# Determining the Linear Viscoelastic Region of Sugar Maple Wood by Dynamic Mechanical Analysis

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Dynamic mechanical analysis (DMA) is a powerful analytical technique to study wood structure and properties. In order to draw firm conclusions from results obtained by DMA, strain rate of tests conducted by DMA should be within the linear viscoelastic region (LVR) of the tested material. In this study, the LVR limit of sugar maple (*Acer saccharum* Marsh.) wood specimens was determined in the three directions under a range of temperature and relative humidity (RH) conditions. The results demonstrated that wood had very different LVR limits in the different directions. The longitudinal direction had much lower LVR limits than the radial and tangential directions. While LVR limits were not strongly affected by changes in temperature and RH in the longitudinal direction, they proved very sensitive to these factors in the tangential direction. The results of this study showed the importance of determining LVR limits before running any test by DMA.

*Keywords: Wood; Linear viscoelastic region (LVR); Sugar maple; Strain; Relative humidity (RH); Temperature*

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## INTRODUCTION

As per Hooke's law, stress in an elastic solid is proportional to strain, the relationship between strain and stress being a constant that is specific to the spring. As the spring constant increases, the material becomes stiffer, and the slope of the strain/stress curve increases, showing an increment in the elastic modulus ($E$). Viscous properties are represented by the curved region, in which strain is not recoverable immediately. Polymeric materials are termed viscoelastic, as they present both viscous and elastic behaviors. After loading and upon unloading, a purely elastic material will immediately return to its initial state, giving back all the mechanically applied energy, while a purely viscous material will show a delay in response, never returning to its initial state and dissipating all the applied energy. Wood is a polymeric composite material displaying viscoelastic behavior, which simply means that its mechanical behavior involves both elastic and viscous components (Navi and Stanzl-Tschegg 2009). Wood elasticity is mainly determined by the stiffness and orientation of the crystalline cellulose microfibrils (*i.e.* microfibril angle (MFA)) within the secondary cell wall (Cave 1968; Salmen and Burgert 2009), while wood viscosity is based on the non-cellulosic polysaccharide matrix (Cave 1968; Navi and Stanzl-Tschegg 2009; Salmen and Burgert 2009).

Dynamic mechanical analysis (DMA) is an analytical technique used to probe and characterize viscoelastic response as a function of time, temperature, and applied stress

(Birkinshaw *et al.* 1986; Jiang and Lu 2008a,b; Obataya *et al.* 2003). The interactions between polymers in polymer blends and in copolymers have been widely investigated using various dynamic measurement techniques. However, wood, which is a natural polymer blend of three main polymers (*i.e.* cellulose, hemicelluloses, and lignin), has not been investigated to the same degree with that tool.

Besides strength and dimensional stability, viscoelastic properties are important in timber applications. The viscoelastic behavior of wood is a key factor in many aspects of the wood industry, particularly wood processing operations such as drying, thermal treatment, panel pressing, wood gluing, and so on. Dynamic mechanical analysis can give useful information on wood compatibility with other polymers, such as needed for the application of glue or paint to wood. The occurrence of defects such as warp, split, and collapse in finished lumber products may also be due to inappropriate wood drying practices. To develop optimal drying scenarios, one must understand the changes in wood properties occurring throughout the drying process, especially as they involve viscoelasticity. Temperature and moisture content levels dramatically affect the viscoelastic behavior of wood (Goring 1963; Irvine 1984; Obataya *et al.* 1998; Ranta-Maunus 1975; Takahashi *et al.* 1998). Many authors have investigated the viscoelastic behavior of various wood constituents (Hilis 1984; Irvine 1984; Matsunaga *et al.* 2000; Obataya *et al.* 1998; Olsson and Salmén 1997; Takahashi *et al.* 1998), wood itself (Backman and Lindberg 2001; Hamdan *et al.* 2000), and chemically treated wood (Obataya *et al.* 2000; Sadoh 1981; Sugiyama *et al.* 1998).

The dynamic rheology experiments conducted in DMA consist of applying a sinusoidally varying strain (within the linear viscoelastic response region, LVR). LVR is defined as the region corresponding to the stress varying linearly with strain for the analyzed sample. In fact, within the LVR of the material, the response (*e.g.*, strain) is directly proportional to the mechanical input (stress); polymer packing is not altered, and the response reflects the polymer structure and organization. Another important aspect of conducting DAM test within the LVR is that stimulus and response of tested materials have the same frequency, which means that the mathematical description of the data is accurate, and this is important when the absolute values of modulus and tan $\delta$ are being used to interpret structure/property relations. The LVR limit is defined as the value of the stress or strain at which the stress/strain plot deviates from linearity, where the degree of deviation is arbitrarily defined by the investigator. Points outside the LVR can cause irreversible physical changes in the normal polymer packing (Menard 2008). The response could then reflect other phenomena, such as rupture mechanisms under extreme strain. The force producing the strain must be sufficient to allow for recovery of the material within its elastic region. In a strain-controlled test, an elongation is specified and the DMA machine applies the force required to produce the necessary strain. As long as the operator chooses a strain such as elongation that remains within the LVR of the material, the data will be reproducible and easy to describe mathematically.

Given their polymeric nature, wood molecules move from the glassy state to a rubbery state as a function of temperature or stress frequency. The response of the material changes with a decrease in the storage modulus and a maximum in damping occurring at the transition between two states (the glass transition, $T_g$).

Although conducting DMA experiments on wood within LVR limits is essential to obtain reliable results, the determination of the LVR limit as a function of wood direction, temperature, and relative humidity (RH) has not received enough attention.

Jiang and Lu (2009) recently studied the impact of temperature on the LVR of wood. Laborie *et al.* (2004), López-Suevos and Frazier (2005 and 2006), and Sun *et al.* (2007) addressed the variation of LVR in dried wood in relation to wood species, grain orientation, and temperature changes. Chowdhury and Frazier (2013) reported that the LVR of yellow poplar (*Liriodendron tulipifera*) is affected by grain orientation, temperature, and solvent. They also emphasized the importance of running DMA tests within the LVR limit. No comprehensive research has yet been conducted on the effects of moisture content and temperature. Most critically, the combined effects of RH and temperature on LVR have not been addressed. Older DMA machines lacked a humidity control function, which made it almost impossible to study the effects of humidity and temperature at the same time. Water is known to act as a very efficient plasticizer in wood, and plasticization affects the mechanical properties of wood, particularly its viscoelastic properties.

The recent introduction of a DMA machine equipped with RH control has paved the way for studies on the concurrent effects of RH and temperature on the LVR limit, which will help researchers to produce data that are both credible and reproducible. The main objective of this study was to determine the LVR limit of sugar maple wood specimens in the three main directions of wood as a function of temperature and RH. Sugar maple was chosen for this study because it is one of most important wood species in Canada with a wide range of applications.

## EXPERIMENTAL

### Materials

The wood specimens used for this study were selected from sugar maple (*Acer saccharum* Marsh.) wood blocks free of any defects, *i.e.* with perfectly straight grain and growth ring orientation. The blocks were selected visually and dried down to constant mass in a dryer at 54.4 °C and 70.9% RH. The blocks were then conditioned at 20 °C and 65% RH. When equilibrium moisture content (EMC) was achieved, the specimens were cut to final sizes, *i.e.*: 40 mm in length x 5 mm in width x 1 mm in thickness.

### Methods

The LVR of the wood was determined with a DMA machine (TA Instruments Q800 DMA) equipped with DMA-RH Accessory, which allows for the mechanical properties of a specimen to be analyzed under constant and/or varying conditions of both RH and temperature. The tests were conducted in single cantilever mode (in a bending stress) under various temperature and RH conditions, *i.e.*: 30, 50, 75 °C and 10, 30, 50, 70, 90%, respectively. Three tests were run for each combination of temperature and RH. The tests were done in the longitudinal direction and, across the grain, in the radial and tangential directions. In each direction, the samples were loaded in a corresponding plane. In other words, when the data obtained in the tangential direction are discussed, it means that DAM machine loads the wood samples in tangential plane.

DMA measurements provide a complex modulus, $E^*$ (or $G^*$), consisting of two components: a) the elastic component ($E'$ or $G'$), which is the storage modulus of the material, representing the material's stiffness and the energy recovered when the stress is released; and b) the viscous component, which is the loss modulus ($E''$ or $G''$), representing the energy lost through friction and molecular motions. The ratio of the loss modulus to the storage modulus is tangent delta (tan $\delta$), which identifies energy dissipation maxima where mechanical stimuli are most effectively absorbed or damped.

To determine the impact of RH and temperature on the LVR, strain sweep tests were conducted in a range of amplitude (1 to 280 µm) and strain (0.0009 to 0.25%) conditions. The frequency was kept at 1 Hz for all measurements. Before the strain sweep tests, the wood specimens were exposed to the test conditions in the DMA humidity chamber until they reached constant weight.

*LVR determination*

It is well known that $E'$ decreases as strain increases. To establish the LVR of wood, $E'$ at 0.009% was considered as $E_0'$. The LVR was defined by the condition corresponding to strain causing a reduction in $E_0'$ of 5% or less. The strain causing an $E_0'$ reduction of exactly 5% determined the LVR limit. The same method was used by Jiang and Lu (2009) to determine the LVR. To normalize the value of E′, first the value of initial $E_0'$ was considered "1". The succeeding normalized E′ was obtained through dividing real value of $E'$ by real value of $E_0'$.

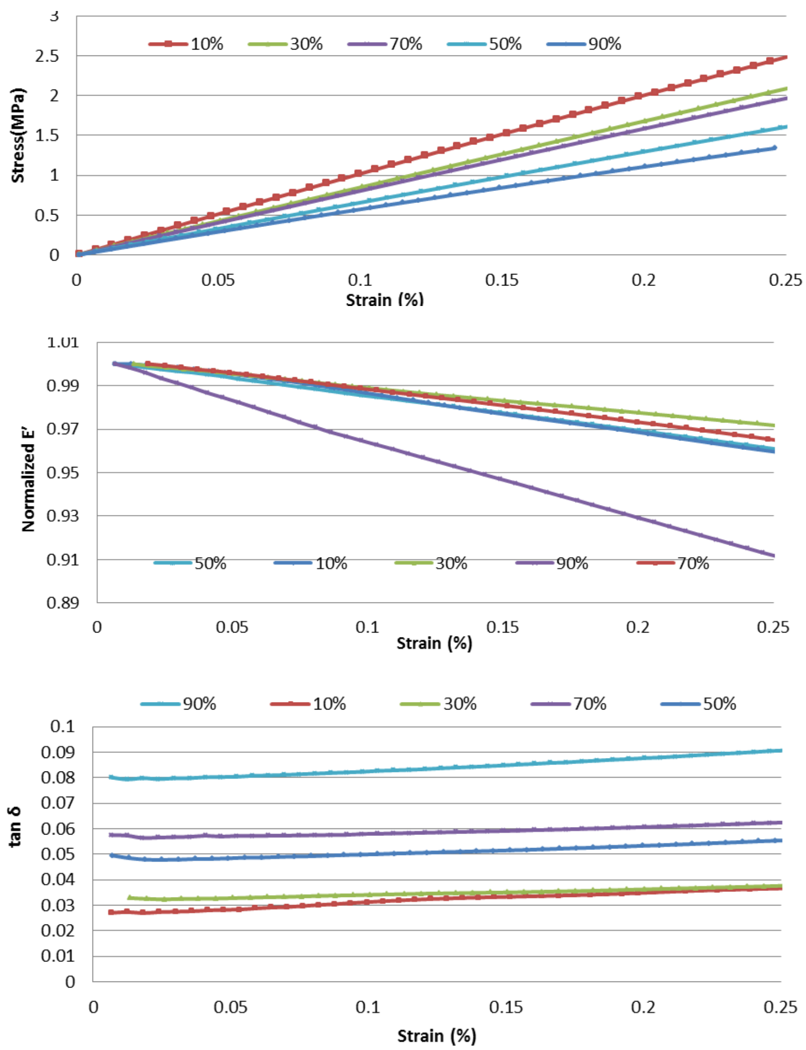


**Fig. 1.** Variations in viscoelastic properties by RH in tangential wood specimens at 30 °C

## RESULTS

### Tangential Direction

Figure 1 shows the results of strain sweep tests at 30 °C for the RH levels under study in the tangential direction. Stress was directly proportional to strain, and RH changes had no effect on proportionality. The minimum stress was found at 90% RH, indicating that a lower force was required at this RH level to induce a given strain. Low stress also meant that mechanical properties were lower at 90% RH than at the other RH levels. With one exception, the wood specimens displayed an elastic response to the load throughout the applied strain range, and the variation in $E'$ always remained below 5% of $E_o$. The exception related to the specimens that had been conditioned at 30 °C and 90% RH, with a LVR limit of 0.137% (Fig. 2). The high RH (90%) acted as a plasticizer and lowered the LVR limit. The absolute values of $E'$ decreased with strain and RH. The tan $\delta$ (loss factor) curves reached their minimum and maximum at 0 and 90% RH, respectively, which indicates that the specimens achieved their lowest and highest dissipated energy levels at the corresponding RH values. The tan $\delta$ curve for 90% RH was considerably higher than for the other levels. Figure 3 displays normalized $E'$, tan $\delta$, and stress for 10, 30, and 50% RH at 50 °C in the tangential direction, which are plotted against strain. No values could be obtained for 70% and 90% RH because conditioning the wood specimens to these levels at a temperature of 50 °C reduced the strength of wood so much that running strain sweep tests proved impossible. Under these conditions, the wood specimens exhibited plastic behavior.

At 10, 30, and 50% RH and 50 °C, the relationship between stress and strain was proportional. The amount of stress needed to apply a given strain decreased as RH increased. As can be seen in the normalized $E'$ curves, variations of $E'$ were always within the LVR and lower than 5% of $E'$. The tan $\delta$ curves had their highest and lowest values in the 10 and 50% RH conditions. No data are available for wood specimens conditioned at 10, 30, 50, 70, and 90% RH at 75 °C in the tangential direction, as a drastic reduction in wood strength of wood made sweep strain experiments impossible. Under these conditions, wood softened and became plastic. Comparisons between the results obtained at the three temperature levels (30, 50, and 75 °C) revealed that, at low RH levels, the difference between measured properties at 30 and 50 °C was not very great. By contrast, the wood specimens conditioned at 75 °C displayed totally different behaviors.

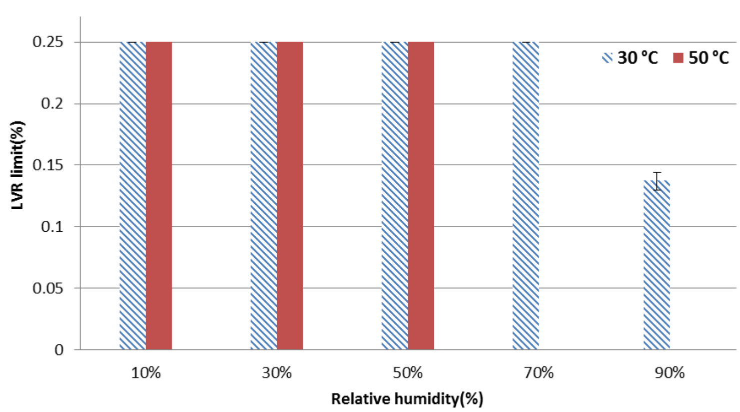


**Fig. 2.** Effect of temperature and RH changes on LVR limit for tangential direction

## Radial Direction

Figure 4 shows the normalized $E'$, tan $\delta$, and stress/strain curves at 30 °C for the different RH values in the radial direction. The stress/strain relationship was proportional. Stress reached its minimum and maximum values at 90 and 10% RH, which means that wood strength decreased with increasing RH. A reduction in $E'$ was observed as a higher strain rate was applied. The tan $\delta$ curves (Fig. 4c) demonstrated that higher RH resulted in higher dissipated energy. The LVR limit increased as the RH increased from 30 to 70% (Fig. 5) but decreased (from 0.203% to 0.142%) when the RH further increased from 70 to 90%. From these results it can be concluded that a little water induced more flexibility in wood but, under saturated conditions, water could lower the LVR limit.

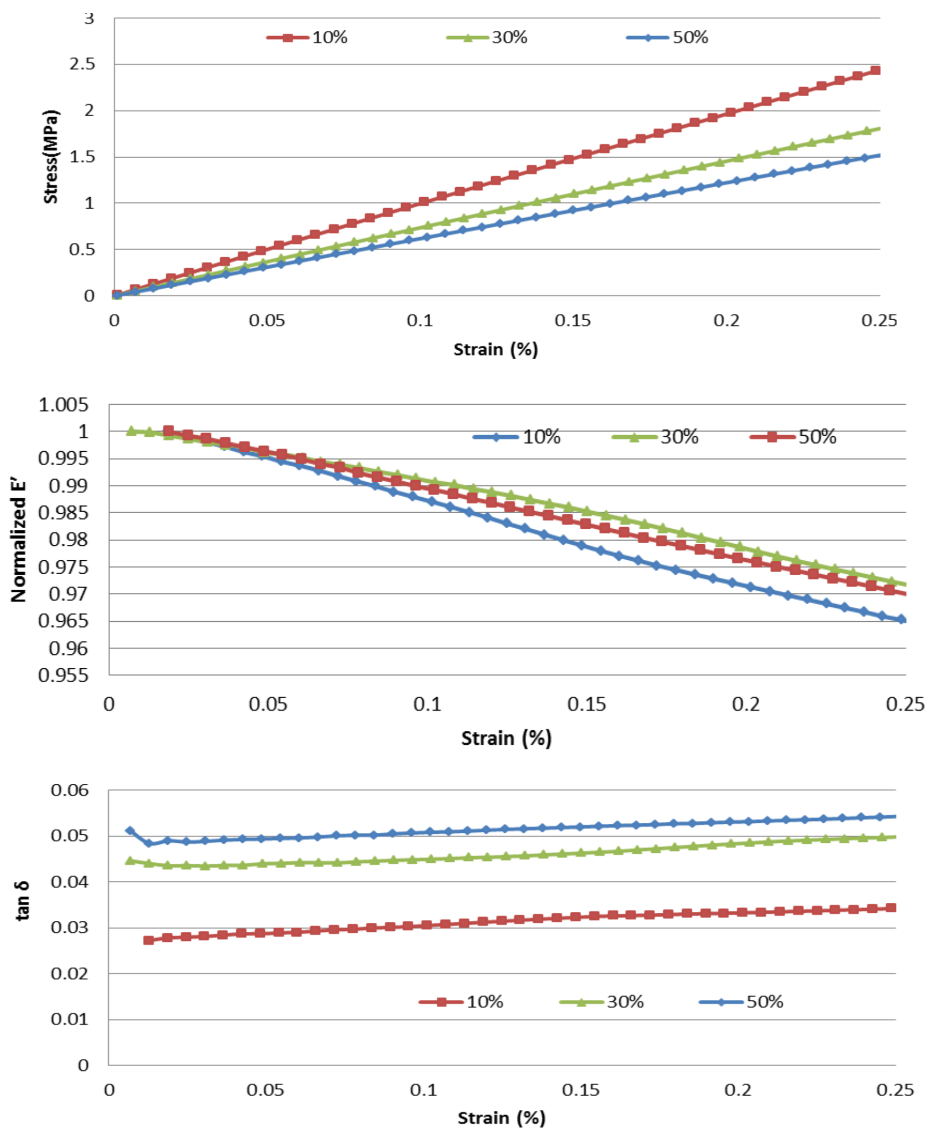


**Fig. 3.** Variations in viscoelastic properties by RH in tangential wood specimens at 50 °C

The normalized $E'$, stress/strain curves, and tan $\delta$ for radial wood specimens conditioned at the different RH levels and 50 °C are given in Fig. 6. The linear relationship between stress and strain was not affected by a rise in temperature from 30 to

50 °C (Fig. 6a). The force required to apply a given strain to the specimens decreased as the RH increased. By comparison with the values obtained at 30 °C, the stress was significantly lower at 50 °C, decreasing from 3.86 to 2.12 MPa (final strain) as the RH rose from 10 to 90%. *E′* progressively decreased as the strain sweep tests proceeded (Fig. 6b). The difference between wood specimens conditioned at 90% RH and the other specimens was more evident. Although the tan *δ* curves of specimens conditioned at 90% RH (Fig. 6c) were significantly higher than the others, the value of tan *δ* remained relatively constant throughout the sweep strain tests.

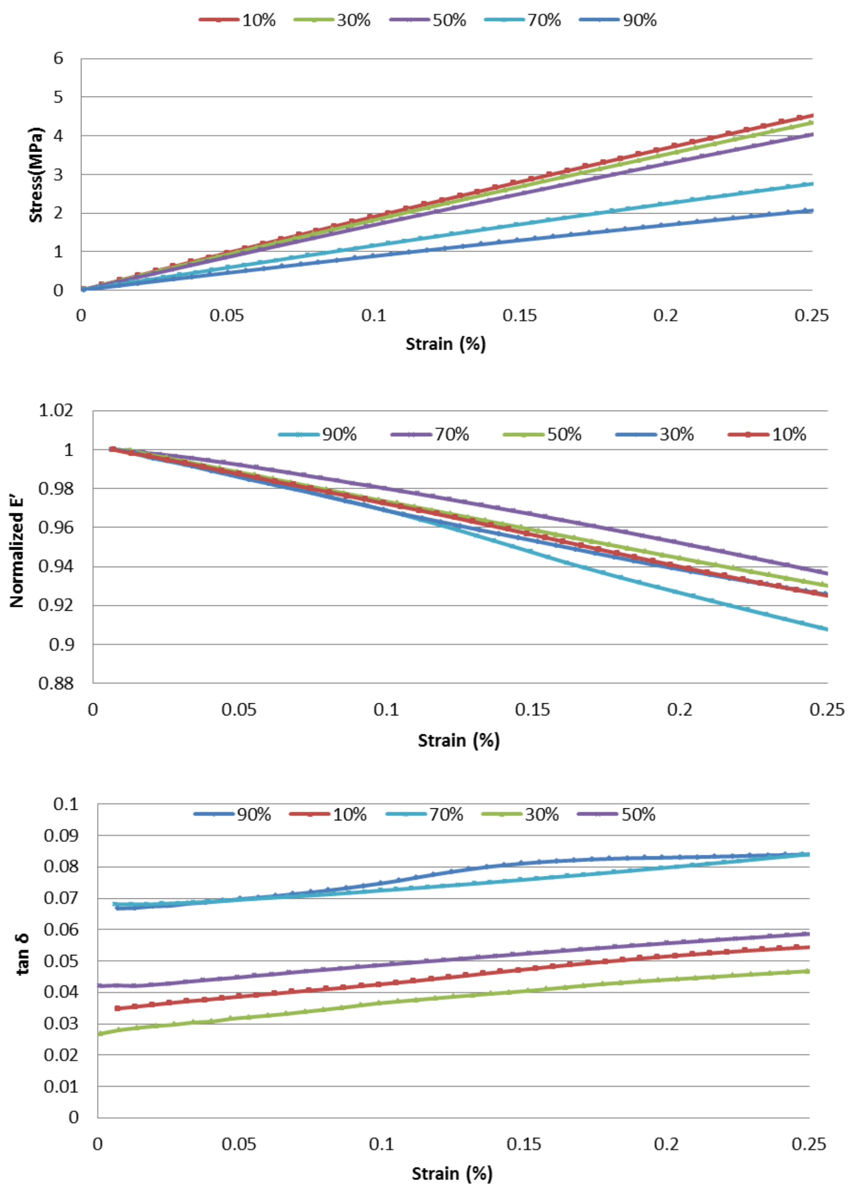


**Fig. 4.** Variations in viscoelastic properties due to RH in radial wood specimens at 30 °C

At 50 °C the LVR limit was affected by the RH level (Fig. 6). It first increased as the RH rose from 10 to 30%, but decreased somewhat as the RH rose further to 50 and then 70%. Conditioning wood at 90% RH greatly increased the LVR limit and kept *E′*

below 5% of $E_o$ up to the end of the sweep strain test, at 0.250% strain. Here again water acted as a plasticizing agent for wood. Enhanced polymer network flexibility due to the replacement of hydrogen bonding within the amorphous components with water-carbohydrate links can explain the increase in LVR limits (Placet *et al.* 2008).

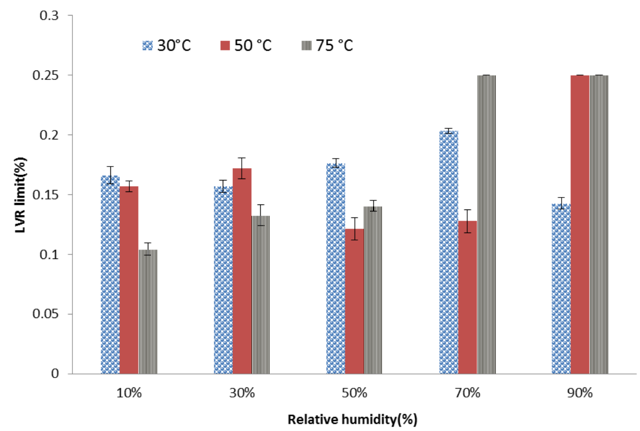


**Fig. 5.** Effect of temperature and RH changes on LVR limit for radial direction

Figure 7 shows the variations in normalized $E'$, stress/strain curves, and tan $\delta$ for radial wood specimens conditioned at various RH levels and 75 °C. The stress/strain relationship remained linear, stress rising constantly with increasing strain. The stress values were lower in wood specimens conditioned at a higher RH, this being particularly clear in specimens conditioned at 90% RH. With regard to the normalized $E'$, it declined as strain increased, the highest reduction in $E'$ being observed in specimens conditioned at10% RH. The tan $\delta$ values were also affected by RH. The tan $\delta$ curves of specimens conditioned at 10% and 70% RH showed the lowest and highest values of tan $\delta$, respectively. As for the LVR limit, it increased with increasing RH (Fig.5), the increase being more evident at 70 and 90% RH, at which point the $E'$ reduction was less than 5% of $E_o$ throughout the sweep strain tests.

Comparisons between the stress and $E'$ values in the radial and tangential directions across the whole range of temperature and RH conditions illustrate that the values of $E'$ were significantly higher in the radial direction than in the tangential direction. Backman and Lindberg (2001) reported that $E'$ radial was about double the value of $E'$ tangential. The difference was attributed to anatomical elements relating to grain orientation. Redman *et al.* (2011) reported that $E'$ was higher in the radial direction than in the tangential direction in four Australian hardwood species. Higher values for stress and $E'$ in the radial direction may be due to several factors. The wood is more uniform in the radial direction than in the tangential direction. The preferential organization of the cells due to the cell lines produced by the same mother cell in the cambial zone may provide another explanation of enhanced rigidity in the radial direction (Placet *et al.* 2007). Cell arrangements in early wood can be different in the radial and the tangential directions. In the radial direction, the cells are assembled in fairly straight rows, whereas in the tangential direction they lay in much a more disorderly manner (Holmberg *et al.* 1999). Panshin and Zeeuw (1980) stated that the differences in mechanical properties between the tangential and the radial directions relate to ray orientation in the radial direction. As the rays are broad in sugar maple (Panshin and

Zeeuw 1980), this factor should play an important role in viscoelastic property differences between the two directions. The ray cells aligned in the radial direction serve as reinforcement, resulting in an increase in the stiffness of the wood structure in that direction. Reiterer *et al.* (2002) also reported on the importance of radial reinforcement of the wood structure due to ray cells. The microfibril angles in the radially- and tangentially-oriented cell walls may differ, a condition which would also affect mechanical properties. Larger microfibril angles in the radial cell walls result in increased stiffness (Holmberg *et al.* 1999).

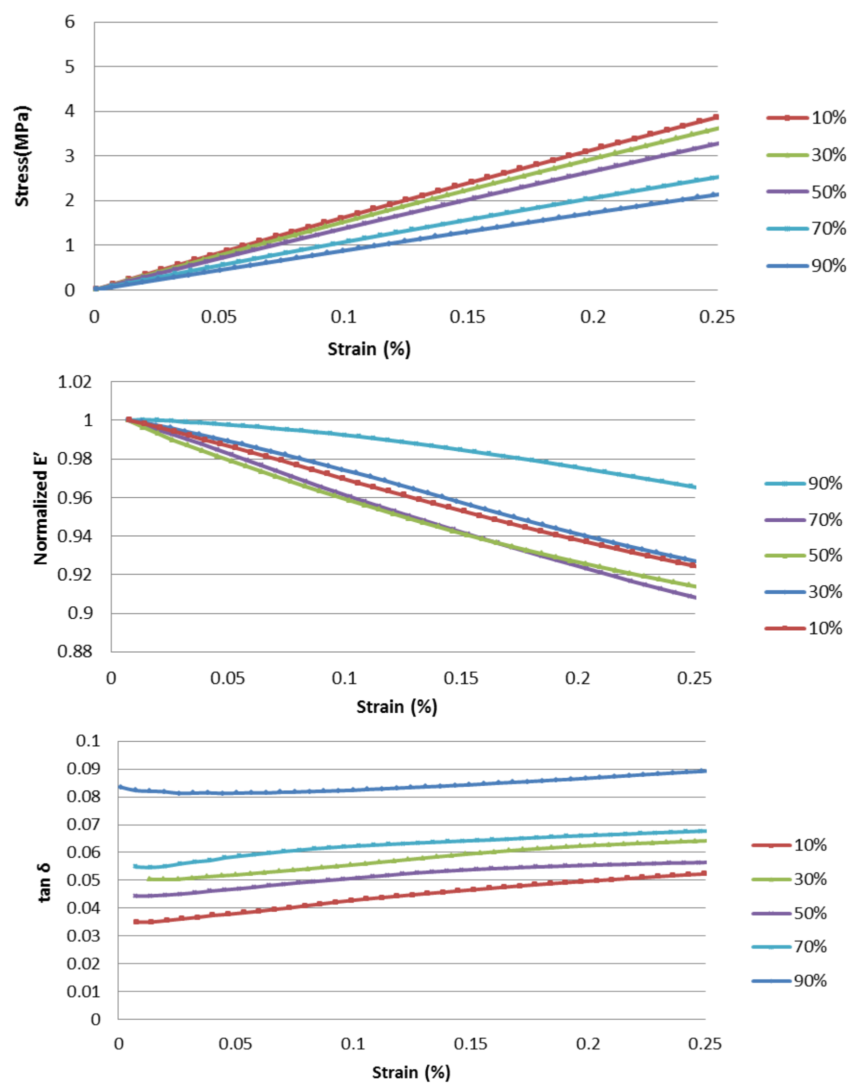


**Fig. 6.** Variations in viscoelastic properties by RH in radial wood specimens at 50 °C

The tangential direction showed higher sensitivity to temperature and RH variations, which was attributed to the role of lignin in the viscoelastic behavior of wood. Lignin softens under high temperature and RH conditions. Viscoelastic measurements conducted in the past revealed many differences in regard to the rheological behavior of wood according to anatomical direction. The greatest influence is believed to be the molecular structure of elemental wood components within the cell wall, which influence softening properties. Placet *et al.* (2007) stated that the viscoelastic wood behavior largely reflects the properties of lignin. To a lesser extent, the microfibril angle of the cell-wall layers may also have an influence. It is well known that wet wood softening occurs in the range of 50 °C to 100 °C, which is closely related to the lignin transition phase. Hemicelluloses and amorphous cellulose in wet wood have lower softening temperatures than lignin (Laborie *et al.* 2001; Olsson and Salmén 1992).

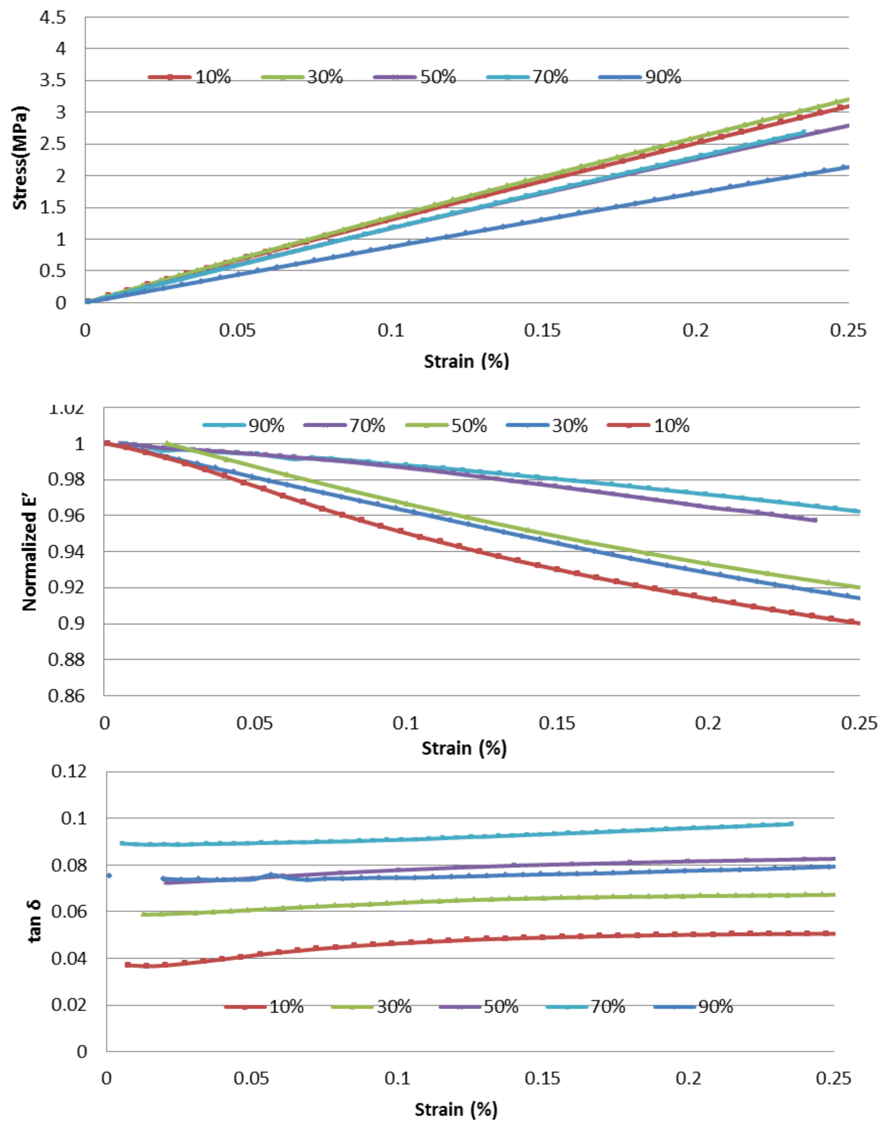


**Fig. 7.** Variations in viscoelastic properties by RH in radial wood specimens at 75 °C

Under water-saturated conditions, the properties of wood reflect, to a large extent, the properties of the wet lignin. Furuta *et al.* (2010), working on Japanese cucumber tree, reported the effects of lignin and hemicellulose on the thermal softening properties of water-swollen wood. Studies showed that the thermal softening temperature was more affected by changes in the quantity and quality of the lignin than by those of the hemicellulose. Salmén (2004) showed that the main wood softening phase, appearing between 50 °C and 100 °C, corresponded to the glass transition temperature of *in situ* lignin. Secondary relaxations corresponding to the softening of the other carbohydrates (amorphous cellulose and hemicelluloses) appeared at lower temperatures (Olsson and

Salmén 1992). As wood dries, hemicellulose plays a more important role on thermal softening temperature (Olsson and Salmén 1997; Yoshizawa *et al.* 1999).

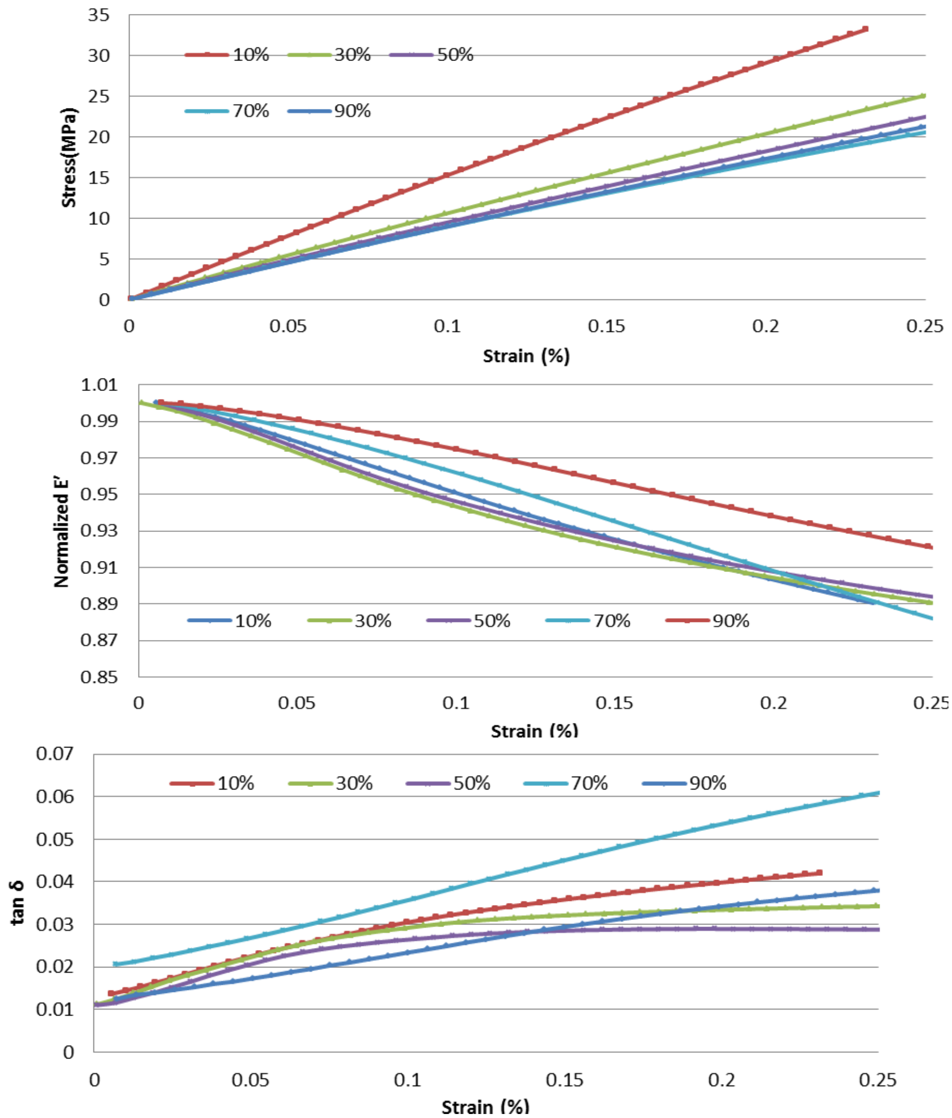


**Fig. 8.** Variations in viscoelastic properties by RH in longitudinal wood specimens at 30 °C

Wood softening was observed at different temperature and RH conditions, depending on wood direction. In the radial direction, the cell walls are mainly loaded in pure tension and compression, whereas, in the tangential direction, they tend to be loaded in bending. The shear stress due to bending induces some cellular sliding, which most probably occurs in the middle lamella. It is well known that the lignin distribution along the double cell wall is heterogeneous (Salmén 2004; Yoshizawa *et al.* 1999). According to Mark (1967), the lignin content is nearly two times higher in the middle lamella than in other wall layers. So it can be concluded that lignin plays a crucial role in the mechanical properties of wood in the tangential direction. Hence, any change in lignin can greatly impact the mechanical integrity of wood in the tangential direction. Given that lignin softens at temperatures as low as 50 °C under water-saturated conditions, the high sensitivity of viscoelastic properties to high temperature and RH in the tangential direction can be explained. It should also be taken into the account that the softening temperature was greater in the radial direction than in the tangential direction.

The tests showed that a small increase in RH can extend the LVR limit. Water has been reported to give rise to hydrogen bonds with methoxyl groups (Birkinshaw 1993; Obataya *et al.* 2003). The replacement of hydrogen bonding within the polymer network of the cell wall by bonds between water-lignin, water-hemicelluloses, and water-paracrystalline cellulose enhances the flexibility of the polymer network. Moisture and temperature likely help lignin in the middle lamella to be somewhat more elastic. However, high temperature and RH can result in wood softening and a drastic decrease in the $E'$ value.

## Longitudinal Direction

Figure 8 shows the results of strain sweep tests at 30 °C for the various RH conditions in the longitudinal direction. Stress and strain exhibited a proportional relationship. The values of stress for a corresponding strain decreased as RH increased. The normalized $E'$ curves were straighter at high RH (70 and 90%). The wood specimens conditioned at 70% RH showed the highest values of tan $\delta$. At low strain, conditioning at 90% RH led to the lowest tan $\delta$ values in all the wood specimens but, at high strain, the specimens conditioned at 50% RH had the lowest tan $\delta$. With an exception, in all RH levels, tan δ increased as strain increased. The exception related to specimens conditioned at 50% RH in which the increase in tan $\delta$ halted at high strain. Although the LVR limit was not influenced by RH changes at low moisture content, an increase in RH to 70 and 90% increased the LVR limit considerably (Fig.9).

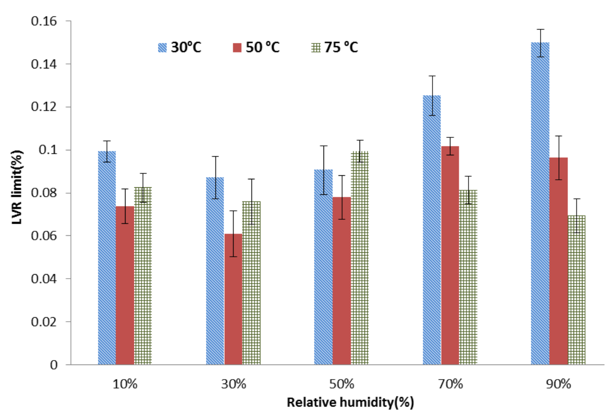


**Fig. 9.** Effect of temperature and RH changes on LVR limit for longitudinal direction

Figure 10 displays the stress/strain, normalized $E'$ and tan $\delta$ curves obtained from sweep strain tests in the longitudinal direction at 50 °C for the various RH conditions. The stress values were lower for 50 °C than for 30 °C, and they decreased with increasing RH. Strain and stress retained a linear relationship throughout the sweep strain tests. The extent of loss in normalized $E'$ values was smoother at low RH levels. The highest loss factors were related to 90% RH conditioning. The loss factor of wood specimens conditioned at 90 and 70% RH increased as strain increased. In the case of wood specimens conditioned at 30, 10, and 50% RH, however, the loss factor increased with the strain rate at the beginning of the tests, and then leveled off at the higher strain rates. For a given RH level, the LVR limit was lower for 50 °C (Fig. 9). At high RH levels (70 and 90%), an increase in RH slightly increased the LVR limit.

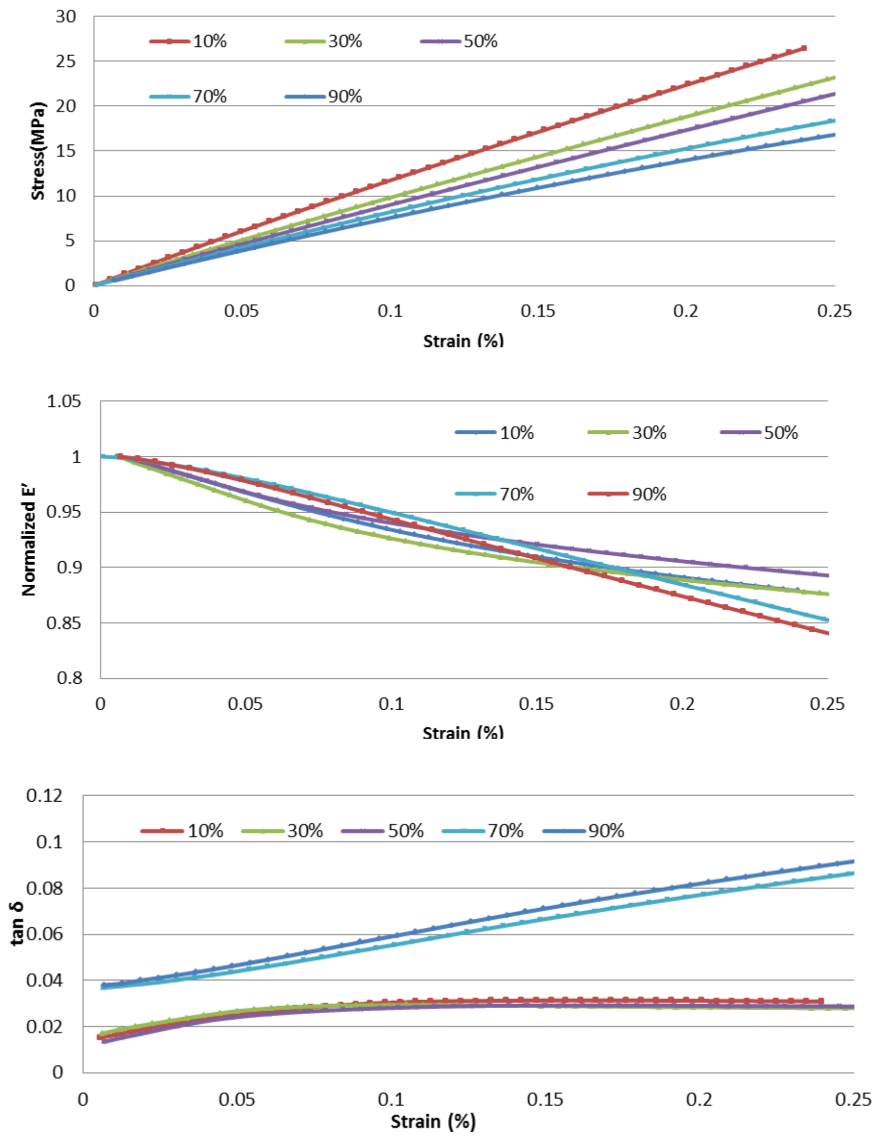


**Fig. 10.** Variations in viscoelastic properties by RH in longitudinal wood specimens at 50 °C

The normalized $E'$, stress/strain and tan $\delta$ curves for longitudinal wood specimens conditioned at the various RH levels and 75 °C are given in Fig. 11. The values of stress and strain were proportional throughout the tests, stress increasing with strain. Although the stress values were lowest at 75 °C, an increase in temperature from 50 to 75 °C led to a lower reduction in stress than an increase in temperature from 30 to 50 °C. Stress decreased with increasing RH. Normalized $E'$ decreased with increasing strain. The extent of the loss in $E'$ with strain was higher at 70 and 90% RH than at 10 and 30% RH. Loss factors were greatly impacted by RH. They were much higher at high RH (70 and

90%), which means that more energy was dissipated at high RH. LVR limits were not significantly affected by RH changes (Fig. 9).

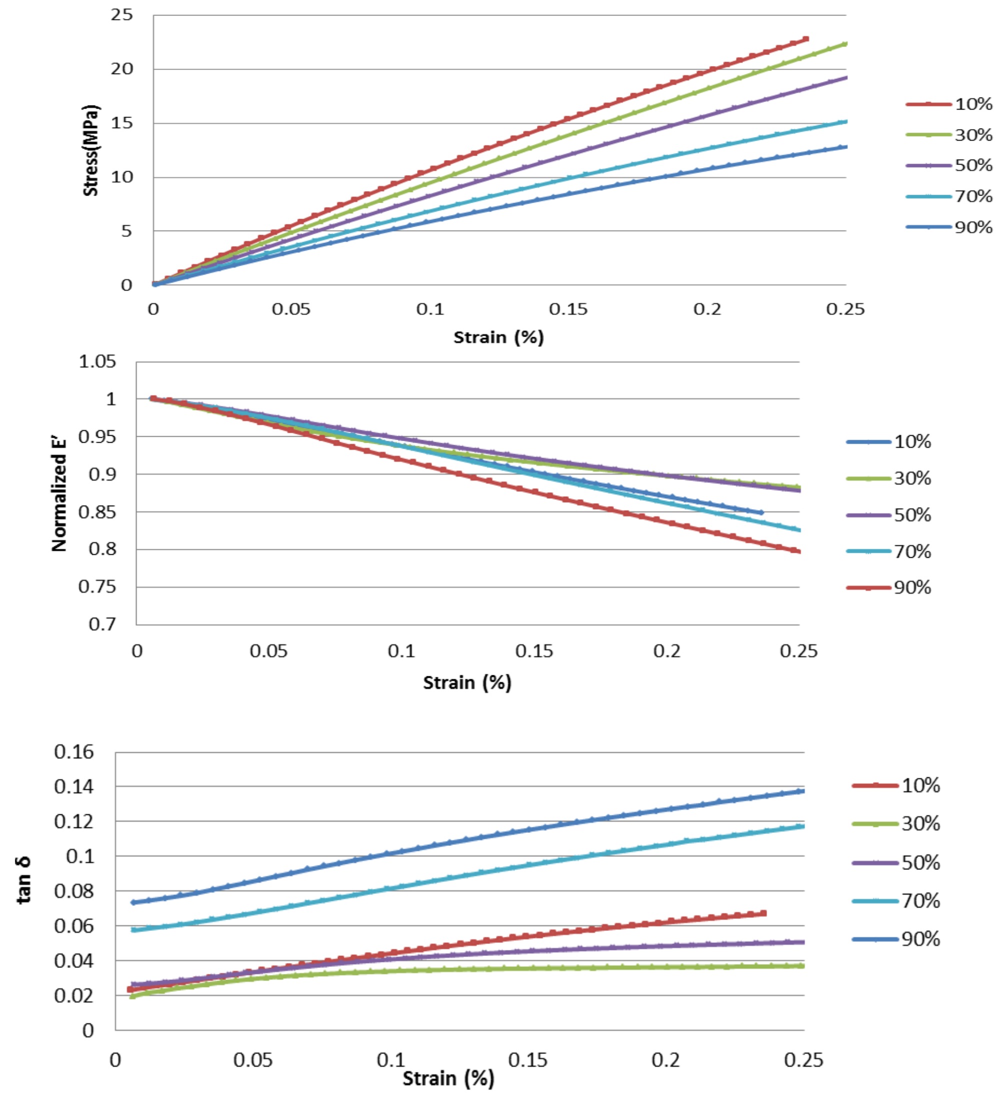


**Fig. 11.** Variations in viscoelastic properties by RH in longitudinal wood specimens at 75 °C

## DISCUSSION

The findings of this research clearly display the anisotropy of LVR. Comparisons between LVR limits in the three directions show that the highest and lowest LVR limits occurred in the tangential and longitudinal directions, respectively. Sun *et al.* (2007) also stated that, in yellow poplar and yellow pine, the LVR limit is greater for bending perpendicular to the grain. Such anisotropy can be related to the non-random organization of amorphous wood polymers in wood, as suggested by various authors (Åkerholm and Salmén 2001; Atalla and Agarwal 1985; Sun *et al.* 2007). Alternatively, the anisotropy might reflect the response of discreet domains that are preferentially sampled when the microfibrils are load-bearing (bending parallel to the grain) or when they are not (bending perpendicular to the grain), as suggested by Åkerholm and Salmén (2003).

It should be noted that LVR limits were most sensitive to temperature and RH changes in the tangential direction, while they were least sensitive in the longitudinal direction. As the properties of the cell wall in the longitudinal direction are mostly affected by the cellulose (Salmén 2004), the low impact of the temperature and RH on LVR limits in this direction can be justified. However, in the transverse directions (tangential and radial directions), the amorphous wood polymers (lignin and hemicelluloses) play a more dominant role in the properties of the cell wall (Salmén 2004). Redman *et al*. (2011) studied the viscoelastic properties of commercially important Australian hardwood species (*Corymbia citriodora* (spotted gum), *Eucalyptus pilularis* (blackbutt), *Eucalyptus marginata* (jarrah), and *Eucalyptus obliqua* (messmate)). It was concluded that viscoelastic wood behavior largely reflects the properties of lignin in the tangential and radial directions, and that, to a lesser extent, the microfibril angle of the cell wall layers may also hold influence. Such a dominant role for lignin would lead to high sensitivity to temperature and RH changes in the transverse directions.

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The results of this research clearly confirm that LVR limits vary with wood directions. Higher LVR limits in the radial and tangential directions suggest that DMA signal quality would be better in these two directions than in the longitudinal direction, as reported by Sun *et al.* (2007). Temperature and RH are other factors that affect the LVR limit. In a test conducted by DMA, variations in temperature and RH led to major variations in LVR limits. A small deviation from the LVR limit can affect the credibility of a data set. Although LVR limits in the tangential and radial directions were high, they were strongly influenced by RH and temperature changes. Such high sensitivity makes it necessary to run tests by DMA (especially in temperature sweep tests) at lower LVRs in order to ensure that the strain rate remains within the LVR limit throughout the tests.

## CONCLUSIONS

1. The results of this study clearly demonstrated the importance of determining the LVR limit of wood specimens prior to conducting any test with a DMA machine.

2. The LVR limit for bending perpendicular to the grain (tangential and radial directions) was much higher than for bending parallel to the grain (longitudinal direction).
3. Stress and strain were proportional (linearly) across the range of conditions under study.
4. Stress and *E′* were much higher for the longitudinal direction than for the tangential and radial directions.
5. Temperature and RH changes also affected the LVR limit of the wood specimens, the effects being much more evident in the tangential and radial directions than in the longitudinal direction. The high sensitivity to temperature and RH changes observed in the tangential and radial directions was attributed to lignin alteration due to temperature and RH changes, and the role of lignin in cell wall properties in the tangential and radial directions.
6. The significant changes in LVR limit observed in the tangential and radial directions demonstrated that analyzing and determining the LVR limit is essential in order to test wood by DMA in a credible way.

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