CHAPTER 3

Effect of Densification on Tensile Strength and Stiffness Parallel to the Grain

3.1 INTRODUCTION

Wood exhibits its highest strength in tension parallel to the grain. Tensile strength parallel to the grain of small clear specimens is approximately 2 to 3 times greater than compressive strain parallel to the grain, about 1.5 times greater than static bending strength and 10 to 12 times greater than shear strength (Biblis, 1969). Although tensile strength parallel to the grain is an important property, it has not been fully determined for all commercial wood species due to several reasons. First, having very low shear strength, wood has a tendency to break in shear or cleavage at the fasteners and joints. Second, knots and growth defects have a great effect in lowering the strength of wood subjected to tension parallel to the grain. In addition, the manufacture of the test specimens is not easy and requires a lot of skilled manual labor. Therefore, the data on the tensile strength and stiffness parallel to the grain in the literature are limited in the number and reliability. Nevertheless, with the development of better mechanical fasteners and synthetic adhesives for wood, higher proportion of the tensile strength can be utilized in modern design of wood structures. Thus, tension parallel to grain properties of solid wood, as well as wood modified by different treatments, should be further investigated.

3.2 BACKGROUND

Tension strength and stiffness parallel to the grain of solid wood has been determined for a number of species. However, very little research has been done to determine tensile strength and stiffness of wood modified by chemical, thermal or compressive treatments. Pioneering research on densified wood, resulting in introduction of the STAYPAK (untreated compressed wood), has shown an increase in bending strength and stiffness (Seborg et al. 1962). Jennings (1993) utilized conditions similar to STAYPAK to densify veneers of yellow-poplar and performed tensile parallel to grain tests on undensified and densified veneers. It was found that the longitudinal modulus of elasticity of the densified samples were approximately 135 percent greater than those of undensified samples. Geimer et al. (1985) investigated the effect of hot-pressing on the tensile properties of individual Douglas-fir flakes and reported a great reduction in tensile strength and stiffness. However, the modulus in this study were calculated based on the movement of the test machine crosshead, which may have introduced an error due to the slippage of the flakes within the test machine grips. It was shown in other studies (Kamke and Casey

1988; Gardner et al. 1993) that wood bending strength and stiffness can be either increased or decreased, depending on the conditions under which the material is processed.

3.3 EXPERIMENTAL

3.3.1 Materials

Material Selection

Loblolly pine (*Pinus taeda*) and yellow-poplar (*Liriodendron tulipifera*) were chosen for this study because they are locally available and commercially important species. Loblolly pine grows from Maryland southward through the Atlantic Coastal Plain and Piedmont Plateau into Florida and westward into eastern Texas (Wood Handbook, 1999). From an anatomical standpoint, loblolly pine, like other softwoods, possess only a few kinds of cells and, thus, has a relatively simple structure. Yellow-poplar grows from Connecticut and New York southward to Florida and westward to Missouri (Wood Handbook, 1999). The wood is straight-grained with pores that are small and fairly uniformly distributed throughout the ring (diffuse-porous). In contrast with ring-porous species, the specific gravity of yellow-poplar does not change drastically throughout its annual growth ring. In addition, these two species represent a potential for future intensive management. Wood from both species can exhibit considerable variation in chemical and anatomical properties dependent on growth rate and proximity to the stem center. To reflect such variability in anatomical and chemical properties within these species, both mature and juvenile wood specimens were obtained. Loblolly pine and yellow-poplar also represent considerable differences in the type and amount of lignin present, a factor which has been shown to influence glass transition behavior (Kelley et al. 1987).

Material for this study was cut from logs of yellow-poplar and loblolly pine obtained from southwestern Virginia. Trees were approximately 40 years old. Logs were cut into cants that were further separated into juvenile and mature portions. Juvenile wood was obtained from the portion inside the tenth growth ring and mature wood was obtained from the portion outside the thirtieth growth ring. The choice of the 10th growth ring as division between juvenile and mature wood was arbitrary. Loblolly pine normally has 6 to 14 or more rings of juvenile wood (Hallock 1968; Clark and Saucier 1989; Bendtsen and Senft 1986). The wood material was then end sealed and allowed to air dry at ambient laboratory conditions for approximately 18 months.

Specimens Preparation

Thin flat-sawn boards (thickness in radial direction) were cut from the air-dried cants. The boards were then reduced in thickness using an abrasive planer to the desired thicknesses (4mm and 3mm for 50% and 25% strain compression levels respectively). Specimens, measuring 120mm by 27mm, were prepared from the boards using a band saw. Care was taken to obtain specimens with straight grain and without defects. Thirty specimens from each species and type (mature/juvenile) were randomly selected for each densification treatment (Table 3.1 and Table 3.2) and 15 specimens were selected as control (ambient temperature and 0% strain). Fifteen specimens out of the first 30 were saved for compression treatment and the other 15 specimens were used as "uncompressed", i.e. subjected to the same environmental treatment at 0% strain, in order to reflect the temperature effect alone. Ovendry weight and dimensions were obtained for each specimen in order to calculate specific gravity (Table 3.3, Table 3.4). Width and length measurements were performed with an electronic digital caliper to the nearest 0.01 mm and thickness was measured with an electronic digital gage to the nearest 0.001 mm at 4 points of the specimen (Figure 3.1). An average value was used for volume calculations.

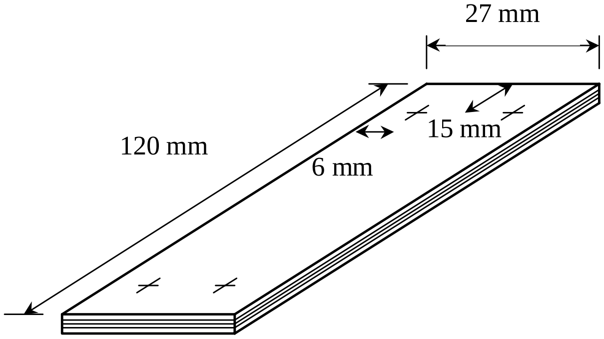


Figure 3.1 Test specimen showing location of thickness measurements.

3.3.2 Methods

The wood specimens were compressed in the hydraulic press shown in Figure 3.8 to either 50% or 25% of their original thickness (Table 3.1) in the radial direction. The platens of the press were 139.7 by 139.7 mm. The top platen was fixed and the bottom platen was traveling. Pressure was applied by a single-acting remote-powered hydraulic cylinder with 20 ton capacity. The cylinder was fixed to the top of the support frame and acted upward with a spring return. Hydraulic power was supplied by a remote power unit located outside the selected environment (oven, environment cabinet or pressure vessel). Wood specimens were pressed to the thickness controlled by metal stops. Rate of compression was controlled by adjusting the rate of flow of fluid into the hydraulic cylinder. Pressure applied to the specimens was 17.2 MPa (2500 psi). Calculations of the pump pressure are listed in Appendix A. All the specimens were conditioned to specific moisture contents prior to densification (Table 3.5), depending on the equilibrium moisture content conditions and pressure.

The samples were compressed at three different environmental conditions (Figure 3.2):

Treatment 1: *200℃, 6.5 % RH (0 % MC), 93 kPa*

Treatment 2: *90℃, 95 % RH (17 % MC), 93 kPa*

Treatment 3: *140℃, 62 % RH (12 % MC), 223.4 kPa*

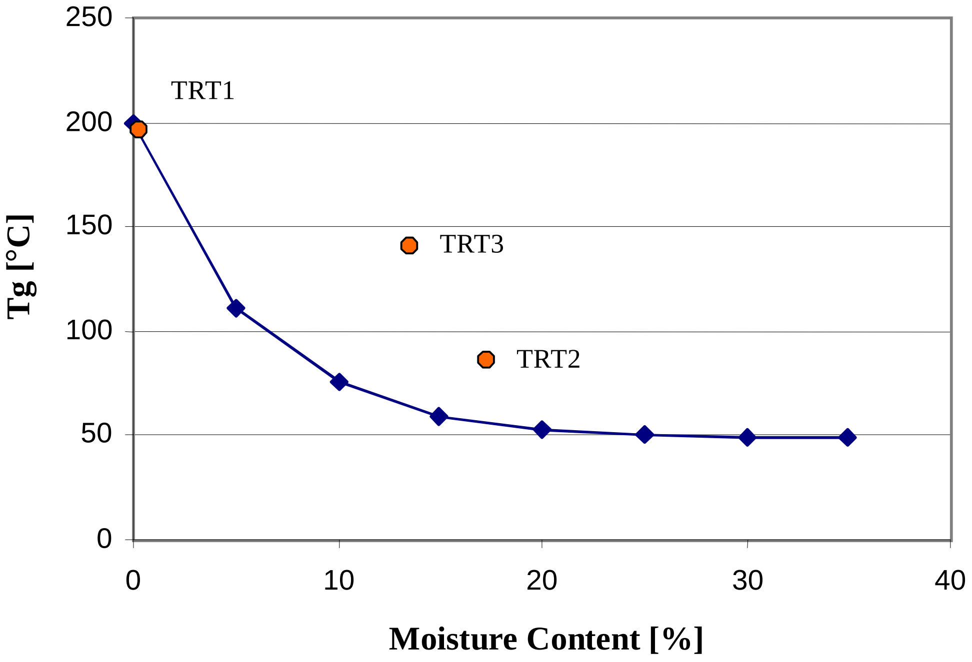


Figure 3.2 T_g of lignin vs. moisture content (by Kwei eguation) and environmental conditions.

Treatment 1 was performed in an oven heated to 200 °C. The hydraulic press was placed into the oven and allowed to heat up to the same temperature. When the press platens reached 200 °C, 15 specimens were placed between the platens of the press (3 in each opening) and the other 15 specimens were placed in an open container inside the oven. Specimens were held in the oven environment for about 25 minutes until they reached 200 °C ± 3 °C. The temperature inside the wood was monitored by inserting a thermocouple into a hole drilled in the center of one of the specimens in the tangential direction. Once the specimens reached the desired temperature, the pressure was applied gradually every 10 seconds up to 50 seconds starting from 1000 psi until it reached the desired final pressure (see Appendix A). Full final pressure and temperature were held for 5 minutes. Then the oven was turned off and air was circulated inside the oven to speed up the cooling process. Pressure was maintained at the same level. After 27 minutes pressure was released and the specimens were taken out of the oven. At the end of the cooling period temperature inside of the specimens was approximately 115 to 125 °C. Immediately after the test the specimens were weighed and measured. To obtain ovendry weight and dimensions, compressed and uncompressed specimens were placed into the conventional oven at 103 ± 2°C until approximately constant weight was attained.

Treatment 2 was carried out in a 1 m^3 environment cabinet with recirculating, forced-air flow (Parameter Generation and Control, Inc.) at 90 °C and 95 % relative humidity. Dry bulb and wet bulb thermocouples were used to monitor temperature and humidity of the environment within 0.1 °C and 0.5 % relative humidity. The specimens were equilibrated to 20 ± 2 % moisture content prior to densification (Table 3.5). The press was placed into the chamber and allowed to heat up to 90 °C. When the press platens reached 90 °C, 15 specimens were placed between the platens of the press and the other 15 specimens were placed in an open container inside the chamber. When the temperature inside the samples reached 90 °C, pressure was applied gradually every 10 seconds up to 50 seconds starting from 1000 psi until it reached the desired final pressure (Appendix A). The time it took to warm up the specimens was different for every group (Table 3.6). Full final pressure and temperature were maintained for 5 minutes. After 5 minutes the chamber was turned off, opened, and air was circulated inside the chamber to speed the cooling process. Specimens were cooled down to about 36 to 40 °C in 48 to 56 minutes. Full pressure was maintained during the cooling period. Once the temperature inside the specimens dropped to the desired value, pressure was released and the specimens were taken out, weighed and measured.

Treatment 3 was conducted in a pressurized vessel that was constructed at Virginia Tech (Lenth, 1999) in order to produce relative humidities sufficient for generating wood EMC conditions from 0% to near fiber saturation at temperatures above 100 °C (Figure 3.8). The device consisted of a 50-liter stainless steel vessel, which could withstand internal pressures in excess of 6 atmospheres. It had computer control of temperature and internal pressure. Water, vapor, air and other gas environments could be introduced to the vessel during testing.

Fifteen specimens were placed into the hydraulic press and the other 15 specimens were placed on the top of the hydraulic press. Water was added into the vessel to generate steam. The vessel then was sealed and heated until the temperature inside of the samples reached 140 °C. Once the desired temperature was reached, the pressure was applied gradually to the samples every 10 seconds up to 50 seconds starting from 1000 psi until it reached the desired final pressure (see Appendix A). The time it took to warm up the samples was different for every group (Table 3.6). Full final pressure and temperature were maintained for 5 minutes. After 5 minutes the cool down sequence was initiated and air and water were circulated inside the vessel. Specimens were cooled down to approximately 40 to 55 °C within 100 minutes. Full pressure was applied on the specimens during the cooling period. Once the temperature inside the specimens dropped to the desired value, pump pressure was released and the specimens were taken out, weighed and measured. The specimens were subsequently oven-dried at 103 ± 2°C.

After the treatments, compressed, uncompressed and control specimens were placed in an environment chamber at 20 °C and 65% relative humidity for several weeks. When a constant moisture content was reached, the dog-bone specimens were cut for tension testing.

Tension Parallel-to-Grain

A tension parallel-to-grain test was performed to determine the ultimate tensile stress and longitudinal modulus of elasticity of compressed, uncompressed and control loblolly pine and yellow-poplar specimens. The standard tension parallel-to-grain test (ASTM standard D143) requires a clear, straight-grained specimen with the length of 460 mm (18 inches). The dimensions of the hydraulic press for densification of the specimens (139.7 mm by 139.7 mm platens) would not allow the standard size; thus, specimens with reduced, but proportional to ASTM, dimensions were prepared (Figure 3.3). The necked-down section was produced using a router and a cutting template.

Since it was important to avoid failure at the grip, the grip area of the test specimens was increased by gluing thin plates (32 x 25.4 x 1.5 mm) of another wood specie (*Quercus sp.)* onto the tensile specimens. A rapid curing ethyl cyanoacrylate adhesive was used for this purpose.

Test Equipment

A universal load and displacement testing machine (MTS Sintech Material Testing Workstation, Sintech 10/GL load frame, 11200 lb. (50kN) capacity) was used for the tensile test. Software (TestWorkes for Windows 95), which provides full machine control, test data storage and management, and advanced data analysis and presentation was utilized. The MTS machine was equipped with self-tightening wedge grips (Advantage™, 6700 lbf. (30 kN) capacity). The 10000 lb. load cell had a full scale precision of 0.015%.

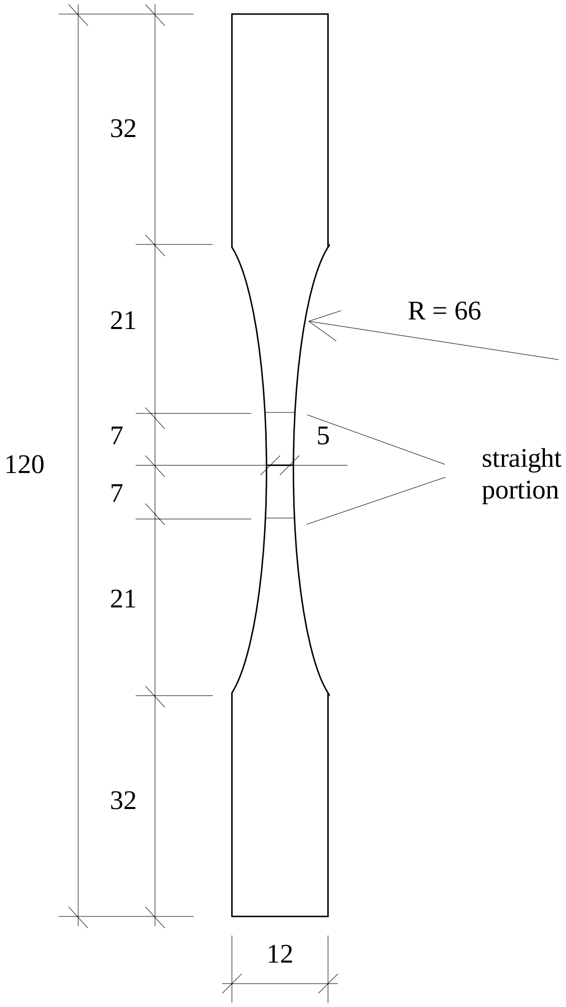
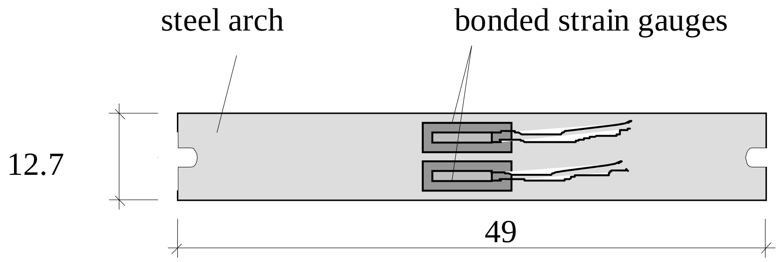


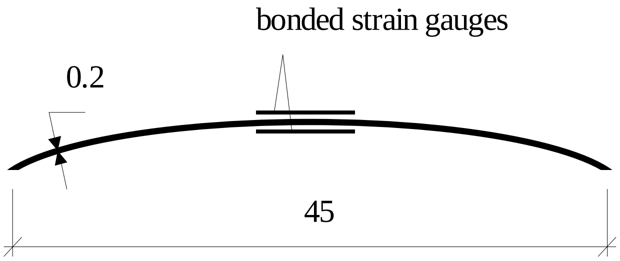
Figure 3.3 Tension parallel-to-grain test specimen (all dimensions are in mm.).

Strain Measurements

Strain measurements in wood samples were performed using a laboratory-built clip-on strain gauge transducer similar to a device reported by Loferski et al. (1989). The clip-on electrical transducer (CET) consisted of a thin, flexible, spring-steel arch clipped onto the surface of the specimen. A clock mainspring, 12.7 mm by 0.2 mm in cross section, was used to make the transducer. Four resistance strain gauges (CEA-06-125UN-120 from Micro-Measurements) were bonded onto the steel arch (Figure 3.4) according to the strain gauge manufacturer's instructions, and arranged in a full Wheatstone bridge circuit to increase the gauge sensitivity.



(a) Top view (when flat)



(b) Side view (original shape)

Figure 3.4 Details of the CET (all dimensions are in mm.).

The CET was calibrated in tension using an extensometer calibrator (Instron Model A18-3A) to a range of 2.54 mm (0.1 in) with precision of 0.0254 mm (0.001 in). The CET was mounted into "L" brackets as illustrated in Figure 3.5 and Figure 3.10. Two CETs per specimen were used to decrease error in strain determination. The CET was prestressed by attaching it to the L-brackets with a slight amount of additional curvature, which gives the capability of elongation (to measure tension strains). L-brackets were attached to the specimen with bolts and nuts. An automatic data acquisition system was used to measure the change in voltage due to the electrical resistance change of the bonded gauges during elongation.

The CET is reusable, accurate, lightweight, and inexpensive. It can also be used to measure strain in wet or dry specimens, because it is not bonded to the wood.

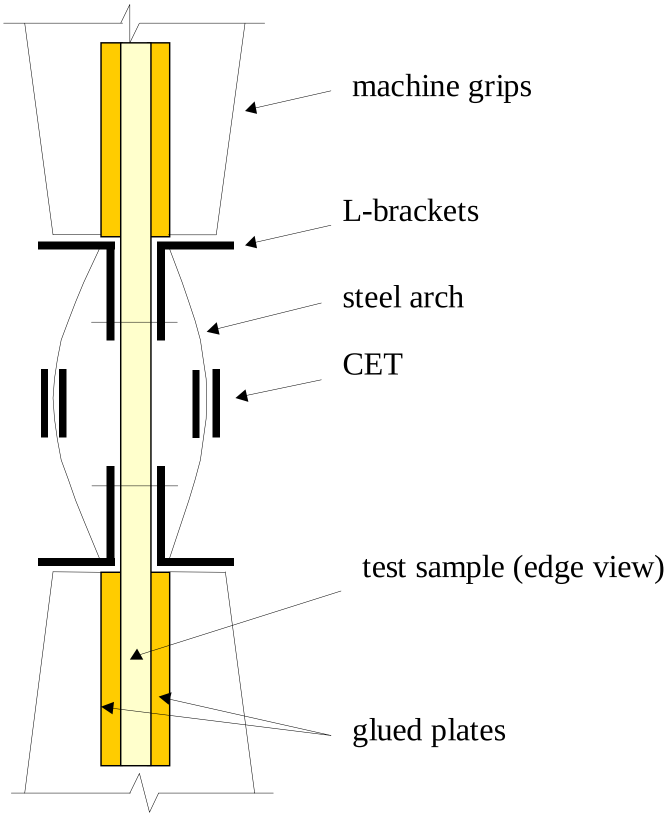


Figure 3.5 Details of the sample test fixture.

Test Procedure

The actual cross-sectional dimensions of each specimen at the minimum section were measured. The load was applied continuously throughout the test at a rate of motion of the movable crosshead of 1 mm/min as specified in ASTM D143. Load-deformation curves were obtained over a 42.8 mm (1.685 in) central gage length on all specimens. The maximum load, maximum stress and voltage from both CETs were obtained. For each CET, a calibration curve was developed by measuring the differential voltage caused by resistance change in the bonded gauges caused by an induced displacement (a known change in gauge length) of the ends of the CET. Deformation (in mm) was calculated using the calibration equation from each CET. The average of the deformation from both CETs was used for strain calculations.

The ultimate tensile stress for each sample was computed by the following equation:

$$G_u = \frac{P_u}{A} \tag{3.1}$$

where:

G_u - ultimate tensile stress, N/mm^2
P_u - ultimate load, N
A - the smallest cross-sectional area, mm^2

Stress and strain values at proportional limit (the point where the stress-strain curve deviates from a straight line) were used to calculate tensile modulus:

$$E = \frac{G_{pl}}{\gamma_{pl}} \tag{3.2}$$

where:

E - modulus of elasticity in tension, N/mm^2
G_{pl} - stress at proportional limit, N/mm^2
γ_{pl} - strain at proportional limit, mm/mm

A small section about 15 mm in length was cut from the reduced section of the specimen near the failure immediately after the test. The moisture content was then determined by the oven-drying gravimetric technique. Moisture content data of the tensile test samples is listed in Table 3.7.

Grain Angle Measurements

One of the most important factors influencing the strength and stiffness of timber is the angle between specimen axis and grain direction. It can be seen from Figure 3.6, the degree of sensitivity varies with mode of stressing, being particularly high in the case of tensile stress parallel to grain. For example, at the grain angle of 15 ° the tensile, static bending and longitudinal compressive strength are reduced to 45, 70 and 80 percent of their respective strengths in straight-grained wood. The sensitivity of stiffness to the angle of the grain appears to be similar to that for strength.

A model for prediction of the failure mode of wood subjected to uniaxial tension at arbitrary angles of load to grain was introduced by Zink et al. (1995). According to this model, for loading at an arbitrary angle to grain, the magnitudes of parallel- and perpendicular-to-grain tensile stresses ($G_{||}$ and $G_{\perp}$, respectively) and parallel-to-grain shear (τ) stresses can be calculated using tensor transformations or the equivalent graphical techniques (Mohr's circle).

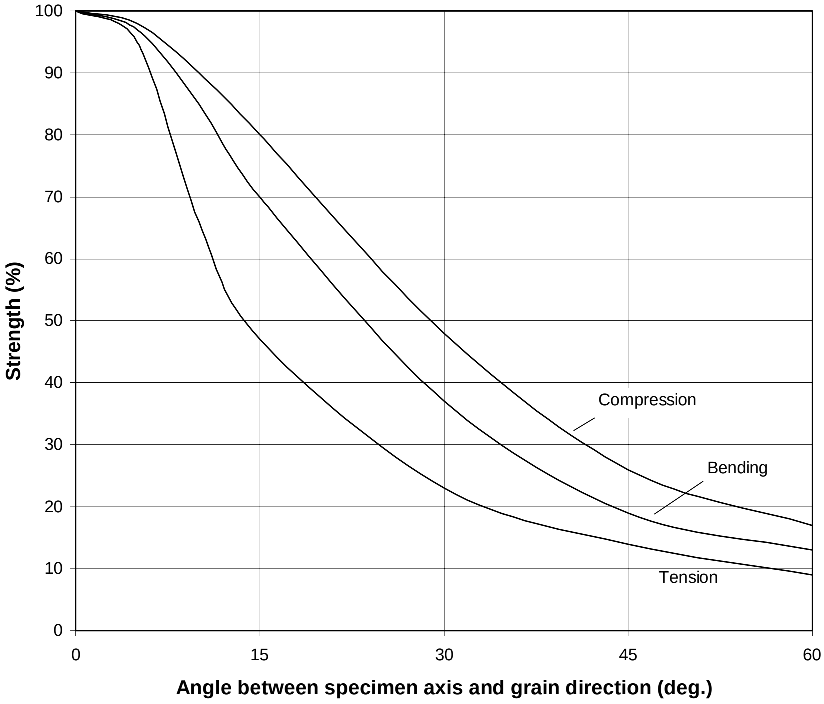


Figure 3.6 Effect of grain angle on the tensile, bending and compression strength of timber (Kollmann, 1968).

For a unit stress, G_0, applied to the specimen shown in Figure 3.7, the normal and shear stress components can be calculated by the following tensor transformations:

$$G_{//} = G_0 \cdot \cos^2 \alpha \tag{3.3}$$

$$G_{\perp} = G_0 \cdot \sin^2 \alpha \tag{3.4}$$

$$\tau = G_0 \cdot \sin\alpha \cdot \cos\alpha \tag{3.5}$$

where:

$G_{||}$ - tensile stress parallel-to-grain
$G_{\perp}$ - tensile stress perpendicular-to-grain
τ - shear stress parallel-to-grain
α - grain angle

Tensile modulus can be computed in the same way as stress.

$$E_{//} = E_0 \cdot \cos^2 \alpha \tag{3.6}$$

where:

$E_{//}$ - tensile modulus parallel-to-grain

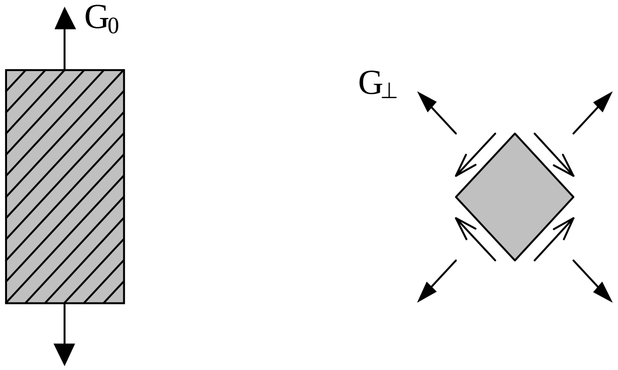


Figure 3.7 Distribution of the stresses on a plain oriented at α degrees to uniaxial load.

After the tensile testing was complete, a razor blade was used to scrape the face and the edge surface in the center of the specimen near the failure, thus providing a smooth surface for microscopic observation. The grain angle was measured using an epi-fluorescence microscope (Zeiss Axioskop) and image analysis software (Image Pro-Plus 3.0, Media Cybernetics). Measurements were made on both the face and the edge of the sample (Figure 3.11) with a magnification of 150 x and 300 x for yellow-poplar and southern pine respectively. The results of the grain angle measurements are listed in Table 3.8.

The following equations were used to compute tensile strength and stiffness parallel-to-grain based on the measured values and the grain angle:

$$G_{//} = \frac{G}{\cos^2 \alpha} \tag{3.7}$$

where:

$G_{//}$ - adjusted ultimate tensile stress parallel-to-grain
G - measured value of ultimate tensile stress
α - grain angle

$$E_{//} = \frac{E}{\cos^2 \alpha} \tag{3.8}$$

where:

$E_{//}$ - adjusted tensile modulus parallel-to-grain
E – measured value of tensile modulus
α - grain angle

3.4 RESULTS AND DISCUSSION

The results of the tensile tests are summarized in the Table 3.10. The data for the ultimate tensile stress and tensile modulus were adjusted based on the grain angle measurements. Specific ultimate tensile stress and specific modulus were obtained by dividing ultimate stress and modulus by ovendry specific gravity at the time of testing (Table 3.11). Average data for ultimate stress, modulus, specific ultimate stress, and specific modulus were separated by each species, strain level at time of densification, treatment, and type (mature/juvenile) and plotted as bar charts (Figures 3.12 – 3.27). A statistical analysis (factorial experiment with analysis of variance and analysis of covariance) was performed in order to evaluate the effect of each factor (species, strain level, treatment, and type of wood) on ultimate tensile stress, tensile modulus, specific ultimate tensile stress, specific modulus, and change in specific gravity of densified wood specimens. The results of the statistical analysis are summarized in Appendix B.

Generally, there was a noticeable increase in ultimate tensile stress and tensile modulus of all the densified samples produced at all the densification treatments at both 25 % and 50 % strain levels.

Effect on ultimate tensile stress

The factorial experiment revealed that the effect of species, strain level and treatment on ultimate tensile stress was significant at $\alpha = 0.05$ level of significance. Strain level and treatment were the most important factors. Type of wood (mature/juvenile) did not cause a significant effect on ultimate tensile stress. A significant interaction was present between the levels of factor “strain” and levels of factor “treatment”, and between levels of factor “species” and levels of factor “treatment” (Figures B1 and B2, Appendix B). Two factors are said to interact if the difference in mean responses for two levels of one factor is not constant across levels of the second factor (Ott, 1993). The species and treatment interaction was orderly (the order of the means for levels of factor species is always the same even though the magnitude of the differences between levels of factor species may change from level to level of factor treatment). Thus, the test on the effect of species was performed. The interaction between strain and treatment was disorderly. Therefore the test on the main effects was not appropriate. The levels of factor "treatment" were compared for each strain level separately.

A multiple comparisons test (Tukey's) was performed in SAS to reveal the difference between levels (Ott, 1993). A significant difference between species was found. Mean ultimate stress for yellow-poplar was higher than for southern pine. Mean values for ultimate stress of the four treatments were not significantly different at 0 % strain. Therefore, it can be concluded that the temperature effect (uncompressed samples) on ultimate tensile stress was not significant. Mean values of ultimate stress were significantly different between TRT1 and TRT2 and between TRT2 and TRT3 for 25 % strain. Mean ultimate stress for TRT2 was the highest (Figure 3.20). At the 50 % strain there was a significant difference between TRT1 and TRT2 and between TRT1 and TRT3. The mean values for ultimate stress in TRT2 and TRT3 were much higher than in TRT1. The difference between TRT2 and TRT3 was insignificant. Figures 3.12, 3.16, and 3.24 illustrate these facts.

Effect on tensile modulus

The effect of all four factors (species, strain level, treatment and type of wood) on tensile modulus was significant at $\alpha = 0.05$ level of significance (Appendix B). A significant interaction was found between the levels of factor "strain" and levels of factor "treatment" (Figure B3, Appendix B). Since it was a disorderly interaction, it was concluded that tests on main effects of strain and treatment were not appropriate.

The results of the Tukey's test (Appendix B) on tensile modulus showed a significant difference between species. The mean modulus was higher for southern pine. A significant difference was also found between mature and juvenile wood. Mature wood had a higher mean tensile modulus. This may be attributed to the larger microfibril angles of juvenile wood and perhaps the difference in chemical composition of mature and juvenile wood. The levels of factor "treatment" were compared for each strain level separately. There was a significant difference between control and TRT2, between control and TRT3, and between TRT1 and TRT2 at the 0% strain. Treatments 2 and 3 had the highest mean values for tensile modulus. Therefore, the temperature exposure alone had some effect on the change in tensile modulus of uncompressed samples in TRT2 and TRT3. At the 25 % strain level no significant difference between treatments was found (Figure 3.20). At the 50 % strain level there was a significant difference between TRT1 and TRT3 and between TRT2 and TRT3. There was no significant difference between TRT1 and TRT2. The highest mean value for the tensile modulus was found in TRT3 (Figures 3.12, 3.16, and 3.24).

Effect on specific ultimate tensile stress and specific tensile modulus

Specific ultimate tensile stress and specific modulus were calculated in order to account for the differences in specific gravity. In the case of densified wood the lumen volume is simply reduced and a greater proportion of cell wall occupies the same bulk volume of wood. For tensile properties parallel to the grain an increase proportional to specific gravity is expected. This, of course, assumes that no changes are realized in the cell wall as a result of the densification process. For example, chemical modifications, thermal degradation, or fractures of the cell wall could occur during densification. Any differences in specific tensile stress or specific modulus, as a result of the treatments, would indicate that something happened to the cell wall. In general, an average specific stress and modulus were lower for compressed specimens than for control or uncompressed. Thus, some deleterious effect occurred to the cell wall as a result of most of the densification treatments.

The statistical analysis had shown a significant effect of all four factors (species, strain level, treatment, and type of wood) on specific ultimate stress at $\alpha = 0.05$ level of significance. Significant interactions were found between the levels of factor ”species” and the levels of factor “treatment” and between the levels of factor “strain” and the levels of factor “treatment” (Figures B4 and B5, Appendix B). The interaction between species and treatment was orderly; thus, the tests on main effects were appropriate. The interaction between strain and treatment, on the other hand, was disorderly and the levels of factor ”treatment” were compared separately for each strain level.

The test for the difference between levels of factor “type” revealed a significant difference between mature and juvenile wood. Juvenile wood had the highest effect on the specific ultimate tensile stress. A significant difference was also found between levels of factor “species”. Mean specific ultimate stress for yellow-poplar was higher than for southern pine. A test for the difference between different treatments at the 0 % strain showed no significant difference between the treatments. As with the ultimate stress, temperature did not have a significant effect on specific ultimate stress of uncompressed samples. At the 25 % strain a significant difference was found between TRT1 and TRT2 and between TRT2 and TRT3. Mean specific ultimate stress was the highest for TRT2 (Figure 3.22). At the 50 % strain TRT1 and TRT2 , TRT1and TRT3 were significantly different. Treatments 2 and 3 were found to have higher means for the specific ultimate stress than TRT1. No significant difference was detected between treatments 2 and 3 (Figures 3.14, 3.18, 3.26).

The effect of all four factors (species, strain, treatment and type) on specific tensile modulus was significant at $\alpha = 0.05$ level of significance (Appendix B). Significant interactions between species and treatment and between strain and treatment were found (Figures B6 and B7, Appendix B). The interaction between species and treatment was orderly (tests on main effects are appropriate) and the interaction between strain and treatment was disorderly (tests on main effects are inappropriate).

The statistical analysis revealed a significant difference between species. Southern pine had the highest mean specific modulus. A significant difference was also found between mature and juvenile wood. Mean specific tensile modulus was the highest for mature wood. Means for the different treatments were compared at each strain level separately. At 0 % strain there was a significant difference between control and TRT2, control and TRT3, and between TRT1 and TRT2. Thus, temperature had an effect on mean specific modulus, especially in TRT2 and TRT3. Treatments 2 and 3 were shown to yield the highest mean specific modulus. At the 25 % strain no significant difference between the treatments was detected (Figure 3.23). Finally, at the 50 % strain only treatments 2 and 3 were significantly different. Mean specific modulus was the highest for TRT3, although it was not significantly different from the mean specific modulus of TRT1 (Figures 3.15, 3.19, 3.27).

The type of failure of the tensile specimens can contribute a significant amount to the reduction in tensile strength and stiffness. Not all the specimens broke in pure tension mode, but partially in shear and perhaps even in cleavage. These types of stresses can cause the failure of the specimen at much lower stress levels than those developed in pure tension. Another factor that could have caused some influence on test results is the fact that strain was measured over the 42.8 mm gage length, which was longer than the straight portion of the specimen (14 mm). However, this difference should not make an effect on the comparisons in strength and stiffness between different densification treatments, since the experimental test setup was not changed throughout the test. Although, absolute values of the tensile properties might be affected by this fact and the results obtained in this study might be different from actual.

Effect on change in specific gravity

The factorial experiment performed to reveal the effect of the four factors on the change in specific gravity showed a significant effect by all four factors at $\alpha = 0.05$. Change in specific gravity was calculated as follows:

$$\Delta G = \frac{G - G_{orig}}{G_{orig}} \qquad (3.9)$$

where:

ΔG = change in specific gravity
G = ovendry specific gravity at time of the test
G_{orig} = original ovendry specific gravity (prior to densification treatment)

The experiment also revealed four significant two-factor interactions between species and treatment, strain and treatment, species and strain, and strain and type. (Figures B9 - B11, Appendix B). Since all these interactions were orderly, the tests on main effects were appropriate. The Tukey's test showed a significant difference in the change of specific gravity between the control and TRT1, control and TRT2, and between control and TRT3. There was no significant differences between three densification treatments, TRT1, TRT2, and TRT3, in terms of the change in specific gravity. A significant difference was found between the strain levels. The highest mean change in specific gravity was observed for 50 % strain. Mean change in specific gravity was also significantly different between the two species, with the highest being southern pine. Finally, a significant difference in mean change of specific gravity was shown for the two types of wood. Juvenile wood had a greater affect on the change in specific gravity than mature wood. Within a given strain level the specimens were compressed equal amounts. Any difference in the change of specific gravity, ΔG, must be due to thickness recovery after compression. The recovery in thickness consisted of “springback” immediately out of the press (elastic recovery), viscous strain due to residual stress, and swelling as a result of moisture gain prior to testing. Each treatment was unique in temperature, moisture content, and time. These treatment conditions will influence the occurrence of cell wall fracture and stress relaxation.

Thermal degradation may have also occurred, with some reduction in the hygroscopic nature of wood.

Analysis of covariance

Analysis of covariance was used in order to decrease the variability in the data due to differences in the original specific gravity of the specimens. The factorial design was performed to examine the effect of four factors (species, strain, treatment and type of wood) on ultimate tensile stress and tensile modulus. Original specific gravity was used as a covariable. The means of the factors were compared after adjusting for differences among the factor levels due to the differences in the covariable.

No linear relationship was found between the covariable (original specific gravity) and the ultimate tensile stress at $\alpha = 0.05$. A significant difference existed between the adjusted means of the two species. The adjusted mean ultimate stress was higher for yellow-poplar. A significant difference between the adjusted mean ultimate stress was found at all the strain levels. The mean ultimate stress was the highest at the 50 % strain. There was a significant difference in adjusted mean ultimate stress between control and TRT1, TRT1 and TRT2, TRT1 and TRT3, between TRT2 and TRT3. The mean ultimate stress significantly decreased in TRT1, slightly decreased in TRT 3 and slightly increased in TRT2 compare to the control. The effect of type (mature/juvenile) on adjusted ultimate stress was not significant.

A significant linear relationship was found between the covariable (original specific gravity) and the tensile modulus (p-value = 0.044) at $\alpha = 0.05$. A significant difference existed between adjusted means of the two species. The adjusted mean tensile modulus was higher for southern pine. A significant difference between the adjusted modulus was found at all the strain levels. The mean tensile modulus was the highest at the 50 % strain. There was a significant difference in adjusted mean modulus between control and TRT2, control and TRT3, TRT2 and TRT3, and between TRT1 and TRT3. The highest adjusted mean modulus was shown for TRT3 and the lowest for the control specimens. The adjusted means for mature and juvenile wood were significantly different. Mature wood had a higher adjusted mean modulus.

3.5 CONCLUSIONS

There was no significant thermal degradation detected in the tensile specimens.

The temperature and moisture content during the densification process influenced the change in tensile strength and stiffness. These differences may be attributed to the degree of plasticization at the time of compression, with the more ductile wood experiencing less residual stress and less damage to the cell wall.

The degree of densification was not significantly affected by the environment during compression.

The strain level employed during compression had the greatest influence on increasing specific gravity and tensile properties.

The degree of densification was dependent on the species and type of wood, with southern pine and juvenile wood exhibiting the greatest increases of specific gravity.

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Table 3.1 Summary of compression levels and environments by specimen type.

Specimen Type	Compression Level	Environmental Conditions
Control	0 % strain	ambient
Uncompressed	0 % strain	TRT1, TRT2, TRT3
Compressed	25* and 50 % strain	TRT1, TRT2, TRT3

*Only specimens of mature yellow-poplar were compressed at 25% strain level

Table 3.2 Environmental conditions and number of replications for densification treatments[1] (420 total specimens).

Species		Strain(%)[2,3]	Control	TRT1	TRT2	TRT3
Yellow-Poplar	Mature 3mm	0	15	15	15	15
		25		15	15	15
	Mature 4mm	0	15	15	15	15
		50		15	15	15
	Juvenile	0	15	15	15	15
		50		15	15	15
Loblolly Pine	Mature	0	15	15	15	15
		50		15	15	15

[1] TRT1 = 200°C, 6.5 % RH (0 % MC), 93 kPa
TRT2 = 90°C, 95 % RH (17 % MC), 93 kPa
TRT3 = 140°C, 62 % RH (12 % MC), 223.4 kPa

[2] Zero percent strain refers to the “uncompressed” specimen type as defined in Table 3.1

[3] Uncompressed specimens underwent the same environmental treatments as their densified counterparts.

Table 3.3 Average data for specific gravity based on the moisture content (control samples)[1].

SPM[2]	**0.57** [0]	**0.55** [11.6]
YPM(4mm)[3]	**0.61** [0]	**0.58** [11.0]
YPM(3mm)[4]	**0.61** [0]	**0.58** [10.8]
YPJ[5]	**0.51** [0]	**0.50** [10.9]

[1] MC (%) is given in brackets

[2] SPM refers to southern pine (mature)

[3] YPM(4mm) refers to yellow-poplar (mature), 4 mm in thickness

[4] YPM(3mm) refers to yellow-poplar (mature), 3 mm in thickness

[5] YPJ refers to yellow-poplar (juvenile)

Table 3.4 Average data for ovendry specific gravity before (G_{orig}) and after (G) each densification treatment and for the change in specific gravity (ΔG).

Species/Type	**Treatment**	**Strain, %**	**Specific gravity**		**ΔG**
			$G_{,\ orig}$	G	
SPM	Control	0	0.57	0.57	0
	TRT1	0	0.57	0.57	0
		50	0.57	1.03	0.81
	TRT2	0	0.56	0.56	0
		50	0.56	1.06	0.89
	TRT3	0	0.60	0.60	0
		50	0.60	1.12	0.87
YPJ	Control	0	0.51	0.51	0
	TRT1	0	0.51	0.51	0
		50	0.51	0.97	0.90
	TRT2	0	0.51	0.51	0
		50	0.51	0.94	0.84
	TRT3	0	0.52	0.52	0
		50	0.52	0.97	0.87
YPM3mm	Control	0	0.61	0.61	0
	TRT1	0	0.61	0.61	0
		25	0.60	0.88	0.47
	TRT2	0	0.60	0.60	0
		25	0.60	0.91	0.52
	TRT3	0	0.61	0.61	0
		25	0.61	0.86	0.41
YPM4mm	Control	0	0.61	0.61	0
	TRT1	0	0.58	0.58	0
		50	0.59	1.03	0.75
	TRT2	0	0.60	0.60	0
		50	0.60	0.98	0.63
	TRT3	0	0.61	0.61	0
		50	0.62	1.05	0.69

Table 3.5 Average moisture content before and after each densification treatment, %.

Sample group	TRT 1		TRT 2		TRT3	
	Before	After	Before	After	Before	After
SPM_u[2]	0	0	20.5	11.6	12.0	8.1
SPM_c[3]	**0**	**0**	**20.5**	**12.7**	**12.0**	**1.3**
YPM(4mm)_u	0	0	21.2	11.9	11.4	4.4
YPM(4mm)_c	**0**	**0**	**21.6**	**12.8**	**11.5**	**1.2**
YPM(3mm)_u	0	0	21.5	9.5	11.2	0.9
YPM(3mm)_c	**0**	**0**	**21.0**	**11.0**	**11.3**	**0.9**
YPJ_u	0	0	18.9	10.8	11.3	5.0
YPJ_c	**0**	**0**	**18.8**	**11.2**	**11.3**	**6.1**

Table 3.6 Time used for each densification treatment, in minutes, and temperature inside the samples at each step of the densification process, °C.

Treatment # 1

Operation	SPM	YPM(3mm)	YPM(4mm)	YPJ
Heating the center of wood	25 min (196°C)	25 min (196°C)	25 min (202°C)	25 min (197°C)
Applying pressure on the samples to the desired level	1 min	1 min	1 min	1 min
Holding full temperature and pressure	5 min (199°C)	5 min (199°C)	5 min (204°C)	5 min (199°C)
Cooling, holding full pressure	27 min (130°C)	27 min (115°C)	27 min (120°C)	27 min (125°C)
Total time	58 min	58 min	58 min	58 min

Treatment # 2

Operation	SPM	YPM(3mm)	YPM(4mm)	YPJ
Heating the center of wood	185 min (88.6°C)	231 min (90°C)	272 min (90.1°C)	155 min (90°C)
Applying pressure on the samples to the desired level	1 min	1 min	1 min	1 min
Holding full temperature and pressure	5 min (89.4°C)	5 min (90.3°C)	5 min (91°C)	5 min (91°C)
Cooling, holding full pressure	50 min (40°C)	49 min (39.3°C)	48 min (40°C)	56 min (36°C)
Total time	241 min	286 min	326 min	217 min

Table 3.6 (cont.) Time used for each densification treatment, in minutes, and temperature inside the samples at the end of each step of the densification process, °C.

Treatment # 3

Operation	SPM	YPM(3mm)	YPM(4mm)	YPJ
Heating the center of wood	325 min (143°C)	273 min (143.5°C)	290 min (142°C)	313 min (142°C)
Applying pressure on the samples to the desired level	1 min	1 min	1 min	1 min
Holding full temperature and pressure	5 min (152°C)	5 min (154°C)	5 min (149°C)	5 min (148°C)
Cooling, holding full pressure	99 min (55.5°C)	101 min (51°C)	99 min (55°C)	98 min (41°C)
Total time	430 min	380 min	395 min	417 min

Table 3.7 Average moisture content of the tensile test specimens, %.

Sample group	Control	TRT 1	TRT 2	TRT 3
SPM[1]	11.6	–	–	–
SPM_u[2]	–	10.5	11.6	9.0
SPM_c[3]	–	9.9	11.2	8.8
YPM(4mm)	11.0	–	–	–
YPM(4mm)_u	–	9.9	11.0	9.1
YPM(4mm)_c	–	9.1	10.7	8.7
YPM(3mm)	10.8	–	–	–
YPM(3mm)_u	–	9.9	11.0	8.8
YPM(3mm)_c	–	9.5	10.7	8.7
YPJ	10.9	–	–	–
YPJ_u	–	9.6	10.7	8.6
YPJ_c	–	8.8	10.3	8.3

[1] control sample

[2] **u** refers to “uncompressed sample”

[3] **c** refers to “compressed sample”

Table 3.8 Average grain angle measured on two orthogonal planes in the narrowest portion of the tensile test specimens, α (degrees).

Sample group	Control	TRT 1	TRT 2	TRT 3
SPM[1]	2.4	–	–	–
SPM_u[2]	–	2.4	1.6	2.2
SPM_c[3]	–	1.6	2.2	2.1
YPM(4mm)	3.9	–	–	–
YPM(4mm)_u	–	3.4	3.8	3.6
YPM(4mm)_c	–	3.1	4.0	3.2
YPM(3mm)	3.6	–	–	–
YPM(3mm)_u	–	4.8	3.0	3.9
YPM(3mm)_c	–	3.1	3.0	3.9
YPJ	2.3	–	–	–
YPJ_u	–	2.2	1.9	1.8
YPJ_c	–	2.3	1.6	1.7

[1] control sample
[2] **u** refers to “uncompressed sample”
[3] **c** refers to “compressed sample”

Table 3.9 Mean and coefficient of variation (COV) for ultimate tensile stress and tensile modulus (adjusted for grain angle), and mean for ovendry specific gravity of the samples tested in tension parallel-to-grain.

Species	Type	Treatment	Strain	Ultimate stress, N/mm^2		Tensile modulus, N/mm^2		Specific	Sample
			%	Mean	COV (%)	Mean	COV (%)	gravity	size
Loblolly pine	Mature	Control	0	117	25.7	21,580	19.0	0.57	15
		TRT 1	0	108	23.8	26,890	19.2	0.57	15
			50	124	18.7	34,850	12.0	1.03	15
		TRT 2	0	117	21.2	25,130	20.7	0.56	15
			50	204	28.3	33,140	31.0	1.06	15
		TRT3	0	91	30.2	25,230	20.6	0.60	15
			50	157	31.0	40,890	16.6	1.12	15
Yellow-poplar	Juvenile	Control	0	127	11.3	15,300	12.6	0.51	15
		TRT 1	0	127	7.8	16,250	19.1	0.51	15
			50	159	11.2	27,070	18.7	0.97	15
		TRT 2	0	121	7.5	17,320	15.2	0.51	15
			50	197	12.5	22,810	21.5	0.94	15
		TRT3	0	131	8.2	19,390	13.1	0.52	15
			50	210	14.7	29,430	16.2	0.97	15
Yellow-poplar 3mm	Mature	Control	0	142	19.2	22,290	12.3	0.61	15
		TRT 1	0	122	23.7	20,780	23.1	0.61	15
			25	159	16.4	27,080	16.1	0.88	15
		TRT 2	0	141	18.7	26,140	10.3	0.60	15
			25	211	18.2	31,080	22.3	0.91	15
		TRT3	0	135	18.8	24,570	11.4	0.61	15
			25	157	27.6	28,210	15.1	0.86	15
Yellow-poplar 4mm	Mature	Control	0	127	18.5	19,920	16.9	0.61	15
		TRT 1	0	125	14.5	21,020	16.7	0.58	15
			50	159	20.3	31,560	18.6	1.03	15
		TRT 2	0	135	21.2	24,350	12.5	0.60	15
			50	181	29.0	27,810	27.4	0.98	15
		TRT3	0	128	19.1	25,410	11.1	0.61	15
			50	194	25.6	35,550	19.5	1.05	15

Table 3.10 Mean and coefficient of variation (COV) for specific ultimate tensile stress and specific tensile modulus, and mean for ovendry specific gravity of the samples tested in tension parallel-to-grain.

Species	Type	Treatment	Strain %	Specific[a] ultimate stress, N/mm^2		Specific[b] tensile modulus, N/mm^2		Specific gravity	Sample size
				Mean	COV (%)	Mean	COV (%)		
Loblolly pine	Mature	Control	0	205	26.2	37,490	17.6	0.57	15
		TRT 1	0	190	24.0	46,840	15.6	0.57	15
			50	121	20.4	33,740	11.1	1.03	15
		TRT 2	0	211	20.3	45,340	19.3	0.56	15
			50	191	26.2	31,060	30.6	1.06	15
		TRT3	0	153	32.5	42,070	19.9	0.60	15
			50	140	30.5	36,440	17.3	1.12	15
Yellow-poplar	Juvenile	Control	0	248	9.1	29,940	16.0	0.51	15
		TRT 1	0	249	6.3	31,960	19.7	0.51	15
			50	164	10.8	27,930	17.5	0.97	15
		TRT 2	0	238	6.4	34,180	17.2	0.51	15
			50	211	12.3	24,460	22.7	0.94	15
		TRT3	0	253	7.0	37,330	13.8	0.52	15
			50	216	11.2	30,350	15.1	0.97	15
Yellow-poplar 3mm	Mature	Control	0	235	21.2	36,690	13.3	0.61	15
		TRT 1	0	200	24.1	33,930	22.4	0.61	15
			25	181	18.1	30,800	18.2	0.88	15
		TRT 2	0	238	20.2	44,130	13.3	0.60	15
			25	234	18.2	34,370	22.8	0.91	15
		TRT3	0	222	17.4	40,640	11.0	0.61	15
			25	181	26.9	32,560	13.1	0.86	15
Yellow-poplar 4mm	Mature	Control	0	209	19.4	32,740	16.4	0.61	15
		TRT 1	0	214	16.6	36,060	17.2	0.58	15
			50	155	19.8	30,720	19.3	1.03	15
		TRT 2	0	226	22.8	40,810	14.1	0.60	15
			50	184	27.8	28,300	25.4	0.98	15
		TRT3	0	211	20.4	41,790	12.4	0.61	15
			50	186	25.1	33,930	17.4	1.05	15

[a] Specific ultimate stress was obtained by dividing ultimate stress by ovendry specific gravity.

[b] Specific tensile modulus was obtained by dividing tensile modulus by ovendry specific gravity.

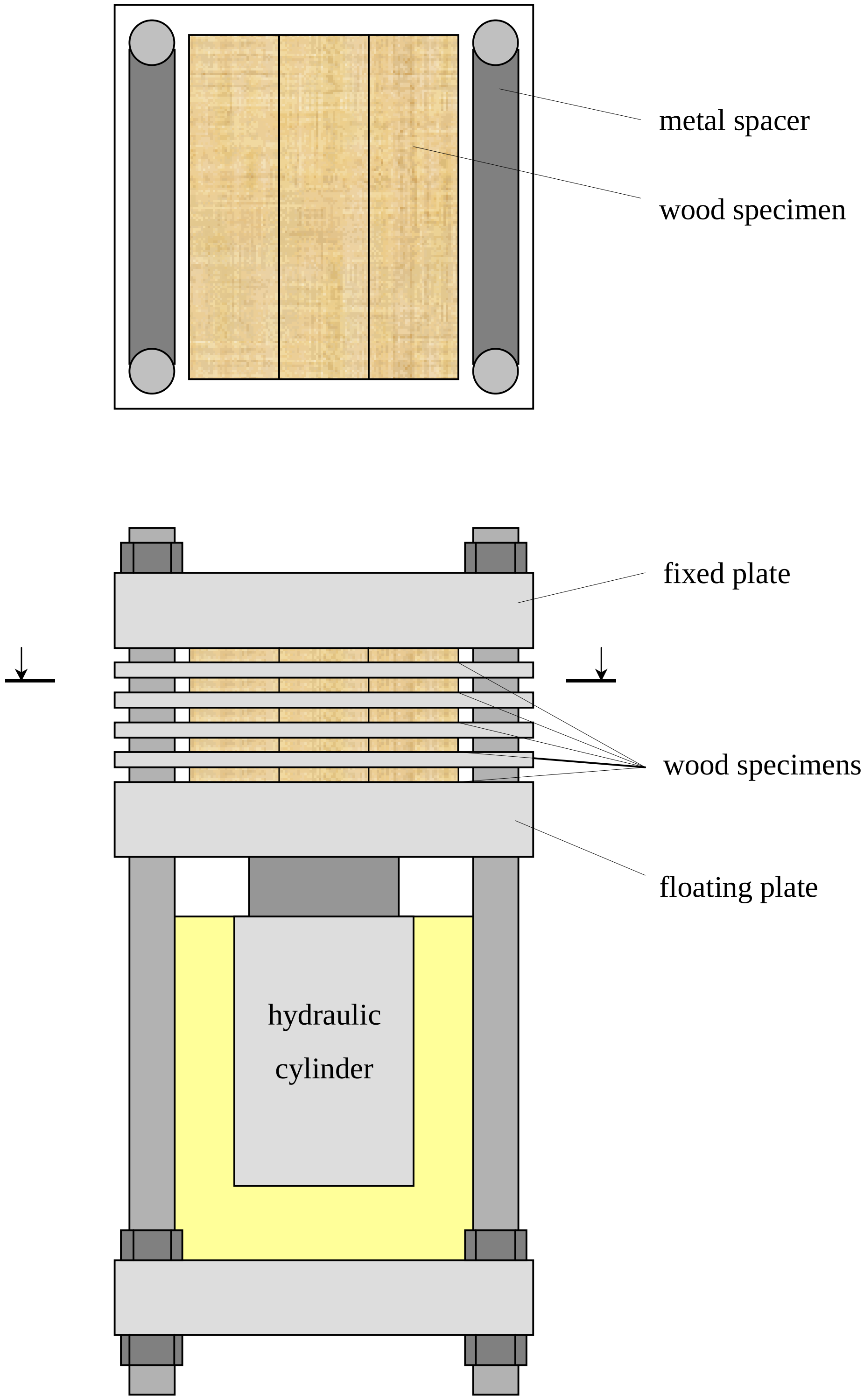
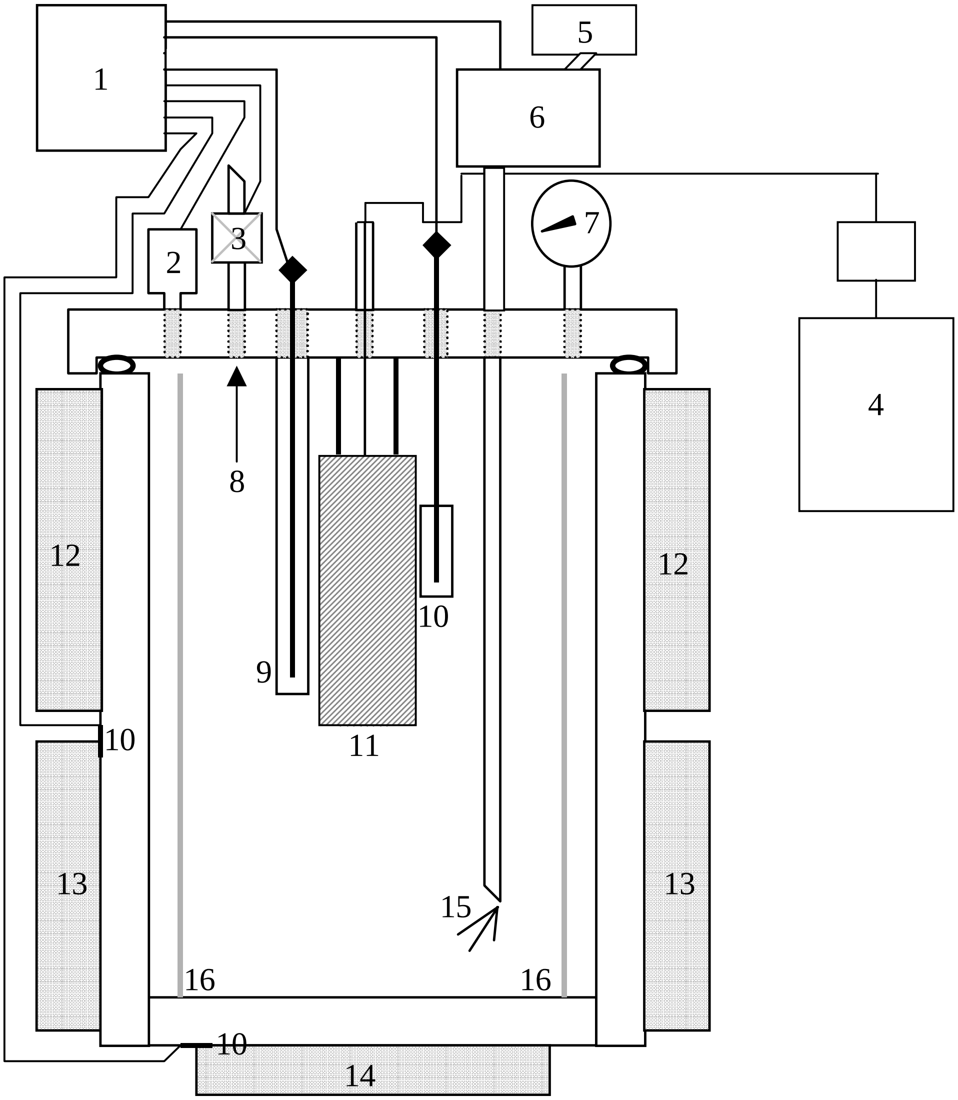


Figure 3.8 Hydraulic press



1 - Computer control and acquisition unit
2 - Pressure transducer
3 - Solenoid valve
4 - Hydraulic power unit with flow control valve
5 - Make-up water reservoir
6 - High pressure water pump
7 - Pressure gauge
8 - Venting port
9 - Thermocouple well
10 - Control thermocouple
11 - Hydraulic press
12 - Secondary heating element
13 - Primary heating element
14 - Tertiary heating element
15 - Water injection port
16 - Radiation shield

Figure 3.9 A diagram of the pressurized sorption apparatus (adopted from Lenth, 1999).

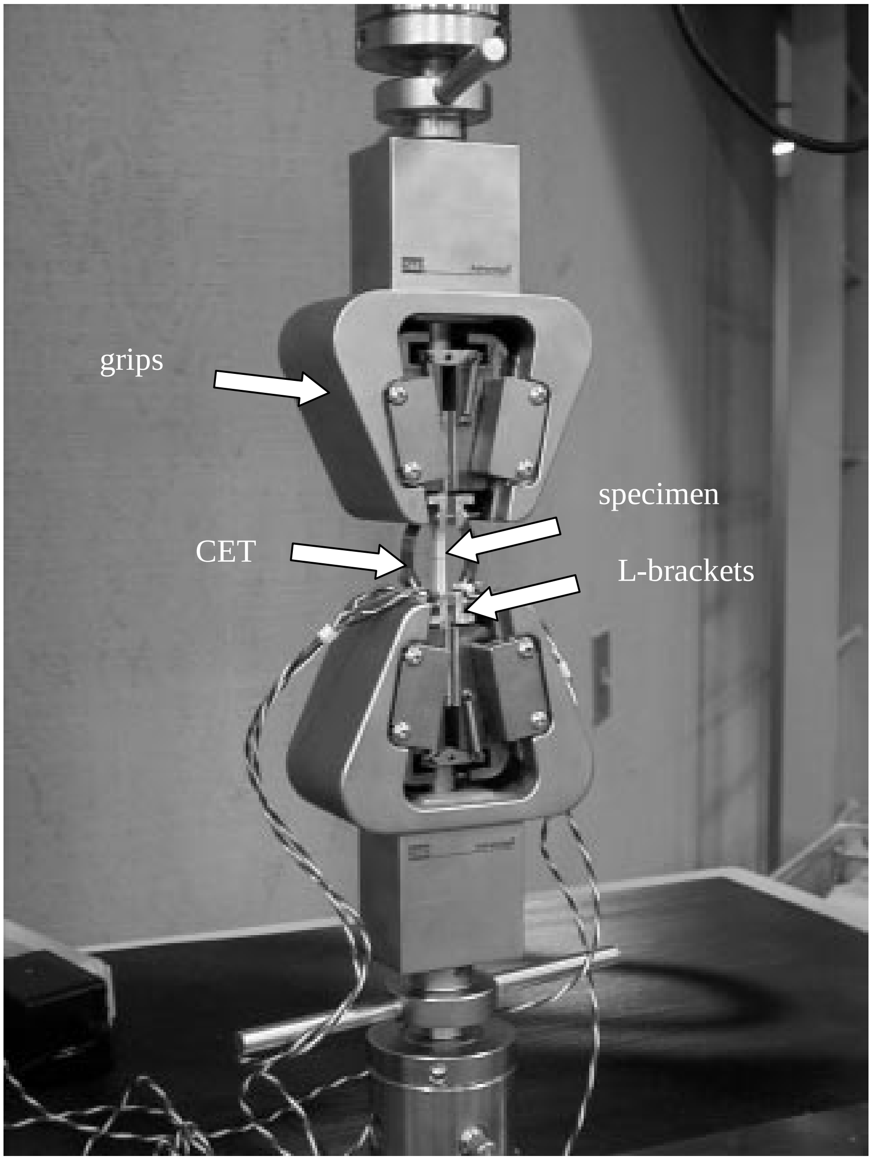


Figure 3.10 Tensile test setup.

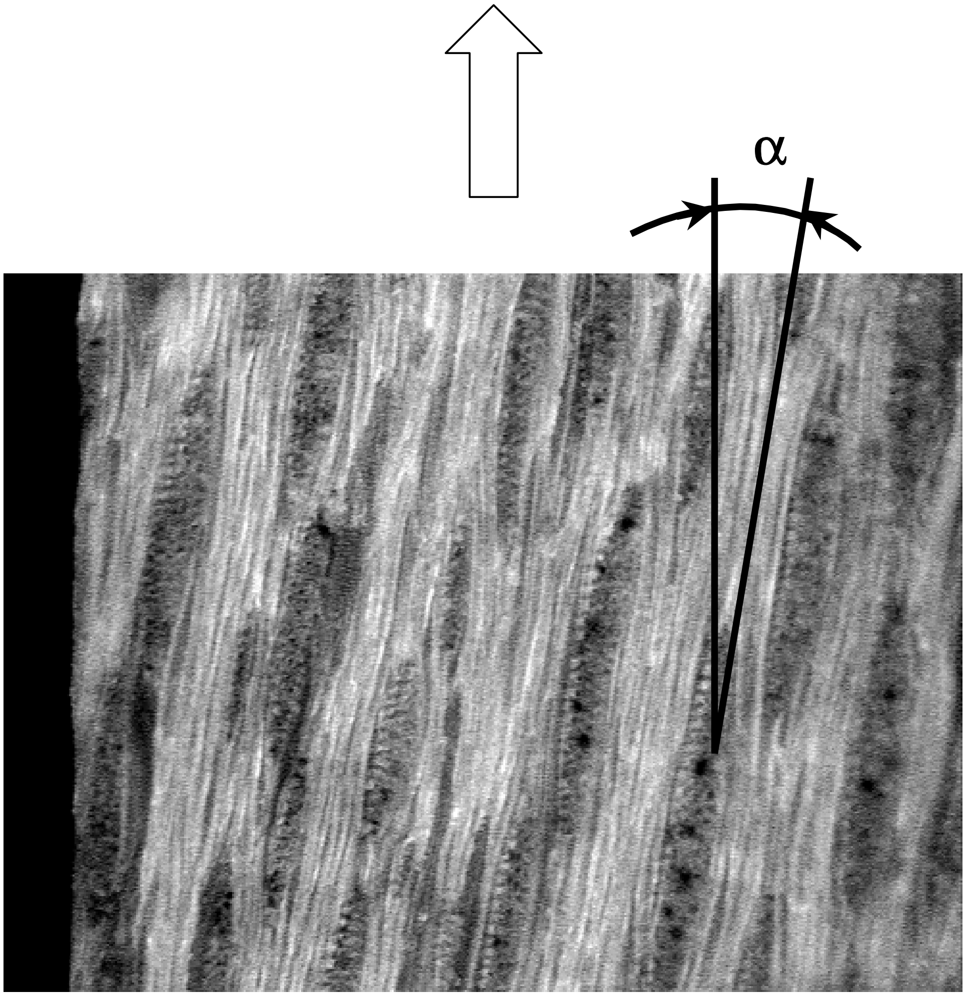


Figure 3.11 An image (150 x) of the tensile test specimen illustrating measurement of the grain angle, α, between direction of load and longitudinal direction of wood.

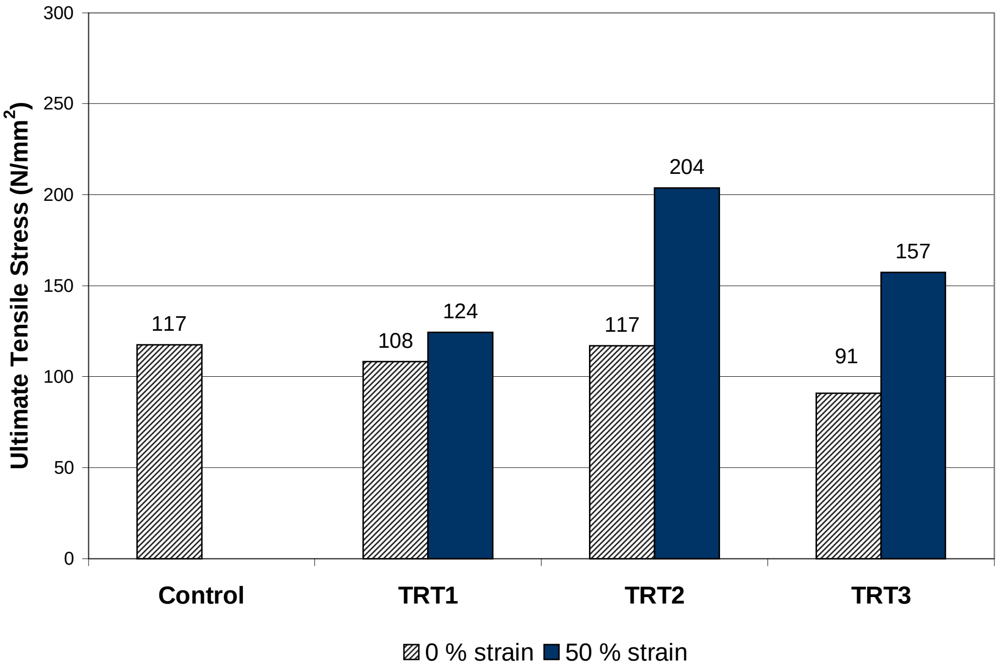


Figure 3.12 Average ultimate tensile stress, N/mm^2, of mature southern pine samples tested in tension parallel-to-grain.

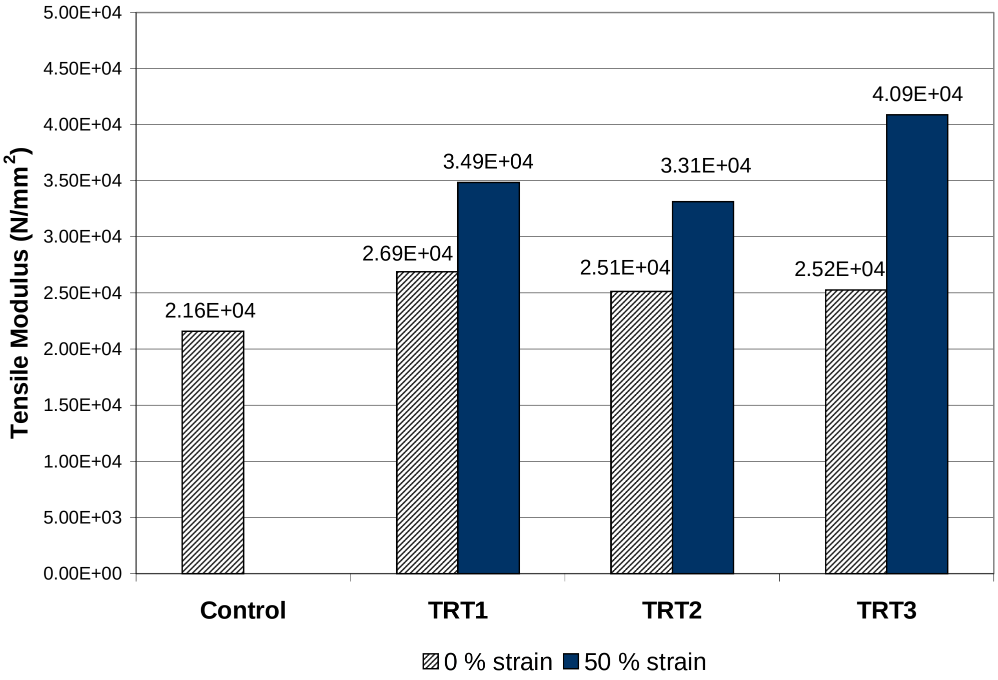


Figure 3.13 Average tensile modulus, N/mm^2, of mature southern pine samples tested in tension parallel-to-grain.

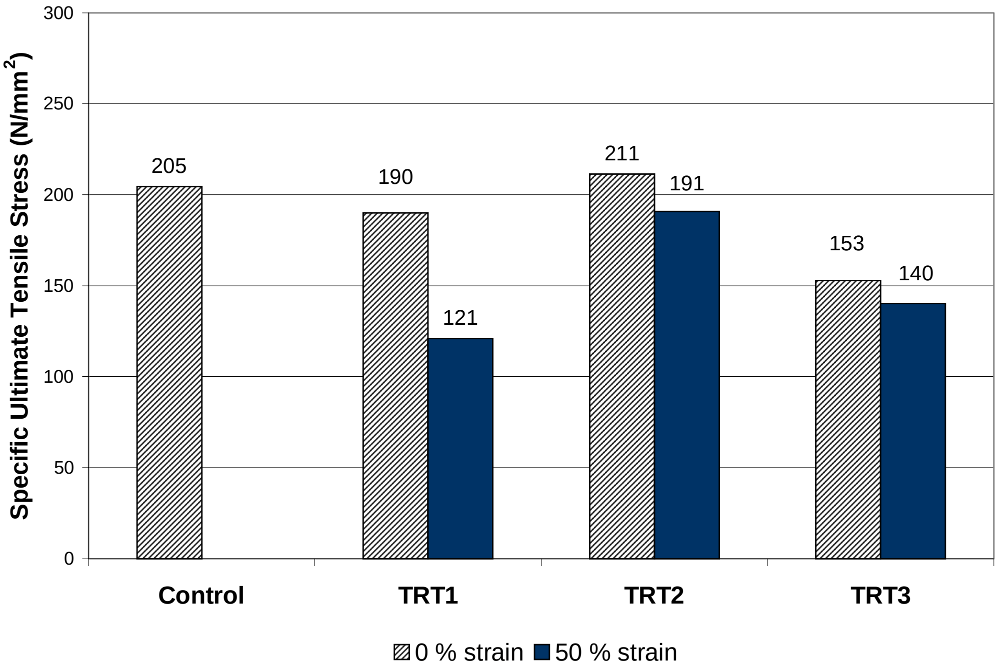


Figure 3.14 Average specific ultimate tensile stress, N/mm^2, of mature southern pine samples tested in tension parallel-to-grain.

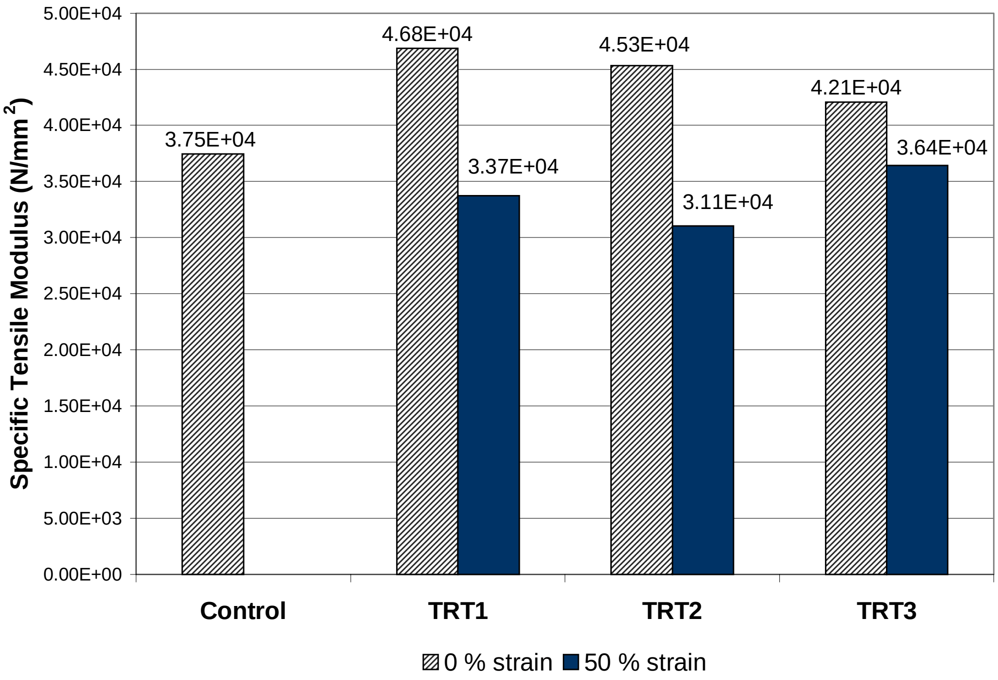


Figure 3.15 Average specific tensile modulus, N/mm^2, of mature southern pine samples tested in tension parallel-to-grain.

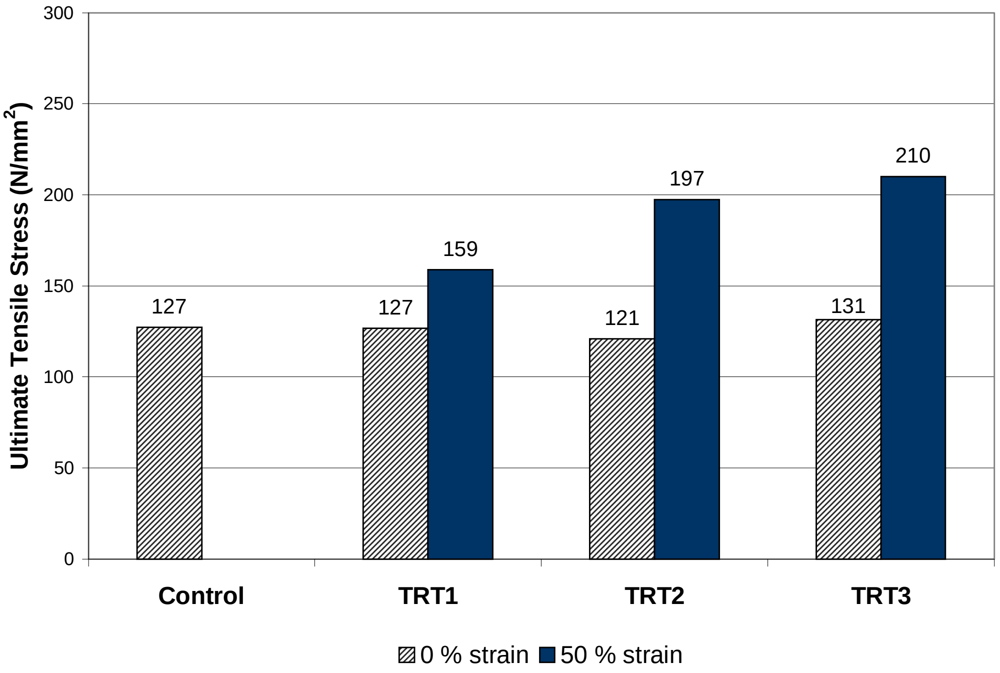


Figure 3.16 Average ultimate tensile stress, N/mm^2, of juvenile yellow-poplar samples tested in tension parallel-to-grain.

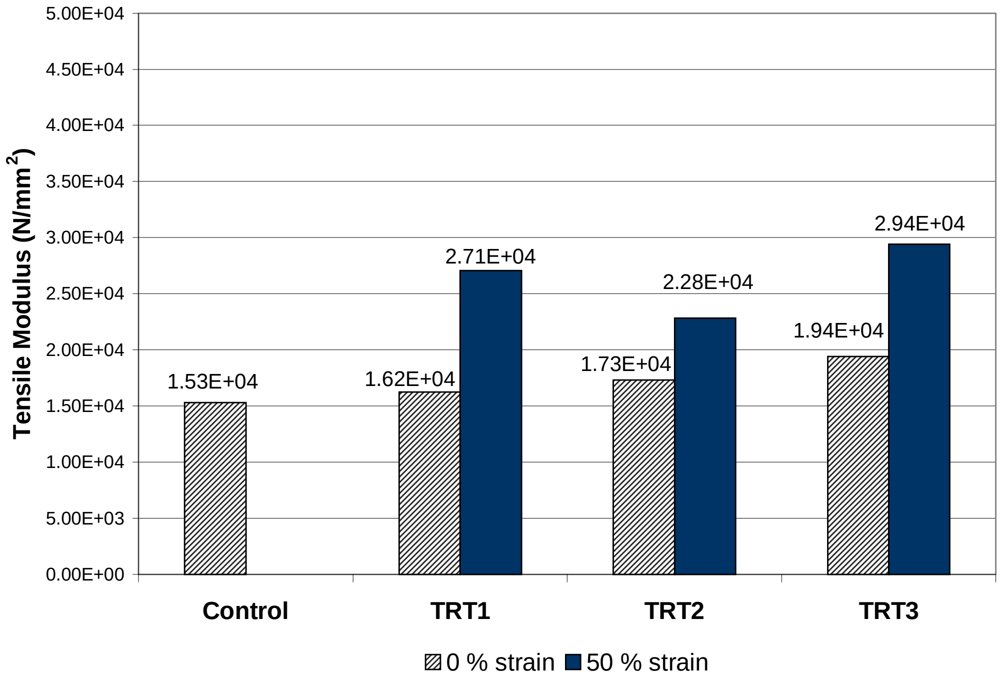


Figure 3.17 Average tensile modulus, N/mm^2, of juvenile yellow-poplar samples tested in tension parallel-to-grain.

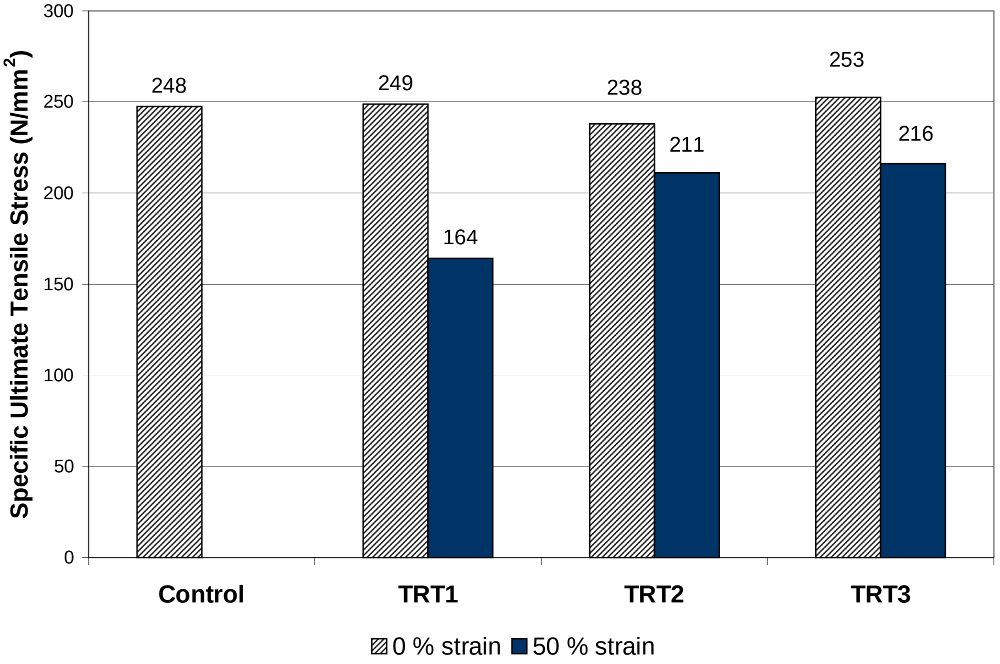


Figure 3.18 Average specific ultimate tensile stress, N/mm^2, of juvenile yellow-poplar samples tested in tension parallel-to-grain.

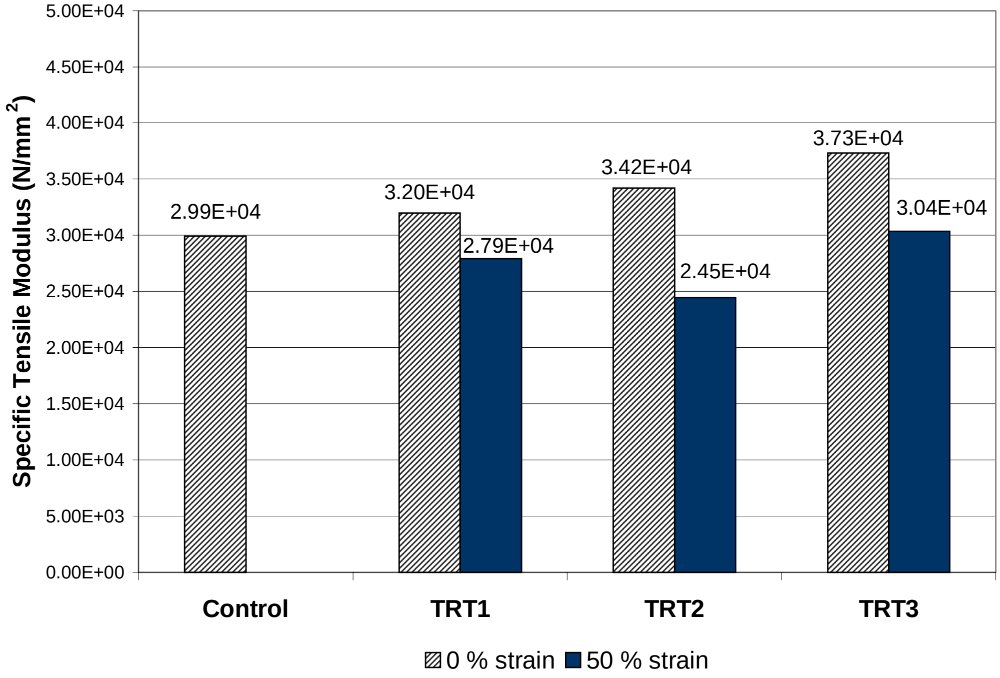


Figure 3.19 Average specific tensile modulus, N/mm^2, of juvenile yellow-poplar samples tested in tension parallel-to-grain.

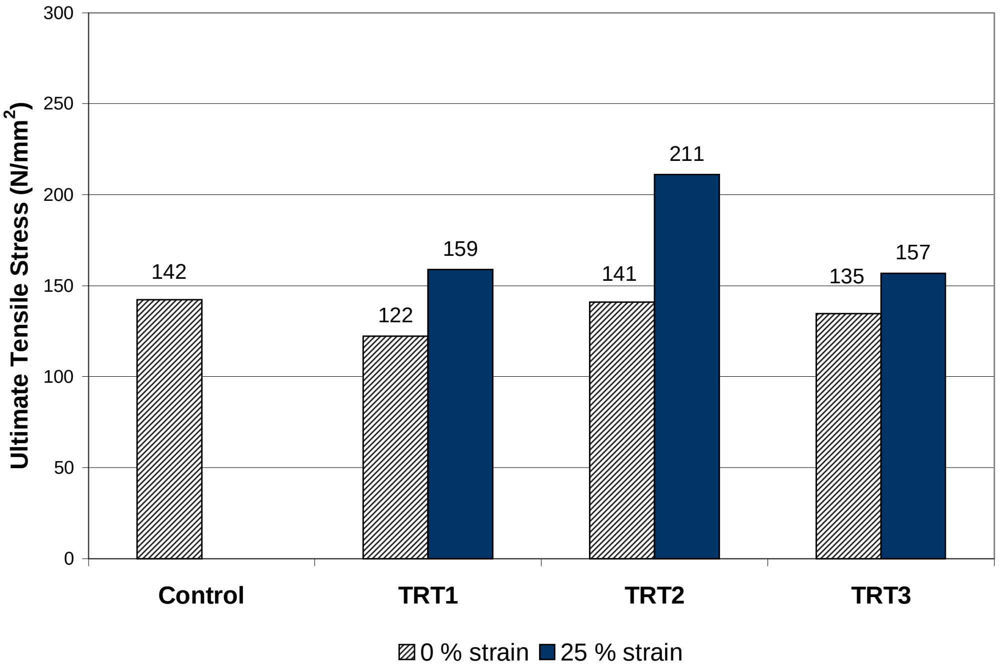


Figure 3.20 Average ultimate tensile stress, N/mm^2, of mature yellow-poplar samples (3mm) tested in tension parallel-to-grain.

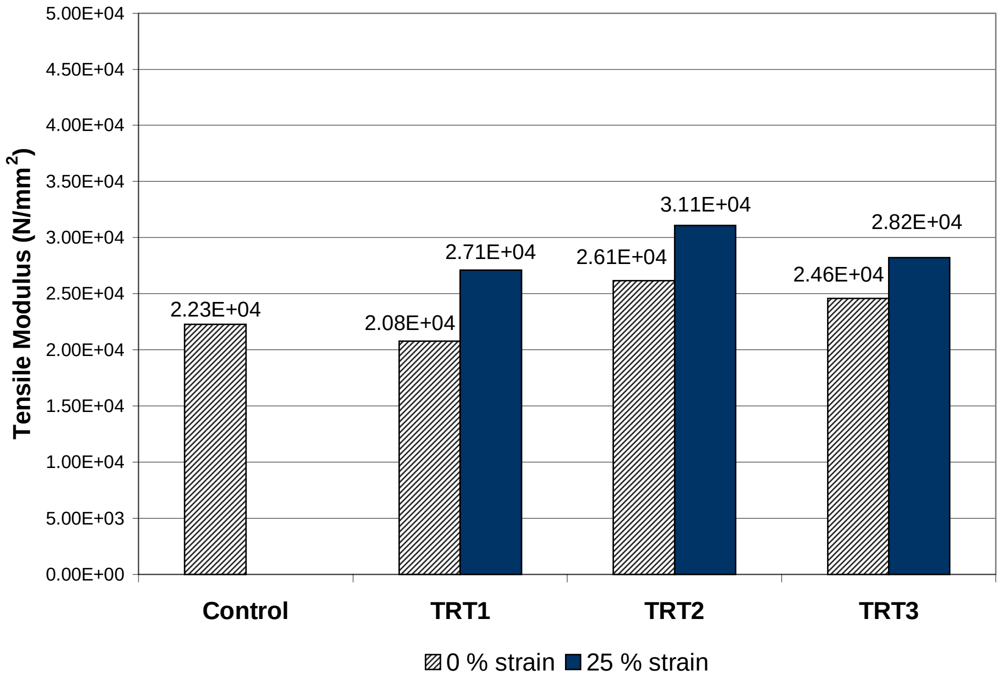


Figure 3.21 Average tensile modulus, N/mm^2, of mature yellow-poplar samples (3mm) tested in tension parallel-to-grain.

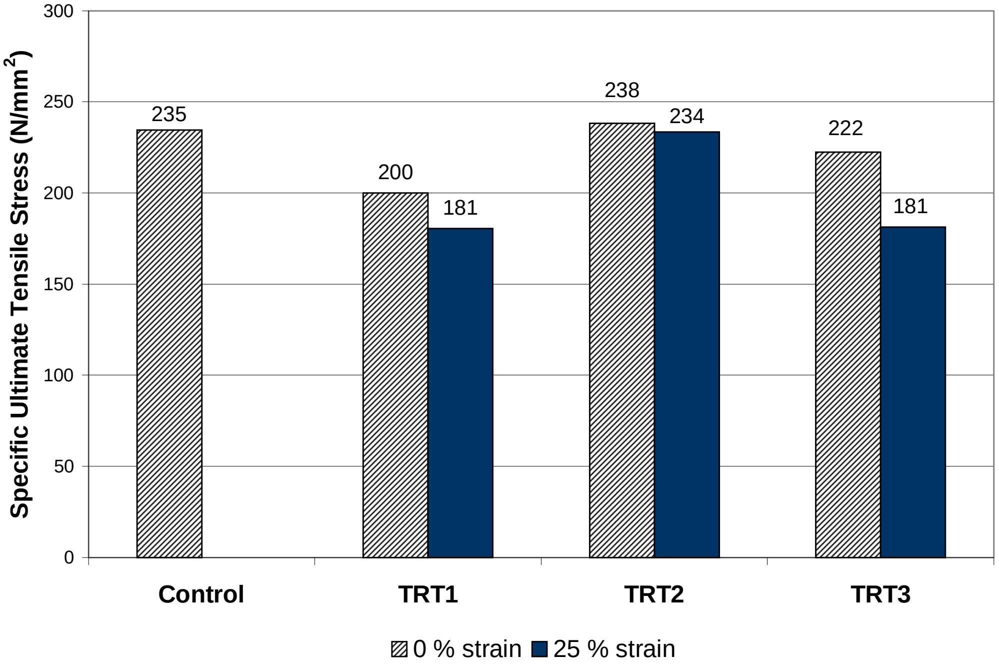


Figure 3.22 Average specific ultimate tensile stress, N/mm^2, of mature yellow-poplar samples (3mm) tested in tension parallel-to-grain.

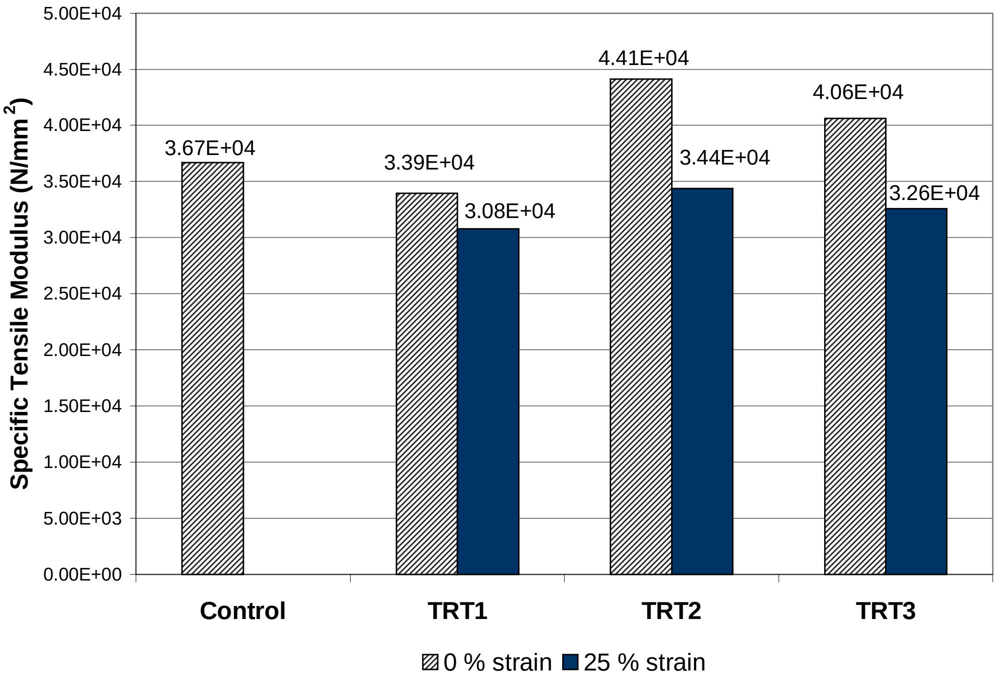


Figure 3.23 Average specific tensile modulus, N/mm^2, of mature yellow-poplar samples (3mm) tested in tension parallel-to-grain.

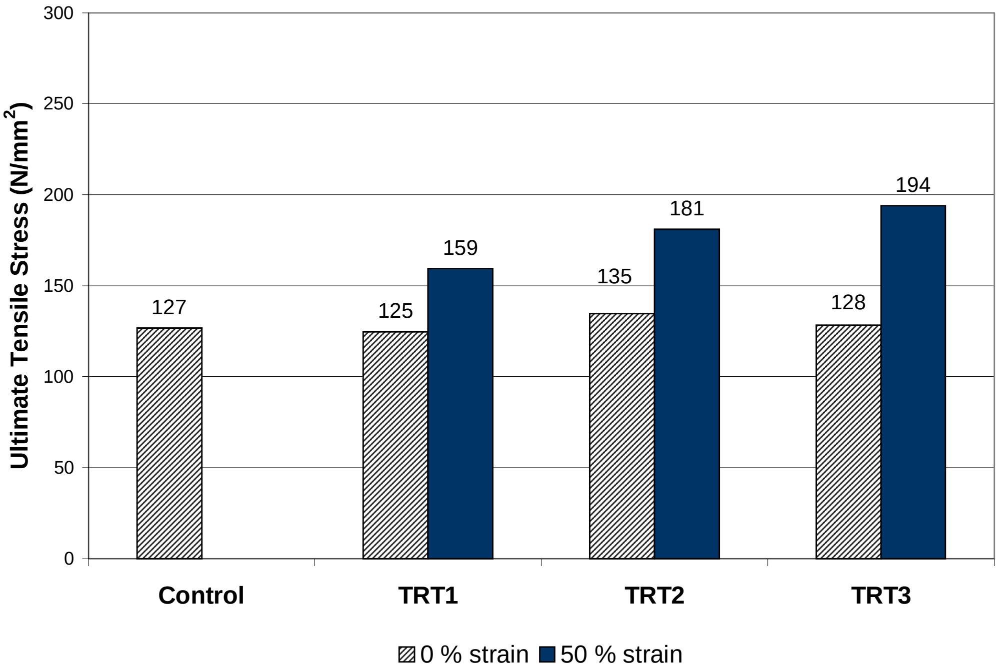


Figure 3.24 Average ultimate tensile stress, N/mm^2, of mature yellow-poplar samples (4mm) tested in tension parallel-to-grain.

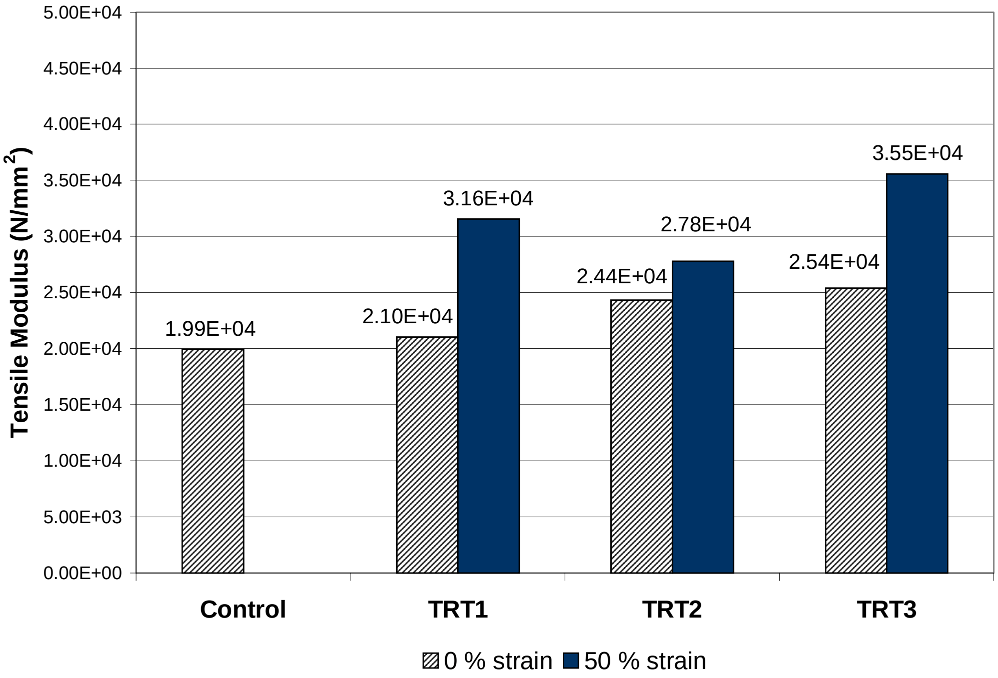


Figure 3.25 Average tensile modulus, N/mm^2, of mature yellow-poplar samples (4mm) tested in tension parallel-to-grain.

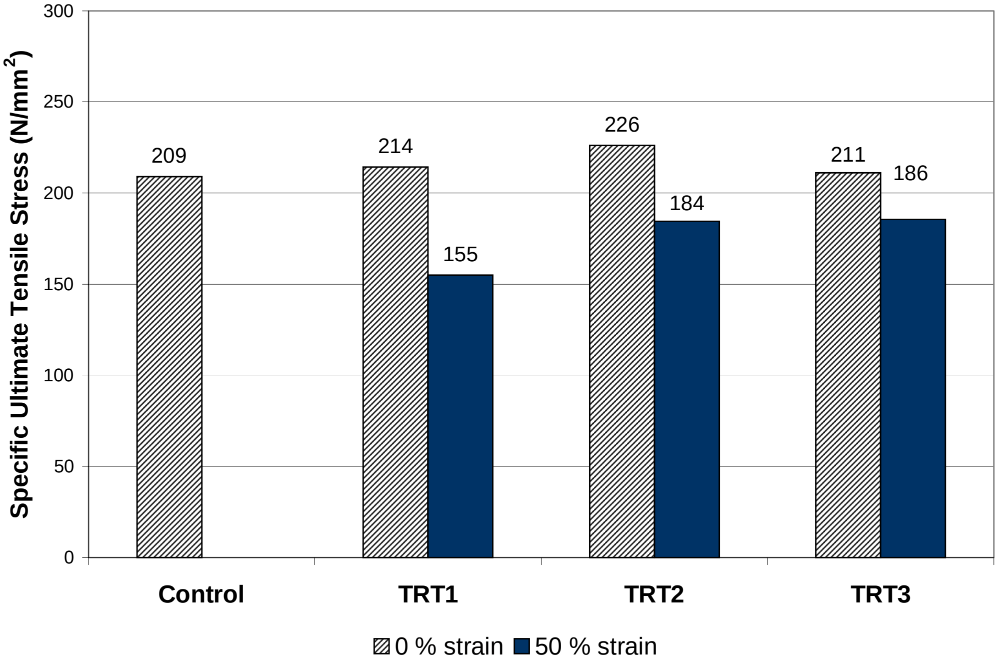


Figure 3.26 Average specific ultimate tensile stress, N/mm^2, of mature yellow-poplar samples (4mm) tested in tension parallel-to-grain.

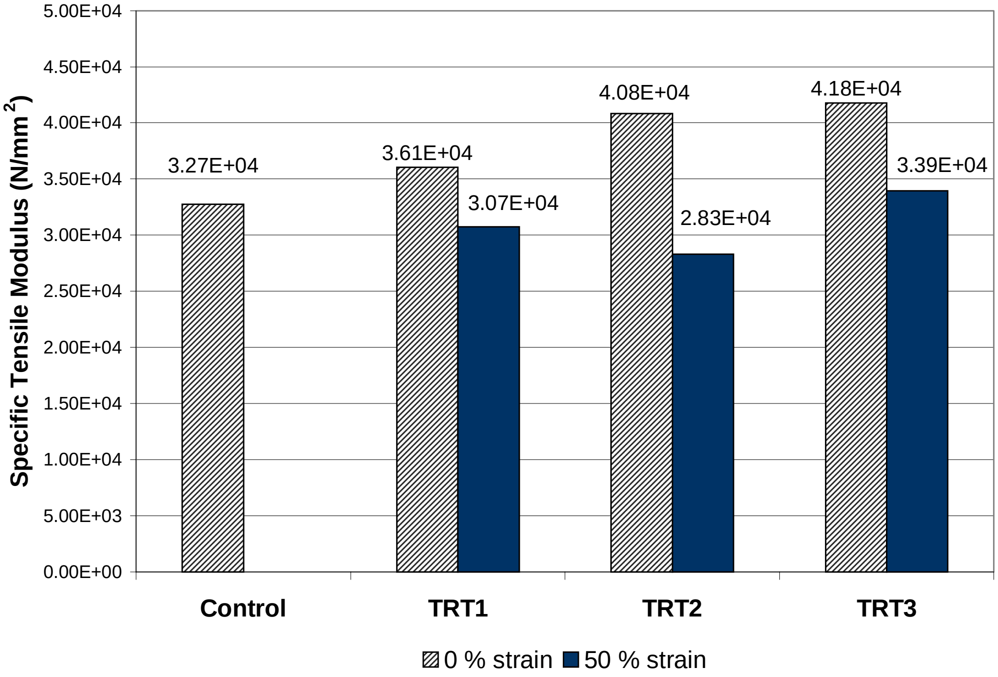


Figure 3.27 Average specific tensile modulus, N/mm^2, of mature yellow-poplar samples (4mm) tested in tension parallel-to-grain.

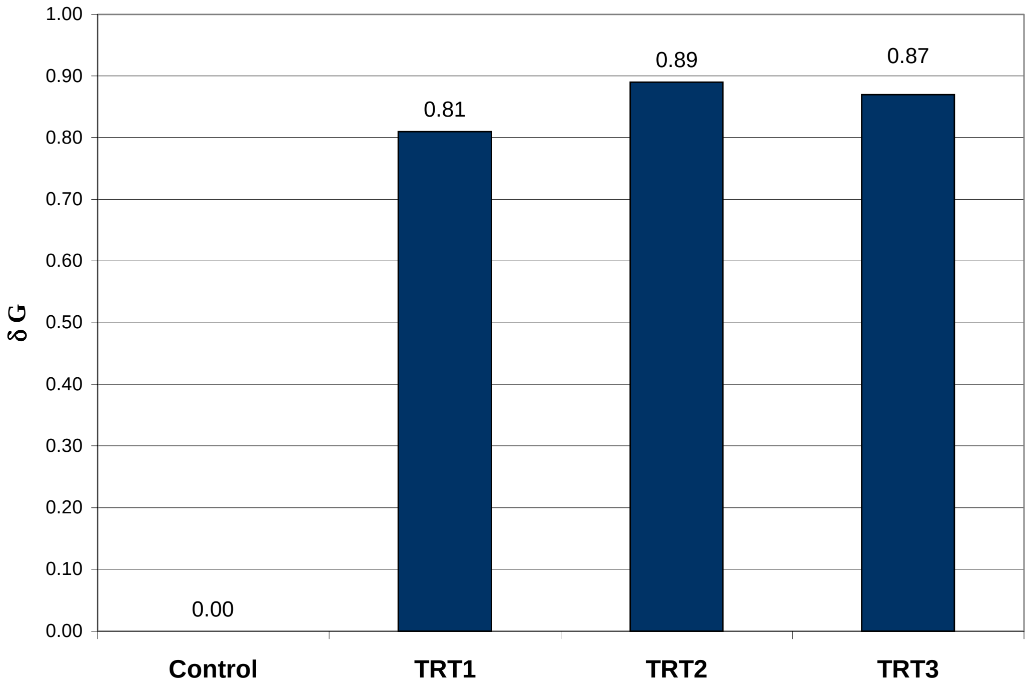


Figure 3.28 Average change in specific gravity of mature southern pine specimens after all densification treatments.

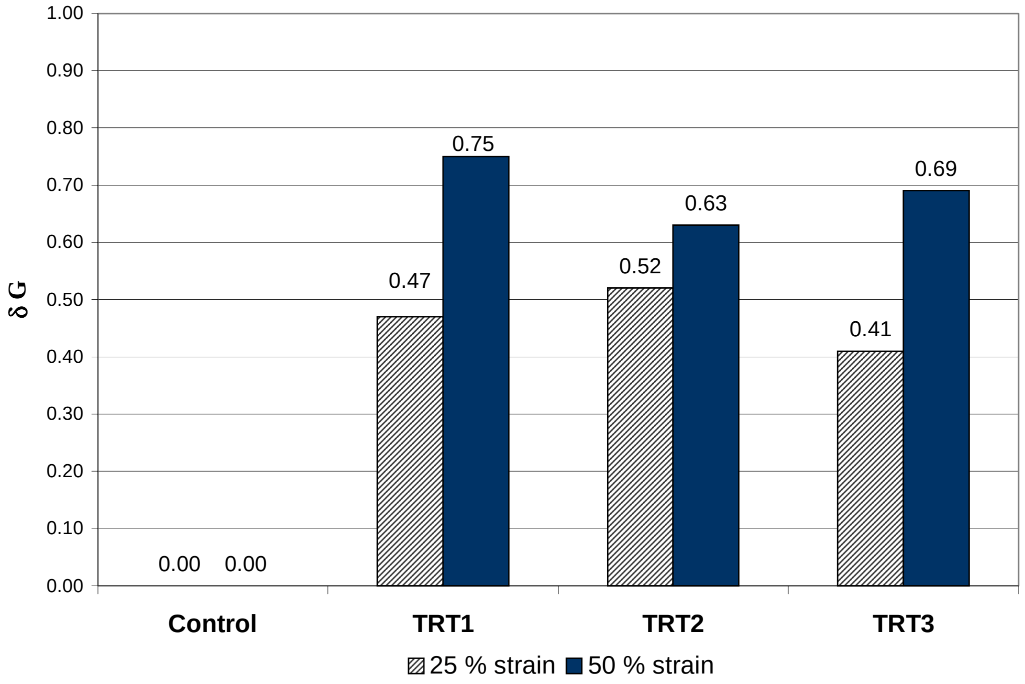


Figure 3.29 Average change in specific gravity of mature yellow-poplar specimens after all densification treatments.

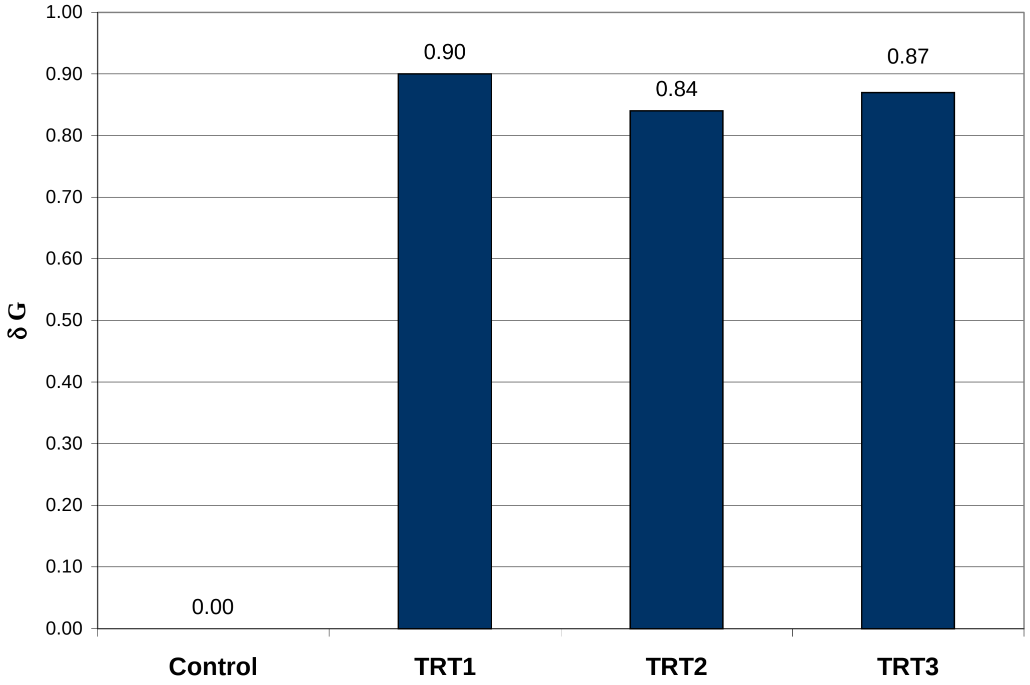


Figure 3.30 Average change in specific gravity of juvenile yellow-poplar specimens after all densification treatments.