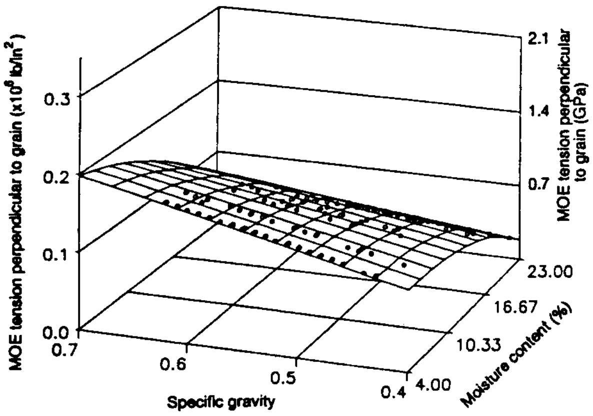

Figure 10—Response surface for tension perpendicular to grain modulus of elasticity (MOE). Dots on surface represent x-y location of test data on surface.

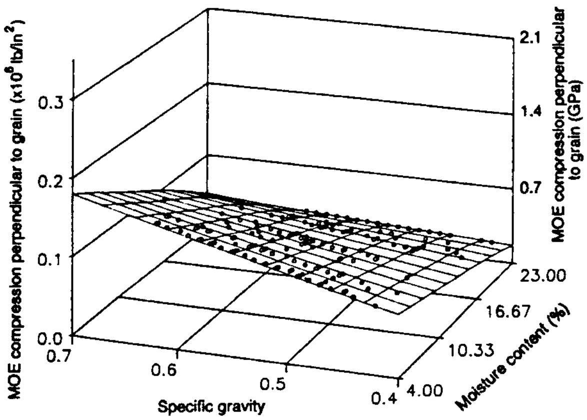

Figure 13—Response surface for compression perpendicular to grain modulus of elasticity (MOE). Dots on surface represent x-y location of test data on surface.

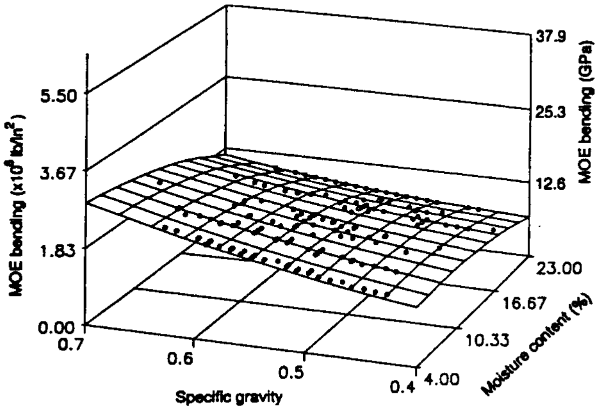

Figure 11—Response surface for modulus of elasticity (MOE) in bending. Dots on surface represent x-y location of test data on surface.

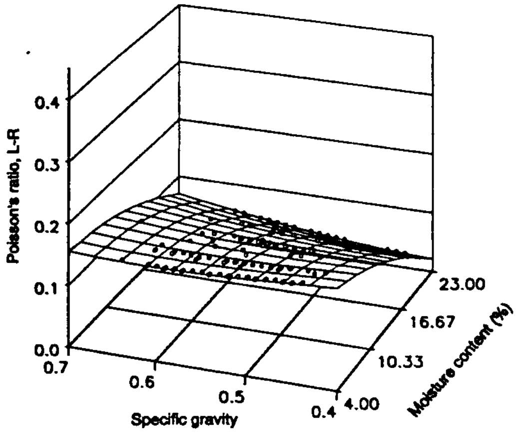

Figure 14—Response surface for Poisson's ratio in the logitudinal-tangential (L-T) direction. Dots on surface represent x-y location of test data on surface.

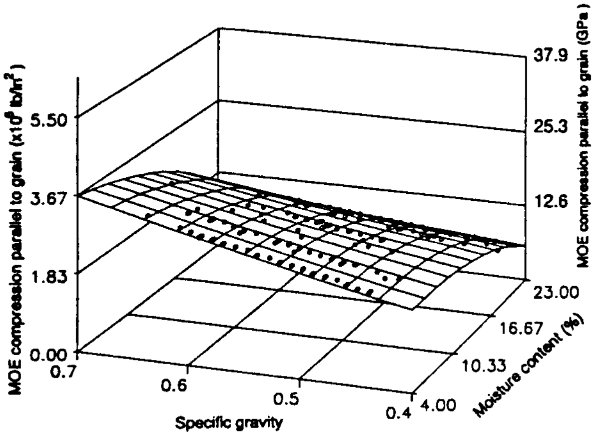

Figure 12—Response surface for compression parallel to grain modulus of elasticity (MOE). Dots on surface represent x-y location of test data on surface.

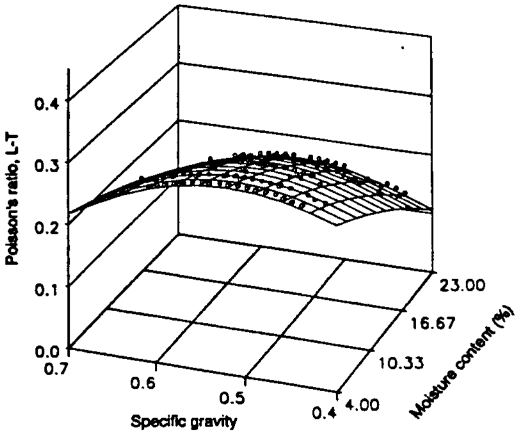

Figure 15— Response surface for Poisson's ratio in the logitudinal-radial (L-R) direction. Dots on surface represent x-y location of test data on surface.