

Effect of Minimum Suppression and Maximum Release Years on Compression Parallel to Grain Strength and Specific Gravity for Small-sized Yellow-poplar (*Liriodendron tulipifera* L.) Specimens

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ABSTRACT

Several researchers have concluded that there is little or no relationship between specific gravity and ring width or growth rate in yellow-poplar (*Liriodendron tulipifera* L.). Because most mechanical properties of wood are also closely related to specific gravity, it would thus be of interest to learn how minimum suppression and maximum release years—evidence that can be extracted from radial growth patterns based on a modified radial growth averaging (RGA) technique—influence the compression parallel to grain strength and specific gravity of wood.

This study is designed to evaluate the effects of growth suppression and release on ultimate crushing stress and specific gravity for small-sized yellow-poplar specimens. Additionally, the relationship between specific gravity and ultimate crushing stress is investigated.

Twenty-three yellow-poplar cores were examined for their growth ring widths. Minimum suppression and maximum release years were identified based on the modified RGA criteria method. From each increment core, three $1 \times 1 \times 4$ mm specimens from both minimum suppression and maximum release years were tested for their ultimate crushing stresses using a micro-mechanical test system. The specific gravity of each specimen was also recorded. These data were analyzed using a paired samples *t* test and a simple linear regression.

The results indicate that the mean ultimate crushing stress and specific gravity of maximum release years were significantly higher than that of minimum suppression years.

Furthermore, the ultimate crushing stress was linearly related to the specific gravity of the specimens.

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Chapter 1 Introduction

1.1 Justification

The relationship between growth rate and wood properties has been investigated by many researchers. Previous investigations have concentrated almost entirely on the affect of growth rate on *specific gravity* (SG) and cell characteristics. Nevertheless, a significant volume of the total wood production is used structurally. In this application, wood is often loaded along the grain; therefore, the axial modulus and *ultimate crushing strength* (σ_u) are important. To provide data regarding the resistance of wood to such axial loads, the compression parallel to grain test is used. However, few studies have explored the influence of growth rate on the mechanical properties of wood. Understanding this relationship is thus important to maximize wood production without impairing its mechanical properties.

The most widely used technique to measure growth rate of a tree is to measure tree ring widths. Tree ring widths are influenced by aging of the tree, thus reducing their effectiveness to determine the growth rate. Above all, most reports conclude that there is little or no relationship between growth rate and specific gravity in diffuse-porous species. Additionally, inconsistent results exist with regard to the effect of growth rate changes on cell length in both conifers and hardwoods.

The *radial growth averaging* (RGA) criteria method is a quantitative, dendroecological technique used for deriving past canopy disturbances. This technique relies on the percent increase or decrease in the running average of tree ring widths over a predetermined period to identify potential growth response—release and suppression years. Release years also convey an idea of periods of increasing tree-ring growth as opposed to suppression years, which are defined as periods of reductions in radial growth. Minimum suppression and maximum release years are introduced and studied as the important events for further investigations. It would thus be of interest to learn how the modified RGA technique may be applied to the study of growth rate of trees.

The study of intra-ring compression strength parallel to grain for small-sized samples (a few cubic millimeters in volume) has proved to be advantageous. These very small specimens, derived from increment cores, allow assessment of wood and fiber properties in a particular year of interest without destroying the trees. To date, this area of work has not been widely investigated or reported.

1.2 Technical objectives

The primary objective of this study is to determine the influence of minimum suppression and maximum release years on ultimate crushing stress and specific gravity of small-sized yellow-poplar (*Liriodendron tulipifera* L.) specimens collected from natural to medium management intensity. The second aim is to determine the relationship between specific gravity and ultimate crushing stress for the specimens.

Chapter 2 Literature Review

2.1 Characteristics of yellow-poplar (*Liriodendron tulipifera* L.)

The demand for less expensive hardwood roundwood has increased in recent years (Luppold et al. 2002). This increased demand can be attributed to increasing volumes of hardwood growing stock and sawtimber, declining volumes of southern softwood growing stock, reduction in the sale of softwood timber from National Forests, and rising demand for homes and paper.

Yellow-poplar is a commercially important diffuse-porous hardwood species in the Eastern United States. As with other diffuse-porous hardwoods, yellow-poplar exhibits little variation in pore size on the transverse plane throughout the growth ring (see Figure 2.1). Live volume of the trees in the U.S. forests was estimated to be around 660 million cubic meters (accounting for 2.6% of all volume) and ranked ninth in 2002 (FIA 2002). It is a moderate- to rapid-growing species and generally selective in soil and moisture requirements: deep, fertile, moderately moist, well-drained, and loose-textured soils. Moreover, its optimum growth develops where rainfall is well distributed over a long growing season, especially if rainfall is adequate during the early growing season (Beck and Della-Bianca 1981).

The wood is straight grained, uniform in texture and moderate to light weight. Yellow-poplar has the reputation of being one of the easiest of all hardwoods to work with hand and machine tools. Their trunks are very straight, tall, slightly tapering, and clear of lower branches

for a considerable height from the ground. The trees generally do not form double or multiple leaders (Gilman and Watson 1993).

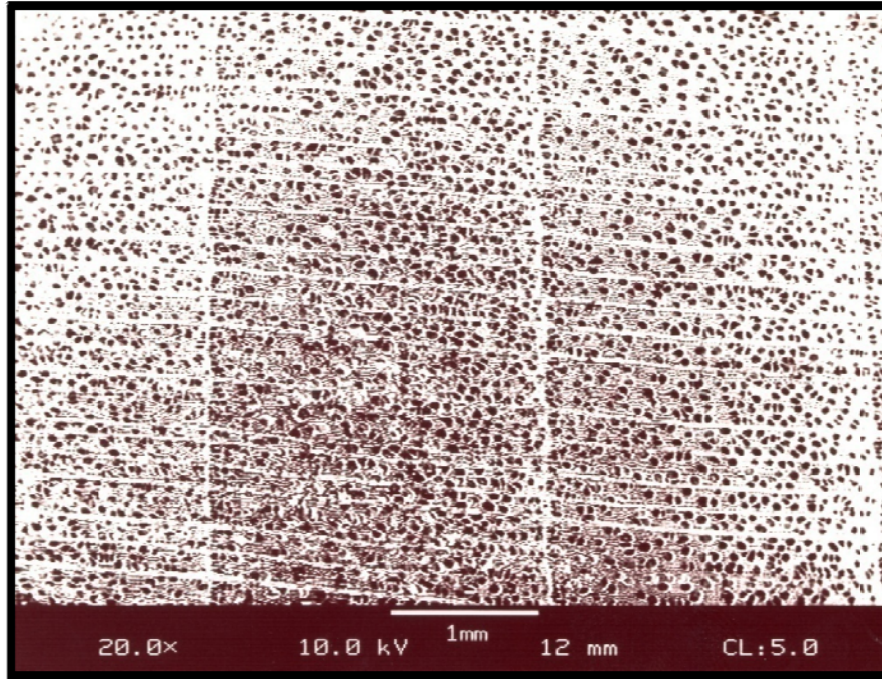


Figure 2.1. A transverse section of the yellow-poplar (*Liriodendron tulipifera* L.)

The vessels are uniform in size and evenly distributed throughout the growth ring. ($\times 20$)

Scanning electron micrograph by Carlile Price, Quantitative Wood Anatomy Laboratory, Virginia Tech

On good sites, yellow-poplar may sustain a height growth of almost 46 cm per year to an age of 100 years and a diameter growth of about 6.4 mm per year in unthinned stands (Hicks 1998). Yellow-poplar trees typically reach heights of 49 m with diameters of 2.4 m. Good second-growth trees may reach heights of over 37 m with a diameter of 46–69 cm in 50 to 60 years (Olson 1969).

Besides being site-sensitive, yellow-poplar is classified as shade intolerant and requires full sunlight to grow well, thus being prone to lose its lower branches in closed stands with live crown developing in the upper part of the bole. Yellow-poplar seedlings grow much faster if

free of all overhead cover. According to Williams (1964), five-year-old yellow-poplar trees on release plots were three times as tall as those not released. The tree is one of the least susceptible of the hardwoods to pests and disease, but prone to fire damage (Hicks 1998). Yellow-poplar responds well to silvicultural treatments: release, thinning, irrigation, and fertilization. Thinning, for instance, results in markedly higher rates of diameter growth and higher yield of high-value products (Beck and Della-Bianca 1981). Fertilization is also responsible for significant diameter and height growth responses (Bollig et al. 1993). By combining irrigation and fertilization, there is a 30% increase in radial growth without any apparent effect on specific gravity, extractive, or fiber length (Thor and Core 1977).

Demand for yellow-poplar stumpage has increased because it is a major raw material for *oriented strand board* (OSB), laminated veneer lumber, and millwork (Luppold et al. 2002). Additionally, its use for construction grade lumber is also increasing because lumber drying technology has improved the quality of yellow-poplar boards (Johnson et al. 1997). In brief, because of its good form, large size, rapid growth, availability, vigorous response to intensive management, high quality, and good working quality, yellow-poplar is a favored species among wood-using industries (Vick 1985).

The increasing need and future use for fast-growing, young trees is inevitable. Forest management is also moving toward enhanced growth and shorter rotation (Barnett and Jeronimidis 2003). Thus, this type of wood is becoming much more common and will have to be accepted. On the more productive sites, yellow-poplar can achieve growth rates similar to those of loblolly pine (*Pinus taeda* L.) with height growth rates of more than 1.22 m per year and diameter growth rates of 12.7 mm per year following 18 years (Clatterbuck 2003). Wood produced from these trees generally will have wider growth rings than natural growth; therefore,

wood properties are often affected. Still, the underlying assumption is that rapid growth and shorter rotations resulting from forest management will not influence the quality of wood (Zobel and van Buijtenen 1989).

2.2 The effect of growth rate on wood properties

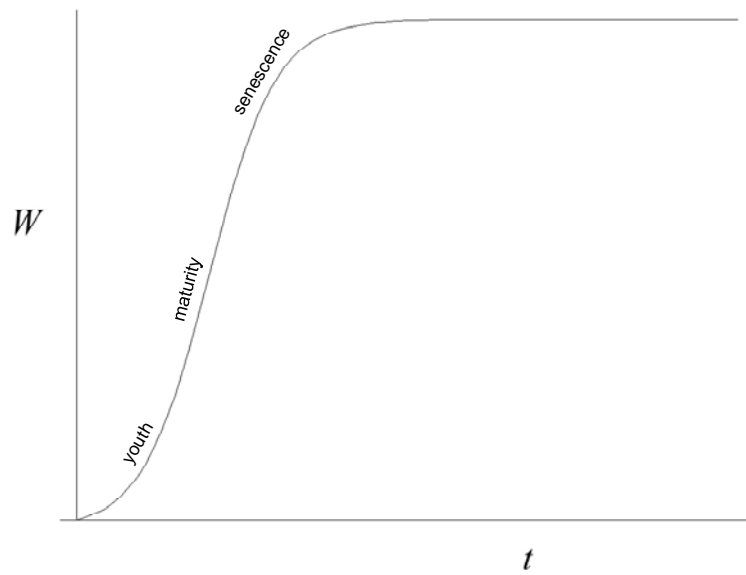
Studies relative to growth rate and wood properties are numerous. Zobel and van Buijtenen (1989) summarized this subject in detail from a whole series of publications. They asserted that the effect of growth rate on wood properties is contingent on species, site, causation of fast growth, and how growth is expressed. Additionally, wood from rapid growth caused by silvicultural manipulations may differ from that caused by genetic improvements. Similarly, the relationships between growth rate and wood properties generally differ between mature and juvenile wood; therefore, the effects of tree age must be considered when studying this subject (Zobel and Sprague 1998).

2.2.1 Measuring growth rate techniques

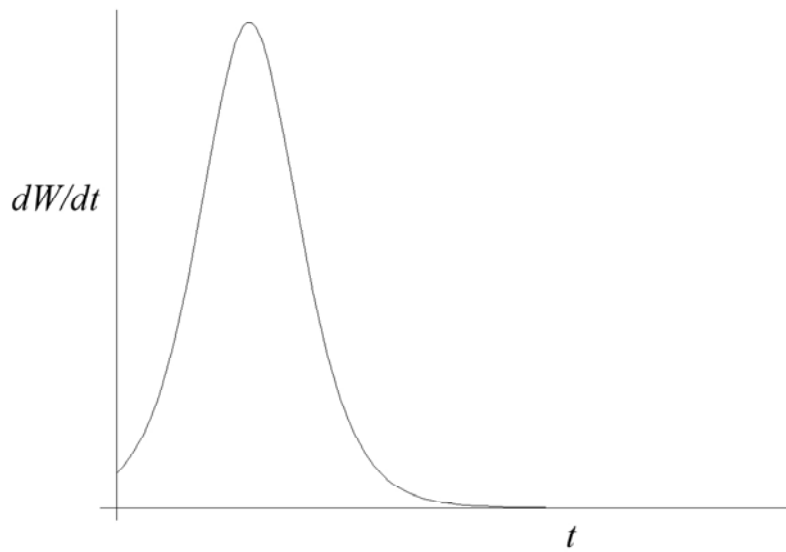
Various techniques are used to measure growth rates such as the measurement of ring width, tree volume, tree basal area, total and merchantable height growth, and diameter growth at breast height and at points up the stem of the tree (Husch et al. 2003). The common goal is to measure the annual increment of wood added to the central stem in that particular year (Kozłowski et al. 1997). Basal area is the cross-sectional area of a tree taken at breast height, 1.37 m above ground. According to Zobel and van Buijtenen (1989), basal area of wood added annually is the true measurement of growth rate, but it is rarely used in the studies relating to growth rate.

In fact, the most widely used technique is measurement of ring width as a good indication of overall tree health, growing conditions, and wood quality (Barnett and Jeronimidis 2003). In temperate regions, a single growth increment of the woody tissue—the initiation and cessation of growth—is recorded annually over the entire surface of the stem, thus revealing a well-defined growth ring (Panshin and de Zeeuw 1980). The great advantage of ring width is that it is easy to measure with straightforward methods and instruments.

As a tree grows older, ring width will naturally be narrower because the tree may not produce the same ring width around an enlarging tree circumference although the tree makes the same or more volume of wood as it ages. In other words, Kozłowski (1971b) describes that cambial growth accelerates annually for a number of years, attains a maximum, and then declines, at first rapidly and then more gradually with each successive xylem ring narrower than the previous one, unless the pattern is altered substantially by environmental influences. Figure 2.2a shows S- or sigmoid-shaped curve of the cumulative size (e.g. volume, weight, diameter, or height of a tree) at any age called cumulative growth curves. A growth curve describing increment at any age, growth rate curve, is plotted in Figure 2.2b. For this reason, ring width measurement is not suitable for measuring growth rate or, especially serious if used without considering the age of the ring (Jeffers 1959; Nicholls et al. 1964). Wide-ringed, short-celled, fast-growing, low density, juvenile wood cannot be compared with narrow-ringed, slower-growing, high density mature wood; otherwise, the juvenile wood will result in an erroneous assessment of the effect of growth rate. Indeed, regardless of the growth rate, wood in the juvenile portions usually differs from that in the mature portions (Zobel and van Buijtenen 1989).



(a)



(b)

Figure 2.2. Time series of tree size

(a) cumulative growth curve, (b) growth rate curve. (W = tree size [height, diameter, basal area, volume, or weight]; t = time).

Graphs adapted from Husch et al. (2003), fig. 15-1. Drawing by Boonyarit Intiyot.

2.3 Tree-ring analysis

In many cases it is difficult and impractical to obtain a whole tree or even a large section from the tree. The use of increment cores is often viewed as a cost-effective, non-destructive, rapid, and accurate sampling approach in forestry and wood technology, and it also can put timber supplies to their best uses (Paul and Baudendistel 1956). Maeglin (1979) reported that increment cores “are used to estimate the ages [at the boring position on the tree] and growth rates of trees, for evaluation of wood properties, decay detection, to determine preservative penetration in poles and ties, and many other uses.” For general purposes, age at breast height is satisfactory without correction for total age (Husch et al. 2003). Moreover, they have also been useful in the determination of volume growth of forest stands and in dendrochronology (Kozlowski 1971a). Zobel and Jett (1995) suggested that a breast height sample can be used to accurately estimate the wood density of the whole tree particularly in the diffuse-porous hardwoods. Determination of wood properties using cores taken at breast height is a commonly applied technique (Kube and Raymond 2002). For example, a commercial Fractometer (IML, Inc, Wiesloch, Germany) has been used to break radial increment cores for the measurement of bending and compression strength along the grain and for the detection of decay and lignin destruction. Although a core sample allows assessment of wood and fiber properties, it is incapable of assessing pulping and paper making traits owing to the small size of samples extracted from the core (Raymond et al. 1998).

Once an increment core is available, its mechanical properties may directly be determined from micromechanical testing made on very small specimens prepared from tree

cores. This may require less time in specimen handling and cost less in running the equipment (Yang and Fortin 2001). To date, this area of work has not been widely investigated or reported.

Because yellow-poplar is among the species for which tree-ring chronologies have been published or possible (Cook and Kairiukstis 1990), the *radial growth averaging* (RGA) criteria methods could be applied. The RGA criteria method is a quantitative, dendroecological technique established by Lorimer and Frelich (1989) for deriving past canopy disturbances. This technique depends upon the percent increase or decrease in the running average of tree ring widths over a predetermined span to identify potential growth response—release and suppression events over a sufficient time period (Copenheaver and Abrams 2003). For the purposes of this paper, periods of release and suppression growth are defined based on the definition provided by the RGA criteria (Nowacki and Abrams 1997), and they can be extracted from radial growth patterns (Lorimer 1985). Generally, release is considered to be periods of above-average radial growth when residual trees have increased resource availability and responded with increased tree-ring growth. For instance, release can be triggered by removing competing trees that overtop or closely encircle desirable trees (residual trees) or by creating canopy openings. In contrast, suppression is defined as periods of reductions in radial growth. The term suppressed or overtopped trees has also been used to describe trees with crowns entirely below the main canopy, receiving no direct sunlight either from above or from the sides (Smith et al. 1997; Nyland 2002), thus resulting in old trees with very dense growth rings. These usages for and suppression will not be applied in this study.

2.4 Significance of specific gravity as an index of wood quality

Despite the very widespread interest and study over the years, there is still much debate over the affect of growth rate on wood properties. Previous investigations have concentrated almost exclusively on specific gravity and cell characteristics (Zobel and van Buijtenen 1989).

Conventionally, many researchers believe that wood specific gravity or density is presumably the most significant wood property in forest products manufacture. Specific gravity is influenced by many interconnecting factors, mostly anatomical and chemical (Quilhó and Pereira 2001). It provides a useful means for predicting yield and quality of fiber products, many physical properties, and general value and quality of wood products. Besides, it closely relates to most of pulp and paper properties, energy yield, many of the individual cells' characteristics, and biomass productivity of a forest. Specific gravity is also rather easy to determine with straightforward methodology.

The length, width, fibril angle, and other characteristics of the cells as well as cell chemistry play an important role in product quality and the use of wood. However, they are relatively less important compared with specific gravity (Zobel and van Buijtenen 1989).

2.4.1 The significance of specific gravity and growth rate in yellow-poplar

Wood specific gravity and its relationship to growth rate have been widely studied. Many investigators concluded that there is little or no relationship between specific gravity and ring width or growth rate in yellow-poplar (Paul and Norton 1936; van Eck and Woessner 1964; Taylor 1965; Kellison 1967; Taylor 1968; Taylor 1977; Thor and Core 1977; Fukazawa 1984; Christian and Stenglein 1986). Likewise, Sluder (1970) stated that basal area growth is not related to specific gravity in yellow-poplar. On the contrary, Paul (1963) found that second-

growth, faster-grown yellow-poplar had an 8 percent higher specific gravity than the old-growth yellow-poplar. Similar results were reported by Bollig (1994) for yellow-poplar, who found that stemwood specific gravity from ground line up to 4 meters is significantly increased by crop tree release that also results in increase in diameter growth.

Unfortunately, the effects of growth rate on cell properties in hardwoods have not been as widely studied as has specific gravity, although fiber length is directly connected with the quality of paper and fiber products. In general, Zobel and van Buijtenen (1989) suggested “no change in fiber lengths with increased radial growth and no effect, or somewhat longer fibers, with increased height growth.”

2.5 Variation among and within trees

Wood property variations result from environmental influences, genetic capabilities, and their interactions (Zobel and Jett 1995). Environmental influences consist primarily of climatic factors, soil factors, topographic characteristics, and competition. They can also be categorized as being stable or transient. Stable factors, such as soil texture and soil nutrient level, do not alter much over the life of a tree. On the other hand, transient factors, such as climate fluctuations and stand competition, change cyclically or unpredictably during the life of a tree (Husch et al. 2003). The combination of all the environmental factors can be expressed as site quality. Additionally, Panshin and de Zeeuw (1980) and Bowyer et al. (2002) include tree (cambial) age as another source of the variation. All these factors and their interactions play a role in the tree growth process as well as its growth rate (Herman et al. 1998).

For yellow-poplar, there are highly significant differences in specific gravity among individual trees growing on the same site (Thorbjornsen 1961; Kellison 1967; Taylor 1968),

thereby describing a genetic contribution to variability (Christian and Stenglein 1986). Similarly, Sluder (1970) found that 52% of the total specific gravity variation is attributed to differences among trees within plots. Likewise, other wood characteristics differ markedly among trees of the same age growing under similar environmental conditions (Zobel and Talbert 1984).

Wood varies not only from tree to tree but also from the pith to the bark within the tree. For radial trends (from the tree center to the bark) of yellow-poplar in typical forest grown trees, most reports agree that specific gravity increases outward from the pith for heights up to 6.1 m (Erickson 1949; Thorbjornsen 1961). Koch et al. (1968) studied the density variation found within a young yellow-poplar tree in West Virginia. Density increases from 0.37 to 0.40 from the pith to bark at selected heights. In addition to this pattern, Taylor (1968) and Sluder (1970) add that specific gravity increases from the center, then remains constant, and then decreases with ring number for a given height. This trend flattens steadily with increasing height up to 18.3 m; thereafter, specific gravity decreases from pith to bark (Wooten et al. 1973). Gilmore (1971) found that juvenile wood is lighter than mature wood. However, a few other studies do not concur; for example, Woodcock and Shier (2002) reported there are increasing, decreasing, or no radial trends in specific gravity of diffuse-porous hardwoods during tree growth.

Fiber lengths for yellow-poplar trees increase rapidly from the pith outward for the first 12 years of the tree's growth. Subsequently, they change insignificantly with the tree age. This similar radial pattern is observed at entire sampling heights (Wooten et al. 1973).

2.6 Effect of site, soil, climate, and geographic area on wood properties

Differences between sites are the major sources of the variation between different stands even when the genetic variation is reduced. Because site is really not definable biologically and is dependent on an interaction of factors such as latitude, altitude, soil fertility, moisture, temperature, light intensity, etc., site is not a very suitable measure for predicting the wood quality.

For yellow-poplar, reports vary from no wood response to site differences to either lighter or denser wood produced on good sites. Thorbjornsen (1961), for example, concluded that no relationship is found between wood properties and site index. Generally, site index is estimated by determining the average height that the dominant and codominant trees in an area will attain at a specified index age such as 50 or 100 years (Husch et al. 2003). A similar result was found by van Eck and Woessner (1964) that there is a limited trend for better sites to produce higher density wood. Taylor (1977) and Thor and Core (1977) agreed that no significant differences among geographic locations are found in either specific gravity or fiber length for yellow-poplar in natural forest. In plantations, Gilmore (1971) also showed that the specific gravity of yellow-poplar is not related to site. In contrast, Thor and Core (1977) argued that as much as 60 percent of the variation in wood properties is associated with a combination of site factors. Barefoot (1963) also concluded that the best sites produce lower density woods. According to Sluder (1970), the higher the site index of areas where yellow-poplar is grown, the less dense the wood. In a study with regard to the effect of compass direction on wood properties of yellow-poplar, Taylor (1968) reported that compass direction is not important relative to wood quality. No specific gravity difference is found between north and south sides of the tree (Erickson 1949).

For geographic variation of wood properties of yellow-poplar from natural stands, Kellison (1967) and Sluder (1970) found clear differences in specific gravity between geographic area. In addition, Kellison added that the piedmont provenance has the highest specific gravities, whereas the coastal plain and mountain provenances are lower in specific gravity and equal to one another. Taylor (1965) concluded that soil variability is associated with major specific gravity differences. Since each site is a unique combination of many factors, Zobel and van Buijtenen (1989) emphasized many times in their book that “the only way to know with certainty what kind of wood will be produced is to grow the trees of interest on the site of interest.”

2.7 The effect of growth rate on mechanical properties

Much of the total wood production is used structurally: for beams, joists, flooring, or supports which bear load. The properties of interest for the designer are then the moduli, the yield or crushing strength, and the toughness (Gibson and Ashby 1997). In structural applications where wood is loaded along the grain, the axial modulus and crushing strength are important. Compression members consist of posts or columns, vertical wall studs, and struts in trusses and girders (Keraiani 1999). To provide data regarding the resistance of wood to such axial loads, the compression parallel to grain test is used. Until recently, strength had usually not been a concern in hardwood utilization since the majority of the wood had been used for decorative veneers and furniture (Cutter et al. 2004).

However, few attempts have explored the influence of growth rate on the mechanical properties of wood (Zhang 1995). Understanding this relationship is thus important to maximize wood production without undermining its mechanical properties. Because the mechanical and physical properties of wood are closely related to specific gravity, the variability of most

mechanical and elastic properties of wood can be estimated by reference to the variation in specific gravity (Panshin and de Zeeuw 1980; Bowyer et al. 2002; Bodig and Jayne [1982] 1993). The relationships between the average various mechanical properties and specific gravity for clear, straight-grained, defect-free wood among species are described as power functions (USDA Forest Serv. Forest Products Lab. 1999). They take the general form:

$$Y = a \cdot SG^b \quad (2.1)$$

where

Y = the strength property of interest,

a, b = parameters determined by the particular mechanical property,

SG = the specific gravity (oven-dry weight/ volume at the specified moisture condition).

For the *ultimate crushing stress* (σ_u , kPa) at 12% moisture content of hardwoods, the ultimate crushing stress-specific gravity relations become

$$\sigma_u = 76,000 \cdot SG^{0.89} \quad (2.2)$$

Generally, the greater the specific gravity of wood, the greater its strength. Albeit a rather good correlation, wood variability is such that, when used for a prediction, these relations between specific gravity and mechanical properties are not accurate enough (Farruggia and Perré 2000). In addition, this relationship is only based on average values for the 66 hardwood species; therefore, the relationship does not accurately predict an individual species or specimen value.

In a study conducted by Zhang (1995) that dealt with four diffuse-porous species, he reported that growth rate has very little effect on both specific gravity and three other mechanical properties: *modulus of rupture in static bending* (MOR), *modulus of elasticity in static bending*

(MOE), and maximum crushing strength in compression parallel to grain. Zhang (1995) went on to say that compared with specific gravity, the mechanical properties are usually more influenced by growth rate. He stated: “therefore, the impact of growth rate on wood mechanical properties in a species cannot be estimated exactly through the relationship of wood specific gravity with growth rate.” Besides the indirect effect of specific gravity on the mechanical properties, growth rate has an extra effect on the mechanical properties that cannot be delineated by specific gravity *per se*. His specimen’s dimensions for compression tests were 2 cm × 2 cm × 2 cm according to the *Chinese National Standard* (NSB). Lei et al. (1997) also concluded that MOR, MOE, and specific gravity of red alder (*Alnus rubra* Bong.) are not affected by growth rate. As Smith et al. (1997) wrote, rapid growth produces no noticeably different strength in diffuse-porous hardwoods. Therefore, it is questionable whether the strength of wood is directly controlled by the rate of growth.

2.8 Significance of vessel, fiber, and ray volume

The average volume proportion of yellow-poplar wood occupied by vessels (36.6%), fibers—specifically, fiber tracheids and libriform fibers (49.0%), and rays (14.2%) accounts for almost 99.8% of total volume (Panshin and de Zeeuw 1980). Because of their considerable volume, vessels and fibers strongly influence wood specific gravity. The high percentage of vessel volume results in low average specific gravities. In addition, wood of high specific gravity has more ray volume than that of low specific gravity (Meyer 1922). Increase in ray volume is attributed to increase in the compression parallel to the grain, even though this relationship is not strong compared with that of ray volume and other mechanical properties. It is highly likely that the rays run perpendicular to an applied force and the fibers. Meyer (1922)

also stated that while a tree was suppressed, the tree lays down less ray content compared with a released tree from which the surrounding trees were removed.

2.9 Micromechanical testing system

The unique properties of wood stem directly from its hierarchical internal structure. The structure of wood spans several spatial scales: from as large as meters for describing the whole tree to as small as nanometers for elaborating the molecular structures of cellulose, hemicellulose, lignin, and their chemical interactions (Moon et al. 2006). The bulk properties of wood result from the conclusion of interactions within and between each length scale. Slight changes of parameters at one length scale influence others, thereby affecting the mechanical and structural properties (Burgert and Frühmann 2003). At the millimeters scale, between or within growth rings, investigations can also provide a deeper understanding of wood response to an applied load or a given environment.

Zink-Sharp and Price (2004) had developed a testing method using a specialized micro-testing system on small-sized specimens (a few mm³ in volume) of pitch pine (*Pinus rigida*) and Virginia pine (*Pinus virginiana*). The testing system was designed to perform compression, tension, and bending tests on growth ring regions of wood. They concluded that this testing system can achieve accurate measurement of maximum load in compression parallel to the grain test. Specimen preparation protocols used in this study can obtain the target dimension. Following the previous research Zink-Sharp (2005) studied intra-ring compression strength parallel to grain for small samples of sweetgum (*Liquidambar styraciflua*), yellow-poplar (*Liriodendron tulipifera* L.), and red maple (*Acer rubrum*) using the developed method. She

found that the compression strength value of red maple cores do not differ among trees. In addition, growth rate did not significantly affect compression strength or specific gravity.

Compared to a test of standard size wood specimens, the testing of small specimens can minimize preparation errors and increase application to a wider range of practical situations. Additionally, Gong and Smith (2004) reported that a small specimen subjected to compression parallel to grain shows a good relationship to a large standard specimen specified by ASTM (2003a) in terms of mechanical behavior and failure mode. Nonetheless, the major disadvantages of testing small specimens are that extreme care is needed for preparing the specimens and that moisture content control must be improved over normal procedures for standard-sized specimens because of the susceptibilities to environmental changes.

2.10 Standard test for compression parallel to grain

Owing to its simplicity, the compression test is one of the most commonly conducted mechanical tests of wood and wood products. The major organizations—the *American Society for Testing and Materials* (ASTM), the *International Organization for Standardization* (ISO), and the *Japanese Industrial Standard* (JIS)—which develop standard test methods also contain compression test for woods (Yoshihara and Yamamoto 2004).

The ultimate crushing stress or ultimate stress of wood in compression is an important mechanical property. Indeed, working stresses, defined by building codes and other standards, frequently apply adjustment factors based on the ultimate crushing stress. As a result, working stresses are a proportion of the ultimate crushing stress. The standard procedure for compression parallel to grain test for a clear, straight-grained wood are designated ASTM D 143-94 (2003a).

2.10.1 Stress-Strain Curves

Bodig and Jayne ([1982] 1993) identify four regions of the stress-strain diagram for wood composites: initial alignment, linear elastic, curvilinear, and post-failure. The linear-elastic portion is a straight line with a steep slope until the *proportional limit* (pl). For this portion of the diagram, the *stress* (σ) is directly proportional to the *strain* (ϵ). This relationship is known as Hooke's law. When a member is loaded and the stress does not exceed the *stress at proportional limit* (σ_{pl}), the member will return to its original dimensions without a permanent plastic deformation when the load is removed (Merritt and Ricketts 2001).

Beyond the proportional limit, wood undergoes a large deformation with a relatively small increase in the applied load producing a region of convex curvilinearity and the total deformation is nonrecoverable and some permanent set is imposed on the specimen (Panshin and de Zeeuw 1980). The peak of the curvilinear region is called the ultimate crushing stress, the stress at which failure occurs (see Figure 2.3).

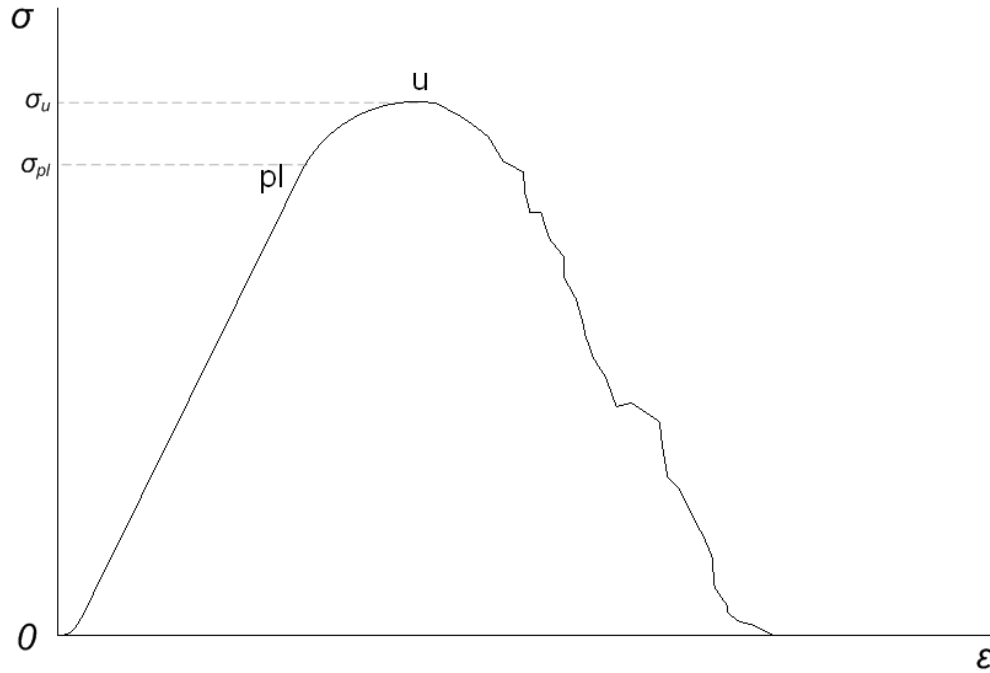


Figure 2.3. Stress-strain diagram for a typical compression parallel-to-grain test

Graph adapted from Bodig and Jayne ([1982] 1993), fig. 2.5.

Ultimate crushing stress is important in the use of wood composite and is not a constant for a given material. It is influenced by factors such as age, temperature, moisture, and strain-rate (Gibson and Ashby 1997). The σ_u can be calculated from the following formula:

$$\sigma_u = P_u / A \quad (2.3)$$

where

σ_u = ultimate crushing stress (Pa = N/m²)

P_u = peak load (N)

A = cross-sectional area (m²).

The post-failure region occurs after the ultimate crushing stress has been reached, it determines whether full or partial failure has occurred (Bodig and Jayne [1982] 1993). Gibson

and Ashby (1997) reported that the post-failure of axial compression for medium-density balsa shows a stress plateau extending to a certain degree of strain, depending on the density of the wood. At the end of the plateau the stress rises steeply.

Chapter 3 Materials and Methods

3.1 Materials

Radial increment cores of yellow-poplar (*Liriodendron tulipifera* L.) from seventeen plots scattered over six southeastern states were used for test specimens. These plots were located in seven sites: Reynolds Homestead (VA), Duke Forest (NC), Clemson Experimental Forest (SC), University of Tennessee Forest (TN), Oconee National Forest (GA), Robinson Experimental Forest (KY), and Long Gone LLC (VA). The total number of cores is 168.

Cores were collected in the summer 2006, from May-August, by staff members of the *Sustainable Engineered Materials Institute* (SEMI). The protocol used to select sampling plots was based on physiographic province and latitude to represent the range in wood properties across the southeastern United States. In addition, the sampling plots were divided into a few management intensities: high, medium, low, and no management or natural stands (see Figure 3.1).

A 0.04-hectare (404.7 m²) circular plot was employed as a sampling unit. At each plot, ten trees representative of the stand evenly distributed across 1-in. diameter classes were chosen and cored. In other words, all stems larger than 5 cm *diameter at breast height* (dbh) were measured for the diameter and were classified into 1-in. diameter classes to develop a diameter distribution for the plot.



Figure 3.1. Examples of three management intensities

(a) natural management in the Duke Forest (plot 2), (b) low management in the Duke Forest (plot 5), (c) low/medium management in the Clemson Experimental Forest (plot 3).

To collect the core, an increment borer was placed at breast height (1.37 m above ground) and aimed toward the center of the tree and perpendicular to the axis of the trunk (see Figure 3.2). Cores were 12.5 mm in diameter and taken by boring through the center and out the other side of the tree. The total height and height to the first green branch of the selected trees were also recorded.



Figure 3.2. Collecting the core at breast height

To minimize fungal activity, extracted cores received a 10-15 minute soak in chlorine bleach (sodium hypochlorite), sealed in a plastic bag, labeled as the S core, and refrigerated. The increment borer bit was also rinsed with bleach after each tree coring to prevent cross contamination. A standardized labeling system was used: (1) the site code—a short three-letter abbreviation for a site, (2) the plot number—two digits, (3) the specie (YP standing for yellow-

poplar), (4) the tree number—three digits, and (5) S (S standing for soaking in bleach). For example, DDF-02-YP-198-S would represent “soaking-in-bleach” yellow-poplar core from the tree number “198” taken at plot “02” from Duke Forest. All cores (N = 168) were returned to the laboratory for examination.

3.2 Measuring tree rings methods

3.2.1 Selecting the core

Not all the collected cores were suitable for the purpose of this study. To be considered, the core had to display the following characteristics:

- 1) No pronounced tension wood (reaction wood of the hardwood species)
- 2) No obvious scar tissue or other evidence of severe injury, which could affect growth
- 3) Distinct ring boundaries for most years
- 4) Intact bark at the end of the core.

Cell morphology of tension wood is different considerably from that in normal wood (Zobel and Jett 1995). Tension wood was detected by visually observing the arrangement of rings within the core. Tension wood zone of the core often had wider rings than that on the opposite side of the core (Bowyer et al. 2002). As a result, cores with asymmetric rings were discarded. Unfortunately, a number of cores did not fit with some of the above criteria, particularly having tension wood. Ring boundaries might not be readily seen when cores had just been removed from the refrigerator and were still moist; however, allowing them to air dry for a few days clarified their ring boundaries.

The core needed to have bark still intact because, without it, the outside ring of the core—the terminal ring—would not positively be dated, although the terminal date when the core was taken was known. The innermost ring indicated when the tree was a seedling.

3.2.2 Mounting the core

All suitable cores periodically received a 10–15 minute soak in chlorine bleach to keep fungal activity to a minimum. They were then cut in half at the pith to have two-half cores per trees (two replications from opposite sides of the stem). Only one of them is examined in this study. The other was refrigerated and may be used if a further study aims at analyzing the variations within and among trees (Fritts 1976). Because cores removed with an increment borer were small and fragile, they had to be mounted onto core mounts before any surfacing could be done.

Cores were allowed to air dry for a few days before mounting so that they would not shrink and pull apart in the core mount. Damage to cores makes measurement difficult. When a core had sufficiently dried, it was glued into a slotted mount and held tightly with adhesive tape, string, or rubber bands while the glue cured. The water-soluble glue was set after 24 hours from the application.

Cores had to be oriented in the mounting block so that the wood grain (vessels and fibers) would be at right angles to the observable finished surface. This orientation could be achieved by observing the innermost end of the core (Stokes and Smiley 1968).

3.2.3 Sanding the core

After the glue was set and the adhesive tape was removed, sanding methods were used to reveal anatomical characteristics and help identify false and light rings. Attempts to read ring

boundaries on unsurfaced cores are unreliable, and the risk of missing very tiny rings or misidentifying false rings is large. Growth rings of diffuse porous species, in this case, yellow-poplar, were not apparently distinguished, making counting or measuring them more difficult (Patterson 1961). Yellow-poplar's growth rings could be delineated by distinct light cream or yellowish line of marginal parenchyma several cells thick. Although this line was visible to the naked eye, sometimes it was so thin that it could not be seen without a hand lens (Hoadley 1990).

Sanding was done first by machine and later by hand. An electric sander with a coarse sanding disc (150 grit) was used to quickly remove thin layers of wood to produce a flat surface on top of the core. Then, hand sanding was lightly applied with progressively finer grades of sandpaper mounted on a small sanding block.

For each core, four grits of sandpaper were used (one at a time)—starting with No. 220, then 320, 400, and finishing with *MICRO-MESH 1500* (Micro-Surface Finishing Products, Inc, Wilton, IA, USA). The coarsest sanding aimed at preparing a flat surface, while the finer sanding at reducing and finally removing the burred edges of the cell walls to sharply and readily define them (Phipps 1985). Figure 3.3 shows a sanded specimen in mount. Last, tentative dating marks were made in pencil along one edge of the core.

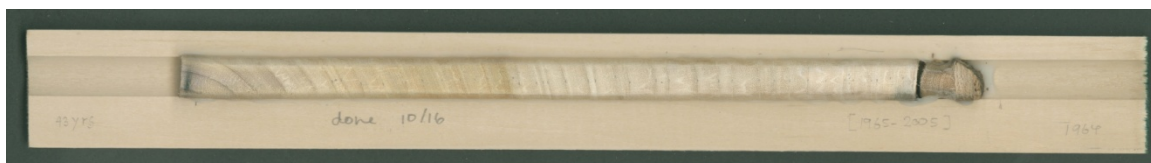


Figure 3.3. A sanded core mounted on support

3.2.4 Crossdating

Crossdating is a procedure ensuring that each individual tree ring is assigned its exact year of formation. It is achieved by matching patterns of narrow and wide rings between cores from the same tree, among nearby trees, and between trees from different locations (Fritts 1976; Martinez 1996). Fritts states that “crossdating is possible because the same or similar environmental conditions limit the ring widths in large numbers of trees, and the year-to-year fluctuations in environmental factors that are similar throughout a region produce synchronous variations in ring structure.”

It was necessary to have a long enough ring sequence to be dated; therefore, only the cores spanning over 25 years were included. Before any actual ring widths were measured and analyzed, the cores within each site had been visually cross-dated by identifying pointer years or narrow rings using a simple method developed by Yamaguchi (1991). Each annual ring was compared with that from the preceding and subsequent ring. If such ring was considerably more narrow than its neighbors, it was a pointer year and formed the basis for cross-dating method of dating (Schweingruber 1988; Cook and Kairiukstis 1990).

Subsequently, the ring widths of each core within the same region (sites having a homogeneous climate) were compared to find shared pointer years. For example, cores collected from DDF and GPF were merged together and cross-dated. Table 3.1 provides a brief description of the sampled trees and site information before grouping of the sites (see Figure 3.4 and Table 3.1).

A common marking system was also used to assist measuring accuracy. A single pencil dot on core’s surface, for instance, indicated the decadal ring. Two dots in a vertical alignment indicated the half-century ring in accordance with Stokes and Smiley (1968).

Table 3.1 The sampled trees and site information

Site code ^a	Plot No.	Number of trees	Chronology span	Mean tree age (yr)	Latitude and longitude	Elevation (m.a.s.l. ^b)	Physiographic province	Management intensity ^c
DDF-02	2	3	1928-2005	66	36°00'22"N, 79°01'05"W	147	Piedmont	Natural
DDF-05	5	2	1940-2005	65	35°59'43"N, 78°56'10"W	156	Piedmont	Low
GPF-01	1	3	1953-2005	48	36°33'09"N, 77°48'16"W	84	Piedmont	Natural
CEF-01	1	3	1929-2005	72	34°37'02"N, 82°50'08"W	210	Piedmont	Natural
CEF-02	2	3	1962-2005	42	34°38'47"N, 82°48'22"W	210	Piedmont	Natural
CEF-03	3	2	1944-2005	61	34°44'45"N, 82°51'55"W	210	Piedmont	Low/Medium
UTF-01	1	2	1916-2005	88	36°00'35"N, 84°11'39"W	333	Ridge and Valley	Natural
UTF-02	2	1	1932-2005	74	36°00'09"N, 84°13'01"W	300	Ridge and Valley	Natural
UTF-04	4	4	1973-2005	31	36°03'54"N, 84°26'03"W	420	Cumberland Plateau	Natural

^aDDF, Duke Forest (NC); GPF, Long Gone LLC (VA); CEF, Clemson Experimental Forest (SC); UTF, University of Tennessee Forest (TN).

^ba.s.l., above sea level.

^cNatural, natural stands; low, plantation, no maintenance; medium, fertilized, weed controlled plantation.

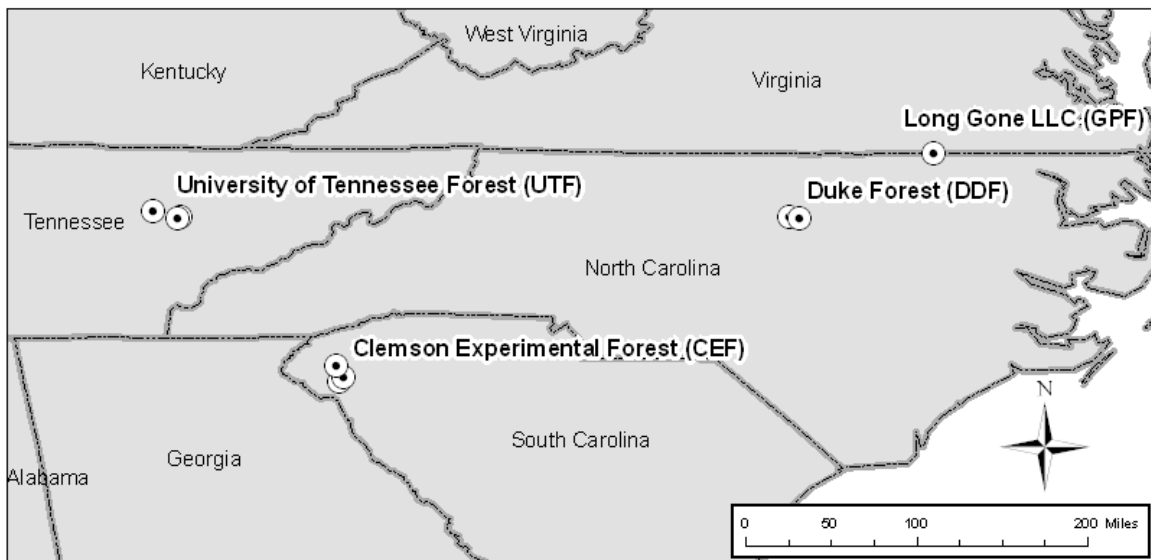


Figure 3.4. Location map of yellow-poplar study sites

(Drawing by Spencer Riddile).

3.2.5 Measuring tree rings equipment

The VELMEX “TA” Tree-Ring Measurement System (Velmex Inc., Bloomfield, NY) was used to measure the ring width (see Figure 3.5). Its encoder was connected to a readout, and the readout was connected to a PC in which the MeasureJ2X[®], a software program providing support for capturing and editing tree ring measurements, was installed.

Magnification of the binocular zoom microscope was 40× which was adequate for clearly viewing the individual cells in each ring. Cross hairs in the ocular served as a reference point for the measurement of ring widths. A specimen was placed on the slide, which would be moved along the stationary microscope by turning a crank so that the cross hairs visually first passed over the earlywood of a ring and on to the outermost margin of the latewood of the same ring. The specimen had to be constantly adjusted so that the direction of the cross hairs was drawn perpendicular across the adjacent ring boundaries (Holmes et al. 1986). The amount of slide movement between the ring boundaries (ring width) was recorded when a handheld button was pressed.

Ring widths were measured to the nearest 0.002 mm resolution. Because the cores were taken during the growing season of the trees, the outermost radial growth would be incompletely formed and it was not measured. If the core did not contain the pith, the innermost ring width also could not be determined. As a result, most of the first measured ring widths were the second formed growth ring.

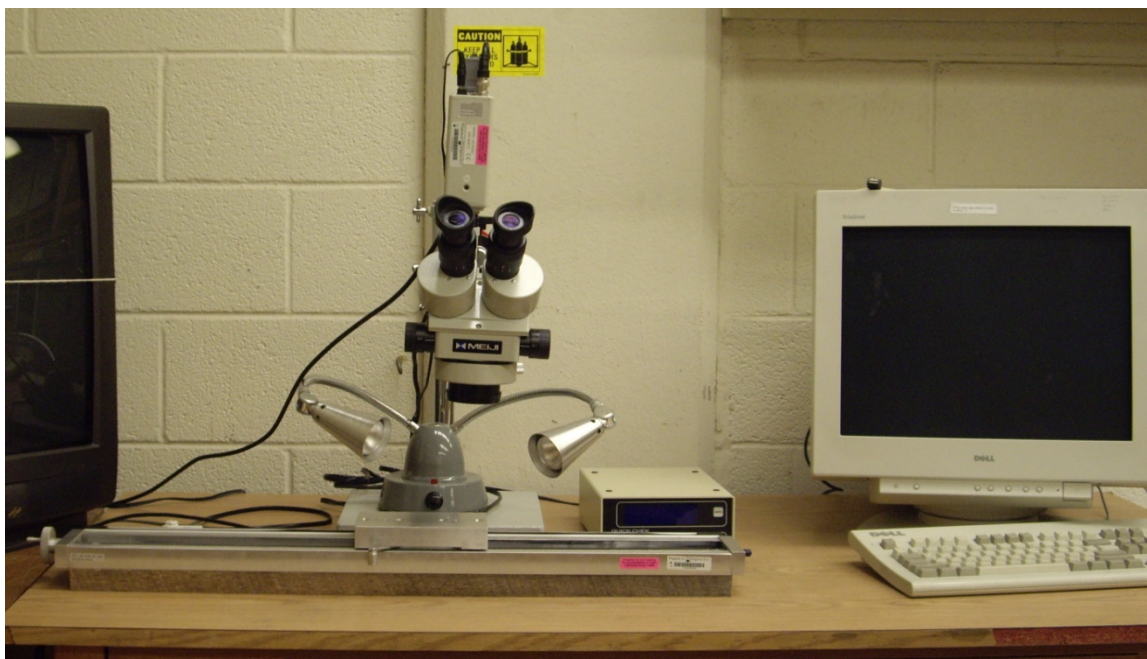


Figure 3.5. The VELMEX "TA" Tree-Ring Measurement System

To assure the ring widths' accuracy, ring widths from the same region were crossdated a second time using a computer-assisted method, Program *COFECHA* available within the Dendrochronology Program Library (<ftp://ftp.cricyt.edu.ar/pub/dendrocronologia>) (Holmes et al. 1986; Copenheaver and Abrams 2003). This method examined all cores in the same region and pointed out ring widths within cores that might have weak or erroneous crossdating or measurement error. For these reasons, the cores and measured ring widths were examined to evaluate the source of weakness and to make corrections. Some cores were rejected for further processing since they had weak crossdating as shown by a low correlation with the others in the same region.

Finally, a second run *COFECHA* verified that all changes were correct, and the data set was clean and ready for the next step. Verification of the visual cross dating with *COFECHA*

provided a series intercorrelation, which is a measure of the amount of common signals among tree-ring sequences, of 0.436, 0.509, and 0.566 for the regions 1-3, respectively (see Table 3.2).

Table 3.2 Descriptive statistics for the yellow-poplar tree chronologies developed from trees sampled at three regions

Region	No. of cores	Chronology span	Mean tree age (yr)	Mean dbh (cm)	Mean height (m)	Mean ring width (mm)	Series intercorrelation
(1) DDF and GPF	8	1928-2005	59	35.0	31	2.34	0.436
(2) CEF	8	1929-2005	58	36.7	31	2.51	0.509
(3) UTF	7	1916-2005	53	26.9	26	1.98	0.566

3.2.6 Processing after Measurement

Radial growth chronologies of sequential five-year ring-width means were used to determine suppression and release events. Only a five-year span from radial growth averaging was used due to the young age of the samples. *Percentage growth change* (%GC) from the previous five years to the following five years across individual tree-ring chronologies was calculated using the Equation (3.1) adapted from Nowacki & Abrams (1997):

$$\%GC = \left[\frac{(M2 - M1)}{M1} \right] \times 100 \quad (3.1)$$

where

%GC = percentage growth change between preceding and succeeding five-year means

M1 = preceding five-year ring-width mean (including a given year)

M2 = subsequent five-year ring-width mean

For instance, to find %GC of the year 1977, we use the Equation (3.1):

$$\%GC_{1977} = \left[\frac{\text{mean}(1978-1982) - \text{mean}(1973-1977)}{\text{mean}(1973-1977)} \right] \times 100$$

Since each %GC value (for an example of the %GC calculation, see Appendix A) represented a ten-year span of ring-width data, empty cells relative to raw tree-ring chronologies inherently occurred at the first four years and last five years (by definition, the index could not be calculated). After the %GCs were calculated, four categories based on %GC were determined based on conservative and moderate criteria adapted from Lorimer & Frelich (1989) and Nowacki & Abrams (1997) as follows (see Figure 3.6):

- 1) Major suppression, $\%GC \leq -50$
- 2) Moderate suppression, $-50 < \%GC \leq -25$
- 3) Moderate release, $25 \leq \%GC < 50$
- 4) Major release, $\%GC \geq 50$.

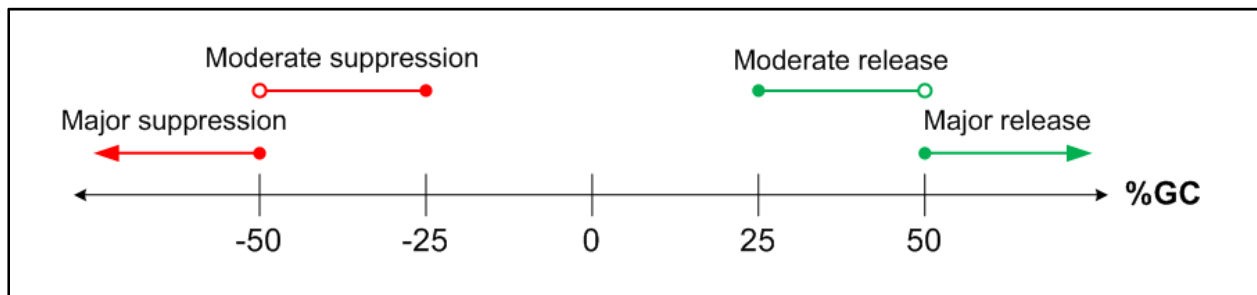


Figure 3.6. Summary diagram of the four categories based on percentage growth change

In addition to the above criteria, some additional rules were also applied to refine the selection criteria as follows:

- The longest and continuous period of major suppression and major release events were considered first.
- Within these events, the year that showed the lowest %GC in suppression event was the suppression event.

- The year that showed the highest %GC in release event was the release event.
- If the major suppression or major release event was absent, the moderate suppression or release events were then considered.
- Within these events, similar rules were applied for choosing the suppression and release year.
- It is possible for trees to experience either only suppressions or only releases. The cores that were collected from these trees were not good representative samples and would be discarded.
- If either suppression or release event was formed during the first ten years, growth rings of the core (rings one through ten), this event might contain juvenile wood and the core would then be discarded.

At this point, we introduced two new terms *period of minimum growth within a suppression event* and *period of maximum growth within a release event*, which would be two of the most significant periods for further investigation. The former or *minimum suppression year* was defined as the narrowest ring from within the suppression event identified by the modified RGA technique. In contrast, the later term or *maximum release year* was defined as the widest ring from within the release event also identified by the modified RGA technique. The minimum suppression year should be the accurate representative of the periods of reductions in radial growth of the trees in the same way as the maximum release year might be the true representative of the periods of increasing tree-ring growth.

In practice, the minimum suppression and maximum release years could only be identified after suppression and release events were determined. Within the subsequent five

years from the suppression event, the year that trees produced the narrowest ring width was the minimum suppression year. In contrast, the year trees producing the widest ring within five years from the release event was the maximum release year (for an example, see Appendix A).

Finally, all suitable twenty-three cores ($n = 23$) were collected, and their minimum suppression and maximum release years were recorded. Next, these cores were used to test the compression parallel to grain strength.

3.3 COMPRESSION PARALLEL TO GRAIN TEST METHODS

3.3.1 Preparing the specimen

The mounted cores were submerged in water for two days to dissolve the adhesive. Because ring boundaries would be difficult to distinguish when the cores were soaked, permanent marks, such as pinpricks by a sharp dissecting needle, were made on their suppression and release years before submerging.

Subsequently, each core was isolated from its mount and cleaned by water to remove the remaining glue. An individual core was cut at the minimum suppression and maximum release years by a powered miter/cut-off saw (see Figure 3.7). Each cut section (disk) was approximately 1-mm thick and parallel to the selected ring boundaries. In case the ring of the target years were less than 1-mm wide as occasionally found at minimum suppression years, wood from their adjacent years would be included to achieve the desired thickness. For a minimum suppression year, narrower ring of the adjacent year (preceding or subsequent year) to it was included first. If this did not add up to 1 mm, the other would be added. For a maximum release year, the same manner for incorporating wood was also applied except that instead of

selecting the narrower ring, wider ring was selected. In case the ring of the target years were more than 1-mm wide as occasionally found at maximum release years, wood from the middle section of the target years would be cut. This way, wood samples had neither large vessels formed in the early part of the growing season nor small vessels formed in the last part of the growing season. At this point, two disks were sampled (one from minimum suppression year, the other from maximum release year).

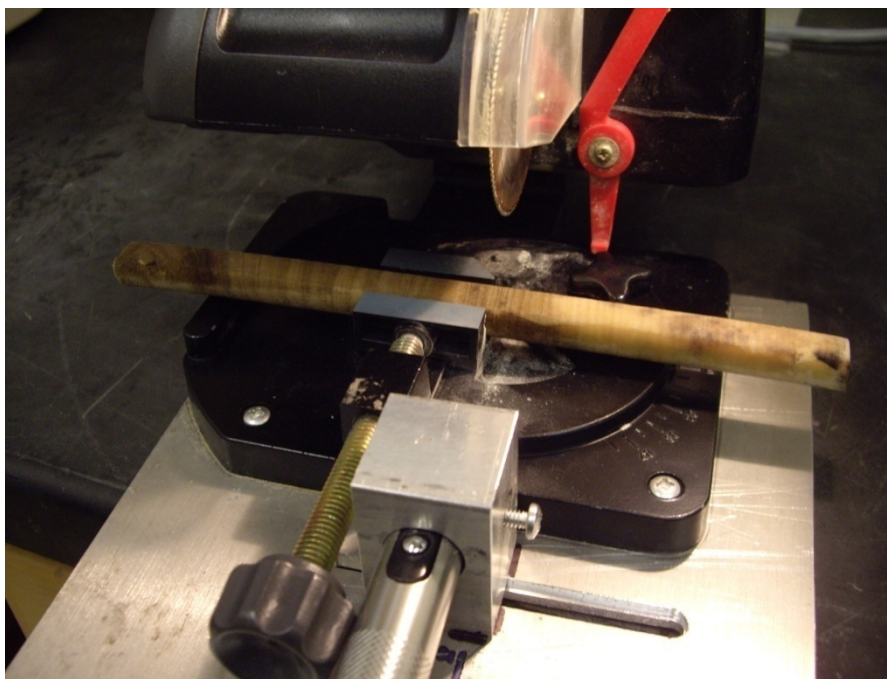
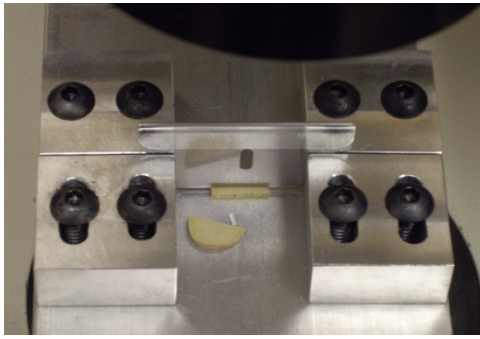


Figure 3.7. Powered miter/cut-off saw

A single-edge razor blade was used to cut a disk parallel to the grain direction—1-mm-wide stick (see Figure 3.8a). Cutting under a stereo microscope, combined with a guide base, increased the accuracy (see Figure 3.8b). The stick was cut again with the razor blade to 4 mm long. Cutting in this manner was intended to avoid the influence of cross grain, which would reduce the ultimate load in proportion to the grain angle.

Because the dimension of a specimen was limited by the core's size (12.5 mm in diameter), the target dimension for all specimens was approximately 1 × 1 mm in cross section and 4 mm along the grain. Figure 3.9 shows a drawing of the test sections (minimum-suppression-year and maximum-release-year sections) and the compression test specimens. Zink-Sharp (2005) also suggested that this size is ideal for intra-ring samples for most tree types and growth conditions. Up to six specimens could be attained from one disk. Finally, specimens from selected growth rings would proceed to moisture conditioning.

Specimens from the same minimum suppression or maximum release year were held in a tray and placed into a temperature/humidity chamber that was used to produce controlled conditions of temperature and humidity at 24°C and 39% *relative humidity* (H) setting for two days. This setting was aimed at creating the same environment in which the samples were tested for the compression strength. The average moisture content (MC) of the specimens after conditioning was 6.7%. A layer of cheesecloth covered the tray to keep the specimens in place (see Figure 3.10).



(a)



(b)

Figure 3.8. (a) one-mm-wide stick cut from a disk, (b) the microscope and guide base aiding cutting

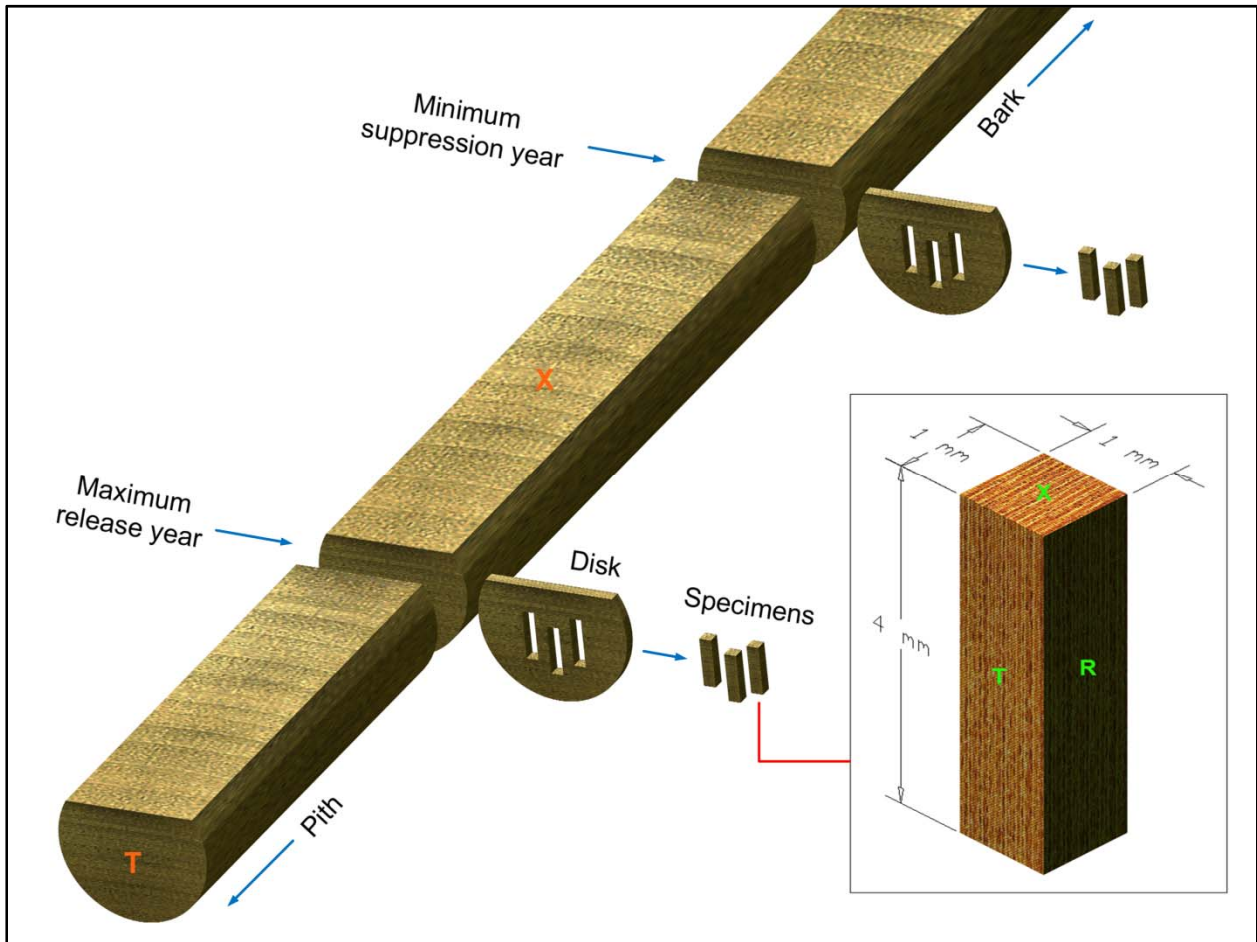


Figure 3.9. Schematic drawing of the test sections and test specimens

X: cross-section, R: radial, T: tangential surface.



Figure 3.10. Specimens placed in a tray

3.3.2 Procedures before compression test

After two days, three specimens ($n = 3$) were randomly selected within the suppression and release year. Six pictures were taken of each specimen (one from each side) by a trinocular stereo zoom microscope with a digital camera and the use of *Image-Pro[®] Plus v. 5.1.2* (Media Cybernetics, Inc.), an image analysis program. A picture of an objective micrometer was also captured to be used for the length calibration. These pictures would be used to justify the correctness of the specimens' dimension, *grain angle* (θ), and *ring angle* (ϕ).

To ignore the effect of cross grain on the ultimate crushing stress, we assumed that the grain angle and ring angle of samples were zero degrees. This meant the orthotropic and geometric axes of samples were coincident (Bodig and Jayne [1982] 1993). Figure 3.11 shows pictures taken from the digital camera of the three surfaces. The cross-sectional dimension and length of the specimen were measured to the nearest 0.01 mm using a digital caliper (Mitutoyo

Corp., ABSOLUTE Digimatic 500-196). The specimen was weighed to the nearest 0.01 mg with a METTLER TOLEDO analytical balance (AB135-S/FACT).

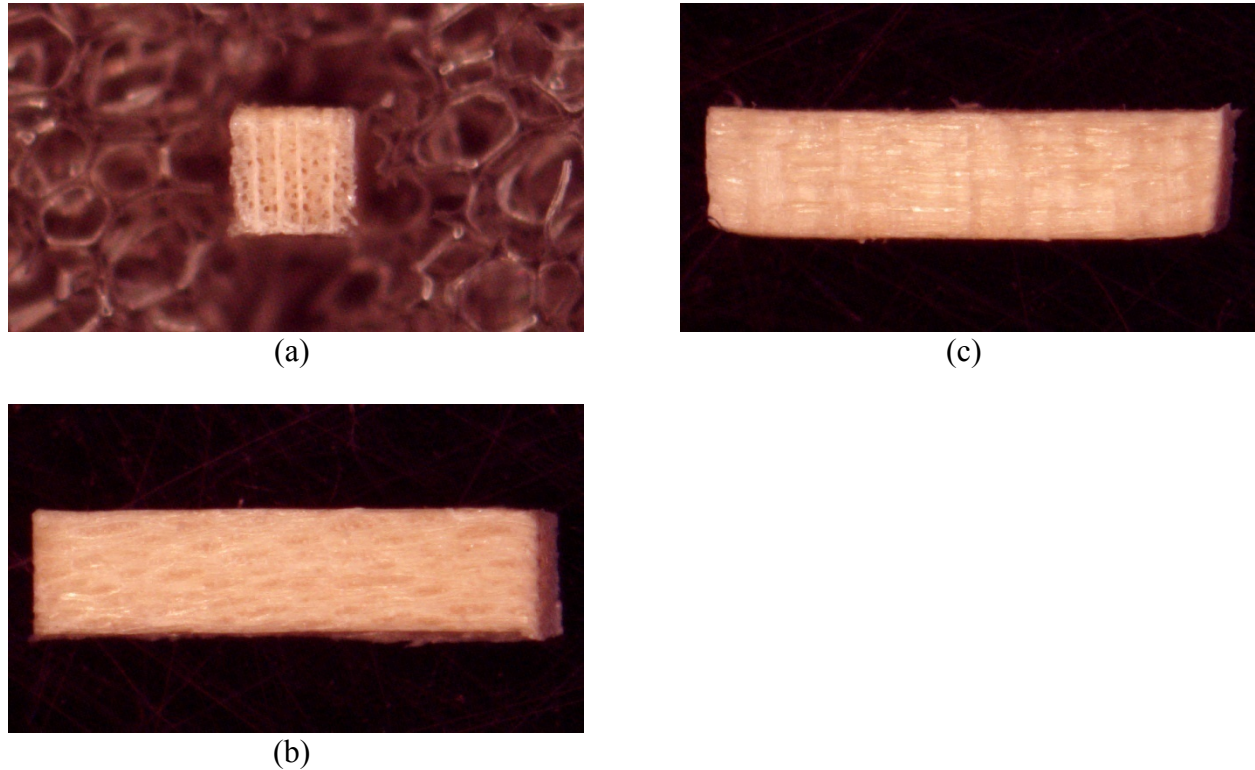


Figure 3.11. An example of specimen's pictures taken from three surfaces

(a) cross-sectional, (b) tangential, (c) radial.

3.3.3 Compression parallel to grain test

Next, a Fullam No. 18200 series, 45.4 kg testing frame equipped with an Admet data acquisition software (Ernest F. Fullam, Inc., Latham, NY, USA), was used to perform the compression parallel to grain test (see Figure 3.12).

The compression tests were performed at the room temperature 24°C and 39% H. A rate of motion of the moveable crosshead of 0.029 mm/min was modified from 0.012 mm/min, according to the ASTM D 143-94 (2003a) for a nominal specimen length of 4 mm, to produce a

continuous and uniform load. A slight preload (0.5 N) was imposed on the specimens to ensure contact with the load faces and minimize shifting during loading. One side of the crosshead was allowed to slightly float and this also aided in minimizing misalignment during loading. These methods followed ones from Zink-Sharp (2005).

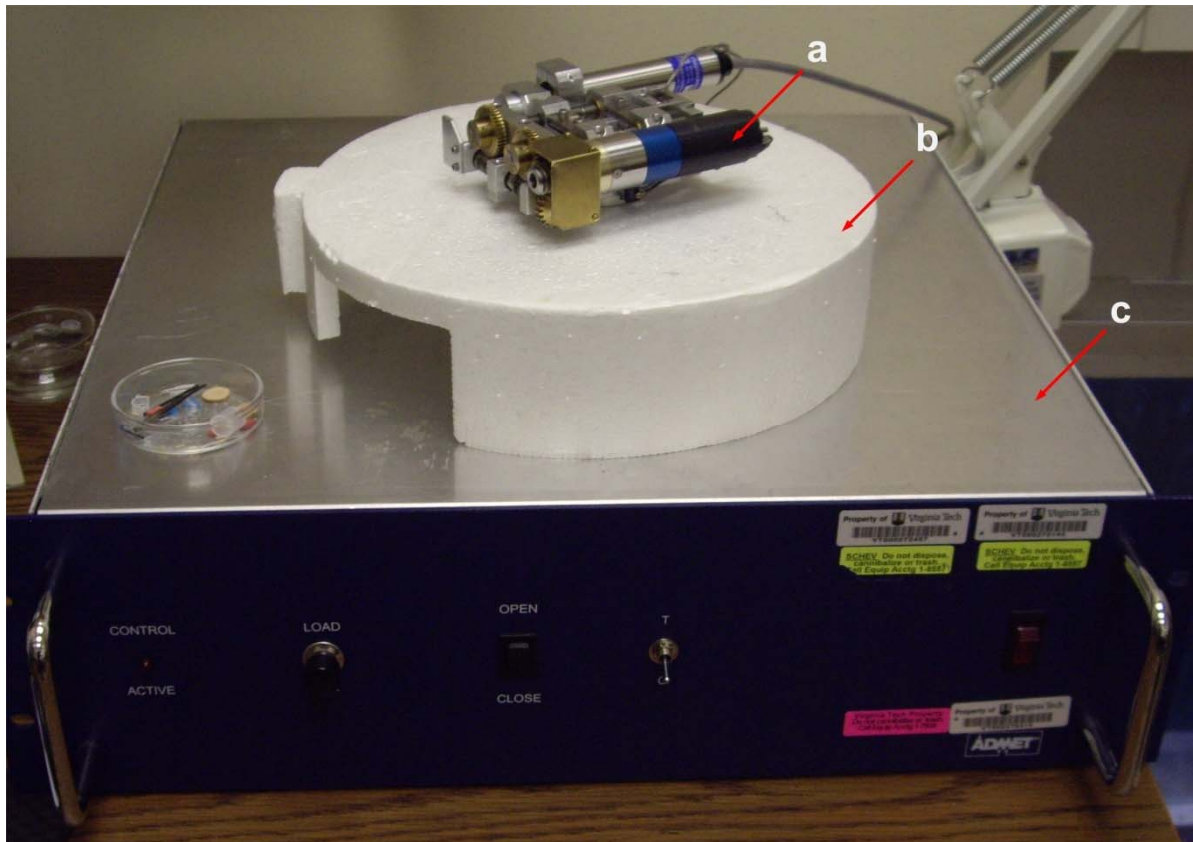


Figure 3.12. Fullam micro-mechanical test system and the Admet control box

(a) Fullam testing frame, (b) foam base, (c) Admet control box.

To assist in loading the specimen, a small support was placed at the center of cross head and then the specimen was laid on top of it (see Figure 3.13). After the preload was applied, the support was removed.

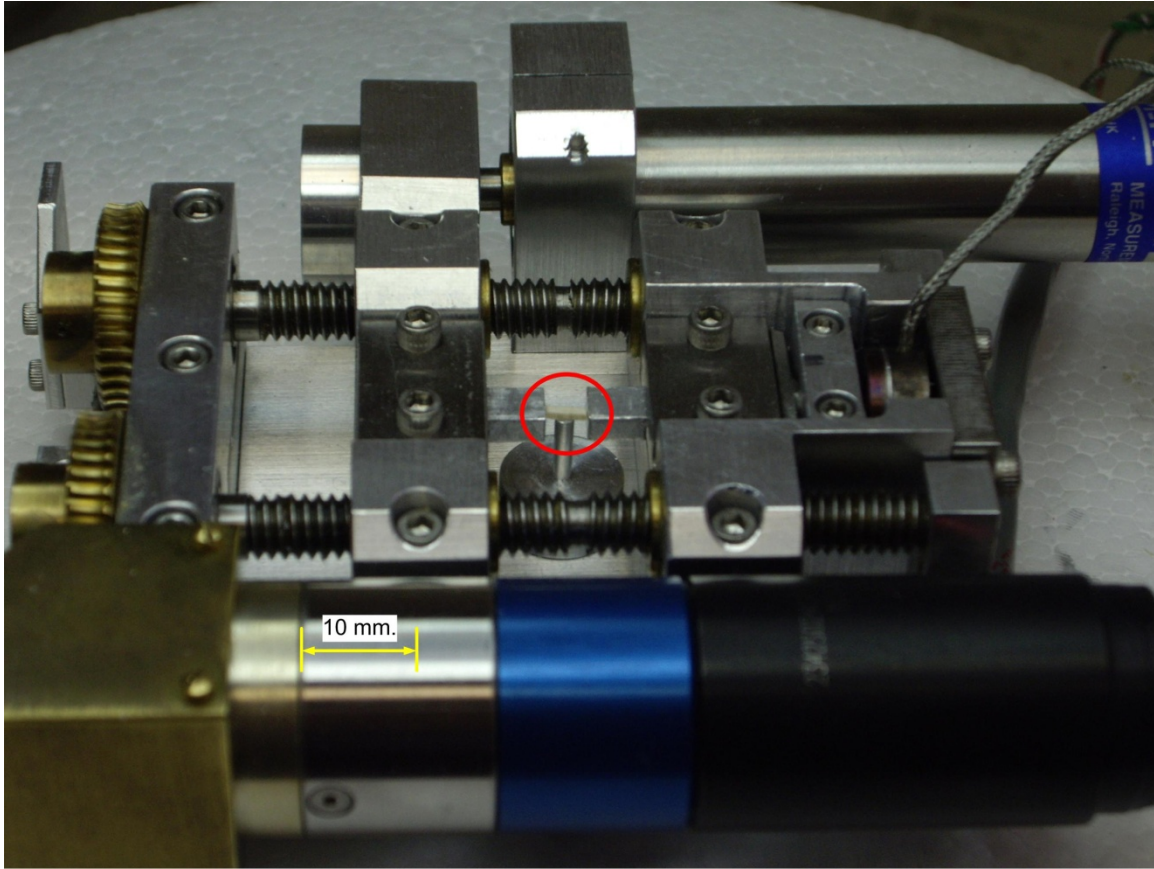


Figure 3.13. Loading a specimen (1×1×4 mm) in place

Red circle, a compression specimen

Load in Newtons and associated deformation in mm were recorded from zero to the load at failure (ultimate load). The deformations were read to 0.1 μm . The ultimate crushing stress (ultimate stress) was calculated by MTESTWindow™ (ADMET, Inc.) and automatically reported on load/position plots. MTESTWindow™ is a Windows-based data acquisition software and a part of the MTESTWindow™ Materials Testing System. The ultimate crushing stress was defined by continuing the testing until failure. In this study, failure was defined by maximum load or by a condition of excessive deformation, whichever occurred first, according to Goodman and Bodig (1971). A five percent strain value was also used to define maximum

allowable strain. Figure 3.14 shows an example of a load-deformation diagram and definition of ultimate crushing stress.

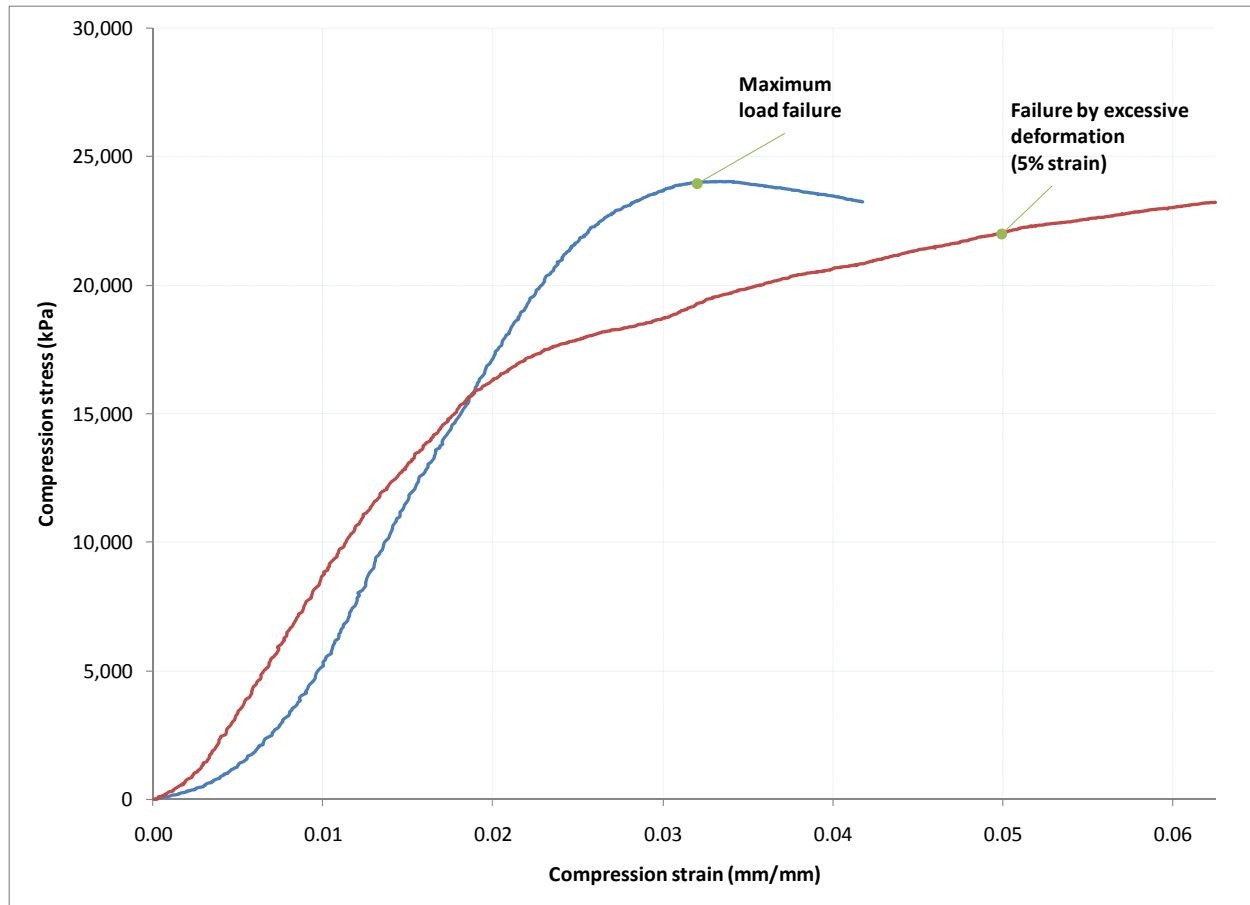


Figure 3.14. Load-deformation diagram and definition of ultimate crushing stress

Graph adapted from Goodman and Bodig (1971).

3.3.4 Procedures after compression test

The moisture content was determined by oven-drying methods outlined in American Society for Testing and Materials (ASTM) D 4442-92, method B (secondary). In addition, specific gravity (SG) was determined by procedures in accordance with ASTM D 2395-02 (2003b), method A (green-volume by measurement and oven-dry weight basis).

3.4 STATISTICAL METHODS

3.4.1 Analysis of variance

The one-factor *analysis of variance* (ANOVA) was used to test hypotheses that three-region means of difference—between the maximum release and minimum suppression years—in the ultimate crushing stress were all equal at $\alpha = .05$. The between-subjects variable was region location (region 1-3), and the dependent variable was ultimate crushing stress. All data sets adhered to the assumptions of independence of observations, equal population variances, and population normality.

3.4.2 Paired sample t test

From each core, the sample mean ultimate crushing stresses and specific gravity from minimum suppression and maximum release years were computed (three samples from both minimum suppression and maximum release year). Because the same core was used to obtain the ultimate crushing stress representing both populations—minimum suppression and maximum release years, we had dependent samples; therefore, the data were thought of as “paired data.” These data were analyzed using a paired samples *t* test. The pairs of interested parameters—ultimate crushing stress and specific gravity—were compared directly to each other by using the difference in their numerical values, paired difference (Johnson and Kubly 2004). These differences then allowed us to concentrate on the effects of suppression and release years that were freed from extensive dissimilarity in the experimental cores such as environmental and genetic influences. The tests were carried out using $\alpha = 0.05$. The data structure of a paired *t* test is given in Table 3.3, where the observations on the *n*th pair are denoted by $(\sigma_{u,Sn}, \sigma_{u,Rn})$.

Table 3.3 Data structure of paired t test sampling

Core	σ_u		$\Delta \sigma_u$
	Suppression	Release	Difference
1	$\sigma_{u,S1}$	$\sigma_{u,R1}$	$d_1 = \sigma_{u,S1} - \sigma_{u,R1}$
2	$\sigma_{u,S2}$	$\sigma_{u,R2}$	$d_2 = \sigma_{u,S2} - \sigma_{u,R2}$
.	.	.	.
.	.	.	.
.	.	.	.
n	$\sigma_{u,Sn}$	$\sigma_{u,Rn}$	$d_n = \sigma_{u,Sn} - \sigma_{u,Rn}$

Additionally, one important assumption or condition for the paired samples t test—the sampling distribution of the population of differences (d_n s) was approximately normal—was tested using the normal probability plot and the Shapiro-Wilk test because in this study we had a small samples (only 23 observations). All statistical calculations were made using a combination of a spreadsheet program—*Microsoft® Office Excel 2007* (Microsoft Corporation)—and a statistical software—*JMP® version 7.0* (SAS Institute Inc., Cary, NC).

3.4.3 Wilcoxon’s matched-pairs signed-ranks test

The Wilcoxon matched pairs signed ranks test is a nonparametric test, which does not require the population distribution to be normal (Johnson and Bhattacharyya 2006). It makes use of the sign and the magnitude of the rank of the differences between pairs of measurements, and it provides an alternative to the paired t test (Ott and Longnecker 2001; Schlotzhauer 2007).

3.4.4 Analysis of covariance

An analysis of covariance (ANCOVA) procedure was conducted to test for the main effects and interaction of the independent variables—using site locations (region 1-3) and sample sections (maximum release vs. minimum suppression year) as the independent variables, with ultimate crushing stress as dependent variable, and using specific gravity as a covariate variable. Analysis of covariance statistical test was used because the regression of ultimate crushing stress on specific gravity for each combination of site location and sample section is of interest to predict the effect of specific gravity on ultimate crushing stress. The null hypotheses for main effects were as follows: (a) there will be no difference in ultimate crushing stress varied according to site location (region 1, region 2, region 3); and (b) there will be no difference in ultimate crushing stress varied according to sample section (maximum release year, minimum suppression year). The null hypothesis for interaction effects was as follows: there will be no influence on ultimate crushing stress associated with the joint effects of site locations and sample sections.

3.4.5 Simple linear regression model

The linear regression analysis was used to predict ultimate crushing stress (dependent variable) based on specific gravity (independent variable) from all three populations (site locations) and from both sections (maximum release and minimum suppression years). A null hypothesis (H_0) that the true slope (β_1) equals 0 was tested. If this $H_0: \beta_1 = 0$ is true, a change in specific gravity yields no predicted change in ultimate crushing stress, and it follows that specific gravity has no value in predicting ultimate crushing stress (Ott and Longnecker 2001). The formal assumptions—the errors are normally and independently distributed with mean 0 and

variance σ^2 , abbreviated NID $(0, \sigma^2)$ — required to derive the significance tests were also checked through residual analysis (Montgomery et al. 2006). The *coefficient of determination* (R^2) that measures the strength of the linear relation between specific gravity and ultimate crushing stress was also attempted.

Chapter 4 Results and Discussion

Figure 4.1 shows an example of radial growth chronologies of a 53-year-old yellow-poplar tree (GPF-01-YP-793-S) established in 1953 and its corresponding suppression, release, minimum suppression, and maximum release years. A pattern of decreasing growth with age was observed from 1953 to 1991, followed by a rapid growth increase until 1996 when its radial growth reached $> 3.3 \text{ mm year}^{-1}$. The tree had a major suppression in 1977 with the lowest %GC of -55%. Within the subsequent 5 years, the minimum ring width occurred in 1982, and by our definition (from Section 3.2.6) this year was the minimum suppression year. The major release year was recorded in 1991 with the highest %GC of 596%. Within the next 5 years, the maximum ring width lay in 1996 which was defined as the maximum release year. As Nowacki and Abrams (1997) and Copenheaver and Abrams (2003) pointed out that at both ends (in this study, the first four years and the last five years) lay the regions that cannot be evaluated with this technique. Consequently, any suppression or release events occurring during these periods (1953-1956 and 2001-2005) could only be determined by visual analysis.

Figure 4.2 illustrated the growth-ring boundaries—including the major suppression, minimum suppression, major release, and maximum release years—of the same sample shown in Figure 4.1 captured by the Microtek ScanMaker 8700 scanner (Microtek International, Inc., Carson, CA, USA).

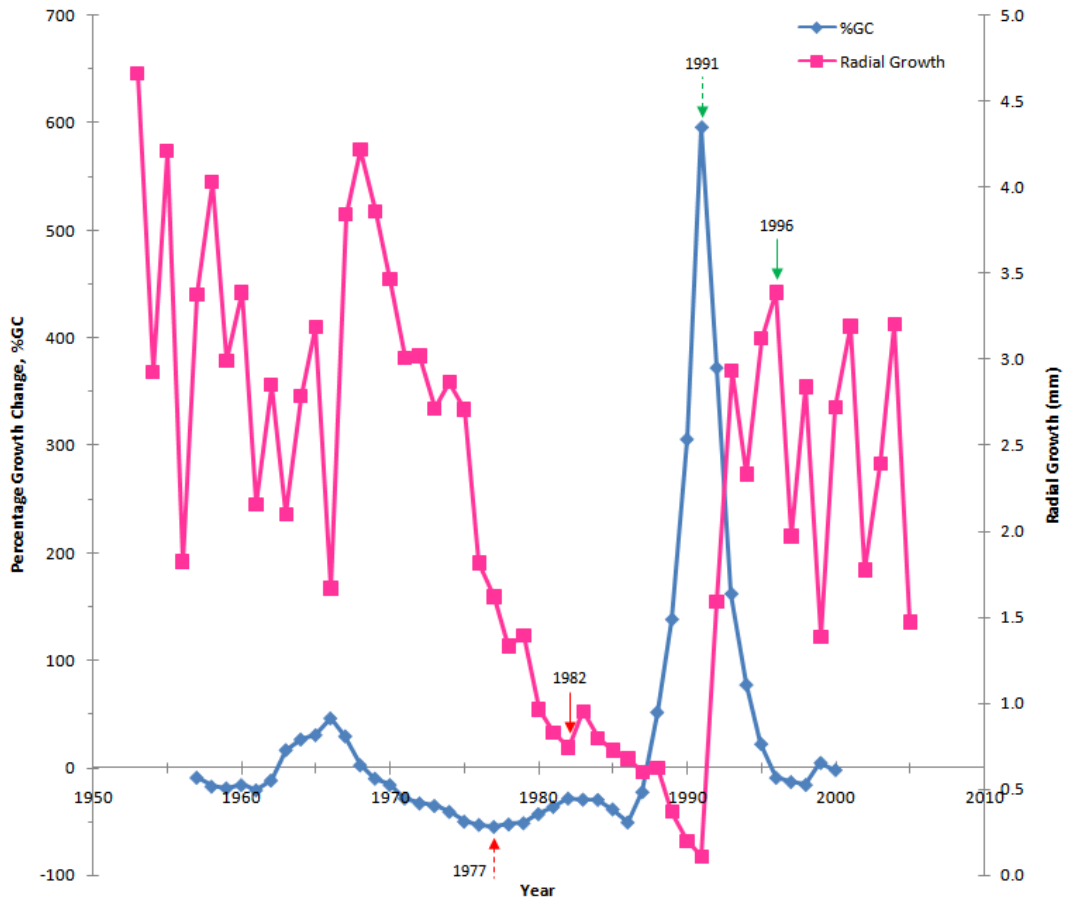


Figure 4.1. An example of the percentage growth change (blue line with diamond) and radial growth chronologies (pink line with square) of a selected core, GPF-01-YP-793-S.

Notes: The dash red arrow demarcates the major suppression year (1977), and the solid red arrow demarcates the minimum suppression year (1982) deriving from the RGA criteria adapted from Lorimer & Frelich (1989) and Nowacki & Abrams (1997).

The dash green arrow demarcates the major release year (1991), and the solid green arrow demarcates the maximum release year (1996).

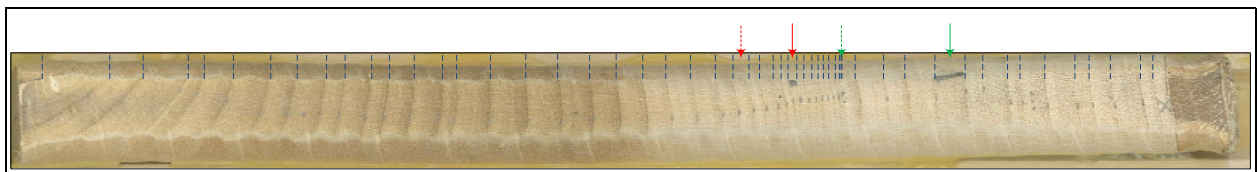


Figure 4.2. An example of a tree ring sequence (GPF-01-YP-793-S)

Note: Dash-blue line, growth-ring boundaries; dash-red arrow, major suppression year; red arrow, minimum suppression year; dash-green arrow, major release year; green arrow, maximum release year.

4.1 Effects of site locations on the mean difference between the minimum suppression and maximum release years wood properties

Ultimate crushing stress data were analyzed to determine the statistical significance of mean ultimate crushing stress differences between minimum suppression and maximum release years among site locations (region 1-3). Results were analyzed using a one-factor ANOVA, between-subject design. This analysis indicated that there were no significant differences in ultimate crushing stress differences between the three site locations, $F(2, 20) = 1.18, p = .328$. The sample means are displayed in Figure 4.3, which shows that the three site locations demonstrated similar difference of the ultimate crushing stress between the maximum release and minimum suppression years, although region 3 appeared to have higher mean difference of ultimate crushing stress than that of region 1 and 2.

Results for the mean, *standard deviation* (SD), *coefficient of variation* (CV), minimum, and maximum of the *ultimate crushing stresses* (σ_u), *specific gravity* (SG), and *ring width* (RW) of minimum suppression and maximum release years are summarized in Table 4.1. Compared with the data of mechanical properties of small clear yellow-poplars at 12% moisture content from the Wood Handbook (1999), the mean ultimate crushing stress of the minimum suppression and maximum release years were lower than that from the Wood Handbook (mean = 38,200 kPa, CV = 18%). In contrast, the mean specific gravity of both minimum suppression and maximum release years were higher than the Wood Handbook (mean = 0.42 based on oven-dry weight and volume at 12% moisture content, CV = 10%).

The conventionally-used bases for determining and comparing compression parallel to grain (a.k.a., ultimate crushing stress) and specific gravity are at green or 12% moisture content

basis (American Soc. for Testing and Materials (ASTM) 2003a). However, for the purpose of this study and because of atypical size ($1 \times 1 \times 4$ mm) of the specimens, the value of ultimate crushing stress and specific gravity (see Table 4.1) may not need to be corrected to 12% moisture content.

It should be noted that the mean ring width of the maximum release year was 4.7 times as wide as that of the minimum suppression year. The minimum suppression year shows a larger variation in all of the variables studied (ultimate crushing stress, specific gravity, and ring width) than the maximum release year, as indicated by the higher numbers of coefficient of variation.

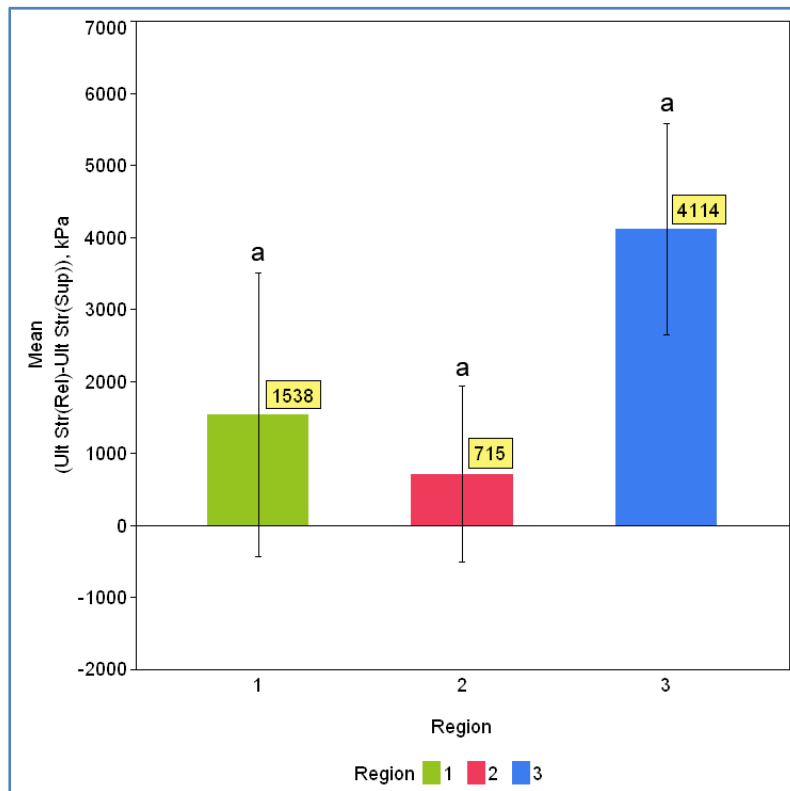


Figure 4.3. Effect of site locations on the mean difference, between the maximum release and minimum suppression years, in the ultimate crushing stress

Notes: Region 1, Duke Forest (NC) and Long Gone LLC (VA); region 2, Clemson Experimental Forest (SC); region 3, University of Tennessee Forest (TN).

The means with the same letter are not significantly different at 95 percent significance level.

Table 4.1. Summary of test results for 23 yellow-poplar trees

	Minimum suppression year	Maximum release year
ULTIMATE CRUSHING STRESS, σ_u		
Mean (kPa)	26,290 A ^d	28,326 B
SD ^a (kPa)	5,107	3,878
CV ^b (%)	19.42	13.69
Minimum (kPa)	18,976	22,681
Maximum (kPa)	36,375	38,052
SPECIFIC GRAVITY^c, SG		
Mean	0.48 a	0.49 b
SD	0.06	0.05
CV (%)	14	10
Minimum	0.34	0.41
Maximum	0.63	0.58
RING WIDTH, RW		
Mean (mm)	0.797	3.738
SD (mm)	0.575	2.134
CV (%)	72.1	57.1
Minimum (mm)	0.118	1.364
Maximum (mm)	2.476	10.202

^aSD, standard deviation

^bCV, coefficient of variation

^cBased on unextracted oven-dry weight and volume at test (ca. 7.6% moisture content)

^dValues with the same capital letter are not statistically different at 95 percent significance level.

4.2 Effects of minimum suppression and maximum release years on ultimate crushing stress

Figure 4.4 shows a bar chart of the ultimate crushing stress of the minimum suppression and maximum release years of all 23 cores. As can be seen, about 70% (16 out of 23 cores) of the cores had maximum release year's ultimate crushing stress higher than that of minimum suppression years.

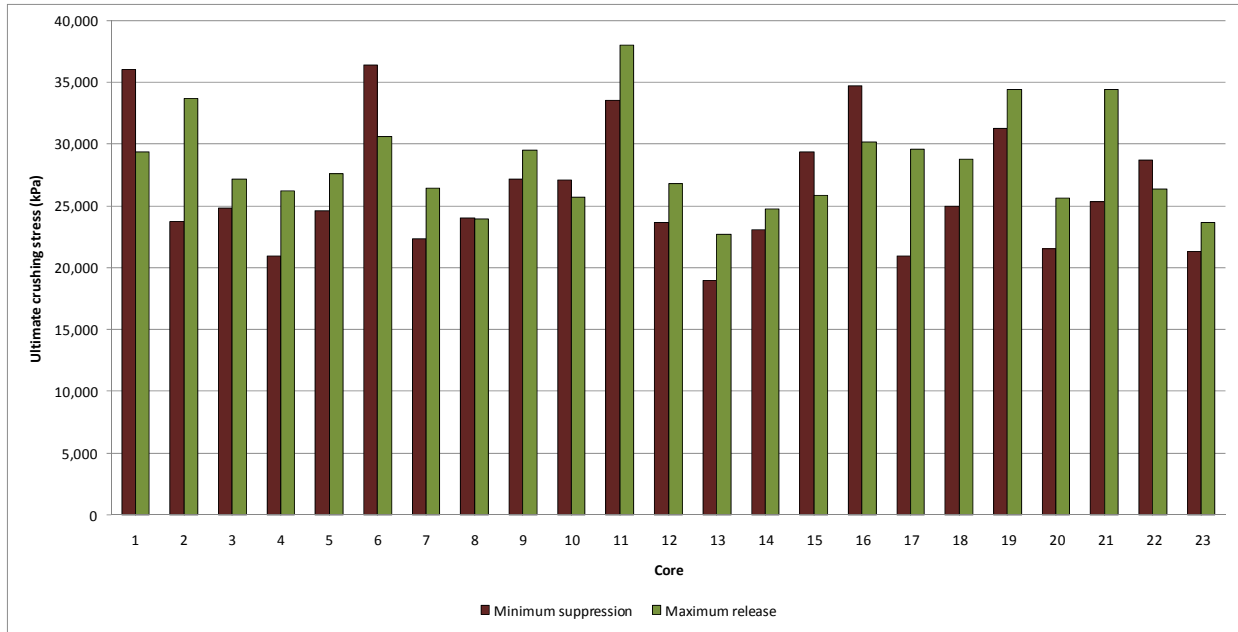


Figure 4.4. Ultimate crushing stress of minimum suppression and maximum release years by cores

Notes: The values for ultimate crushing stress at test (ca. 7.6% moisture content).

Cores no. 1–8 were collected from Duke Forest (NC) and Long Gone LLC (VA). Cores no. 9–16 were collected from Clemson Experimental Forest (SC). Cores no. 17–23 were collected from University of Tennessee Forest (TN).

Results were analyzed using a paired-sample *t* test. This analysis revealed a significant difference between mean ultimate crushing stress observed in the minimum suppression and maximum release years, $t(22) = 2.188$; $p = .02$, which indicated that the mean ultimate crushing stress of maximum release year was higher at the .05 level of significance. Figure 4.5 shows a boxplot of ultimate crushing stress by sample section that suggests that mean ultimate crushing stress appears higher in the maximum release year than in the minimum suppression year (28,326 kPa vs. 26,290 kPa). The difference between the stress was 2,036 kPa, and the 95% confidence interval for the difference extended from 106 to 3,965 kPa.

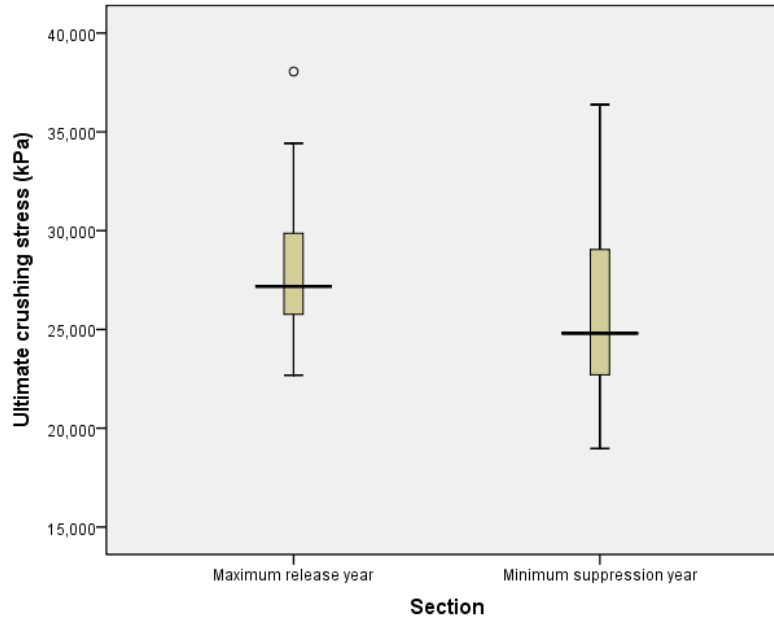


Figure 4.5. Ultimate crushing stress as a function of sample section

Note: The line through the middle of the box represents the median. Box extends from 25th to 75th percentile. Whiskers (bars) extend above and below the box observed values within 1.5 box lengths. The outlier (o) is the value between 1.5 and 3 interquartile range (IQR) from the end of the box.

By using the RGA technique combined with the micromechanical evaluation of wood, we can examine how strong the wood produced in minimum suppression and maximum release years are. Additionally, if we are interested in wood of a particular year, the micromechanical technique also allows us to do such a test. If the objectives of the landowner are to grow yellow-poplar trees having high compression strength, these results suggest that management practices producing conditions similar to those where a maximum release year occurs be followed. Another great advantage of maximum release year is that wood produced has a comparatively wider growth ring width, thus creating a bigger tree. Although we can readily identify where a maximum release and minimum suppression years are in a tree ring sequence, there is no systematic approach to predict when they will occur. A maximum release year always occurs

after a release year in the same way that a minimum suppression year follows a suppression year. It is more understandable and applicable to create released growth if a max release year is needed.

Limited studies have been reported on the effect of suppressed or released growth on the mechanical properties of wood especially by using the RGA technique. One of the main reasons is that the RGA technique has mainly been used in dendrochronological studies, e.g., for deriving past canopy disturbances, reconstructing past insect outbreaks, and recreating stand dynamics. None of the previous uses appear to be directly applicable to mechanics of wood.

Since density and specific gravity is positively correlated to ultimate crushing stress of a wood specimen, the following section will investigate this relationship.

4.3 Effects of minimum suppression and maximum release years on specific gravity

The other main question addressed in this study was that how wood specific gravity was influenced by minimum suppression and maximum release years. Figure 4.6 shows a bar chart of the specific gravity of the minimum suppression and maximum release years of all 23 cores. As can be seen, only 61% (14 out of 23 cores) of the cores had maxi. release year's specific gravity higher than that of minimum suppression years.

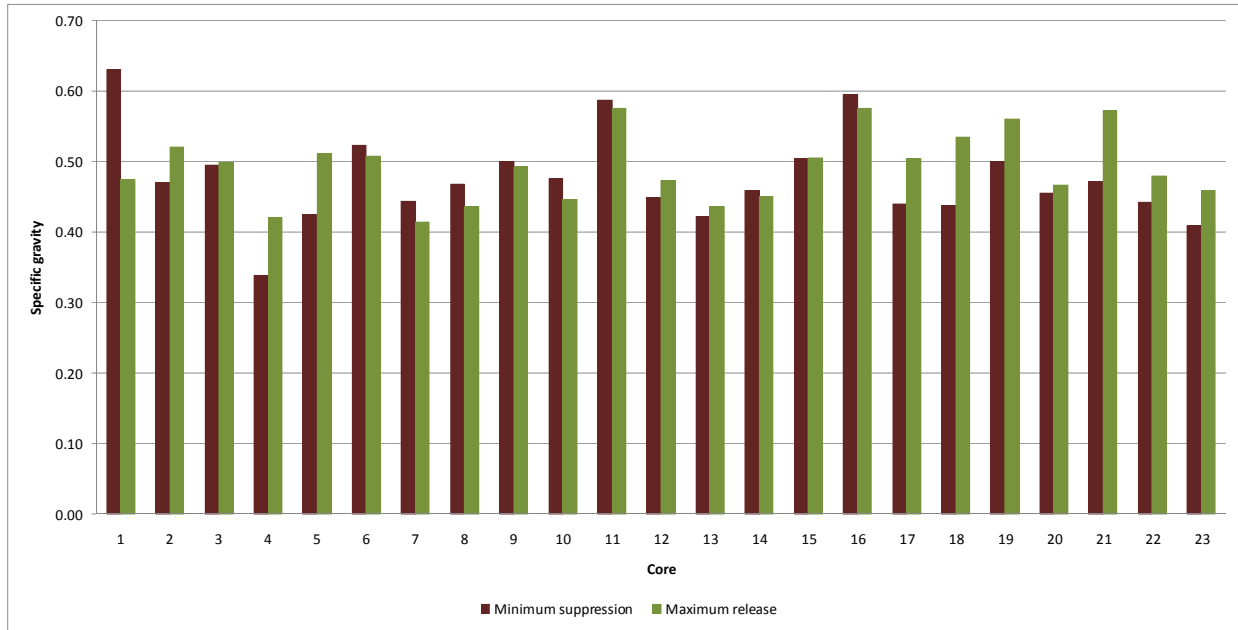


Figure 4.6. Specific gravity of minimum suppression and maximum release years by cores

Note: The values for specific gravity are based on unextracted oven-dry weight and volume at test (ca. 7.6% moisture content) basis.

A boxplot and normal Q-Q (quantile-quantile) plot of the specific gravity differences between minimum suppression and maximum release years are given in Figure 4.8 and Figure 4.9, respectively. The Q-Q plot shows the observed value and the value that is expected if the data are a sample from a normal distribution. If the data are a sample from a normal distribution, points should cluster along a straight line (Norusis 2006). The differences have an outlier and appear to not follow a normal distribution.

Thus, we applied the Wilcoxon matched pairs signed ranks test to evaluate the differences in specific gravity from minimum suppression and maximum release years. This analysis revealed a significant difference between mean specific gravity observed in the minimum suppression and maximum release years ($p = .042$) which indicated that the mean specific gravity of maximum release year was higher than that of minimum suppression year at

the .05 level of significance. Figure 4.7 shows a boxplot of specific gravity by sample section from which we can see that mean specific gravity appears somewhat higher in the maximum release year than in the minimum suppression year.

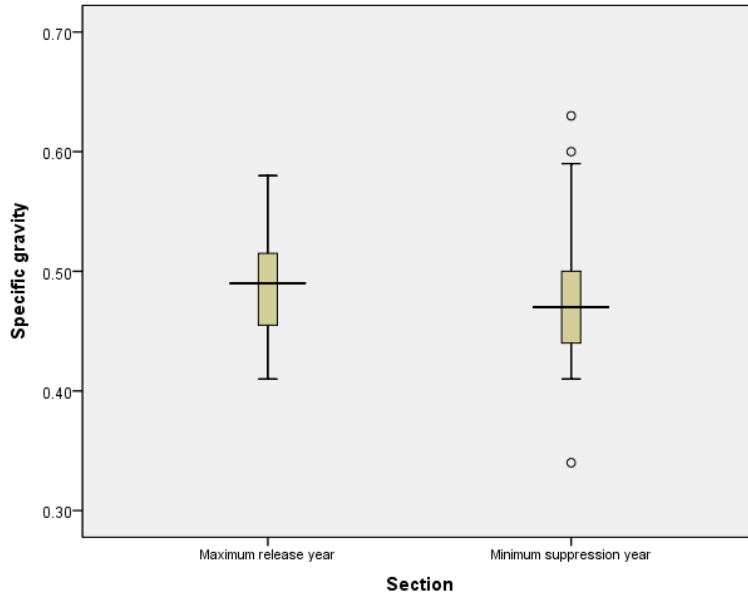


Figure 4.7. Boxplot of specific gravity by sample section

Note: Boxplot as in Figure 4.5.

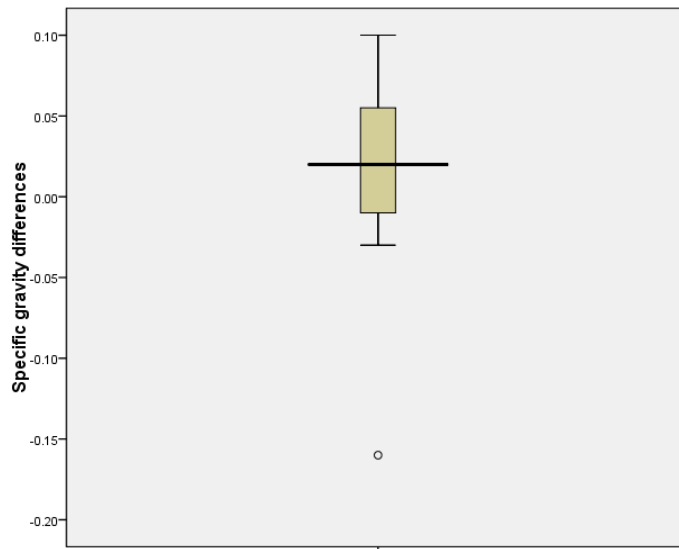


Figure 4.8. Boxplot of specific gravity differences

Note: Boxplot as in Figure 4.5.

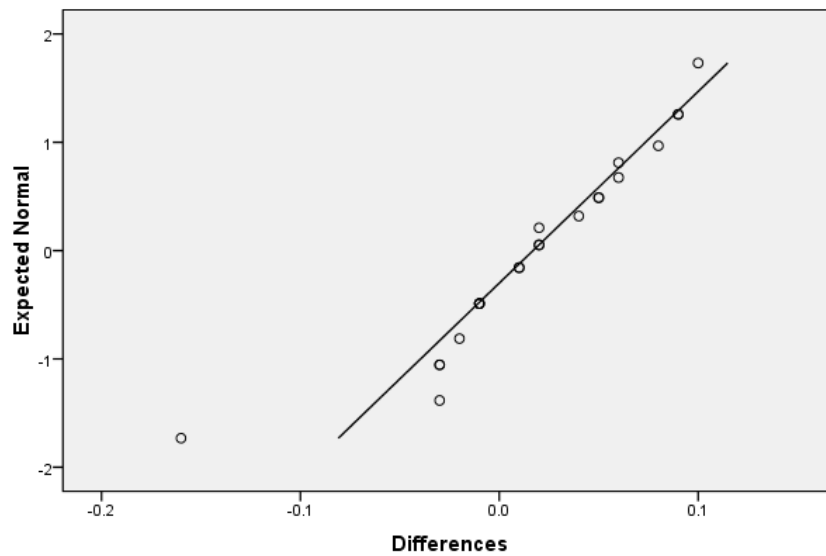


Figure 4.9. Normal Q-Q plot of specific gravity differences

The specific gravity of a given annual ring is a function of the average size of the completed cells and of their wall thickness, both of which depend heavily on whether they were differentiated during the early or late part of the season, that is in the case of conifers, the proportion of earlywood-to-latewood in an annual ring (Megraw 1985). In general, latewood—having a larger proportion of cell wall substance per unit volume than the earlywood in the same ring—has relatively higher specific gravity, and it would, in turn, be speculated that wood having a higher percentage of latewood would be stronger than that containing a smaller amount (Wakefield 1957). In hardwoods, specific gravity is influenced by vessel volume, ray volume, fiber diameter, wall thickness, fiber length, and parenchyma cells. Even though, yellow-poplar is one of the diffuse-porous hardwoods, which are composed of different kinds and varying proportions of cells, the similar idea of how cell anatomy affects the specific gravity can be applied (Zobel and Jett 1995).

The effect of suppression is typically to decrease total xylem increment and to change its distribution along the tree stem and branches. These changes may stem from late initiation of cambial growth, early growth cessation, or decrease in growth rate under extreme competition. The greater the level of suppression, the less likely a tree is to maintain physiological activity for a long time and consequently its competitive ability declines rapidly in the latter part of the growing season (Kozlowski 1971a).

Paul and Norton (1936) made a generalized assessment that in old yellow-poplar trees wood of low specific gravity caused by competition (for growing space, sunlight, moisture, and so forth) or other agencies will in turn result in the gradual suppression. They also added that: “Not only is the amount of wood actually formed much less, but also, since it contains a greater proportion of large thin-walled cells, the wood is lighter and softer.” On the other hand, the harder and heavier wood is formed during the early life of the tree while there is sufficient growing space.

According to Wooten et al. (1973), specific gravity increases slightly following release in yellow-poplar. Bollig (1994) found stemwood specific gravity of yellow-poplar from ground line to 4 m is significantly increased by crop tree release. This study shows a similar result that trees responds favorably to maximum release years by increasing specific gravity. Because specific gravity is a simple measure of the amount of cell wall substance present in a piece of wood, wood of higher cell wall substance occurs in maximum release years. The specific gravity in yellow-poplar is directly related to fiber wall thickness and vessel volume, i.e., thick-walled fibers and decrease in vessel volume were associated with greater specific gravity (Taylor 1965). Because trees have increased resource availability during maximum release years, it is

hypothesized that the trees lay down thicker cell wall throughout the annual ring in combination with smaller lumens, which can be varied with the environment (Zobel and Jett 1995).

4.4 Effect of specific gravity on ultimate crushing stress

An ANCOVA revealed no significant main effects for site locations ($F = 1.24, p = .303$) and for sample sections ($F = 0.12, p = .734$). There was no significant site location \times sample section interaction ($F = 0.86, p = .432$). Also, no significant interactions were present between specific gravity and either site location ($F = 1.53, p = .231$) or sample section ($F = 0.26, p = .611$). The specific gravity had an effect on ultimate crushing stress ($F = 63.22, p < .0001$). Now it would be safe to conduct a regression analysis, with specific gravity as the independent variable and ultimate crushing stress as the dependent variable for the combined values from all three site locations (region 1, 2, and 3) and from both sample sections (maximum release and minimum suppression years).

A linear regression analysis shown in Table 4.2 and Figure 4.10 indicated that 69.9% of the variation in ultimate crushing stress could be explained by specific gravity, $F(1, 44) = 102.19, p < .0001$, adjusted $R^2 = 0.69$. Because the p -value was fairly small, we could reject the hypothesis that specific gravity has no effect on ultimate crushing stress. Obviously there was evidence that ultimate crushing stress was linearly related to the specific gravity of a wood specimen, and specific gravity can explain large part of variation in ultimate crushing stress. The prediction equation is as follows: $\sigma_u = 67,003 (SG) - 5,101$. From the results we can infer that maximum release year creates a growing condition that leads to higher specific gravity which, in turn, is attributed to higher ultimate crushing stress.

Table 4.2. Results of fit ultimate crushing stress by specific gravity (SG) for combined populations

Linear Fit				
Ultimate crushing stress = -5100.962 + 67002.633*SG				
Summary of Fit				
RSquare		0.699018		
RSquare Adj		0.692178		
Root Mean Square Error		2552.233		
Mean of Response		27307.92		
Observations (or Sum Wgts)		46		
Analysis of Variance				
		Sum of		
Source	DF	Squares	Mean Square	F Ratio
Model	1	665644147	665644147	102.1883
Error	44	286611415	6513895.8	Prob > F
C. Total	45	952255562		<.0001*
Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-5100.962	3228.008	-1.58	0.1212
SG	67002.633	6628.133	10.11	<.0001*

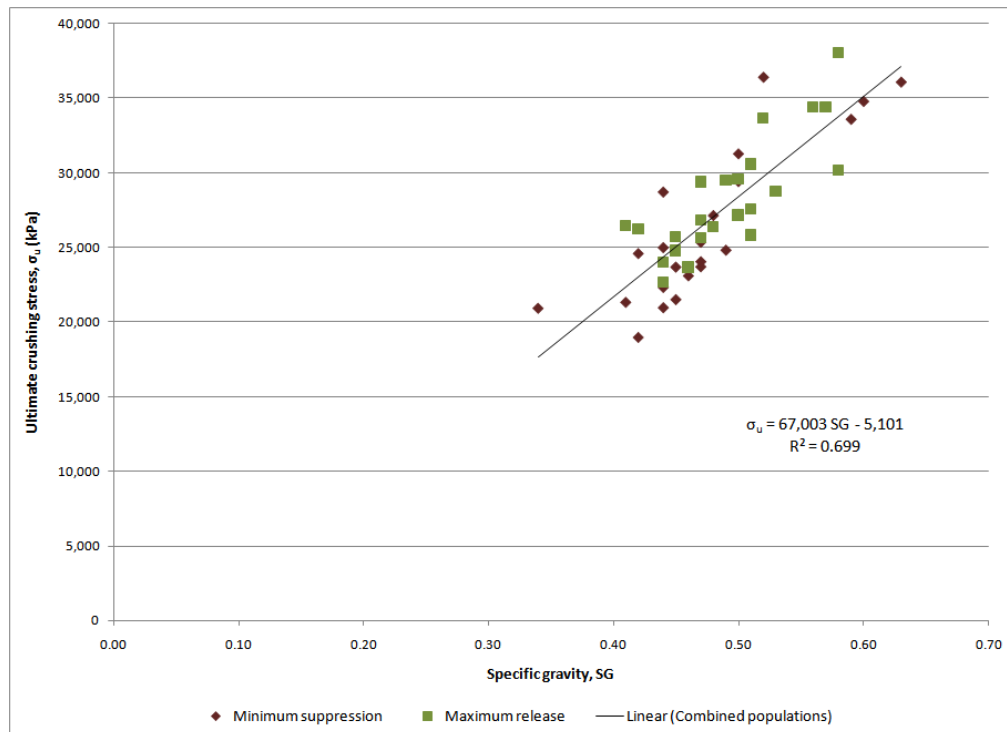


Figure 4.10. Scatter diagram of ultimate crushing stress versus specific gravity for combined populations

Note: The values for specific gravity are based on unextracted oven-dry weight and volume at test (ca. 7.6% moisture content) basis.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

The main purpose of this study is to better understand the effects of growth suppression and release on ultimate crushing stress and specific gravity for small-sized yellow-poplar (*Liriodendron tulipifera* L.) specimens. In addition, the relationship between specific gravity and ultimate crushing stress is investigated. The radial growth averaging (RGA) criteria method was modified and used to identify minimum suppression and maximum release years. Based on the present study, the following conclusions can be drawn:

- The mean ultimate crushing stress of maximum release years was significantly higher than that of minimum suppression years.
- The mean specific gravity of maximum release years was significantly higher than that of minimum suppression years.
- The ultimate crushing stress was linearly related to the specific gravity of a wood specimen.

Smith et al. (1997) stated that a forest stand is a dynamic, ever-changing, and living structure. The history of a tree is recorded by the sequences of wide and narrow rings (both gradual and abrupt). These patterns, including climatic and non-climatic information, could be

decoded by examining the tree growth rings. If the objective of foresters is to select wood suitable for structural applications or improving mechanical properties of wood, the modified RGA criteria proves to be reasonable.

5.2 Recommendations

Future research efforts that could be performed based on the results of the information developed in this study include the following:

1. It is hard to achieve the desired dimension of the specimens ($1 \times 1 \times 4$ mm) and the grain and ring angle of zero degrees. There is a good possibility that some error is associated with deviating from the target. Further investigations of sample preparations will certainly improve the precision of the end result.
2. Although the effects of minimum suppression and maximum release years on anatomical characteristics of wood were not performed in this study, variations in the ultimate crushing stress and the specific gravity are closely linked to the changes in cell characteristics. An analysis of the amount of cell wall substance present in the samples will gain an understanding of how cell characteristics may be affected by minimum suppression and maximum release years including suppression and release years in general.

Appendix A

An Example of the %GC Calculation Table

Year	Ring Width (mm)	%GC	Category
1953	4.662	NA	
1954	2.930	NA	
1955	4.212	NA	
1956	1.828	NA	
1957	3.380	-9.276	
1958	4.034	-17.590	
1959	2.996	-19.185	
1960	3.390	-16.214	
1961	2.160	-21.015	
1962	2.854	-11.896	
1963	2.102	16.398	
1964	2.788	26.283	
1965	3.190	30.335	
1966	1.672	45.978	
1967	3.846	29.269	
1968	4.220	2.291	
1969	3.860	-10.138	
1970	3.468	-16.032	
1971	3.008	-28.595	
1972	3.022	-33.201	
1973	2.718	-35.556	
1974	2.870	-41.084	
1975	2.712	-50.147	
1976	1.818	-53.135	
1977	1.624	-55.033	Major suppression year
1978	1.336	-52.722	
1979	1.398	-51.620	
1980	0.968	-43.141	
1981	0.832	-36.473	
1982	0.746	-28.636	Minimum suppression year
1983	0.954	-29.686	
1984	0.800	-29.860	
1985	0.730	-38.700	
1986	0.682	-50.869	
1987	0.602	-22.665	
1988	0.630	51.510	
1989	0.372	138.064	
1990	0.204	305.542	
1991	0.114	595.838	Major release year
1992	1.594	371.997	
1993	2.934	161.824	
1994	2.334	77.131	
1995	3.122	21.985	
1996	3.390	-9.361	Maximum release year
1997	1.974	-13.291	
1998	2.842	-15.986	
1999	1.390	4.529	
2000	2.722	-2.192	
2001	3.194	NA	
2002	1.778	NA	
2003	2.394	NA	
2004	3.206	NA	
2005	1.476	NA	

The table shows an example of the %GC calculation derived from the RGA technique. A 53-year-old yellow-poplar tree (GPF-01-YP-793-S) established in 1953. Its suppression and release years were 1977 and 1991, respectively. Accordingly, the minimum suppression and maximum release years were 1982 and 1996.

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