ACOUSTIC AND ADSORPTION PROPERTIES OF SUBMERGED WOOD

by

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Abstract

Wood is a common material for the manufacture of many products. Submerged wood, in particular, is used in niche markets, such as the creation of musical instruments. An initial study performed on submerged wood from Ootsa Lake, British Columbia, provided results that showed that the wood was not suitable for musical instruments. This thesis re-examined the submerged wood samples.

After allowing the wood to age unabated in a laboratory setting, the wood was retested under the hypothesis that the physical acoustic characteristics would improve. It was shown, however, that the acoustic properties became less adequate after being left to sit.

The adsorption properties of the submerged wood were examined to show that the submerged wood had a larger accessible area of wood than that of control wood samples. This implied a lower amount of crystalline area within the submerged wood. From the combined adsorption and acoustic data for the submerged wood, relationships between the moisture content and speed of sound were created and combined with previous research to create a proposed model to describe how the speed of sound varies with temperature, moisture content and the moisture content corresponding to complete hydration of sorption sites within the wood.

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Quotes

"We need new noise – new art for the real people."

- Refused

"You met me at a very strange time in my life."

"If you wake up at a different time in a different place, could you wake up as a different person?"

- The Narrator (Fight Club)

"Déjà vu - all over again."

"I know."

- Han Solo (Star Wars: Episode V - The Empire Strikes Back)

1. Introduction

Wood is a common material used in the creation of a wide variety of products such as furniture, building components, artwork, and niche products such as sports equipment. A key reason is because of the abundance of the material and adaptability to various uses. In the case of musical instruments, wood has been used for centuries in many types of instruments such as guitars, bagpipes, xylophones, pianos, organs and violins. Even despite the availability of other materials with suitable acoustic properties, wood remains the primary material used for musical instruments.

Much research has taken place to examine wood resonating ability and examine how to improve its physical acoustical characteristic. Likewise, much research has taken place to examine why some woods are more suitable than others for instruments [1]. Of particular interest is examining new sources of wood for such suitability.

Wood that has been underwater in anaerobic environments for long periods of time is known as submerged wood. Due to the lack of oxygen, submerged wood is not subject to the same degradation that can occur from fungi when left in humid environments [2]. This makes submerged wood a viable source of lumber for the industry. Also, musical instrument makers, in particular, use submerged wood due to the belief that the wood is more resonant.

There is a popular belief that submerged wood is suitable for use as musical instruments, the submerged wood located in Ootsa Lake, British Columbia, holds potential as resonant wood. This belief is supported by the results of Parfitt [3] that showed that wood located in British Columbia has the potential for use as resonance wood due to suitable acoustic constant values.

To explore the suitability of the wood from Ootsa Lake, a previous study was conducted on pine and spruce wood samples taken from the lake. The results showed that the submerged wood from Ootsa Lake was not suitable for use as musical instruments [4]. At the outset of this study it was believed that, by letting the wood age untouched, its physical acoustic characteristics could improve.

In Chapter 3 of this thesis, the submerged wood from Ootsa Lake was re-examined to determine the suitability for use as musical instruments with the hypothesis that the wood would be more suitable after being allowed to condition in room temperature and humidity. After comparing the speed of sound, density, characteristic impedance and acoustic constant with that of the previous study, as well as to expected values of resonant wood, it was determined that the wood was less suitable for use as musical instruments.

It was believed that the wood samples were less suitable for use as musical instruments due to the decreased amount of crystalline areas within the wood. Since there is a the relationship between the ability of sound to propagate through wood and the crystallinity of wood, having a decreased amount of crystallinity and a larger amount of amorphous areas within the wood could lead to a lower speed of sound.

The hypothesis of larger amorphous areas within the submerged wood from Ootsa Lake was examined in Chapter 4 of this thesis report. This was done by measuring the moisture content within the submerged wood at varying levels of relative humidity, obtaining the adsorption isotherm of the submerged wood, and comparing it with that of control samples. A higher ability to retain moisture within wood would indicate a larger amorphous area within the wood. The adsorption isotherms were modelled using the Hailwood-Horrobin sorption isotherm model. It was determined that the submerged wood had a higher ability to retain moisture than that of the control samples. Additionally, the adsorption isotherms and equilibrium moisture contents were similar to those of wood from previous studies that had been submerged, buried and otherwise degraded and had been measured to have lower crystallinity than the respective control samples. This supported a conclusion that the submerged wood had a lower crystallinity.

To examine the dependence of the speed of sound on the amorphous areas of wood, in Chapter 5, the speed of sound was compared to the fraction of wood available to water, known as the accessible fraction. A relationship was found between the speed of sound and inaccessible fraction. This relationship allowed the speed of sound to be related to the moisture content at which all of the available sorption sites within the wood are completely hydrated (m_0). By comparing the relationship between the speed of sound and that of m_0 to a relationship from a previous study between the speed of sound through wood and the moisture content of wood, it was possible to determine a possible relationship between the speed of sound, moisture content, temperature and m_0. Subsequently, this relationship could be extended to the accessible fraction of water within wood.

The relationship produced from Chapter 5 supports that increasing values of the speed of sound through wood are related to increasing values of crystallinity. It also supported the hypothesis that the lower speed of sound through the submerged wood samples from Ootsa Lake were due to larger amorphous areas within the wood. Lower speed of sound measurements were related to higher accessible fraction amounts which indicate higher amounts of amorphous wood and lower crystalline areas.

2. Background

A. Wood Acoustics

Wood has long been used in the creation of musical instruments due to the abundance of the material, the ease of creating instruments and the acoustical properties [1]. The selection of wood for use in making an instrument has traditionally fallen upon experienced instrument makers. Instrument makers choose wood through training and experience with the requirement of fulfilling a minimal aesthetic and acoustical quality, whereas researchers often rely upon measurements of different mechanical properties of wood, such as the speed of sound and density, to evaluate the acoustical properties of wood.

Despite the development of alternatives to wood-based products, wood remains the main product for use in the manufacturing of many chordophones such as guitars, violins and pianos; aerophones, such as the oboe or bagpipes; and percussion instruments such as xylophones and drums. However, due to the inhomogeneous nature of wood, there is a large variety between wood species [1] as well as between individual samples within a species that can impact the acoustic properties. Spruce, for example, is a common material in building soundboards for violins and guitars [4], due to its resonant properties and is studied extensively [3] [5] [6]. Many other woods are used in instrument construction, though, depending on its desired use [1].

a. Measurements by Instrument Makers

Instruments makers use qualitative means to choose wood that is suitable for instrument making. The choice to use a piece of wood normally comes from a combination of training and experience of the instrument maker.

Some key characteristics that wood must have in order to be chosen include:

- must be devoid of imperfections such as knots, compression wood or free of fungal attacks;
- a suitable ring width and colour;
- to be aesthetically suitable.

An instrument maker will then perform a tap test, or similar test, to determine if the wood is acoustically suitable. A tap test involves physical tapping of the sample of wood and listening to the resonance. The varying levels of resonance can be desirable for the instrument and is determined through the experience of an instrument maker based on what instrument is being made. Guitar necks, for instance, may require a higher density to withstand tension while it is more important for the soundboard of a guitar to resonate.

The difficulty in using the above methods for choosing a suitable wood arises from the lack of strict definition in the selection process as well as the large variance of wood properties both between and within species. While it may be possible for an individual piece of wood to be selected this is not an easy process when dealing with large scale manufacturing of instruments; nor is it a viable option for researchers who may not have specific experience in the building of instruments or easy access to experienced instrument makers. In order to compensate for this it is possible to look at the physical acoustic characteristics (PAC) of the wood and define what physical characteristics are desired for different types of instruments

b. Quantitative Measurements

There are many physical acoustic characteristics of wood that directly or indirectly influence its suitability for instrument construction. Wood must be strong and dense enough to hold its shape under the stresses of daily use while at the same time it must be easily cut or bent in order to create the instrument. Depending on the type of instrument, the wood must be able to resonate for long periods of time or to have a sharp drop off after immediately being caused to resonate. For instruments that are directly exposed to moisture, such as wind instruments [1], the wood must be resistant to moisture while at the same time able to accommodate moisture in the wood structure [1]. Wood must also be able to transfer vibrations into the air or have vibrations passed to it from strings.

Before examining which woods are generally used for different types of instruments, it is important to determine the most important properties as well as the different ways these properties are related. The density of the wood is one of the most important properties as it relates to the acoustic characteristics [1] and is relatively simple to determine. The density at a specific moisture content, ρ_{MC}, is found using:

$$\rho_{MC} = \frac{m_{MC}}{V_{MC}}$$

Equation 2.1

where m_{MC} is the mass (kg) and V_{MC} is the volume (m^3) at moisture content MC. Denser woods are required for the construction of instrument components that must withstand large amounts of constant stress [1], such as the fingerboard of a guitar.

In addition to the density, the Modulus of Elasticity (also known as Young's Modulus; the elastic modulus; or the longitudinal modulus of elasticity), E, is used to describe how well sound is able to move through wood. E is a ratio of stress, or the force per unit area, to deflection from origin, that is placed upon the wood. Combining E with ρ can describe how sound moves through an instrument in different ways.

The speed of sound, c, through wood is determined by:

$$c = \sqrt{\frac{E}{\rho}}$$

Equation 2.2

where E is the modulus of elasticity (Pa), ρ is the density (kg/m^3) and c has units of m/s.

This describes the one dimensional velocity of sound propagation within wood and is a measure that can be nearly considered independent of the species of wood [1].

When the speed of sound is combined with density, two more acoustic measurements are obtained: a) the wood's characteristic impedance (Equation 2.3) and b) the acoustic constant (Equation 2.4). In both the equations for the impedance and for the acoustic constant it is also possible to use E and ρ to obtain the coefficients. The selection of which equation is appropriate is dependent on whether c or E is measured directly.

The impedance of wood, z, is found by multiplying the speed of sound of an object (c) by the density (ρ) [1], with units Pa·s/m:

$$z = c \cdot \rho = \sqrt{E \cdot \rho}$$

Equation 2.3

The characteristic impedance is a measurement of a material's ability to propagate vibrations. In the case of wood and musical instruments, the impedance is a measure of the wood's ability to propagate sound waves between mediums such as from the soundboard of an instrument to the resonator [1].

The acoustic constant, AC is a measure of the vibration within the wood as it is damped by radiating sound [1], is determined using:

$$AC = \frac{c}{\rho} = \sqrt{\frac{E}{\rho^3}}$$

Equation 2.4

and has units of $m^4kg^{-1}s^{-1}$. The acoustic constant is also known as the sound radiation coefficient (R) [1], and acoustical coefficient (*K*) [7].

c. Wood suitability for instruments

Different types of instruments require different wood properties and therefore certain species are generally more suitable for certain instruments. Spruce, for example, is well known for its suitability in making soundboards for many stringed instruments, including violins and guitars [4] [6].

There are five instrument classifications using the von Hornbostel and Sachs classification system [8]: a) chordophones, b) aerophones, c) idiophones, d) membranophones and e) electrophones. The suitability of wood for each instrument is described below.

i. Chordophones

Chordophones are some of the most common instruments found and consist of any instrument in which sound is created by plucking or striking a string and allowing the string to vibrate [1]. Chordophones fall into two sub-categories: chordophones with resonators and chordophones without resonators [8].

For chordophones with resonators, the string is attached to the top plate of a hollow resonator by the bridge which in turn transfers vibration from the string to the top plate. From the bridge, vibrations are passed throughout the resonator's sound posts, ribs, sides and back plate [1]. The sound is transferred to the air inside the resonator and transmits outwards from the instrument depending on the shape and material [1]. The type of hole cut into the top plate and the shape of the instrument, can positively or negatively affect the vibration and air passage as it oscillates out of the resonator [1]. Arching and rounding the instrument or placing f-holes on the body are all traditionally done to improve the instrument's resonance [1]. Examples of chordophones with resonators include violins, guitars, dulcimers, and ukuleles.

Chordophones without resonators, such as pianos and harpsichords, work by having the string caused to vibrate by either striking or plucking it. The vibration is then transferred directly to a soundboard which, in turn, vibrates the surrounding air. Bows for musical instruments, such as for violins, are also classified as chordophones without resonators [1].

While there are distinct differences in their construction that lead to differences in wood suitability, there are a few factors that remain common for all chordophones. Sounding boards are required to propagate sound throughout efficiently which requires a high speed of sound and, in turn, requires a higher modulus of elasticity, and acoustical constant [9] [7] [10]. Additionally, a lower dampening coefficient allows the vibrations to resonate without dropping off and increase the time in which vibration occurs [10] [7] [9]. A lower dampening coefficient will also increase the AC as it is inversely proportional to $tan(\delta)$.

Differences between the two subcategories are based on the wood density. While it is important to maintain a lower density so that sound can propagate throughout the soundboard, chordophones must have an adequate resistance to the constant stress of the strings and repeated playing. Pianos, in particular, must have a high toughness to withstand decades of repeated impacts [1]. Also, bows for violins must be light enough so that the musician is able to maintain proper control over the bow and that the bow maintains a constant tension [1]. Finally the wood must be able to be easily crafted into the desired shape of the instrument.

ii. Aerophones

Aerophones produce and radiate sound by exciting air within the body of the instrument [1]. Examples include the recorder, flute, saxophone, oboe, and bagpipes. Much like chordophones, not all aerophones are made of wood. However, many of the instruments that are not made primarily of wood still use reeds to excite the instrument [11].

When selecting wood for aerophones, a high modulus of elasticity and low dampening coefficient are not strict requirements. This is because the wood itself is not required to sustain vibration as it is for chordophones. Instead, wood that is more dense and resistant to changes in the environment such as temperature or humidity, is preferred as long as it can be drilled and formed adequately [1]. Woodwinds will also be susceptible to moisture introduced in the form of saliva from the musician's mouth and must be dimensionally stable to these changes in moisture [1].

iii. Idiophone

Wood is a common material for the use in construction of idiophones such as xylophones and wood blocks. Idiophones produce sound by being struck by a mallet, vibrating, and having those vibrations propagate to the air. As idiophones are repeatedly struck throughout their lifespan, they must have a high density in order to withstand damage [1]. Additionally, in order to transfer vibrations into the surrounding environment, idiophones are required to have a low loss coefficient and low dampening [1] as well as an appropriate characteristic impedance [12].

iv. Membranophones and Electrophones

Membranophones and electrophones are the final two classifications of instrument [8]. Electrophones are the newest category of instrument and consist of instruments that produce sound through electronic means. Examples include electric keyboards or other synthesizers.

Membranophones are instruments in which a membrane stretched over the instrument produces sound. As neither membranophones nor electrophones use wood as the primary means of producing sound they are not further discussed.

B. Wood/Water interactions

The hygroscopic nature of wood can cause changes to the wood structure and properties created through wood adsorbing and desorbing moisture to reach an equilibrium moisture content with its surroundings. Due to changing moisture content, the physical properties of wood will also change. In addition, when wood is exposed to moisture in aerobic conditions, it can become susceptible to degradation from fungal attack, rot and weathering. However, in anaerobic environments, such as those experienced by submerged wood, the wood will not undergo the same degradation due to fungi and rot.

a. Cellular composition of wood

Wood is a hygroscopic, complex polymer made up of regular sections of cellulose surrounded by non-uniform sections of lignin and hemicellulose. These are organised into the S1, S2 and S3 layers (Figure 2.1) which, in turn, are the main components of tracheids, the main method of water transport throughout softwood. Because the tracheids transport water, the S1, S2 and S3 layers and, consequently, the hemicellulose, lignin and cellulose of the wood, are also exposed to water. Additionally, the wood also contains P and ML layers that correspond to the primary wall and middle lamella. As these layers are not discussed in further detail in this thesis, more information on the cellular structure of wood can be found in Skaar [13].

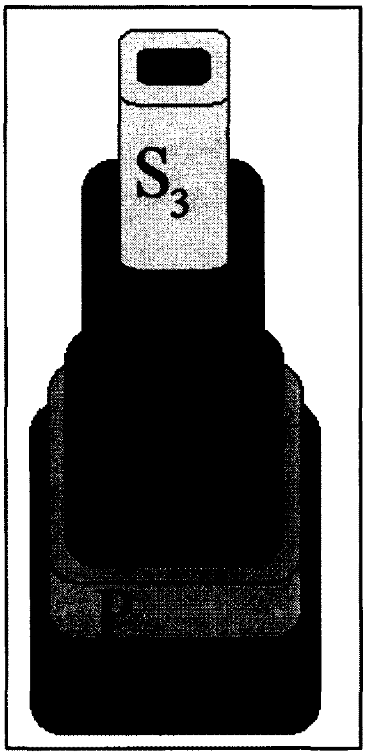

Figure 2.1 – Cell Wall of Wood

b. Wood crystallinity

When the molecules of wood become more tightly and densely packed, the wood will become more crystalline [14]. The cellulose of wood contains mostly crystalline regions while the hemicellulose and lignin are mostly non-crystalline (or amorphous). Cellulose that is crystalline will be less accessible to water while amorphous areas of cellulose, as well as hemicellulose and lignin, will be more accessible to water [14].

The regions between crystalline and amorphous areas of the wood are not well defined and, as such, it is difficult to entirely distinguish the two regions from each other [15]. Instead it is sometimes more appropriate to refer to areas of the wood that are either accessible or not accessible to water. While using the accessible fraction of wood to water will not provide an exact measurement of the crystallinity, it can be used to compare the amount of amorphous areas between two wood samples by comparing the amount of water each wood sample adsorbs [16].

c. Water interactions with wood

Water exists within wood in three states: bound water, free water, and vapour. Free water is water that has filled the cavities of wood and takes little energy for it to be transported into and out of wood. Bound water is water that has become chemically bound to the wood itself; this type of water requires a much larger amount of energy to be removed from the wood.

The fibre saturation point (MC_{fsp}) is the point during the wetting or drying of wood at which, below this moisture content, only bound water remains inside the wood. Above the fibre saturation point free water is the predominant type of water that enters and exits the wood. When bound water interacts with the wood, either by entering or exiting, many physical properties of the wood change. As the moisture content decreases, the wood will shrink; the thermal conductivity and electrical conductivity will decrease; and the density will decrease.

The movement of water in and out of the wood below the fibre saturation point can be described by the water sorption theory; the sorption of water by wood is an important physical characteristic of wood. When water becomes bound to the wood it is known as adsorption, and when water becomes unbound and leaves the wood it is known as desorption. By measuring the adsorption and desorption of wood as it equilibrates with its surroundings, a sorption isotherm curve can be used to obtain information about the sample such as its thermal properties or its crystallinity. This occurs by fitting a sorption isotherm model to the experimental data and determining the constants that satisfy the experimental equation and will be described later in the thesis.

Wood will adsorb or desorb water accordingly to create an equilibrium with the ambient relative humidity and temperature [17]. When the wood reaches an equilibrium the moisture content at which this occurs is known as the equilibrium moisture content (EMC) [17].

d. Wood sorption theory

Water located within wood primarily exists as either bound water or free water. Bound water interacts with the wood by being chemically bounded to what is known as internal sorption sites within the wood. This is known as chemical sorption or adsorption. According to the Hailwood-Horrobin isotherm model, some of the water that is sorbed by the wood will create a hydrate [13]. From this, the cell wall of the wood is considered to be either dry wood, hydrated wood or dissolved water. The dissolved water is considered to be an ideal solution.

This definition allows the molecular weight of dry wood, hydrated wood and dissolved water to be compared with the dry weight of wood and the molecular weight of water to obtain the moisture content for dissolved water and hydrated water within wood as it varies with humidity [13]. The unimolecular sorption isotherm is:

$$M_h = \frac{0.018}{W} \cdot \left(\frac{K_1 \cdot K_2 \cdot h}{1 + K_1 \cdot K_2 \cdot h}\right)$$

Equation 2.5

and the dissolved water sorption isotherm is:

$$M_s = \frac{0.018}{W} \cdot \left(\frac{K_2 \cdot h}{1 - K_2 \cdot h}\right)$$

Equation 2.6

where h is the relative humidity, W is the proposed molecular weight of dry wood (mol/kg) and K_1 and K_2 are equilibrium constants for the hydrated and dissolved wood, respectively.

When Equation 2.5 and Equation 2.6 are combined together this provides the Hailwood-Horrobin model for sorption isotherm:

$$M = M_h + M_s = \frac{0.018}{W} \cdot \left(\frac{K_1 \cdot K_2 \cdot h}{1 + K_1 \cdot K_2 \cdot h} + \frac{K_2 \cdot h}{1 - K_2 \cdot h}\right)$$

Equation 2.7

Additionally, $\frac{0.018}{W}$ is the moisture content at which all of the sorption sites within the wood are completely hydrated [13], and is denoted by m_0. Moisture content and relative humidity are both represented as a per cent.

e. Wood degradation due to water

Wood that is exposed to water will undergo decay that is different from the regular degradation of wood. When exposed to water, wood is susceptible to fungi that can destroy the lignin, hemicellulose and cellulose in the wood or cause decolourisation [18]. This decay can occur when the moisture content of the wood is greater than 20%, normally beginning at the fibre saturation point [18].

To prevent the occurrence of fungi within wood requires controlling the levels of oxygen, temperature or moisture that the wood is exposed to [19]. If wood is kept below the fibre saturation point, ideally below a moisture content of 20% [18], fungi will not be able to develop. To control the amount of oxygen that the wood is exposed to, it is possible to completely saturate the wood; if the wood has a moisture content above 100% this will prevent the fungi from receiving oxygen.

Even when steps are taken to mitigate the effects of fungi wood will still be susceptible to degradation due to the weathering effects of water. Constant exposure to high and lower moisture contents can cause erosion as well as splitting or checking due to the shrinking and expanding of wood [19]. Aside from the physical erosion of the wood, these effects can also be prevented through maintaining the wood in stable conditions with non-changing moisture contents or through use of preservatives [19].

In anaerobic environments, wood may undergo degradation due to bacterial attack. This degradation is a much slower process than that from fungal attacks [2]. Archaeological wood that has been preserved under water for centuries will degrade when removed from the water if not properly preserved [20]. This degradation leads to higher moisture contents within the wood, lower density, increases in lignin and decrease in cellulose as well as lower elastic properties [21].

f. Submerged Wood

Wood that is fully submerged in water remains in an anaerobic state and will not face attack from fungi, due to the lack of oxygen. While it is still susceptible to long-term degradation due to microbacterial attack, the preservation of wood from other types of degradation while under water makes submerged wood a viable supply of wood for industry.

Submerged wood has been harvested by many companies such as Triton Logging Inc. [22], and Timeless Timber [23]. The wood harvested is considered to be more environmentally conscientious when compared with that of live trees that are cut from forests. Additionally, removing trees from lakes is said to be beneficial to improving dam performance through removal of debris in the water caused by trees; reduces dangers to recreational usage in the lakes from sunken trees; and benefits the surrounding economies by providing lumber for use or removing hurdles presented to fishing or recreational markets [24]. Recovered submerged wood is often used in niche markets such as for veneers for flooring [25], by local artisans for their products [25] as well as for use in the manufacturing of musical instruments [26].

3. Acoustical Measurements of Submerged Wood

A. Introduction

During an initial study performed in 2007 [4], density and acoustic constant measurements of pine and spruce wood that had been submerged were taken to determine the suitability of the wood for musical instruments. The hypothesis for that study was that the submerged wood would be adequate or better as a material for acoustic properties leading to instrument making. The results, however, showed the wood was not suitable for this application due to a lower speed of sound and corresponding acoustic constant when compared to normal values for resonant wood. However, for this research, it was believed that allowing the wood to sit untouched and age in a laboratory environment would increase the acoustical properties of the samples [1].

In this chapter, the results of the acoustical measurements on the same submerged wood samples were compared with the initial findings from the initial report by Woodward [4] four years later. Comparisons were also made to known and accepted values of both common wood samples and resonant wood samples.

B. Sample preparation

The initial selection and preparation of the wood samples was described in Woodward [4] as follows:

- Triton Logging removed submerged wood from Ootsa Lake, British Columbia (Figure 3.1) in September of 2006; the logs had been submerged since 1952 when damming caused the size of Ootsa Lake to increase and flood the landscape

- The logs were transported to Carrier Lumber Ltd and were air dried until November, 2006, when the lower parts of 12 tree trunks were taken to the University of Northern British Columbia.
- This wood was identified as Lodgepole pine (*Pinus contorta.*) and interior spruce (*Picea spp.*), which is a hybrid species of Englemann spruce (*Picea engelmannii*) and White spruce (*Picea glauca*); the average age of the trees was 133 years, prior to submersion.
- Logs 1-5, 7 and 12 were identified as pine and logs 6, and 8-11 were spruce. One disk was removed from the upper part of each log and 7cm thick disks were cut. Disks 1-5, 7 and 12 were pine and disks 6, 8-11 were spruce.

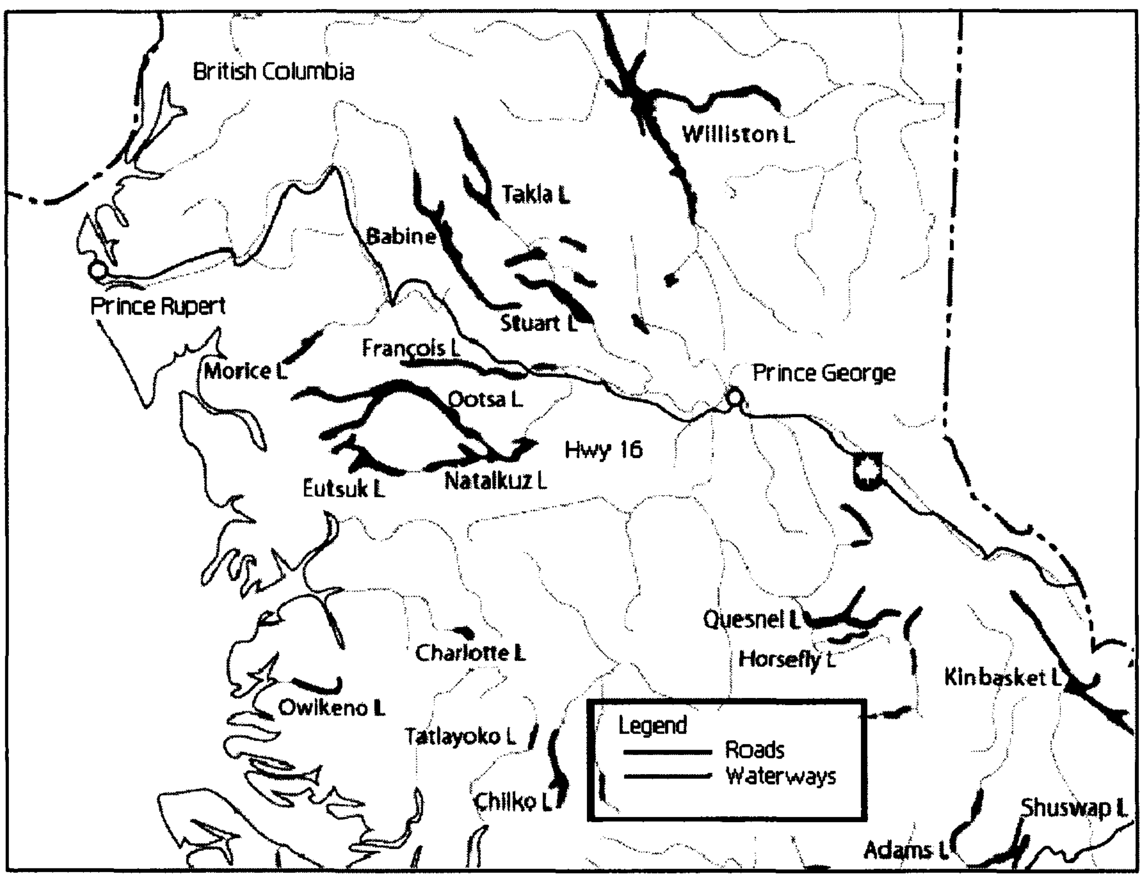

Figure 3.1 - Ootsa Lake, British Columbia [27]

- From each disk, 35 to 40 samples were cut according to the method described in Licko [28] with approximate dimensions of 55 mm x 15 mm x 15 mm, making sure to exclude defects such as cracks or knots. These samples were dried in a convection oven (Figure 3.2) to an equilibrium moisture content of 12% by oven drying a sample set to ensure the correct moisture content. The samples were then sealed in a container to maintain moisture content.

After the acoustic constant measurements were performed the samples were resealed and left untouched in the Advanced Wood Laboratory prior to measurement in 2010. No additional preparation of the samples was performed for measurements and the samples reached an equilibrium moisture content of approximately 6%.

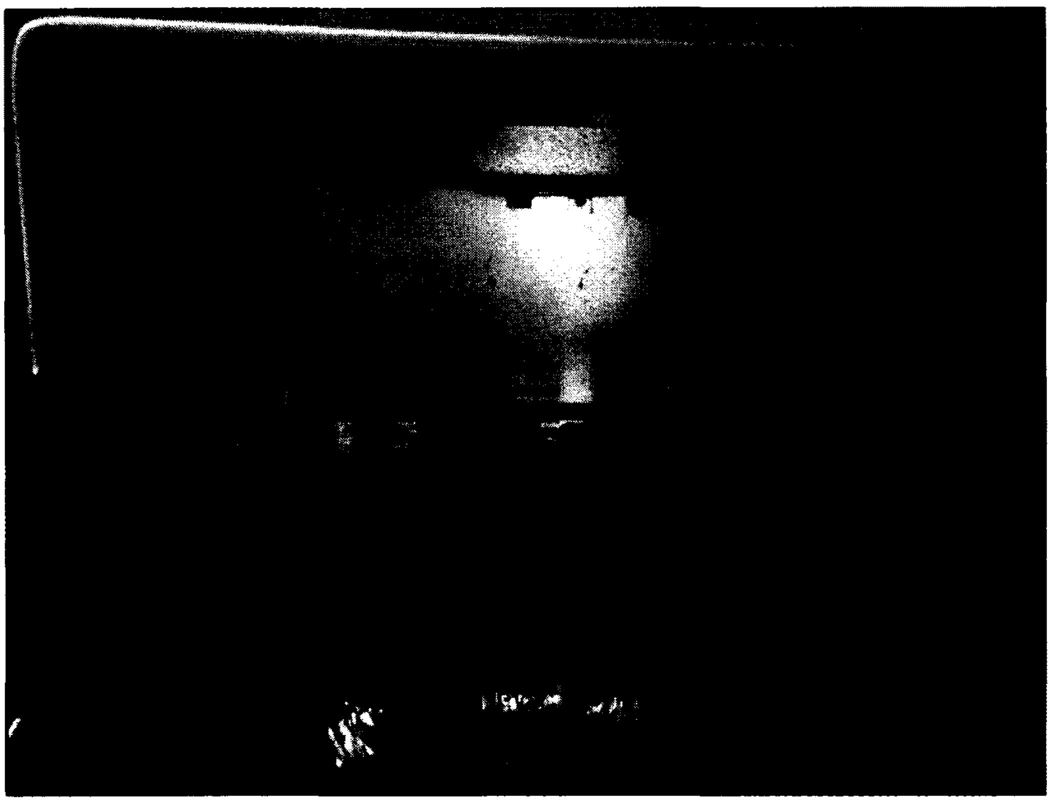

Figure 3.2 - Oven drying of samples

Figure 3.3 - Metriguard stress wave tester, Model 239

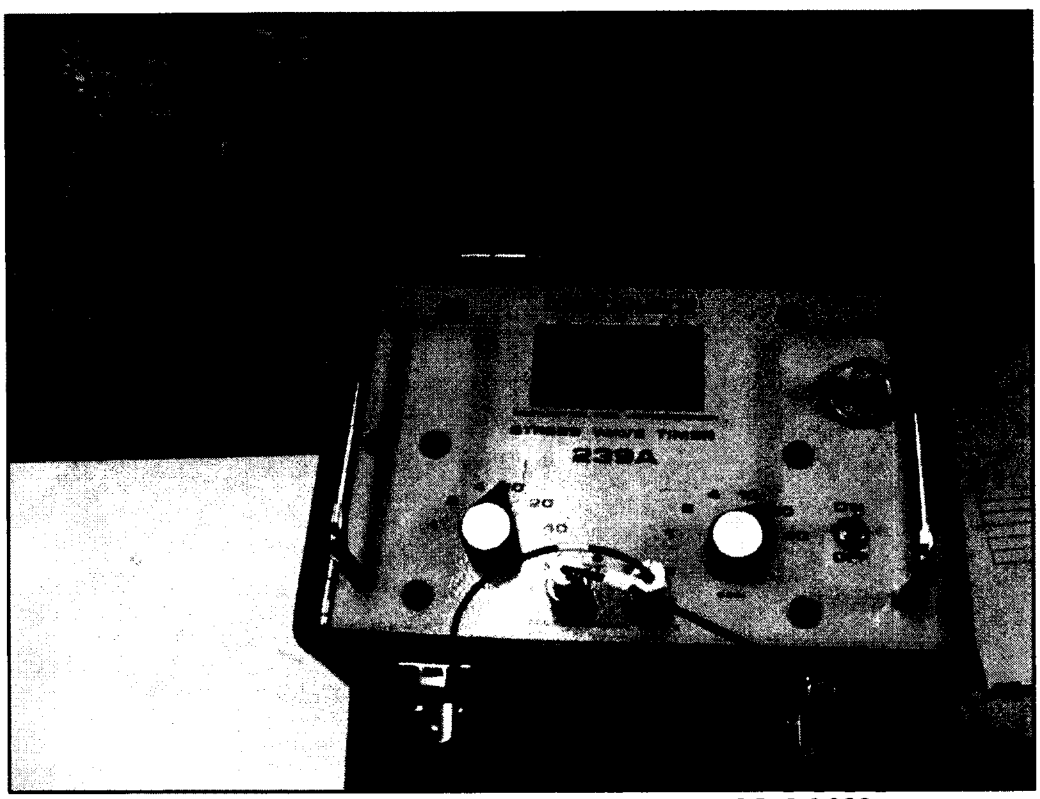

Figure 3.4 - Metriguard stress wave tester, Model 239

C. Experiment

The 366 samples were measured with the same Metriguard stress wave tester - Model 239 (Figure 3.3) used in 2007 to determine the amount of time it took for a sound wave, caused by a pendulum striking the wood, to travel through to the receiver; this measurement was taken five times. The length of wood that the sound wave travelled was measured and, together with the time, the speed of sound through the wood was determined:

$$c = \frac{l}{\bar{t}}$$

Equation 3.1

where c was the speed of sound, l was the length in metres and $\bar{t}$ was the average time ($\bar{t} = \frac{t_1+t_2+t_3+t_4+t_5}{5}$) in seconds. The mass of each wood sample was also taken at this time.

The error in the speed of sound, δc, was found using:

$$\delta c = c \cdot \sqrt{\left(\frac{\delta l}{l}\right)^2 + \left(\frac{\delta \bar{t}}{\bar{t}}\right)^2}$$

Equation 3.2

where δl is the error in the length and $\delta \bar{t}$ is the error in the average time. The error in the average time was found using Equation 3.9 and Equation 3.10.

The width and height of each sample was measured to calculate the density of each using Equation 2.1. The mass was measured with the OHAUS™ Scout Pro SP402 that contains an error of $\pm$ 0 .01g. The error in the density, $\delta\rho$, was found using:

$$\delta \rho = \rho \cdot \sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta V}{V}\right)^2}$$

Equation 3.3

The volume, V (m^3), was determined using:

$$V = l \cdot h \cdot w$$

Equation 3.4

with l, h and w being length, height and width, respectively, using a Powerfist™ digital calliper with an error of ± .2mm. Length, height and width have units of metres.

The error in the volume, δV, was found using

$$\delta V = V \cdot \sqrt{\left(\frac{\delta l}{l}\right)^2 + \left(\frac{\delta h}{h}\right)^2 + \left(\frac{\delta w}{w}\right)^2}$$

Equation 3.5

where δl, δh, and δw are the error in length, height and width respectively.

Using the mean speed of sound and calculated density, the acoustic constant (AC) and characteristic impedance (z) were obtained using Equation 2.4 and Equation 2.3 respectively. The errors in the acoustic constant, δAC, and the error in the characteristic impedance, δz, were found using:

$$\delta AC = AC \cdot \sqrt{\left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2}$$

Equation 3.6

$$\delta z = z \cdot \sqrt{\left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta \rho}{\rho}\right)^2}$$

Equation 3.7

where δc and $\delta \rho$ are the errors in speed of sound and density.

The mean, standard deviation and error in the mean were determined using:

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$$

Equation 3.8

where $\bar{x}$ is the arithmetic mean, x_i is the ith measurement and n is the number of measurements taken;

$$\sigma_{sd} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (\bar{x} - x_i)^2}$$

Equation 3.9

is the standard deviation; and the error of the mean is found with:

$$\delta\bar{x} = \frac{\sigma_{sd}}{\sqrt{n}}$$

Equation 3.10

To statistically compare sets, Welch's two sample t-test was chosen due to the unequal variance between some sets and the sets being unpaired. Here the t-statistic was calculated using:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1{}^2}{n_1} + \frac{s_2{}^2}{n_2}}}$$

Equation 3.11

where x_1 and x_2 are the sample means; s_1^2 and s_2^2 are the sample variances; and n_1 and n_2 are the sample sizes for the first and second samples respectively.

The degrees of freedom for Welch's two sample t-test is found using:

$$v = \frac{\left(\frac{s_1{}^2}{n_1} + \frac{s_2{}^2}{n_2}\right)^2}{\frac{s_1{}^4}{n_1{}^2 \cdot (n_1 - 1)} + \frac{s_2{}^4}{n_2{}^2 \cdot (n_2 - 1)}}$$

Equation 3.12

D. Results

An example of the data collected in order to obtain the acoustic constant is provided in Table 3.1.

Table 3.1 – Summary Data and Acoustic Calculations for Disk 2

Disk 2 - Pine

Sample	m *kg*	l *m*	h *m*	w *m*	V *m^3*	δV *m^3*
Error	*±1E-05*	*±2E-04*	*±2E-04*	*±2E-04*		
1	5.042E-03	5.573E-02	1.44E-02	1.45E-02	1.16E-05	2.E-07
2	5.413E-03	5.567E-02	1.40E-02	1.47E-02	1.15E-05	2.E-07
3	5.232E-03	5.592E-02	1.45E-02	1.46E-02	1.18E-05	2.E-07
4	5.075E-03	5.586E-02	1.41E-02	1.48E-02	1.17E-05	2.E-07
5	5.408E-03	5.586E-02	1.44E-02	1.46E-02	1.17E-05	2.E-07
6	5.005E-03	5.583E-02	1.44E-02	1.46E-02	1.17E-05	2.E-07
7	5.192E-03	5.584E-02	1.44E-02	1.45E-02	1.17E-05	2.E-07
8	4.763E-03	5.589E-02	1.45E-02	1.41E-02	1.14E-05	2.E-07
9	5.462E-03	5.569E-02	1.46E-02	1.43E-02	1.16E-05	2.E-07
11	4.925E-03	5.577E-02	1.50E-02	1.41E-02	1.18E-05	2.E-07

Sample	ρ kg/m^3	δρ kg/m^3	t_1 μs	t_2 μs	t_3 μs	t_4 μs	t_5 μs
1	433	9	23	21	20	19	19
2	472	10	21	19	18	18	19
3	442	9	22	20	19	19	19
4	435	9	24	22	21	21	22
5	460	9	21	19	20	19	20
6	426	8	20	21	20	20	20
7	445	9	23	21	20	21	21
8	417	8	20	19	21	19	18
9	470	9	21	19	19	19	20
11	418	8	22	23	24	24	25

Sample	$\bar{t}$ *μs*	σ_{sd} *μs*	$\delta\bar{t}$ *μs*	c *m/s*	δc *m/s*	AC $m^4kg^{-1}s^{-1}$	δAC $m^4kg^{-1}s^{-1}$	z *MPa•s/m*	δz *MPa•s/m*
1	20.4	1.50	0.7	2730	90	6.30	0.2	1.18	0.05
2	19.0	1.10	0.5	2930	76	6.20	0.2	1.38	0.05
3	19.8	1.17	0.5	2820	75	6.39	0.2	1.25	0.04
4	22.0	1.10	0.5	2540	57	5.83	0.2	1.11	0.03
5	19.8	0.75	0.3	2820	49	6.13	0.2	1.30	0.03
6	20.2	0.40	0.2	2760	26	6.48	0.1	1.18	0.03
7	21.2	0.98	0.4	2630	55	5.91	0.2	1.17	0.03
8	19.4	1.02	0.5	2880	68	6.91	0.2	1.20	0.04
9	19.6	0.80	0.4	2840	53	6.05	0.2	1.33	0.04
11	23.6	1.02	0.5	2360	46	5.66	0.2	0.99	0.03

a. Speed of Sound

i. Speed of Sound Comparison with Previous Data

The mean value of the speed of sound for each disk was found to be lower compared with the data obtained by Woodward [4]; the difference of the means between both sets of data was higher than the uncertainty in the respective arithmetic means (Table 3.2 and Table 3.3). In each disk, the difference in the speed of sound was statistically significant.

Table 3.2 - Welch Two Sample t-test results for Speed measurements (By Disk)

Speed of Sound							
Pine		Mean	St. Dev.	Error	Welch Two Sample t-test		
			(m/s)		t	df	p-value
Disk 1	(2010)	2540	207	40	-6.21	52	9.17E-08
	(2007)	2910	222	40			
Disk 2	(2010)	2670	174	30	-9.31	56	5.82E-13
	(2007)	3090	168	30			
Disk 3	(2010)	2680	135	30	-9.08	46	8.77E-12
	(2007)	3100	200	40			
Disk 4	(2010)	2520	195	40	-9.49	52	6.58E-13
	(2007)	3120	281	50			
Disk 5	(2010)	2560	198	40	-8.06	62	3.33E-11
	(2007)	2990	217	40			
Disk 7	(2010)	2670	214	40	-4.96	52	7.99E-06
	(2007)	3000	286	50			
Spruce		Mean	St. Dev.	Error	Welch Two Sample t-test		
			(m/s)		t	df	p-value
Disk 6	(2010)	2440	183	30	-12.63	49	< 2.2E-16
	(2007)	3230	288	50			
Disk 8	(2010)	2580	193	30	-15.28	64	< 2.2E-16
	(2007)	3340	204	40			
Disk 9	(2010)	2590	165	30	-18.19	59	< 2.2E-16
	(2007)	3500	237	40			
Disk 10	(2010)	2530	199	30	-13.01	67	< 2.2E-16
	(2007)	3230	251	40			
Disk 11	(2010)	2560	182	40	-12.01	47	5.70E-16
	(2007)	3270	233	50			

Comparing the pine and spruce samples separately from each other showed that there was a larger decrease in the speed of sound of the spruce samples from 2007 to 2010 than there was for the pine samples. The difference of the means for spruce was approximately 780 m/s while the difference in means for pine was approximately 440 m/s and the differences were statistically significant (Table 3.3).

From Chan [29] it is predicted that the speed of sound will decrease as moisture content increases. The samples from the previous study were measured at a moisture content of approximately 12% [4] and the samples from the current study were measured at a moisture content of approximately 6%. The speed of sound for the data from 2010 should have been higher than that of the data from 2007. However, it was shown that the speed of sound values for the 2010 were lower.

Table 3.3 - Welch Two Sample t-test results for Speed of Sound measurements

		Speed of Sound					
		Mean	St. Dev.	Error	Welch Two Sample t-test		
			(m/s)		t	df	p-value
All Samples	(2010)	2570	200	10	-30.87	588	< 2.2E-16
	(2007)	3170	291	20			
Pine Samples	(2010)	2600	201	20	-17.97	333	< 2.2E-16
	(2007)	3040	245	20			
Spruce Samples	(2010)	2540	207	40	-29.91	289	< 2.2E-16
	(2007)	3320	265	20			

ii. Speed of Sound Comparison with Known Values

For choosing wood to create musical instruments, it is important that sound is able to easily travel through the wood. Therefore, a high speed of sound is required for most resonance wood. In general, a speed of sound of higher than 3000 m/s is required while a speed of sound between 4000 m/s and 6500 m/s is preferred for soundboards [30]. For spruce, an average speed of sound of 5600 m/s (with a range of 5200 m/s to 6300 m/s) in wood chosen for musical instruments is appropriate [31]. Sound velocities for pine have an average value of 3500 m/s [32].

Table 3.4 - Range of values for Speed of Sound

Speed of Sound					
		Mean	Error	Range	
				Minimum	Maximum
		(m/s)		(m/s)	
All Samples	2010	2570	10	2010	3050
	2007	3170	20	2270	3930
Pine Samples	2010	2600	20	2010	3050
	2007	3040	20	2270	3570
Spruce samples	2010	2540	20	2030	2990
	2007	3320	20	2500	3930

Compared to the range of sound velocities for resonant woods, all of the data collected from 2010, as well as the data collected by Woodward in 2007 [4], were below the minimum requirements for wood used in sounding boards (Figure 3.5). The highest measurement for the 2010 data was from Disk 7, Sample 8, with a value of 3050 m/s; for the 2007 data, the highest measurement was from Disk 9, Sample 22 at 3930 m/s (Table 3.4).

In addition to being lower than the average velocities of resonant wood, the speed of sound for the wood samples measured in 2010 were all lower than 3500 m/s, the average speed of sound for pine [32]. This was in contrast to the data collected in 2007 in which, both spruce and pine had values within the average range (Figure 3.6), with the average for the spruce disks being within the normal range of velocities of sound through wood (Figure 3.7).

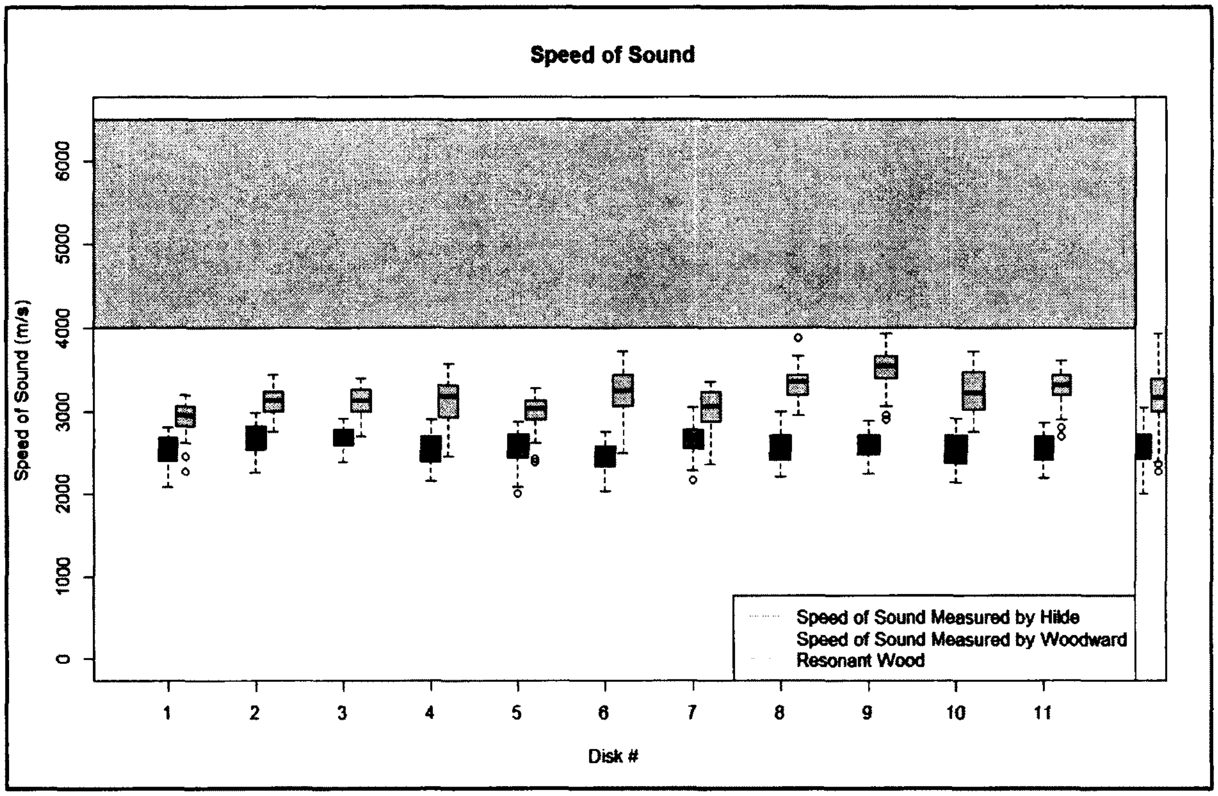

Figure 3.5 – Speed of Sound Comparison by Disk

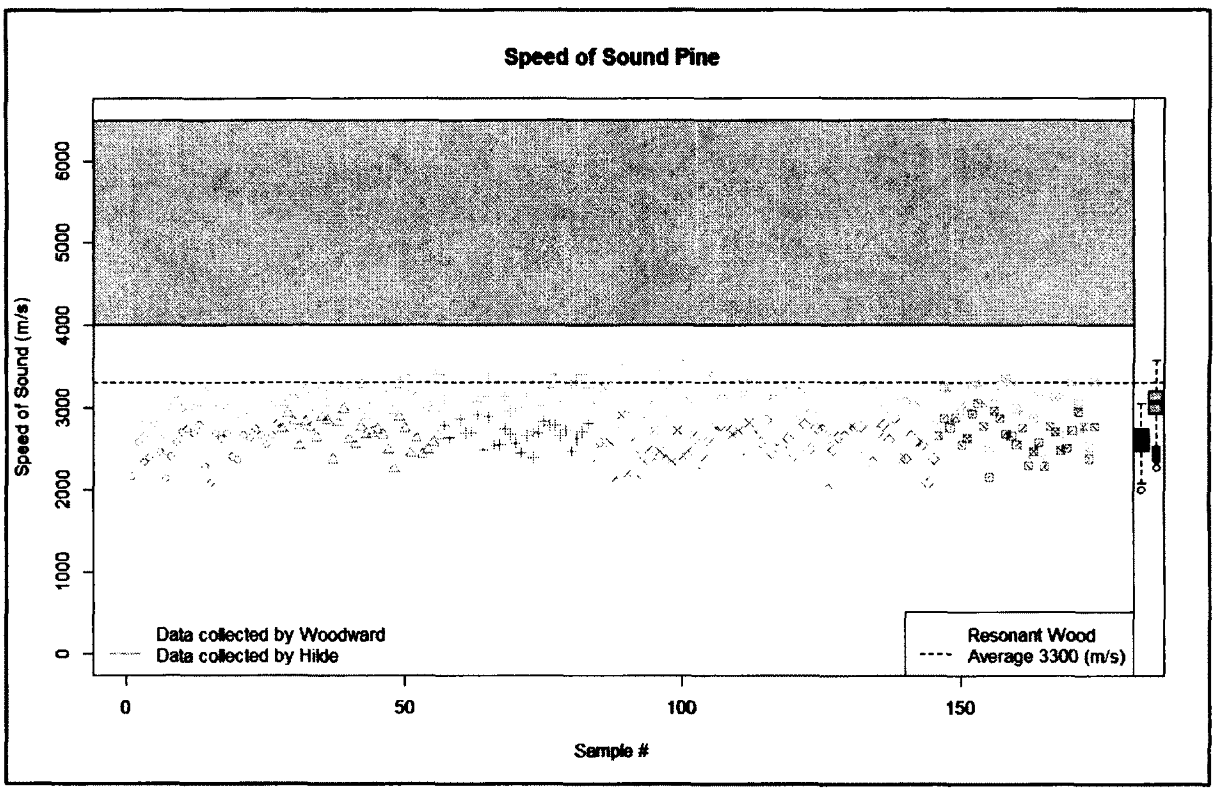

Figure 3.6 – Speed of Sound Comparison (Pine)

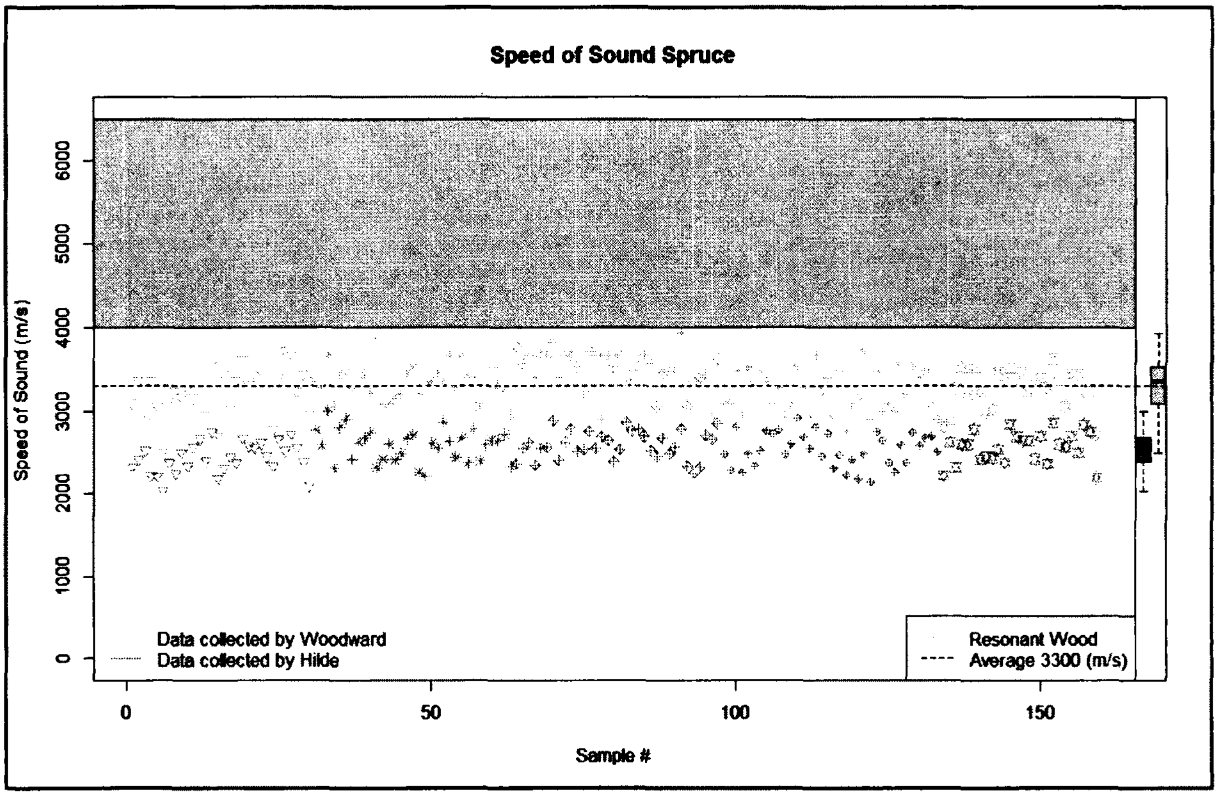

Figure 3.7 – Speed of Sound Measurements for Spruce

b. Density

i. Density Comparison with Previous Data

Similar to the speed of sound, the density showed statistical differences between the 2007 measurements and the 2010 measurements. With the exclusion of Disk 7, which yielded a p-value of 0.882, every disk showed a statistically significant difference between the two sets of measurements with a 95% confidence level (Table 3.5).

Table 3.5 - Welch Two Sample t-test results for Density measurements (By Disk)

Density							
Pine		Mean	St. Dev.	Error	Welch Two Sample t-test		
			(kg/m^3)		t	df	p-value
Disk 1	(2010)	470	32	6	-3.03	52	3.84E-03
	(2007)	496	29	6			
Disk 2	(2010)	450	30	5	-4.45	50	4.90E-05
	(2007)	480	20	4			
Disk 3	(2010)	508	26	5	-3.39	52	1.34E-03
	(2007)	532	24	5			
Disk 4	(2010)	464	38	7	-4.16	58	1.05E-04
	(2007)	507	39	7			
Disk 5	(2010)	433	41	7	-3.06	61	3.32E-03
	(2007)	466	45	8			
Disk 7	(2010)	508	52	10	-0.15	56	0.882
	(2007)	510	54	10			
Spruce		Mean	St. Dev.	Error	Welch Two Sample t-test		
			(kg/m^3)		t	df	p-value
Disk 6	(2010)	393	22	4	-5.42	58	1.22E-06
	(2007)	425	23	4			
Disk 8	(2010)	335	14	2	-4.13	63	1.08E-04
	(2007)	351	16	3			
Disk 9	(2010)	429	14	2	-3.49	64	8.72E-04
	(2007)	442	17	3			
Disk 10	(2010)	386	33	6	-3.88	70	2.33E-04
	(2007)	418	36	6			
Disk 11	(2010)	363	31	6	-2.80	50	7.29E-03
	(2007)	389	33	7			

Comparing the pine and spruce separately, there was a significant difference between the 2007 data and the 2010 data. A similar decrease occurred for each with a difference in means for pine of approximately 27 kg/m^3 and a difference of approximately 24 kg/m^3 for spruce. Overall the two sets of data were statistically different with a difference of means of approximately 25 kg/m^3 (Table 3.6).

It is important to note that, although there is a statistically significant difference between the 2007 samples and the 2010 samples, this change was possibly due to the difference in moisture content. The 2010 samples were measured at a lower moisture content which would lead to a lower overall density in the samples.

Table 3.6 - Welch Two Sample t-test results for Density measurements

Density								
		MC	Mean	St. Dev.	Error	Welch Two Sample t-test		
		(%)	*(kg/m^3)*			t	df	p-value
All Samples	(2010)	~6	429	62	3	-5.17	664	3.16E-07
	(2007)	~12	454	63	3			
Pine Samples	(2010)	~6	471	47	4	-5.46	344	9.28E-08
	(2007)	~12	498	43	3			
Spruce Samples	(2010)	~6	382	40	3	-5.12	315	5.36E-07
	(2007)	~12	406	42	3			

ii. Density Comparison with known values

Depending on the specific purpose, the density required for different musical instruments can range between 300 kg/m^3 and 1400 kg/m^3. For soundboards, though, a lower density is preferred. According to Wegst [30], the density should be between approximately 320 kg/m^3 and 530 kg/m^3; more specifically, Bocur [31] suggests a tighter density range for spruce between 440 kg/m^3 and 480 kg/m^3. Average values of (green) Lodgepole pine range from approximately 400 kg/m^3 to 450 kg/m^3, while different spruce species in British Columbia have a range of 266 kg/m^3 to 518 kg/m^3 for Engelmann spruce and 257 kg/m^3 to 540 kg/m^3 for White spruce [33].

The average values for both the 2007 data and the 2010 data fell within the range of values preferred for resonant wood as suggested by Wegst (Table 3.7 and Figure 3.8) for both pine and spruce. The pine samples had both a higher density and a higher maximum range than the spruce samples for both years; both sets of data had values for pine that were above normal range of resonant wood. The spruce samples, however, fell entirely below the maximum values of resonant wood: 530 kg/m^3 from Wegst [30] and 480 kg/m^3 from Bocur [31] for the 2010 data (Table 3.7). The data for the spruce samples collected by Woodward was also predominately within normal ranges for resonant wood, although the maximum measurement for the density of spruce in this set was 486 kg/m^3 which was higher than the maximum from Bocur [31] of 480 kg/m^3.

Table 3.7 - Range of values for Density

Density					
		Mean	Error	Range	
				Minimum	Maximum
		(kg/m^3)		*(kg/m^3)*	
All Samples	2010	429	3	311	581
	2007	454	3	319	606
Pine Samples	2010	471	4	353	581
	2007	498	3	394	606
Spruce samples	2010	382	3	311	475
	2007	405	3	319	486

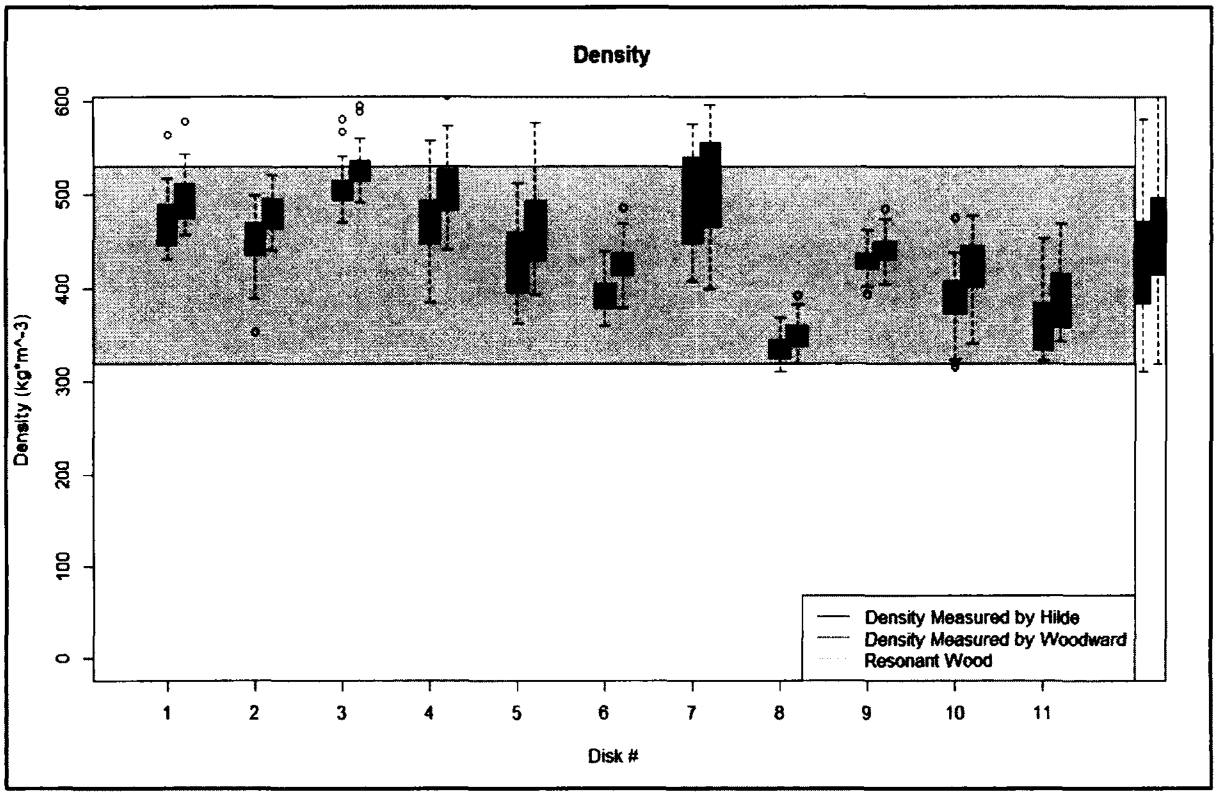

Figure 3.8 - Density Comparison by Disk

Comparing the density values obtained for pine with the range in values for Lodgepole pine [33], many of the measurements were higher than the average values (Figure 3.9). The average values were also above the maximum value of 450 kg/m^3 provided; 2010 data average was approximately 471$\pm$4 kg/m^3 and the 2007 value was approximately 498$\pm$3 kg/m^3. By contrast, the spruce samples for both Woodward's 2007 data and the current 2010 data all fell within the range of average densities (Figure 3.10).

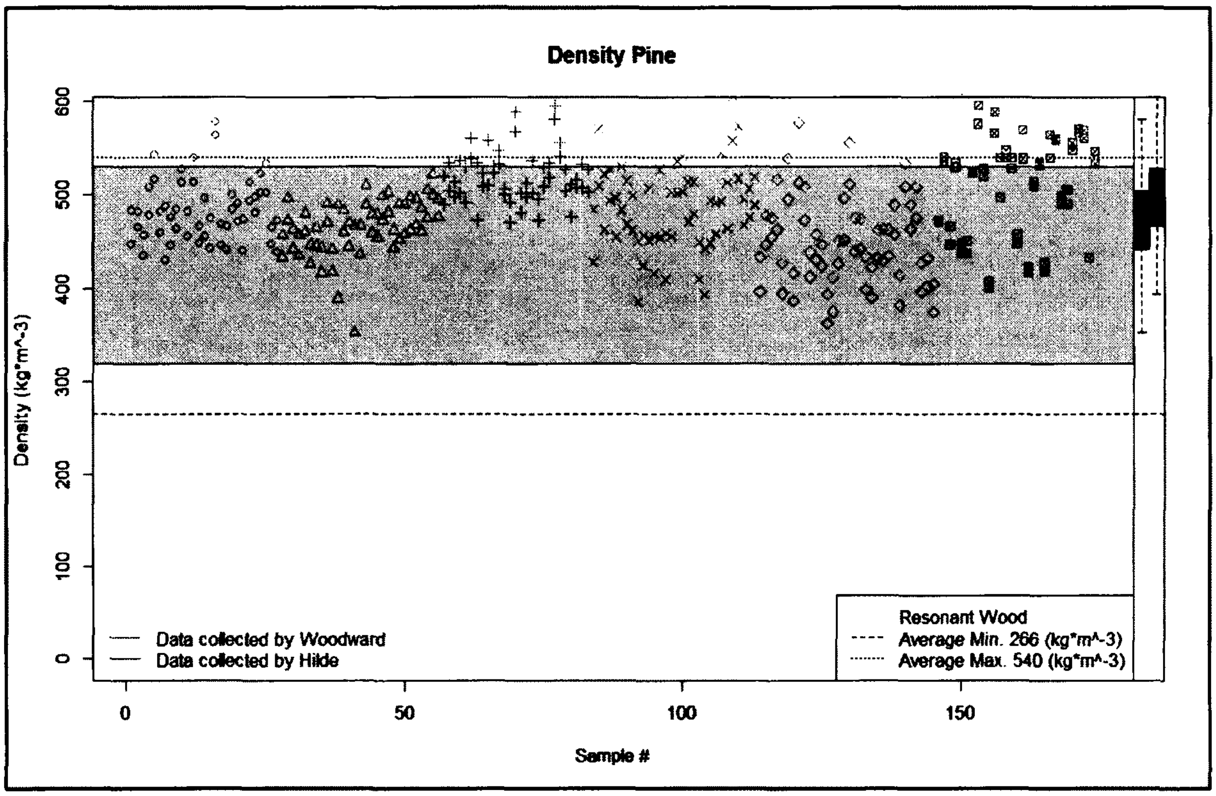

Figure 3.9 - Density Comparison, Pine

The data obtained for spruce was also very similar from a study performed in 2005 on possible resonant wood in British Columbia [3]. In that report, mean density values of 386 kg/m^3 and 419 kg/m^3 for two different sites were reported. The 2010 data for spruce reports an average of 382±3 kg/m^3 with Disk 10 (Table 3.5), in particular, having a value of 386±6 kg/m^3, indicating that the spruce in this study was very similar to spruce within the area.

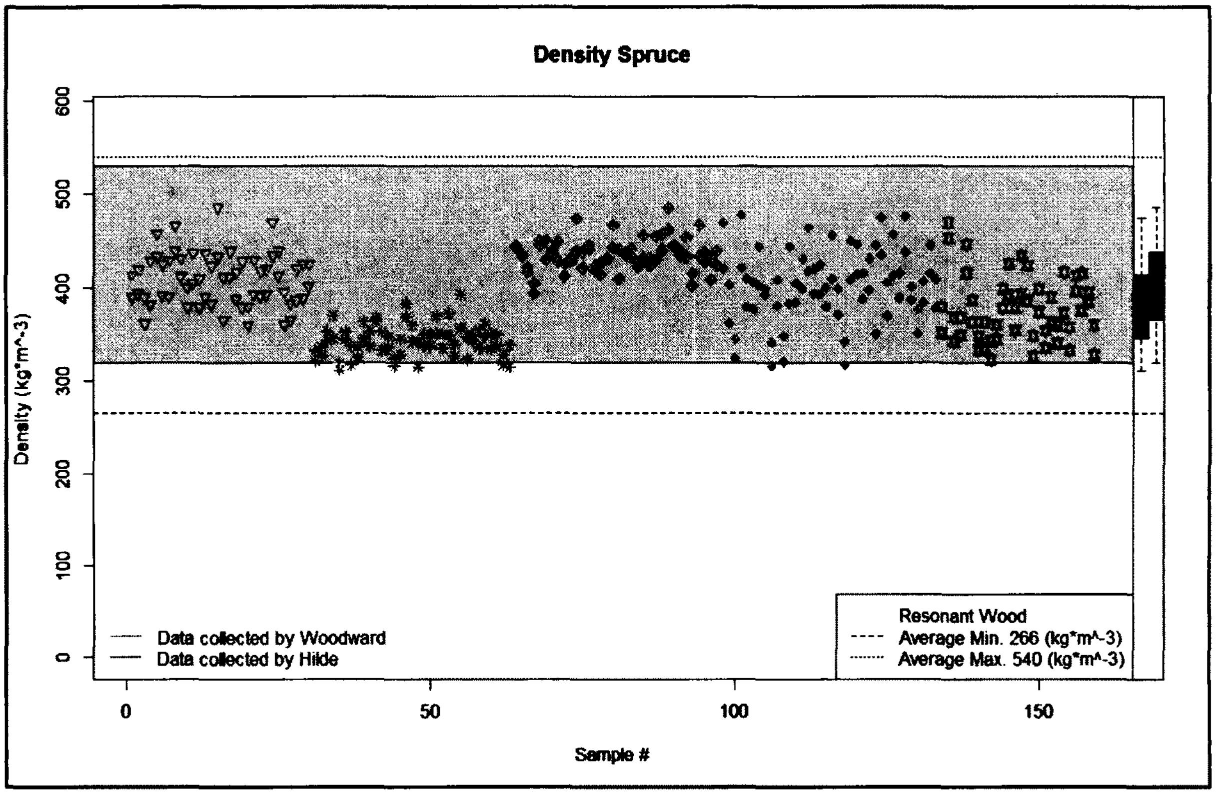

Figure 3.10 - Density Comparison, Spruce

c. Acoustic Constant

i. Acoustic Constant Comparison with Previous Data

Between 2007 and 2010 data sets, the values for the acoustic constant were lower. For each disk and for each species, for all the samples combined, there was a statistically significant difference between the two sets of data (Table 3.8 and Table 3.9). This was expected as there was a significant difference between the 2010 samples and 2007 samples for each of the velocity measurements and all but one of the density measurements.

Table 3.8 - Welch Two Sample t-test results for AC measurements (By Disk)

Density							
Pine		Mean	St. Dev.	Error	Welch Two Sample t-test		
		($m^4kg^{-1}s^{-1}$)			t	df	p-value
Disk 1	(2010)	5.41	0.46	0.09	-3.43	51	1.22E-03
	(2007)	5.89	0.53	0.1			
Disk 2	(2010)	5.95	0.58	0.1	-3.77	49	4.45E-04
	(2007)	6.45	0.39	0.07			
Disk 3	(2010)	5.28	0.38	0.07	-5.11	51	4.73E-06
	(2007)	5.85	0.42	0.08			
Disk 4	(2010)	5.44	0.42	0.08	-6.96	57	3.58E-09
	(2007)	6.16	0.37	0.07			
Disk 5	(2010)	5.95	0.50	0.09	-4.01	61	1.70E-04
	(2007)	6.44	0.45	0.08			
Disk 7	(2010)	5.27	0.34	0.06	-5.60	49	9.48E-07
	(2007)	5.91	0.50	0.09			
Spruce		Mean	St. Dev.	Error	Welch Two Sample t-test		
		($m^4kg^{-1}s^{-1}$)			t	df	p-value
Disk 6	(2010)	6.22	0.67	0.1	-6.64	52	1.77E-08
	(2007)	7.65	0.94	0.2			
Disk 8	(2010)	7.71	0.61	0.1	-12.38	64	< 2.2E-16
	(2007)	9.53	0.57	0.1			
Disk 9	(2010)	6.04	0.41	0.07	-14.78	57	< 2.2E-16
	(2007)	7.94	0.61	0.1			
Disk 10	(2010)	6.61	0.85	0.1	-5.48	69	6.43E-07
	(2007)	7.80	0.97	0.2			
Disk 11	(2010)	7.09	0.56	0.1	-6.57	42	6.23E-08
	(2007)	8.48	0.90	0.2			

As with both density and the speed of sound, there was a larger decrease in the acoustic constant of the spruce samples when compared to the pine samples. The spruce samples decreased from 8.27±0.09 $m^4kg^{-1}s^{-1}$ to 6.72±0.07 $m^4kg^{-1}s^{-1}$ (a decrease of 1.55 $m^4kg^{-1}s^{-1}$) while the pine acoustic constant changed from 6.13±0.04 $m^4kg^{-1}s^{-1}$ to 5.56±0.04 $m^4kg^{-1}s^{-1}$ (a decrease of .57 $m^4kg^{-1}s^{-1}$) (Table 3.9).

Table 3.9 - Welch Two Sample t-test results for Acoustic Constant measurements

Acoustic Constant							
		Mean	St. Dev.	Error	Welch Two Sample t-test		
		($m^4kg^{-1}s^{-1}$)			t	df	p-value
All Samples	(2010)	6.12	0.93	0.05	-30.87	588	< 2.2E-16
	(2007)	7.15	1.35	0.07			
Pine Samples	(2010)	5.56	0.54	0.04	-29.91	289	< 2.2E-16
	(2007)	6.13	0.51	0.04			
Spruce Samples	(2010)	6.72	0.89	0.07	-17.97	333	< 2.2E-16
	(2007)	8.27	1.07	0.09			

ii. Acoustic Constant Comparison with Known Values

Higher acoustic constant values are preferred for musical instruments, primarily when creating soundboards. Soundboard woods require a high speed of sound and a low density leading to preferred values between 9 $m^4kg^{-1}s^{-1}$and 16 $m^4kg^{-1}s^{-1}$ [30]. Wood for other instruments, such as xylophone bars or violin bows, must have desired acoustic constants between 4 $m^4kg^{-1}s^{-1}$and 8 $m^4kg^{-1}s^{-1}$ [30]. For spruce in British Columbia, acoustic constant values of 11.15 $m^4kg^{-1}s^{-1}$and 10.67 $m^4kg^{-1}s^{-1}$ were determined [3].

The mean values for pine, spruce, and for all the samples combined were below 7 $m^4kg^{-1}s^{-1}$, including error. This implies none of the disks would be suitable as wood for soundboards as described by Wegst [30]. Additionally, the maximum acoustic constant measured was 9.02 $m^4kg^{-1}s^{-1}$ which was slightly above the minimum amount preferred for soundboards. The 2007 data measured by Woodward [4] had values that were within range of resonant wood (Table 3.10); the maximum amount for spruce was 10.77 $m^4kg^{-1}s^{-1}$ and Disk 8 falls mostly within the range of resonant woods (Figure 3.11). Disk 8 is also the disk that, for the 2010 data, had the highest acoustic constant.

Table 3.10 - Range of values for Acoustic Constant

Acoustic Constant					
		Mean	Error	Range Minimum	Range Maximum
		($m^4kg^{-1}s^{-1}$)		($m^4kg^{-1}s^{-1}$)	
All Samples	2010	6.12	0.05	4.32	9.02
	2007	7.15	0.07	4.78	10.77
Pine Samples	2010	5.56	0.04	4.32	7.23
	2007	6.13	0.04	4.78	7.30
Spruce samples	2010	6.72	0.07	5.03	9.02
	2007	8.27	0.09	5.55	10.77

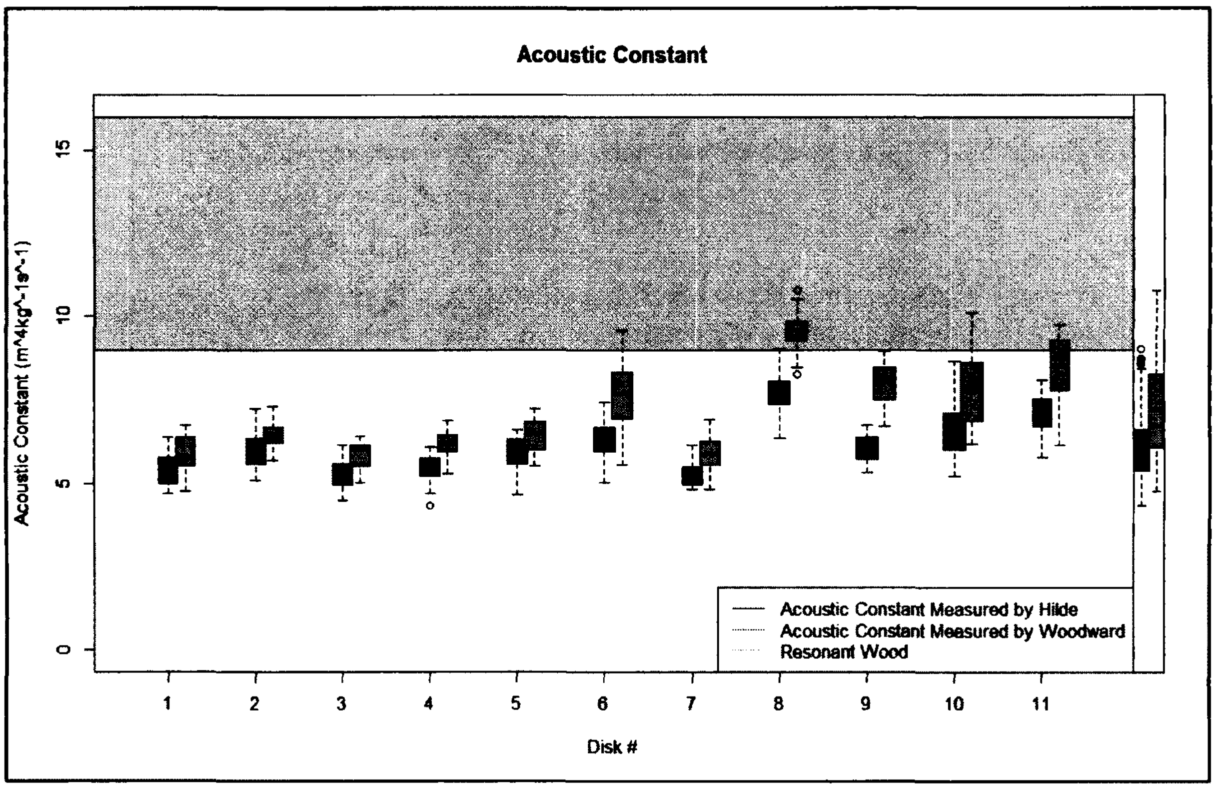

Figure 3.11 - Acoustic Constant Comparison by Disk

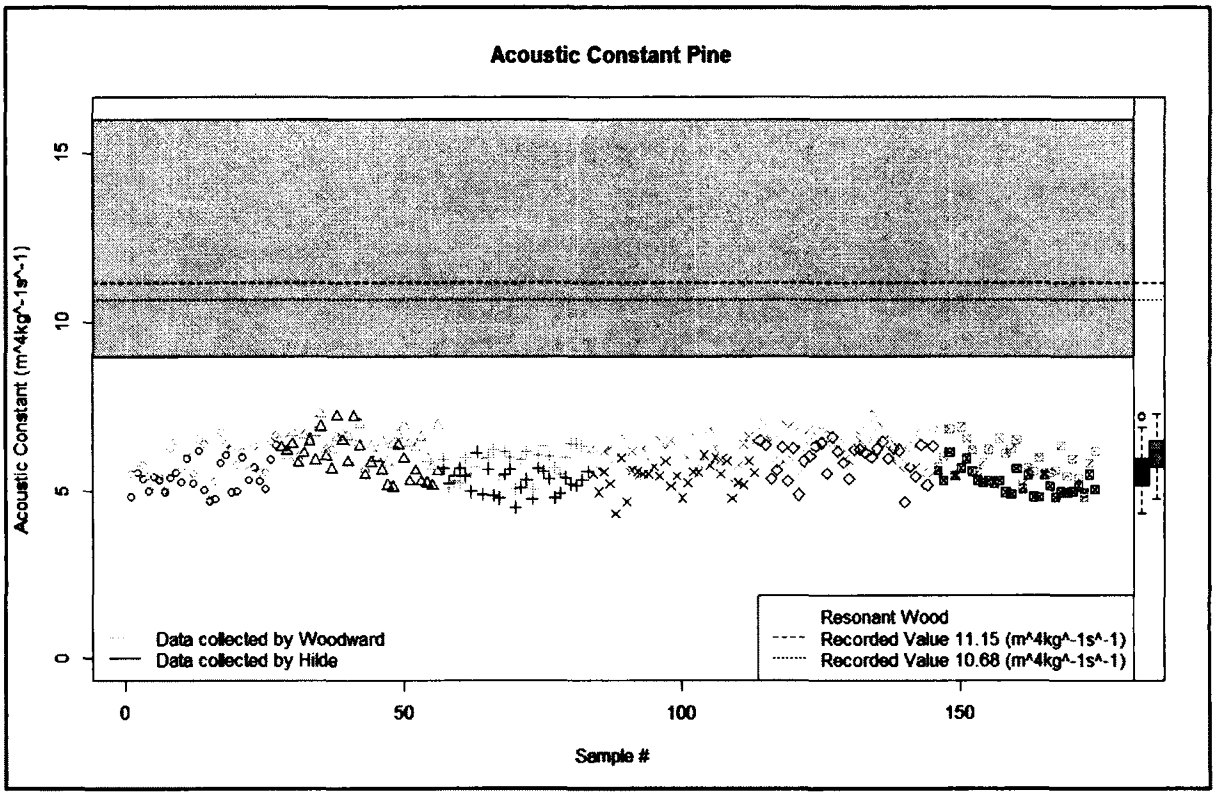

Figure 3.12 - Acoustic Constant Comparison, Pine

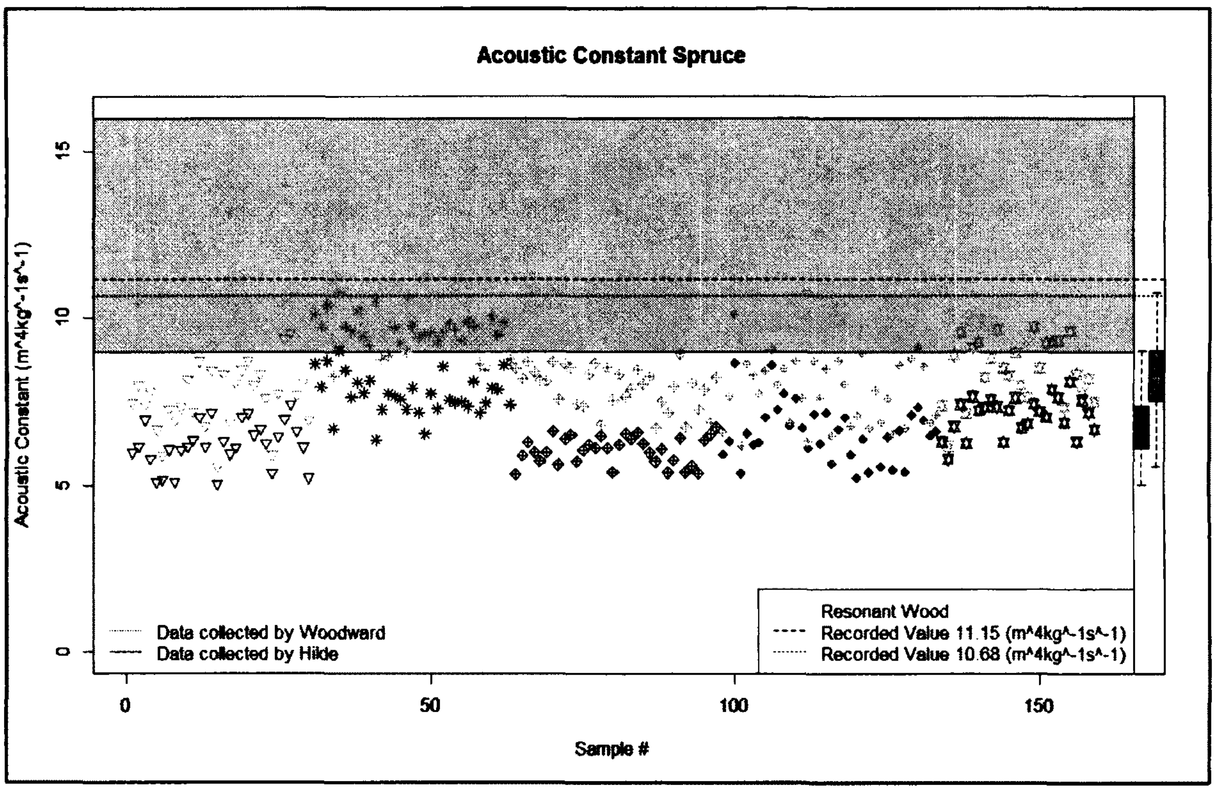

Figure 3.13 - Acoustic Constant Comparison, Spruce

Although the acoustic constant values obtained were not appropriate for sounding boards, they did fall within the range of possible appropriate values for xylophones, violin bows, and other types of instruments; all of the measurements were above 4 $m^4kg^{-1}s^{-1}$, the minimum value provided by Wegst [30].

d. Characteristic Impedance

i. Characteristic Impedance Comparison with Previous Data

The characteristic independence was lower in the 2010 measurements than it was for the 2007 measurements for every disk and for both pine and spruce. This was expected as both the density and speed of sound measurements were lower in the 2010 data. These differences were statistically significant (Table 3.11 and Table 3.12). The mean impedance for the spruce samples was lower than that of the pine samples for both sets of data.

Table 3.11 - Welch Two Sample t-test results for Impedance measurements

Characteristic Impedance							
Pine		Mean	St. Dev.	Error	Welch Two Sample t-test		
		(MPa•s/m)			t	df	p-value
Disk 1	(2010)	1.20	0.15	0.03	-6.05	52	1.58E-07
	(2007)	1.44	0.15	0.03			
Disk 2	(2010)	1.20	0.11	0.02	-9.65	56	1.66E-13
	(2007)	1.49	0.11	0.02			
Disk 3	(2010)	1.36	0.10	0.02	-8.74	46	2.44E-11
	(2007)	1.65	0.14	0.03			
Disk 4	(2010)	1.17	0.16	0.03	-7.76	51	3.46E-10
	(2007)	1.59	0.24	0.04			
Disk 5	(2010)	1.11	0.16	0.03	-5.94	57	1.75E-07
	(2007)	1.40	0.22	0.04			
Disk 7	(2010)	1.36	0.23	0.04	-2.66	55	1.02E-02
	(2007)	1.54	0.27	0.05			
Spruce		Mean	St. Dev.	Error	Welch Two Sample t-test		
		(MPa•s/m)			t	df	p-value
Disk 6	(2010)	0.96	0.07	0.01	-17.48	49	< 2.2E-16
	(2007)	1.37	0.11	0.02			
Disk 8	(2010)	0.87	0.08	0.01	-13.08	59	< 2.2E-16
	(2007)	1.17	0.11	0.02			
Disk 9	(2010)	1.11	0.08	0.01	-17.48	59	< 2.2E-16
	(2007)	1.55	0.12	0.02			
Disk 10	(2010)	0.98	0.11	0.02	-12.82	65	< 2.2E-16
	(2007)	1.35	0.14	0.02			
Disk 11	(2010)	0.93	0.12	0.02	-9.18	49	3.09E-12
	(2007)	1.27	0.14	0.03			

Table 3.12 - Welch Two Sample t-test results for Impedance measurements

Characteristic Impedance							
		Mean	St. Dev.	Error	Welch Two Sample t-test		
		(MPa•s/m)			t	df	p-value
All Samples	(2010)	1.11	0.20	0.01	-20.20	662	< 2.2E-16
	(2007)	1.44	0.22	0.01			
Pine Samples	(2010)	1.23	0.18	0.01	-22.01	283	< 2.2E-16
	(2007)	1.52	0.22	0.02			
Spruce Samples	(2010)	0.97	0.12	0.01	-13.27	338	< 2.2E-16
	(2007)	1.35	0.18	0.01			

ii. Characteristic Impedance Comparison with Known Data

Wood must be able to transfer vibrations to the air efficiently. For sound boards Wegst [30] suggests a value of between 1.2 MPa·s/m and 3.392 MPa·s/m and between 1.68 MPa·s/m and 5.76 MPa·s/m for other instruments such as woodwind instruments and wood for xylophones. Higher characteristic impedance values are required for idiophones such as xylophones as the wood must not transfer vibrations to its supports whereas wood in sound boards must have a characteristic impedance value that is able to interact with the surrounding air accordingly [1]. Pine has been reported to have an average value of 1.57 MPa·s/m [32].

Table 3.13 - Range of values for Characteristic Impedance

Characteristic Impedance					
		Mean	Error	Range	
				Minimum	Maximum
		(MPa•s/m)		(MPa•s/m)	
All Samples	2010	1.11	0.01	0.70	1.76
	2007	1.44	0.01	0.94	2.02
Pine Samples	2010	1.23	0.01	0.73	1.76
	2007	1.52	0.02	1.00	2.02
Spruce samples	2010	0.97	0.01	0.70	1.26
	2007	1.35	0.01	0.94	1.73

For the 2010 data, the mean value for the characteristic impedance of spruce was below the accepted value of z for soundboards. Additionally, the highest value was 1.26

MPa·s/m which is just within range of appropriate soundboard values. The pine samples were within range of both sounding boards and wood used for other instruments. The 2007 samples, by contrast, had values appropriate for both sounding boards and wood for other instruments for both spruce and pine sample (Figure 3.14 and Table 3.13).

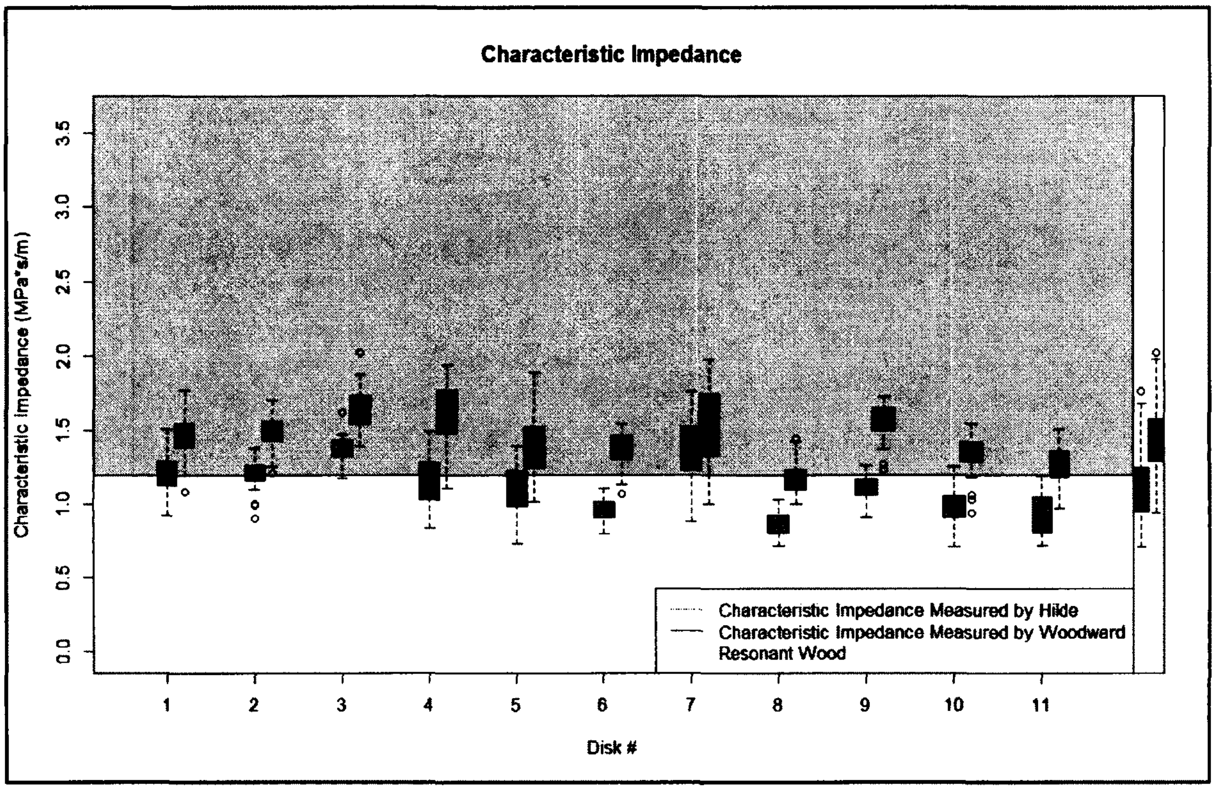

Figure 3.14 - Characteristic Impedance Comparison by Disk

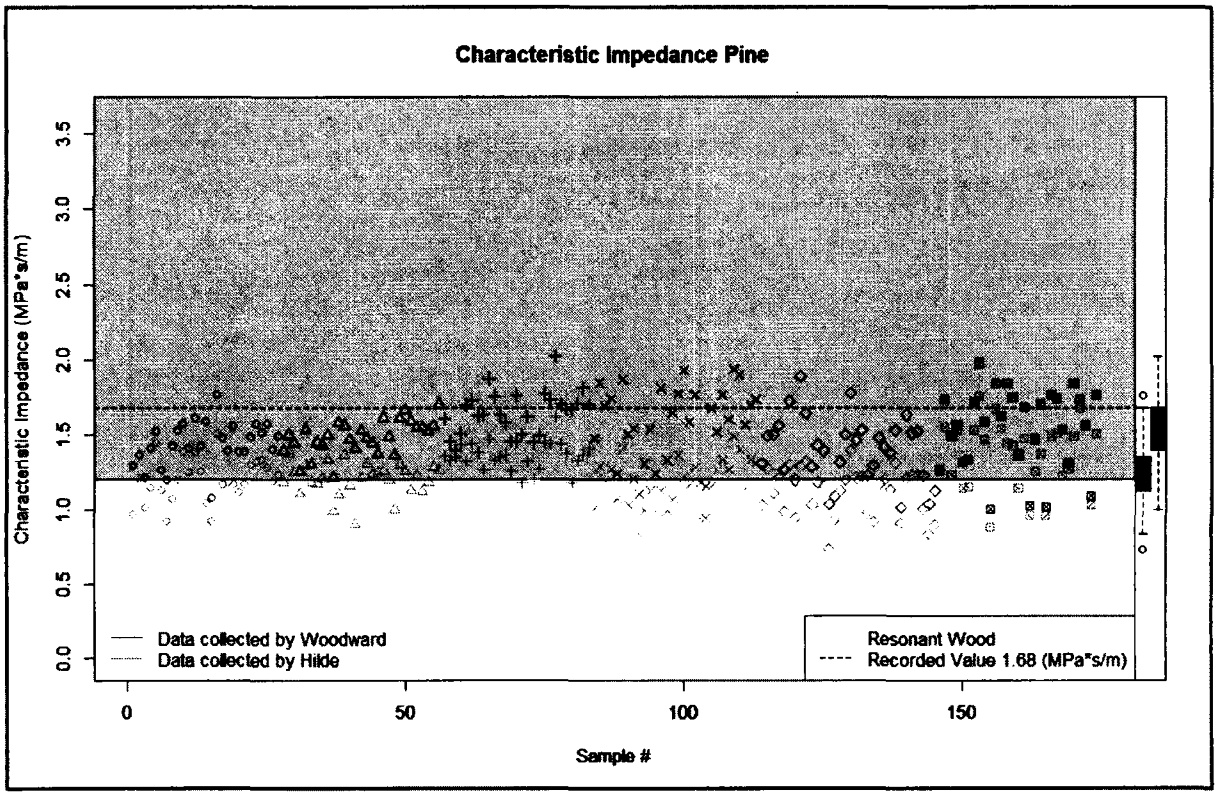

Figure 3.15 - Characteristic Impedance Comparison, Pine

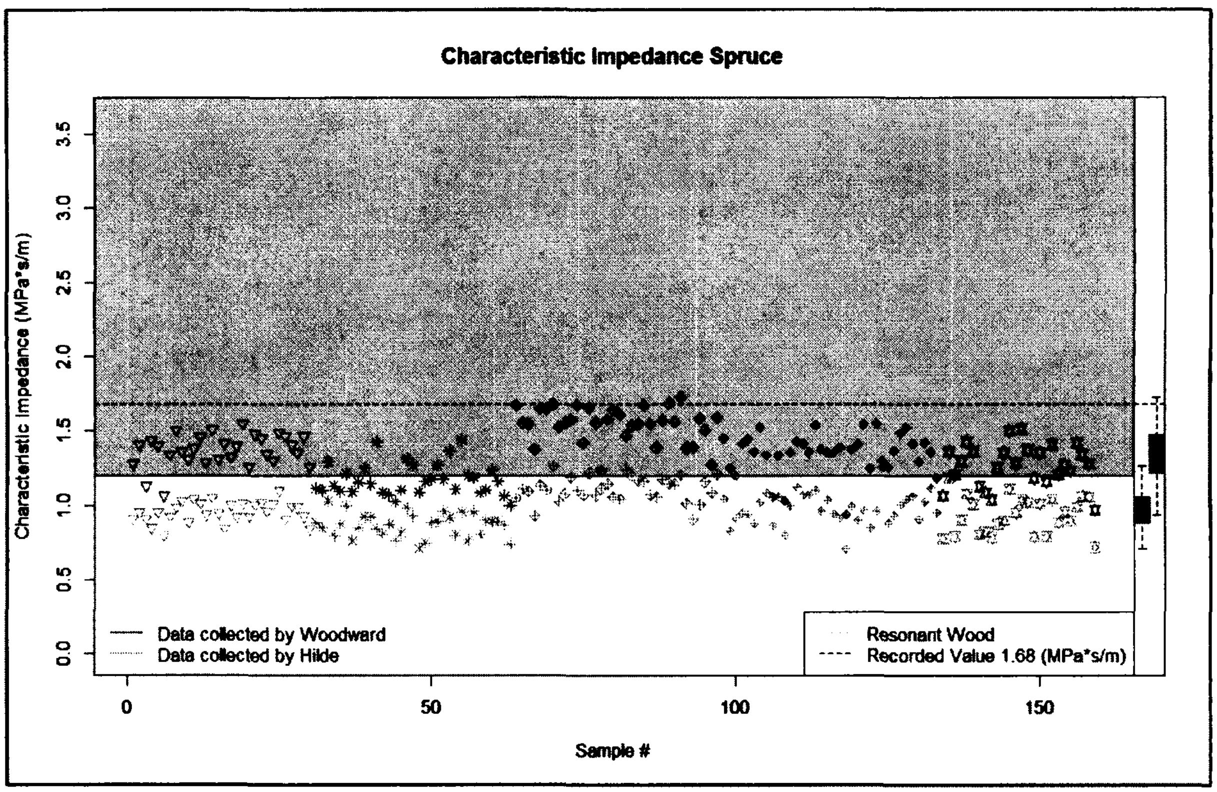

Figure 3.16 - Characteristic Impedance Comparison, Spruce

E. Discussion

Overall, the speed of sound measurements did not vary as much as the density measurements. The per cent differences between the maximum value and mean value, and the minimum value and mean value for density were 36% and 27%, respectively. For the speed of sound, the values were both lower at 19% and 22%. When comparing the 2010 data to the 2007 data, the speed of sound had a larger per cent difference between the years at 23% and density had a per cent difference of only 6%.

Density and speed of sound can be compared using a material property chart as outlined by Wegst [30]. By plotting the density of each sample against the speed of sound through the wood on a logarithmic scale it was possible to show how the submerged wood compares to appropriate values for resonant woods.

Table 3.14 - Per cent Difference comparisons with Mean value

		Max	Mean	Min	% diff. Max	% diff. Min	2007 Mean	% diff 2007 data
Density		581	429	311	36%	27%	454	6%
Pine	*(kg/m^3)*	581	471	353	23%	25%	498	6%
Spruce	*(kg/m^3)*	475	382	311	24%	19%	406	6%
Speed		3050	2570	2010	19%	22%	3170	23%
Pine	*(m/s)*	3050	2600	2010	17%	23%	3040	17%
Spruce	*(m/s)*	2990	2540	2030	18%	20%	3320	31%

When comparing the current data with the range of accepted values for soundboards from Wegst [30], which was represented by the grey and green rectangles on Figure 3.17, the submerged wood had a range of densities that was comparable to that of soundboards, but had noticeably lower values of the speed of sound (as described previously). Based on this comparison, Figure 3.17 reaffirms that the submerged wood does not have suitable speed of sound values and, consequently, did not have suitable values for acoustic constant when compared to soundboards.

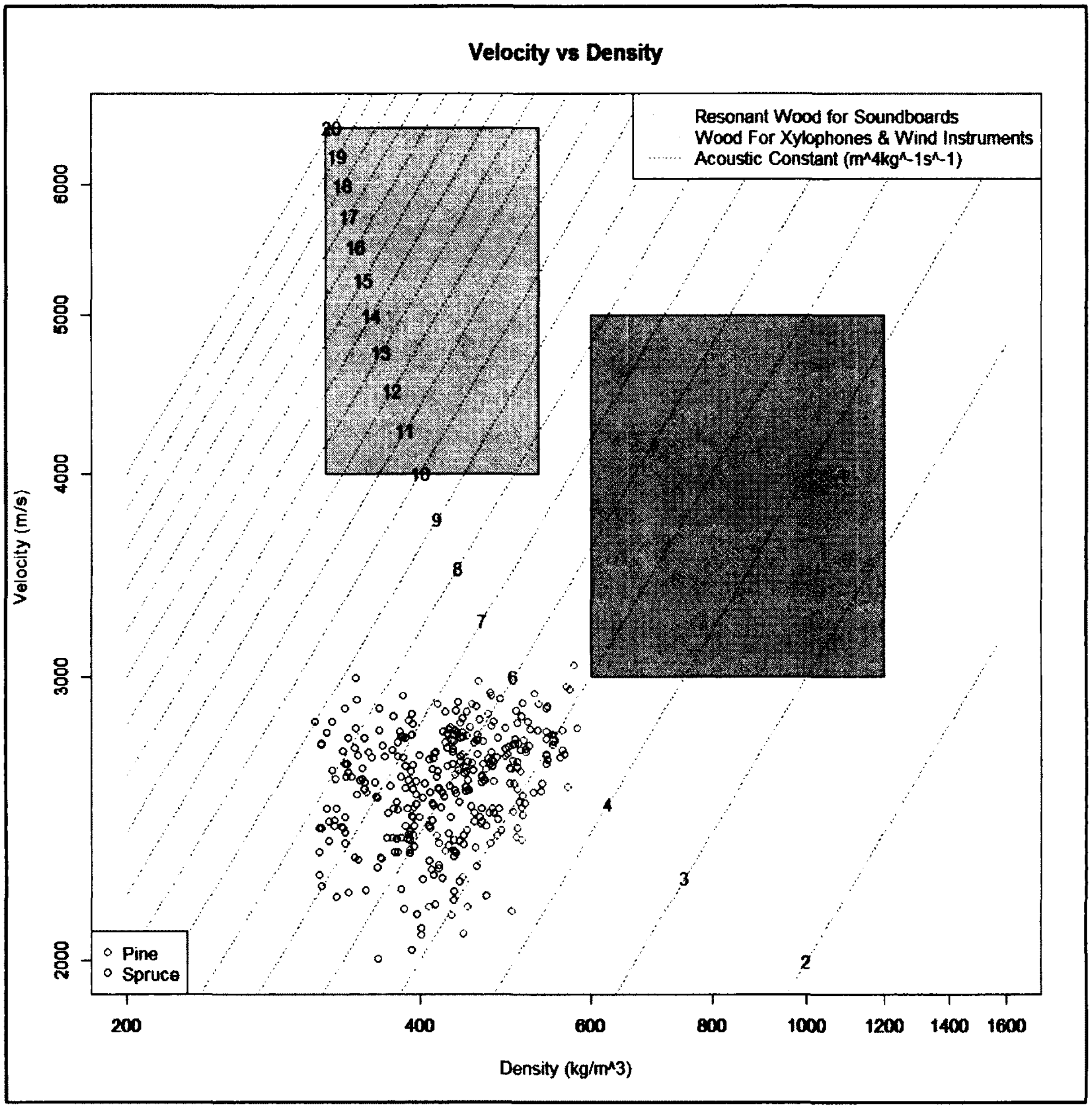

Figure 3.17 – Speed vs. Density Scatterplot with Acoustic Constant (Logarithmic Scale)

The slope of the acoustic constant in Figure 3.17 was not appropriate for soundboards but, according to Wegst, was suitable for other musical instruments. This supports the previous statements in which both pine and spruce samples were not in the appropriate range for sound boards but were in an appropriate range for other instruments. Despite having an appropriate acoustic constant for other instruments, the characteristic impedance was not found to be within range of appropriate characteristic impedance values for other instruments (Figure 3.18). The submerged pine samples, however, were found to be within the range of appropriate characteristic impedance values for sounding boards even though the acoustic constant values were not Figure 3.18.

Because the submerged pine and spruce samples have either characteristic impedance or acoustic constant values that are too low for sounding boards or other instruments it can be concluded that neither is appropriate for use as resonant wood for either soundboards or for other instruments such as xylophones or woodwind instruments.

Additionally, the suitability of the wood for use as instruments decreased from the initial measurements performed by Woodward [4] which was the opposite of what was expected.

When examining the data provided by disk for the density, speed of sound, acoustic constant and characteristic impedance (Figure 3.19), it appears that changes to the acoustic constant were caused primarily by changes in the density. Small changes in density lead to larger changes in the acoustic constant (Figure 3.20). The speed, however, remained much more constant throughout and did not appear to cause large variations in the acoustic constant. This was supported by the fact that the speed of sound through wood is dependent on the density, in addition to the modulus of elasticity.

The dependence of the acoustic constant on the density can be further shown when comparing changes in the acoustic constant and density for each disk individually. In Figure 3.20 it can be observed that the acoustic constant responded inversely to changes in the density. The same dependence was not seen when examining the acoustic constant against the speed of sound in the wood; the acoustic constant fluctuates independent of changes to the speed of sound through the wood Figure 3.21.

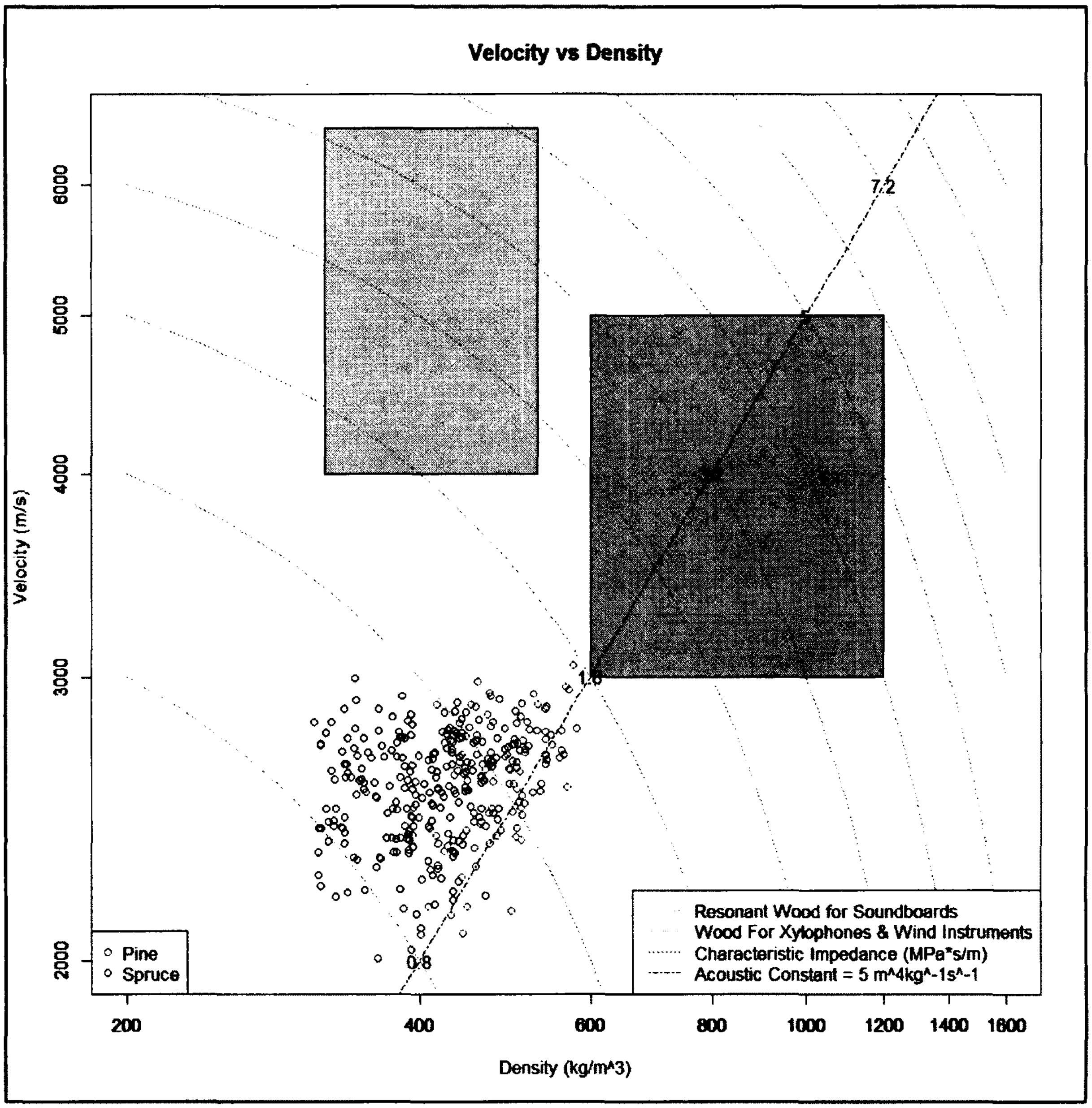

Figure 3.18 – Speed vs. Density Scatterplot with Impedance (Logarithmic Scale)

The main impact that the speed of sound holds over the acoustic constant was in its overall magnitude. When the speed of sound was high, in addition to having a low density, such as disk 10 (Figure 3.19), this resulted in a much higher acoustic constant. The lower than average speed of sound was most likely the cause of the lower than average acoustic constant values compared to resonant woods.

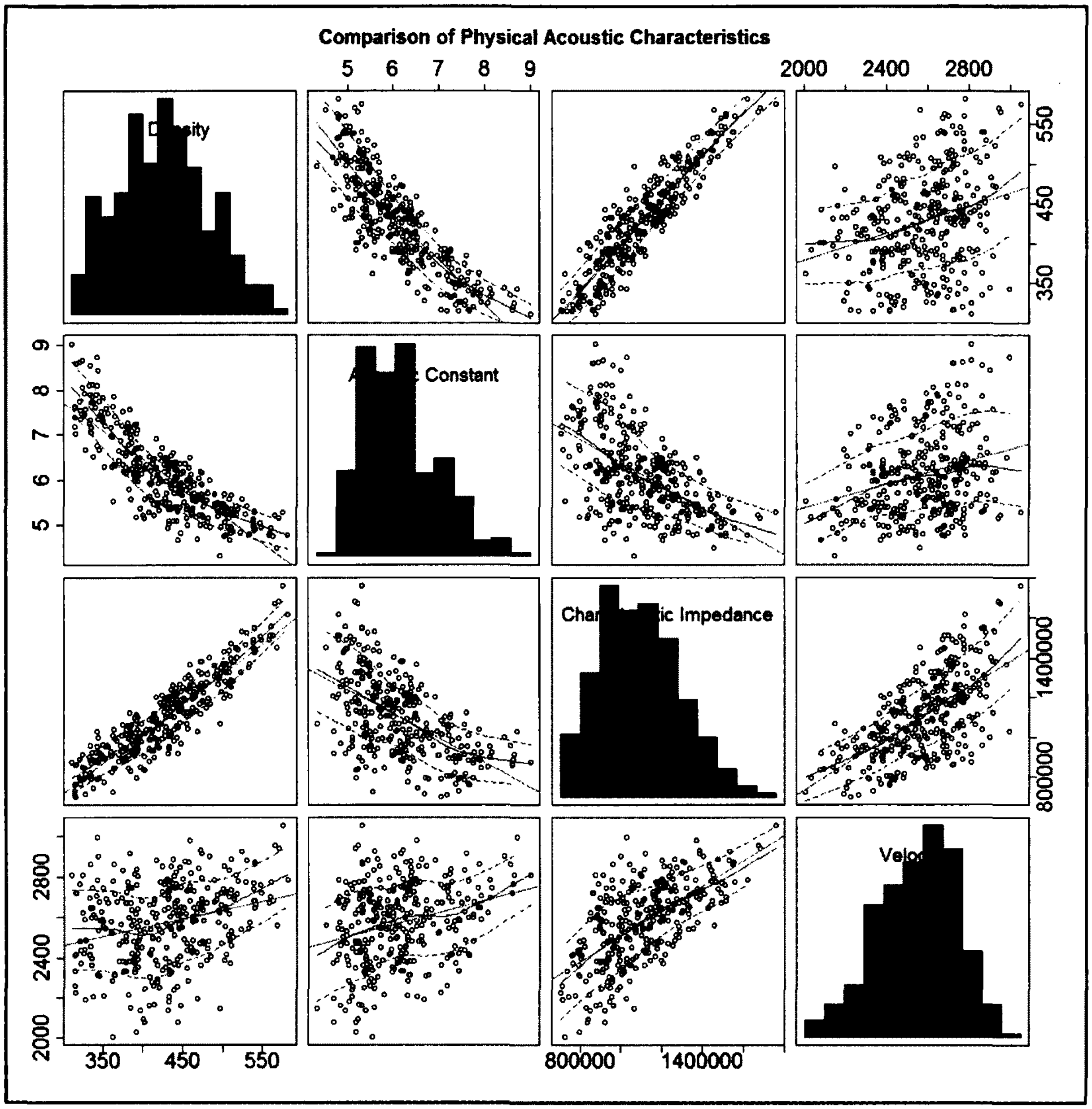

Figure 3.19 – Comparison of Physical Acoustic Characteristics

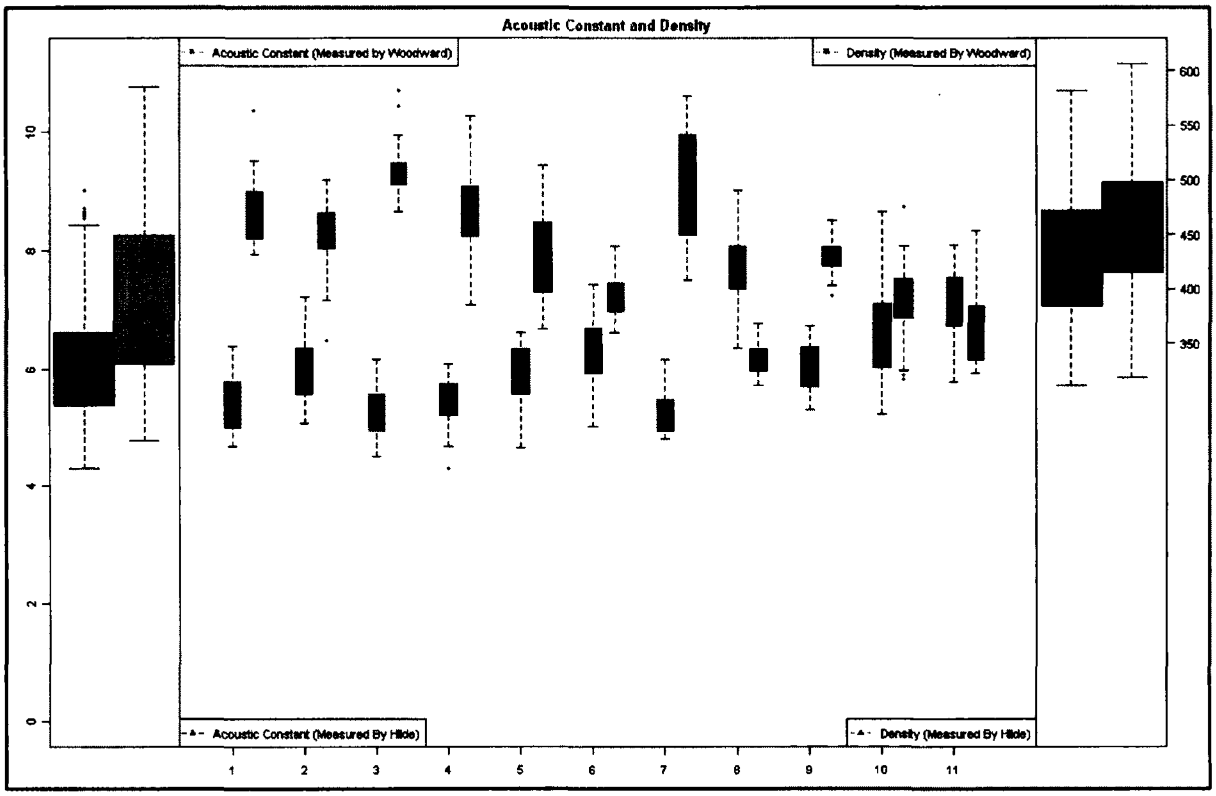

Figure 3.20 - Acoustic Constant and Density Comparison by Disk

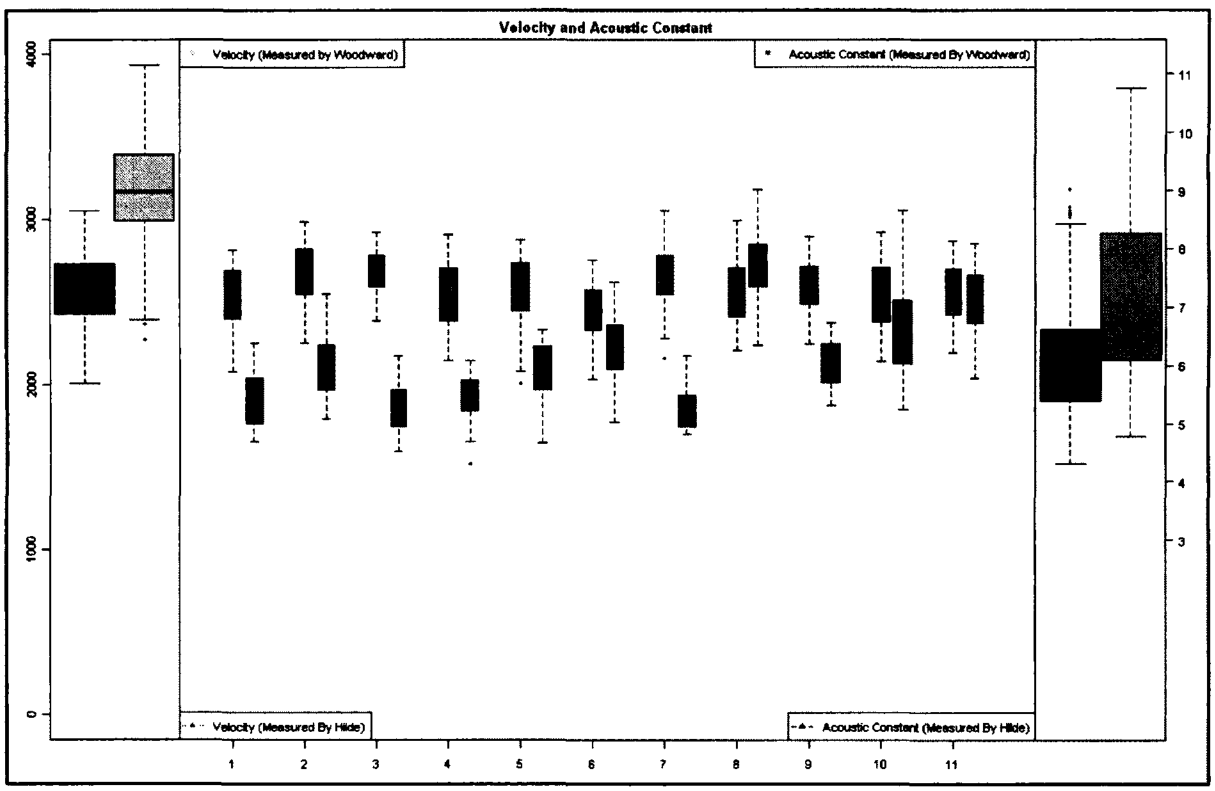

Figure 3.21 – Speed of Sound and Acoustic Constant Comparison by Disk

F. Summary

After an initial study performed on submerged wood revealed that the wood was not suitable for use as musical instruments [4], the wood was left to sit, untouched, in a laboratory environment. It was believed that the physical acoustic properties of the wood, such as the density, speed of sound and, consequently the acoustic constant and characteristic impedance, would improve. As presented in this chapter, however, the acoustic properties of the submerged wood did not improve and instead became less desirable.

Both the density and speed of sound through the submerged wood decreased (Figure 3.5 and Figure 3.8) when compared with the measurements from 2007. The lower speed and density caused a lower characteristic impedance due to the direct relationship between them (Figure 3.14). Although a lower density would normally cause the acoustic constant to increase as there is an inverse relationship between the two, the speed of sound decreased by a larger magnitude and caused a lower overall acoustic constant when compared to the data from 2007. This decrease was seen for both pine and spruce.

The characteristic impedance and acoustic constant of the submerged wood was compared with that of normal values for resonant wood used in soundboards, xylophones and wind instruments. It was found that a few spruce samples were within the minimum range required for the acoustic constant of soundboards but that the characteristic impedance was not appropriate for soundboards. Pine samples, however, had an appropriate characteristic impedance for soundboards but did not have an appropriate acoustic constant. The density values for both species were within an appropriate range but it was determined that the speed of sound through the wood was too low and, thus, the sound would not be able to propagate through the wood or be transferred between the wood and other materials (such as the strings or the air) efficiently enough.

Both pine and spruce samples were within the acceptable range of values for acoustic constant when compared to xylophones and woodwind instruments but did not have an appropriate characteristic impedance. While the speed of sound was adequate for these types of instruments, both xylophones and woodwind instruments require a higher density which the submerged wood samples did not have.

One possible explanation as to why the speed of sound may have been much lower compared to resonant woods could be due to degradation in the cellulose. Submerged wood, and other aged wood, has been shown to have a lower crystallinity when compared to that of control woods, caused by a more amorphous cellulose [34] [35] [36].

4. Adsorption Properties of Submerged Wood

A. Introduction

Wood samples from Ootsa Lake, British Columbia, were measured to determine their suitability for musical instruments. Initial testing performed by Woodward [4] showed that the submerged wood samples were not well suited when compared to normal resonant wood. It was believed that this was either due to improper drying or the fact that the wood had been submerged. The wood was subsequently left to sit untouched in a lab and retested to see if there was an improvement in the physical acoustic properties. After retesting, the wood samples were shown to be less suited for musical instruments.

As noted in Chapter 3, the retesting revealed that the speed of sound of the submerged wood had decreased and that this speed was both lower than average values and lower than values expected for resonant wood used in soundboards. The density, however, was within normal levels. It was hypothesized that the lower speed of sound values were due to degradation in the cellular structure of the wood, particularly the cellulose. Degradation in the cellulose would cause more amorphous areas and impede the ability of the sound to travel through the wood.

In this chapter, this hypothesis is examined by determining the moisture content of the submerged wood samples at varying levels of relative humidity. Higher levels of moisture content would suggest a larger amount of wood is accessible to water which would suggest a lower crystallinity. The results were compared with control samples. Comparisons were also made to previous studies performed on submerged, buried and ancient wood samples.

B. Sample Preparation

In July, 2011, two sets of samples were chosen from the submerged wood used in the previous study of the physical acoustic characteristics: Disk 2 (pine) and Disk 6 (spruce). The first twenty samples from each set were cut in half, with the halves being labelled 'a' and 'b', respectively, to form matched specimens. Control samples were obtained at Windsor Plywood and were from a local sawmill supplier. The samples were identified as Lodgepole pine and spruce. The samples were kiln-dried to 15-19% MC (in accordance to industry standards) and reached an equilibrium of approximately 10% MC while sitting untouched. These samples were prepared and labelled in the same way as the submerged wood samples (Table 4.1).

Table 4.1 - Labelling of Wood Samples

Sample Group 1				Sample Group 2			
Disk 2: Pine (P)		Disk 6: Spruce (S)		Disk 2: Pine (P)		Disk 6: Spruce (S)	
Submerged	Control	Submerged	Control	Submerged	Control	Submerged	Control
1a	1a	1a	1a	1b	1b	1b	1b
2a	2a	3a	2a	2b	2b	3b	2b
3a	3a	4a	3a	3b	3b	4b	3b
4a	4a	5a	4a	4b	4b	5b	4b
5a	5a	6a	5a	5b	5b	6b	5b
6a	6a	7a	6a	6b	6b	7b	6b
7a	7a	8a	7a	7b	7b	8b	7b
8a	8a	9a	8a	8b	8b	9b	8b
9a	9a	11a	9a	9b	9b	11b	9b
11a	10a	12a	10a	11b	10b	12b	10b
Sample Group 3				Sample Group 4			
Disk 2: Pine (P)		Disk 6: Spruce (S)		Disk 2: Pine (P)		Disk 6: Spruce (S)	
Submerged	Control	Submerged	Control	Submerged	Control	Submerged	Control
12a	11a	13a	11a	12b	13b	13b	13b
13a	12a	14a	12a	13b	14b	14b	14b
14a	13a	15a	13a	14b	15b	15b	15b
15a	14a	16a	14a	15b	16b	16b	16b
16a	15a	17a	15a	16b	17b	17b	17b
17a	16a	18a	16a	17b	18b	18b	18b
18a	17a	19a	17a	18b	19b	19b	19b
19a	18a	20a	18a	19b	20b	20b	20b
20a	19a	21a	19a	20b	21b	21b	21b
21a	20a	22a	20a	21b	22b	22b	22b

C. Experiment

a. Adsorption Isotherm Measurements

Samples from Group 1 and Group 2 were initially weighed and then placed with Drierite™ (anhydrous calcium sulfate) inside of an oven and left to dry. Once the moisture was removed from the samples by the drying process, each sample was again weighed and the oven-dry weight (W_0) was obtained (Step 1, Table 4.2).

Group 1 and Group 2 were then placed in two separate desiccators that had been prepared with the saturated salt-solution lithium bromide to create a relative humidity inside the desiccator of 6%. The samples remained at this relative humidity until equilibrium moisture content was reached. While equilibrium was being reached in Group 1 and Group 2 at the first relative humidity level, the oven-dry weight of the samples in Group 3 and Group 4 were determined by drying them in the oven until the moisture was removed (Step 2, Table 4.2). Groups 1 and 2 were dried for 20 days. Groups 3 and 4 were dried for 8 days.

Table 4.2 - Order of increasing Relative Humidity for each Group

Step	1	2	3	4	5	6	7	8	9	10	11
Group 1 & 2	0%	6%	11%	20%	32%	43%	66%	79%	93%	100%	-
Group 3 & 4	-	0%	6.37%	11%	20%	32%	43%	66%	79%	93%	100%

When equilibrium was reached in Group 1 and in Group 2, the equilibrium moisture content for each sample was found:

$$EMC = \frac{W_{RH} - W_O}{W_O} \cdot 100\%$$

Equation 4.1

where W_{RH} is the mass at a specific relative humidity (i.e. 6 %) and W_0 is the oven-dry weight. There error in the equilibrium moisture content, δEMC, was found using:

$$\delta EMC = EMC \cdot \sqrt{\left(\frac{\sqrt{\delta W_{RH}{}^2 + \delta W_O{}^2}}{W_{RH} - W_O}\right)^2 + \left(\frac{\delta W_O}{W_O}\right)^2} = EMC \cdot \sqrt{\left(\frac{\sqrt{2 \cdot 10^{-4}}}{W_{RH} - W_O}\right)^2 + \left(\frac{.01}{W_O}\right)^2}$$

Equation 4.2

where δW_{RH} and δW_O are there errors in the mass at a specific relative humidity and error in the oven-dry weight of the wood sample. Both had an error of $\pm.01$g when measured with the OHAUS™ Scout Pro SP402.

Once equilibrium was reached for each of the samples in all four groups, Group 1 and 2 were moved into two desiccators with a salt solution of lithium chloride to create a relative humidity of 11%; Group 3 and Group 4 were moved into the desiccators containing lithium bromide (Step 3, Table 4.2). The equilibrium moisture content was found for all the samples and the Groups were moved to desiccators with a relative humidity as described by Step 4, Table 4.2. This process was repeated until the samples moved through all eleven steps and EMC values were determined for each wood sample at each relative humidity. Throughout the temperature was maintained at approximately 20±2°C.

Table 4.3 – Saturated Salt Solutions and Associated Relative Humidity Levels

Name	Chemical Name	Relative Humidity (%)
Lithium Bromide	LiBr	6 [37]
Lithium Chloride	LiCl	11 [37]
Potassium Acetate	CH_3CO_2K	20
Calcium Chloride	$CaCl_2$	32 [38]
Potassium Carbonate	K_2CO_3	43 [37]
Sodium Nitrite	$NaNO_2$	66 [39]
Ammonium Chloride	NH_4Cl	79 [40]
Sodium Sulphate	Na_2SO_4	93
Water (deionized)	H_2O	100

b. Sorption Isotherm Modelling

In order to model the adsorption isotherms for the submerged wood, the equilibrium moisture contents were plotted against the relative humidity. Using the statistical program, R, the Hailwood-Horrobin model (Equation 2.7) was fit to the data; this provided the coefficients of W, K_1, and K_2 where W has units of mol/kg.

c. Unimolecular and Dissolved Water Adsorption

Using the W, K1 and K2 coefficients found when modelling it was possible to plot the unimolecular adsorption (M_h) and dissolved water adsorption (M_s) for both the submerged and control samples using Equation 2.5 and Equation 2.6.

To statistically compare the sets of data in Table 4.7, Table 4.11, and Table 4.15, Welch's two sample t-test was chosen due to the unequal variance between some sets and the sets being unpaired. Here the t-statistic was calculated using Equation 3.11.The degrees of freedom for Welch's two sample t-test was found using Equation 3.12.

The 95% confidence interval was then found using:

$$95\%\ Confidence\ interval = \bar{x} \pm v \cdot p$$

Equation 4.3

where p is the probability associated with corresponding degrees of freedom obtained from a t-table, and $\bar{x}$ is the mean.

The difference between the mean values for two sets was determined using:

$$\Delta Mean = \overline{x_1} - \overline{x_2}$$

Equation 4.4

The relative difference between the mean values was found with:

$$d_r = \frac{|\overline{x_1} - \overline{x_2}|}{\left(\frac{|\overline{x_1} + \overline{x_2}|}{2}\right)}$$

Equation 4.5

To determine the goodness of fit for the Hailwood-Horrobin model when applied to the data points, the R^2 value was determined using:

$$R^2 = 1 - \frac{RSS}{SS} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}$$

Equation 4.6

where RSS is the residual sum of squares, SS is the total sum of squares, and y_i, $\hat{y}_i$, and $\bar{y}_i$ are the i[th] value of the variable to be predicted, variable predicted with the model, and mean value, respectively.

D. Results

An example of the data collected to plot the sorption isotherm for the wood samples is provided in Table 4.4, Table 4.5, and Table 4.6.

Table 4.4 - Sample data (Group 1, Pine, Submerged), Measured Mass of Samples

Group 1 (Pine, Submerged)											
Date	RH	1a	2a	3a	4a	5a	6a	7a	8a	9a	11a
	(%)	Measured Mass									
		(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)
02/08/11	0	2.24	2.39	2.47	2.62	2.87	2.19	2.61	2.44	2.86	2.08
16/08/11	6	2.29	2.45	2.52	2.67	2.93	2.24	2.66	2.49	2.91	2.12
12/09/11	11	2.30	2.45	2.52	2.67	2.94	2.24	2.67	2.49	2.91	2.13
26/09/11	20	2.32	2.47	2.55	2.71	2.97	2.27	2.71	2.53	2.94	2.15
11/10/11	32	2.36	2.51	2.59	2.76	3.00	2.3	2.73	2.56	2.99	2.19
21/10/11	43	2.42	2.56	2.65	2.82	3.09	2.34	2.80	2.62	3.07	2.24
16/12/11	66	2.47	2.63	2.71	2.88	3.15	2.41	2.88	2.69	3.14	2.31
24/12/11	79	2.51	2.67	2.77	2.94	3.22	2.45	2.92	2.73	3.2	2.34
10/01/12	93	2.64	2.82	2.96	3.09	3.38	2.57	3.06	2.88	3.35	2.45
30/01/12	100	2.77	2.93	3.05	3.26	3.53	2.70	3.20	2.98	3.54	2.58
		Error in mass = ±0.01g									

Table 4.5 - Sample data (Group 1, Pine Submerged), EMC of Samples

Group 1 (Pine, Submerged)											
Date	RH	1a	2a	3a	4a	5a	6a	7a	8a	9a	11a
	(%)	Calculated Equilibrium Moisture Content									
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
16/08/11	6	2.23	2.51	2.02	1.91	2.09	2.28	1.92	2.05	1.75	1.92
12/09/11	11	2.68	2.51	2.02	1.91	2.44	2.28	2.30	2.05	1.75	2.40
26/09/11	20	3.57	3.35	3.24	3.44	3.48	3.65	3.83	3.69	2.80	3.37
11/10/11	32	5.36	5.02	4.86	5.34	4.53	5.02	4.60	4.92	4.55	5.29
21/10/11	43	8.04	7.11	7.29	7.63	7.67	6.85	7.28	7.38	7.34	7.69
16/12/11	66	10.27	10.04	9.72	9.92	9.76	10.05	10.34	10.25	9.79	11.06
24/12/11	79	12.05	11.72	12.15	12.21	12.20	11.87	11.88	11.89	11.89	12.50
10/01/12	93	17.86	17.99	19.84	17.94	17.77	17.35	17.24	18.03	17.13	17.79
30/01/12	100	23.66	22.59	23.48	24.43	23.00	23.29	22.61	22.13	23.78	24.04

Table 4.6 – Sample data (Group 1, Pine Submerged), *δEMC*

Group 1 (Pine, Submerged)											
Date	RH	1a	2a	3a	4a	5a	6a	7a	8a	9a	11a
	(%)	Error in Equilibrium Moisture Content									
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
16/08/11	6	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
12/09/11	11	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
26/09/11	20	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
11/10/11	32	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
21/10/11	43	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
16/12/11	66	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
24/12/11	79	0.6	0.6	0.6	0.5	0.5	0.6	0.5	0.6	0.5	0.7
10/01/12	93	0.6	0.6	0.6	0.5	0.5	0.7	0.5	0.6	0.5	0.7
30/01/12	100	0.6	0.6	0.6	0.5	0.5	0.7	0.5	0.6	0.5	0.7

a. Pine

i. Comparison with control data

Comparing the moisture content measurements between the submerged wood samples and the control wood samples shows that there was a significant difference at each relative humidity (Table 4.7). For pine, at each level, the submerged wood had a higher average moisture content than the control wood samples. The difference between the mean of the two sets increased starting at RH=11%; the relative difference remained above 10% and eventually increased to over 21%. Figure 4.1 shows graphically the increasing difference in the means.

Table 4.7 - Group 1 - 4 (Pine), Comparison of Submerged and Control

Group 1, 2, 3 and 4 (Pine)									
		Moisture Content			Welch Two Sample t-test			ΔMean	d_r
RH	Pine	Mean	St. Dev.	Error					
		(%)			t	df	p-value	(%)	(%)
6.37%	Submerged	1.95	0.53	0.1	3.18	75	2.11E-03	0.25	13.50
	Control	1.71	0.44	0.1					
11%	Submerged	2.21	0.46	0.1	3.29	78	1.51E-03	0.24	11.66
	Control	1.96	0.46	0.1					
20%	Submerged	3.74	0.45	0.1	5.32	76	1.00E-06	0.42	11.86
	Control	3.32	0.53	0.1					
32%	Submerged	4.85	0.68	0.2	5.93	71	9.99E-08	0.56	12.24
	Control	4.29	0.49	0.1					
43%	Submerged	6.59	0.91	0.2	4.80	77	7.76E-06	0.66	10.60
	Control	5.92	0.81	0.2					
66%	Submerged	9.82	0.94	0.2	8.51	72	1.68E-12	1.13	12.23
	Control	8.69	0.70	0.2					
79%	Submerged	12.18	0.57	0.1	14.87	72	< 2.2E-16	1.59	13.99
	Control	10.59	0.76	0.2					
93%	Submerged	17.67	1.06	0.2	19.19	75	< 2.2E-16	2.95	18.21
	Control	14.72	0.85	0.2					
100%	Submerged	23.19	1.22	0.3	23.88	78	< 2.2E-16	4.59	21.96
	Control	18.60	1.18	0.3					

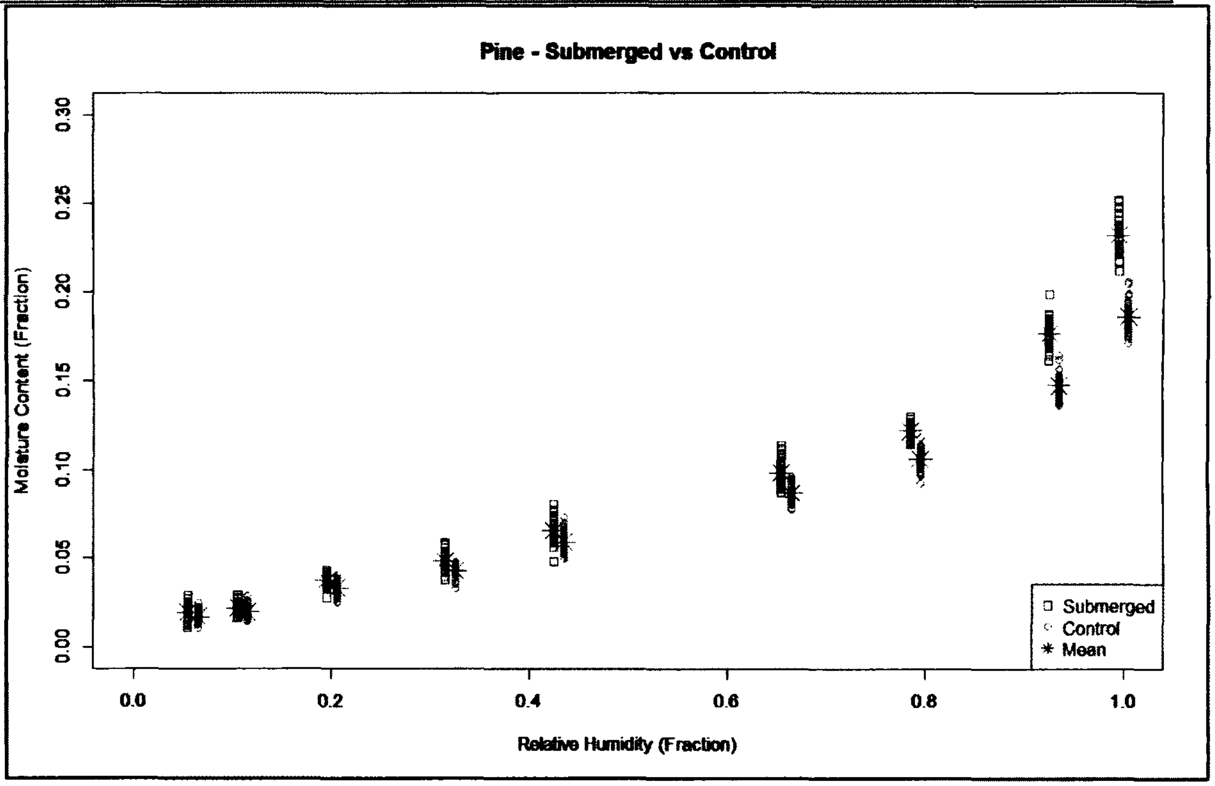

Figure 4.1 - Group 1 - 4 (Pine), Comparison of Submerged and Control

ii. Modelling Pine with Hailwood-Horrobin model

Using the statistical computing program, R, the Hailwood-Horrobin model (Equation 2.7) was fit to the submerged wood data as well as to the control pine samples. The *W*, *K1* and *K2* coefficients, as well as the t value, p value and degrees of freedom, were found using the statistical software, R, as follows:

When compared with control samples, the mean value for *W* was found to be lower for the submerged wood, while the mean values for *K1* and *K2* were higher in the submerged wood than they were for the control wood samples. The values for both *W* and *K2* were not within error of each other implying that the values would never have the same mean. The *K1* value for the two sets, however, was within error of each other (Table 4.8). Due to the lower W values for the submerged wood this indicated a higher amount of available sorption sites in the submerged wood.

Table 4.8 - W, K1 and K2 values for Pine

Group 1-4 (Pine)								
		Modelled	Std. Error	t value	Pr(>|t|)	df	95% Confidence Interval	
							Min	Max
W $\left(\frac{kg}{mol}\right)$	Submerged	0.364	4.95E-03	73.57	<2E-16	357	0.354	0.374
	Control	0.383	6.25E-03	61.37	<2E-16	357	0.371	0.395
K1	Submerged	8.51	5.42E-01	15.68	<2E-16	357	7.43	9.58
	Control	7.63	4.94E-01	15.45	<2E-16	357	6.65	8.61
K2	Submerged	0.791	2.94E-03	269.07	<2E-16	357	0.785	0.797
	Control	0.755	3.99E-03	188.94	<2E-16	357	0.747	0.763

Table 4.9 – Goodness of Fit for Hailwood-Horrobin model, Pine.

Goodness of Fit, Pine			
	RSS	SS	R^2
Submerged	0.015	15.718	0.999
Control	0.012	10.174	0.999

The modelled adsorption isotherm for the submerged and control samples was plotted in Figure 4.2. From that figure it can be shown that the sorption isotherm for the submerged samples is vertically higher than that of the control samples. For both the submerged and control samples the R^2, representing the goodness of fit for the Hailwood-Horrobin model, was approximately 99.9% (Table 4.9).

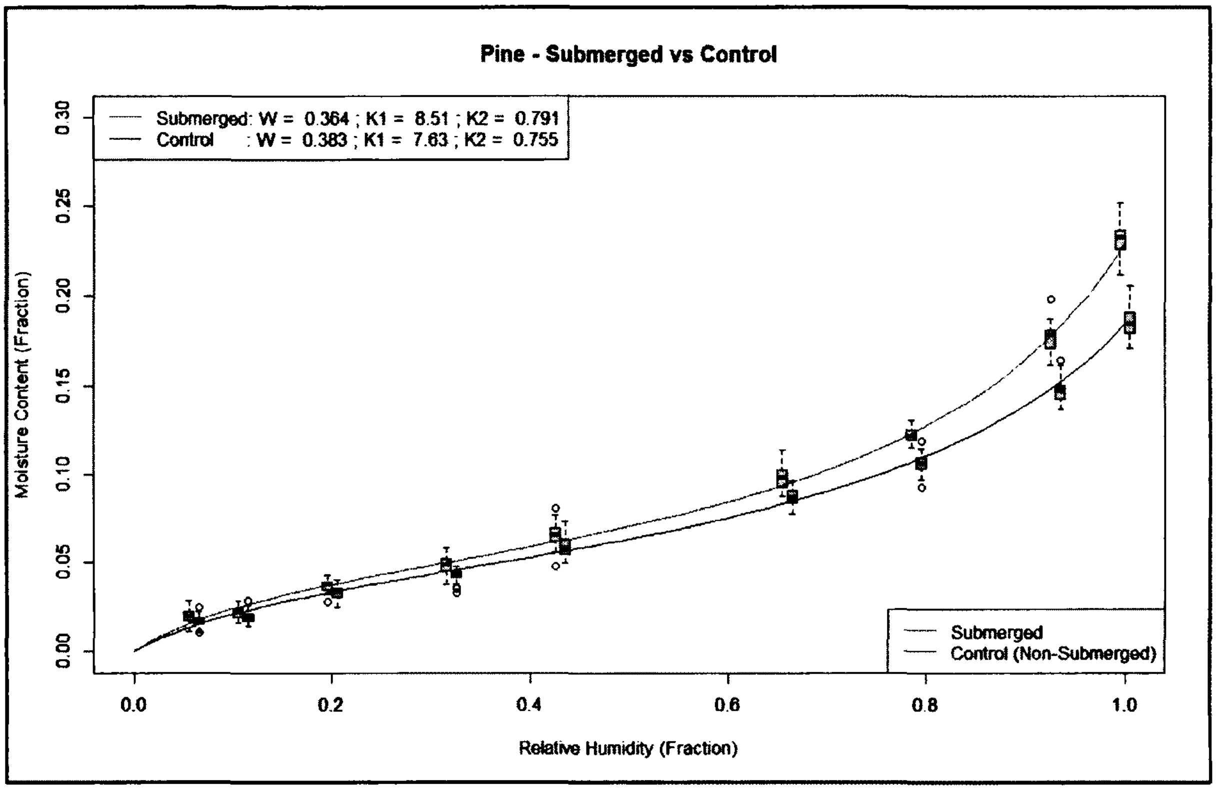

Figure 4.2- Pine (Submerged vs. Control) H-H Isotherm

Next it was assumed that, as all of the samples are from the same disk of wood, the *K1* and *K2* that were determined from all of the wood samples would be appropriate for each of the individual samples. The Hailwood-Horrobin isotherm was then fit to each of the individual samples in order to determine the *W* coefficient while keeping the *K1* and *K2* coefficients constant (Table 4.10). *K1* and *K2* were kept constant as they are equilibrium constants used in the equation and have less physical meaning than *W*, and *W* was to be compared with the speed of sound in later Chapter 5.

Table 4.10 – W coefficient for individual samples (Pine)

Group 1		Group 2		Group 3		Group 4	
Sample	W	**Sample**	W	**Sample**	W	**Sample**	W
#	(kg/mol)	#	(kg/mol)	#	(kg/mol)	#	(kg/mol)
1	0.355	**1**	0.365	**12**	0.383	**12**	0.368
2	0.366	**2**	0.364	**13**	0.391	**13**	0.366
3	0.350	**3**	0.351	**14**	0.355	**14**	0.348
4	0.352	**4**	0.342	**15**	0.357	**15**	0.352
5	0.363	**5**	0.359	**16**	0.354	**16**	0.374
6	0.365	**6**	0.352	**17**	0.372	**17**	0.387
7	0.369	**7**	0.367	**18**	0.371	**18**	0.369
8	0.368	**8**	0.362	**19**	0.370	**19**	0.379
9	0.365	**9**	0.363	**20**	0.387	**20**	0.379
11	0.351	**11**	0.361	**21**	0.359	**21**	0.364

iii. Unimolecular and Dissolved water Adsorption

The unimolecular and dissolved water adsorption isotherms for pine were plotted using the *K1*, *K2* and *W* coefficients presented in Table 4.8 in Figure 4.3.

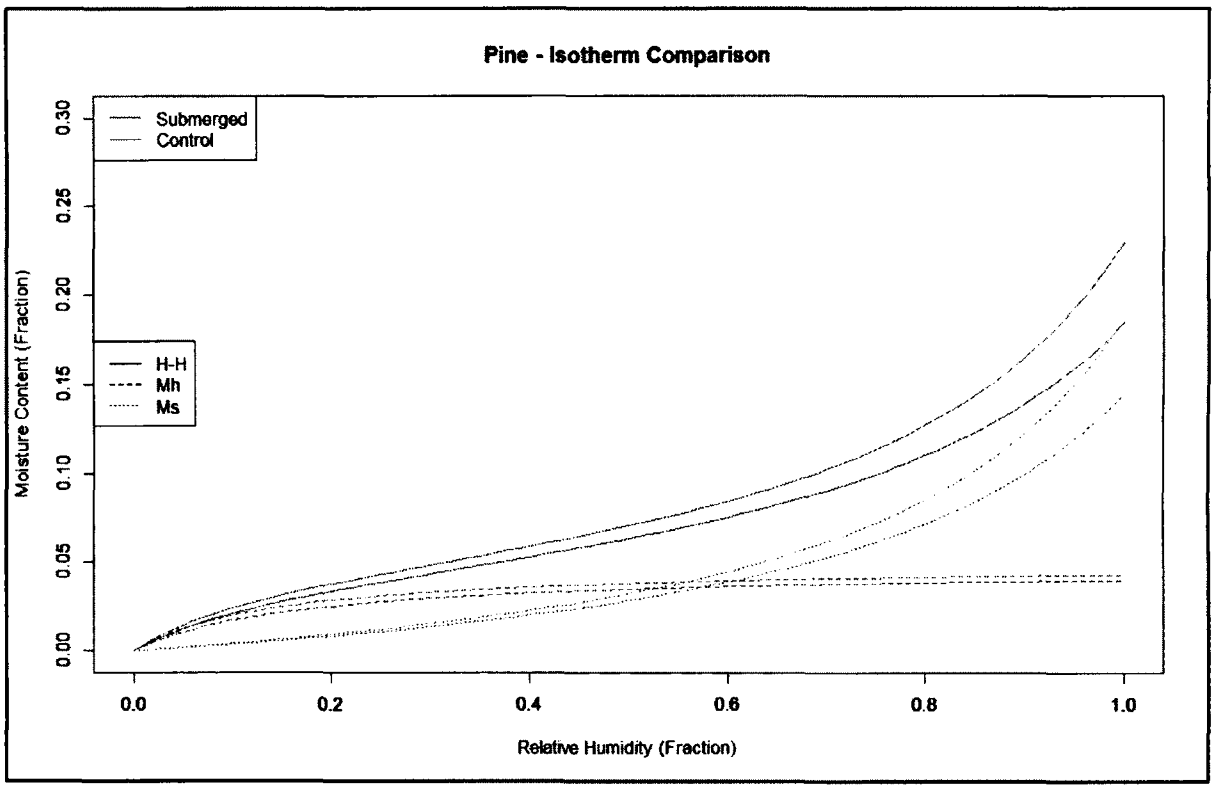

Figure 4.3 - Pine, Unimolecular (M_h) and Dissolved water (M_s) Adsorption Isotherms

For both the unimolecular adsorption isotherms and dissolved water adsorption isotherms the submerged wood was vertically higher than the control wood (Figure 4.3).

b. Spruce

i. Comparison with control data

There was a significant difference at every level of relative humidity when the submerged and control samples of spruce were compared. The average moisture content for the submerged wood was higher than the control samples at each relative humidity level. The relative difference in the two sets remained under 10% for relative humidity levels higher than 20%. The measurements and the mean values of each set are presented graphically in Figure 4.4.

Table 4.11 - Group 1 - 4 (Spruce), Comparison of Submerged and Control

Group 1, 2, 3 and 4 (Spruce)									
		Moisture Content			Welch Two Sample t-test			ΔMean	d_r
RH	Spruce	Mean	St. Dev.	Error					
		(%)			t	df	p-value	(%)	(%)
6.37%	Submerged	2.29	0.90	0.2	2.43	68	1.76E-02	0.30	13.91
	Control	1.99	0.60	0.1					
11%	Submerged	2.62	0.63	0.1	4.32	68	5.25E-05	0.37	15.14
	Control	2.25	0.42	0.09					
20%	Submerged	4.21	0.70	0.2	3.58	58	7.08E-04	0.32	7.88
	Control	3.89	0.36	0.08					
32%	Submerged	5.34	0.72	0.2	2.55	70	1.28E-02	0.26	4.92
	Control	5.08	0.51	0.1					
43%	Submerged	7.29	1.13	0.3	2.42	70	1.80E-02	0.38	5.34
	Control	6.91	0.79	0.2					
66%	Submerged	10.46	0.88	0.2	4.40	74	3.56E-05	0.56	5.49
	Control	9.90	0.70	0.2					
79%	Submerged	12.98	0.84	0.2	3.25	77	1.73E-03	0.47	3.69
	Control	12.51	0.96	0.2					
93%	Submerged	18.71	0.93	0.2	3.42	70	1.05E-03	0.62	3.38
	Control	18.09	1.31	0.3					
100%	Submerged	24.29	1.65	0.4	4.21	76	6.98E-05	1.23	5.18
	Control	23.06	1.98	0.4					

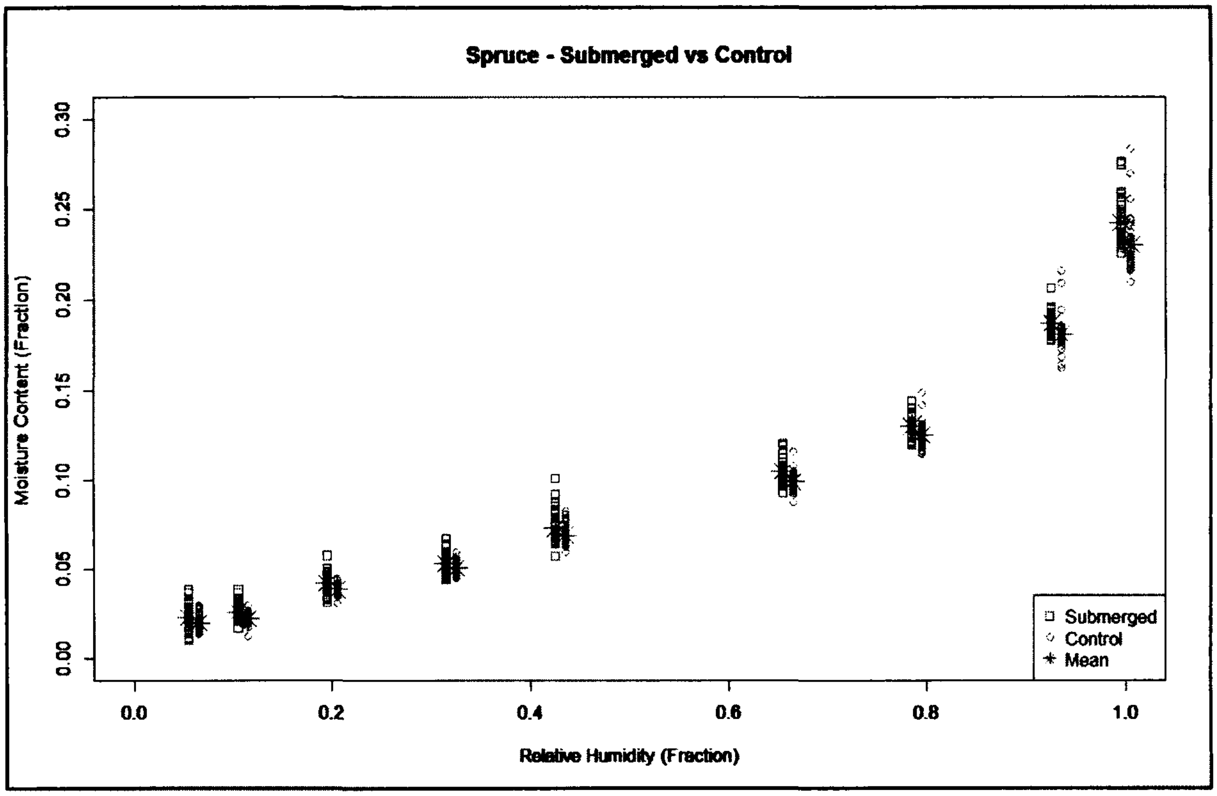

Figure 4.4 - Group 1 - 4 (Pine), Comparison of Submerged and Control

ii. Modelling Spruce with Hailwood-Horrobin model

The Hailwood-Horrobin model was fit to the submerged and control spruce samples using the R statistical software and provided the *W*, *K1* and *K2* coefficients as well as the t value, p-value and degrees of freedom found in Table 4.12.

Table 4.12 - W, K1 and K2 values for Spruce

Group 1-4 (Spruce)								
		Modelled	Std. Error	t value	Pr(>|t|)	df	95% Confidence Interval	
							Min	Max
W $\left(\frac{kg}{mol}\right)$	Submerged	0.342	4.90E-03	69.51	<2E-16	357	0.332	0.352
	Control	0.344	5.50E-03	62.37	<2E-16	357	0.334	0.355
K1	Submerged	10.34	7.28E-01	14.19	<2E-16	357	8.89	11.78
	Control	8.20	5.84E-01	14.05	<2E-16	357	7.04	9.35
K2	Submerged	0.786	3.30E-03	241.91	<2E-16	357	0.780	0.793
	Control	0.779	3.60E-03	215.25	<2E-16	357	0.772	0.786

Table 4.13 - Goodness of Fit for Hailwood-Horrobin model, Spruce

Goodness of Fit, Spruce			
	RSS	SS	R^2
Submerged	0.020	16.901	0.999
Control	0.019	15.746	0.999

The mean value of *W* for the submerged samples of spruce was found to be lower than the control values. However, the two means were within error of each other (Table 4.12). Both *K1* and *K2* were larger for the submerged wood and the *K1* value was not within error between the sets. The modelled adsorption isotherms for both control and submerged were plotted in Figure 4.5. The R^2 value for both the submerged and control samples was approximately 99.9%.

Using the *K1* and *K2* values presented in Table 4.12, the Hailwood-Horrobin adsorption isotherm was fit to each of the individual samples. This yielded the *W* values found in Table 4.14. Similarly to pine, the *K1* and *K2* values were kept constant to remove variability in the equations and to allow comparison of *W* with the speed of sound in Chapter 5.

Table 4.14 - W coefficient for individual samples (Spruce)

Group 1		Group 2		Group 3		Group 4	
Sample #	W (kg/mol)	**Sample #**	W (kg/mol)	**Sample #**	W (kg/mol)	**Sample #**	W (kg/mol)
1	0.346	**1**	0.347	**12**	0.348	**12**	0.338
2	0.350	**2**	0.351	**13**	0.353	**13**	0.349
3	0.333	**3**	0.342	**14**	0.347	**14**	0.339
4	0.342	**4**	0.358	**15**	0.347	**15**	0.340
5	0.306	**5**	0.350	**16**	0.340	**16**	0.335
6	0.312	**6**	0.352	**17**	0.331	**17**	0.319
7	0.340	**7**	0.331	**18**	0.365	**18**	0.334
8	0.357	**8**	0.347	**19**	0.354	**19**	0.316
9	0.354	**9**	0.360	**20**	0.351	**20**	0.345
11	0.329	**11**	0.327	**21**	0.336	**21**	0.341

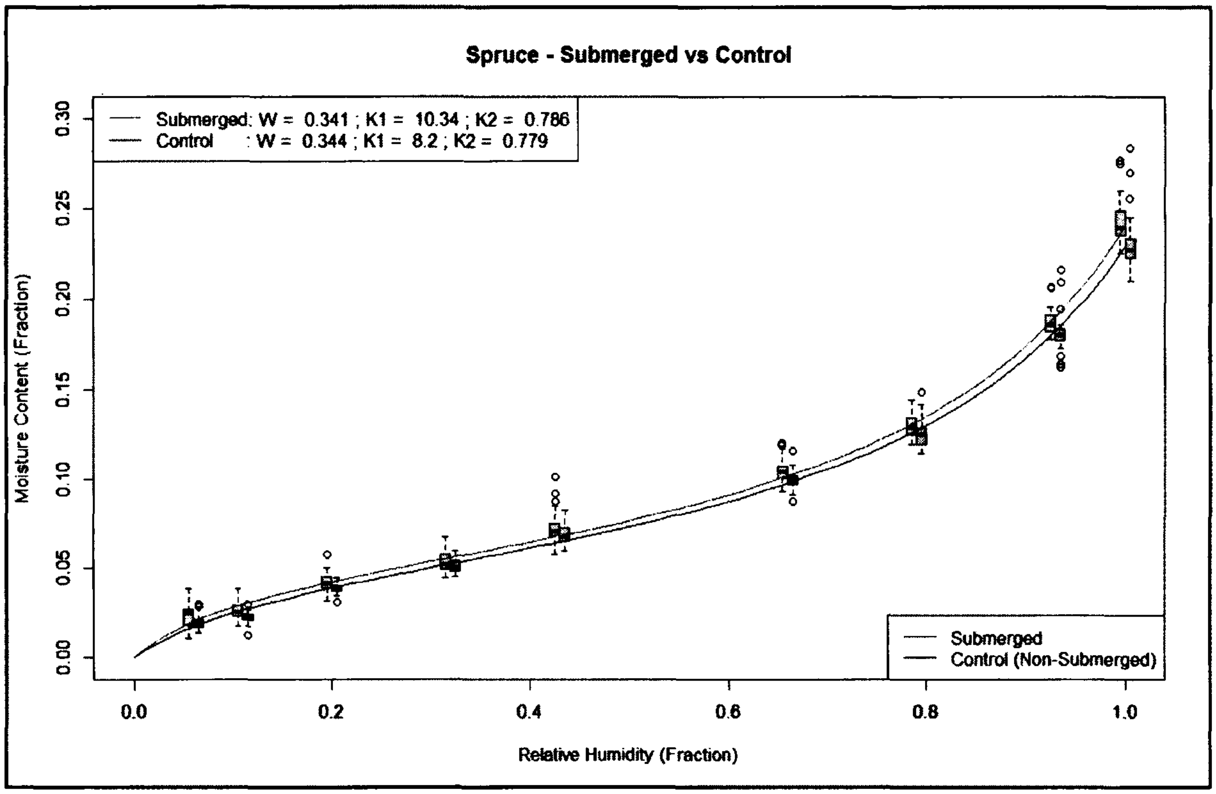

Figure 4.5 - Spruce (Submerged vs. Control) H-H Isotherm

iii. Unimolecular and Dissolved Water Adsorption

The unimolecular and dissolved water adsorption isotherms for spruce were presented in (Figure 4.6). The unimolecular isotherm (M_h) is higher for the submerged wood than it was for the control wood although not by a large margin. The dissolved water isotherm for spruce was also higher for the submerged wood although the difference was not noticeable until approximately 50% relative humidity.

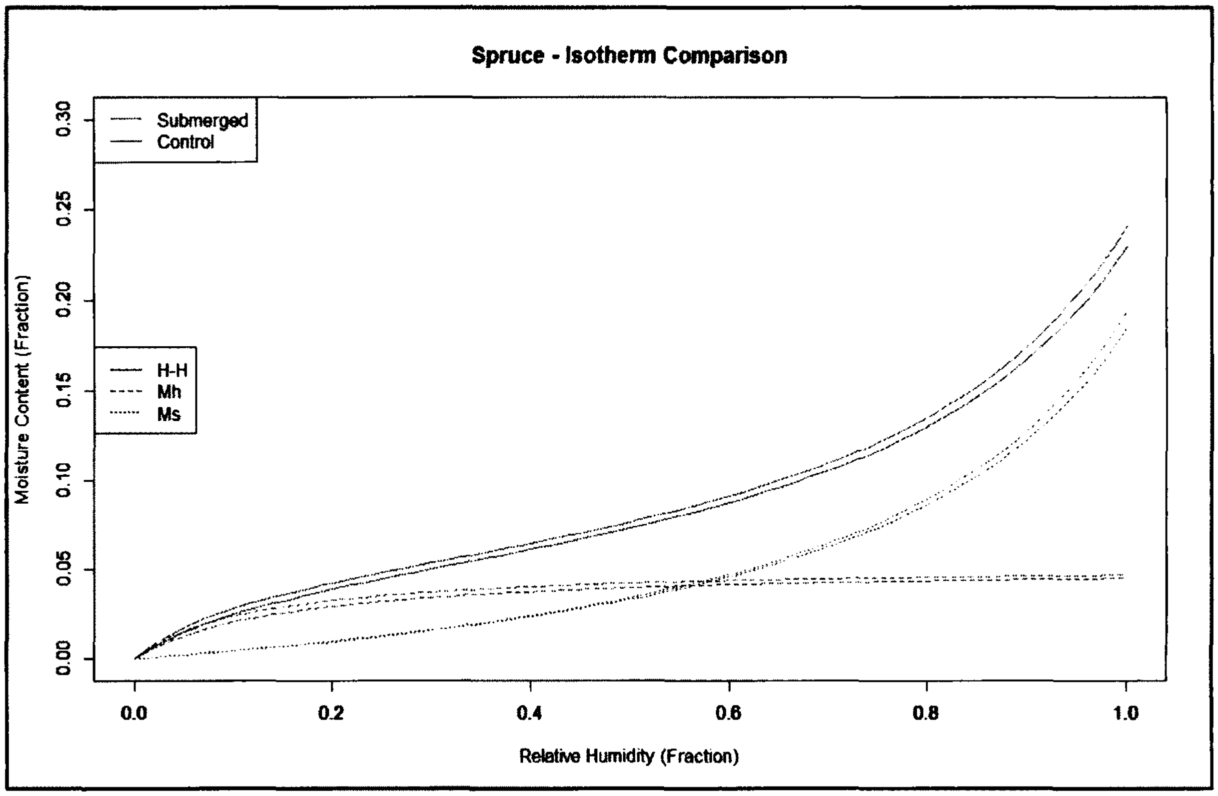

Figure 4.6 - Spruce, Unimolecular (M_h) and Dissolved water (M_s) Adsorption Isotherms

c. Spruce and Pine comparison

At each relative humidity level the average moisture content of the submerged pine samples was lower than the average moisture content of spruce. The two sample sets were statistically different (Table 4.15). The moisture content for both the pine and spruce samples was plotted against the relative humidity in Figure 4.1.

Table 4.15 - Pine vs. Spruce (Submerged)

Group 1, 2, 3 and 4 (Pine vs. Spruce, Submerged)							
RH	Wood Type	Moisture Content			Welch Two Sample t-test		
		Mean	St. Dev.	Error			
		(%)			t	df	p-value
6.37%	Pine	1.95	0.53	0.1	-2.86	63	5.72E-03
	Spruce	2.29	0.90	0.2			
11%	Pine	2.21	0.46	0.1	-4.72	72	1.15E-05
	Spruce	2.62	0.63	0.1			
20%	Pine	3.74	0.45	0.1	-4.93	67	5.68E-06
	Spruce	4.21	0.70	0.2			
32%	Pine	4.85	0.68	0.2	-4.29	78	5.17E-05
	Spruce	5.34	0.72	0.2			
43%	Pine	6.59	0.91	0.2	-4.27	75	5.72E-05
	Spruce	7.29	1.13	0.3			
66%	Pine	9.82	0.94	0.2	-4.34	78	4.21E-05
	Spruce	10.46	0.88	0.2			
79%	Pine	12.18	0.57	0.1	-6.98	68	1.52E-09
	Spruce	12.98	0.84	0.2			
93%	Pine	17.67	1.06	0.2	-6.55	77	6.00E-09
	Spruce	18.71	0.93	0.2			
100%	Pine	23.19	1.22	0.3	-4.71	72	1.20E-05
	Spruce	24.29	1.65	0.4			

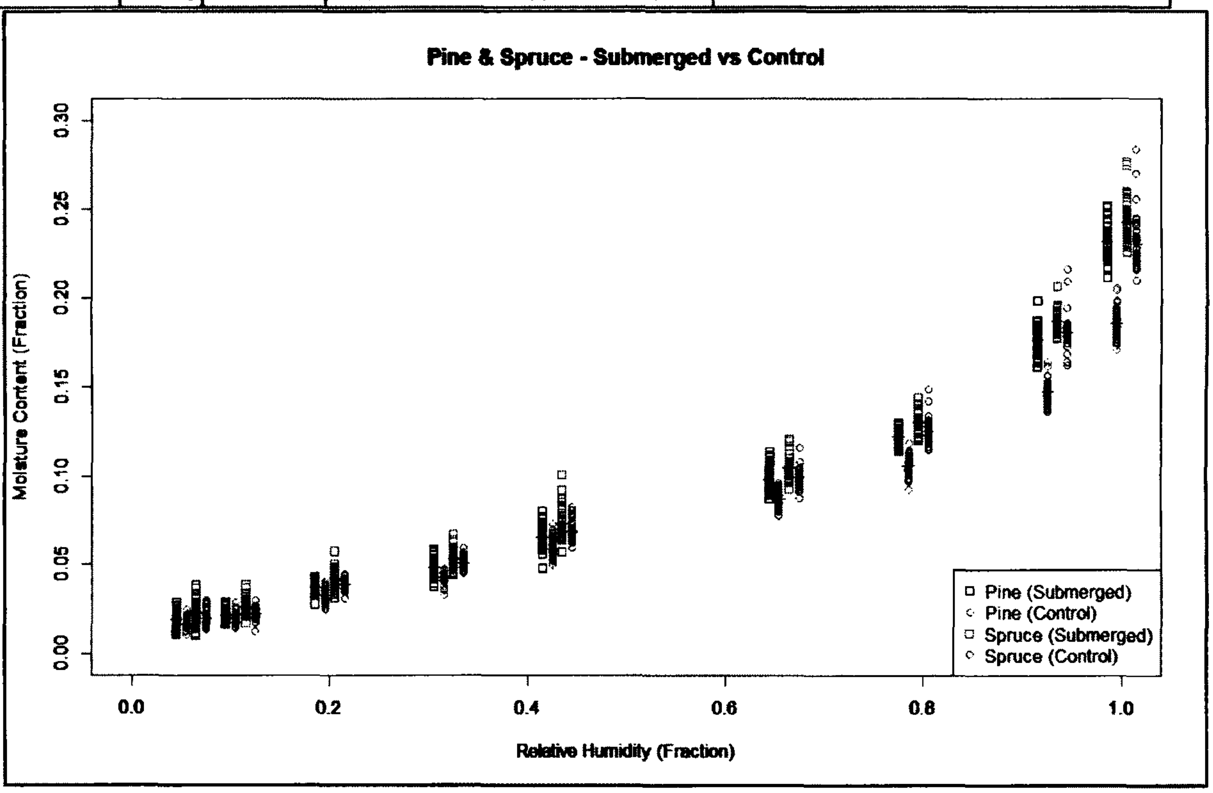

Figure 4.7 - Pine vs. Spruce comparison

Compared to the Hailwood-Horrobin isotherm models for submerged spruce samples, the submerged spruce samples had a lower *W* coefficient than the submerged pine samples and the mean values were not within error of each other. The spruce samples had a larger *K1* value than the pine and these, also, were not within error of each other. The *K2* values for both species were within error of each other with the pine samples having a slightly larger value (Table 4.16 and Figure 4.8).

Table 4.16 - Hailwood-Horrobin coefficient comparison (Pine and Spruce)

Group 1-4 (Pine vs. Spruce)								
		Modelled	Std. Error	t value	Pr(>|t|)	df	95% Confidence Interval	
							Min	Max
W $\left(\frac{kg}{mol}\right)$	Pine	0.364	4.95E-03	73.57	<2e-16	357	0.354	0.374
	Spruce	0.342	4.91E-03	69.51	<2e-16	357	0.332	0.352
K1	Pine	8.51	5.42E-01	15.68	<2e-16	357	7.43	9.58
	Spruce	10.33	7.28E-01	14.19	<2e-16	357	8.89	11.78
K2	Pine	0.791	2.94E-03	269.07	<2e-16	357	0.785	0.797
	Spruce	0.786	3.25E-03	241.91	<2e-16	357	0.780	0.793

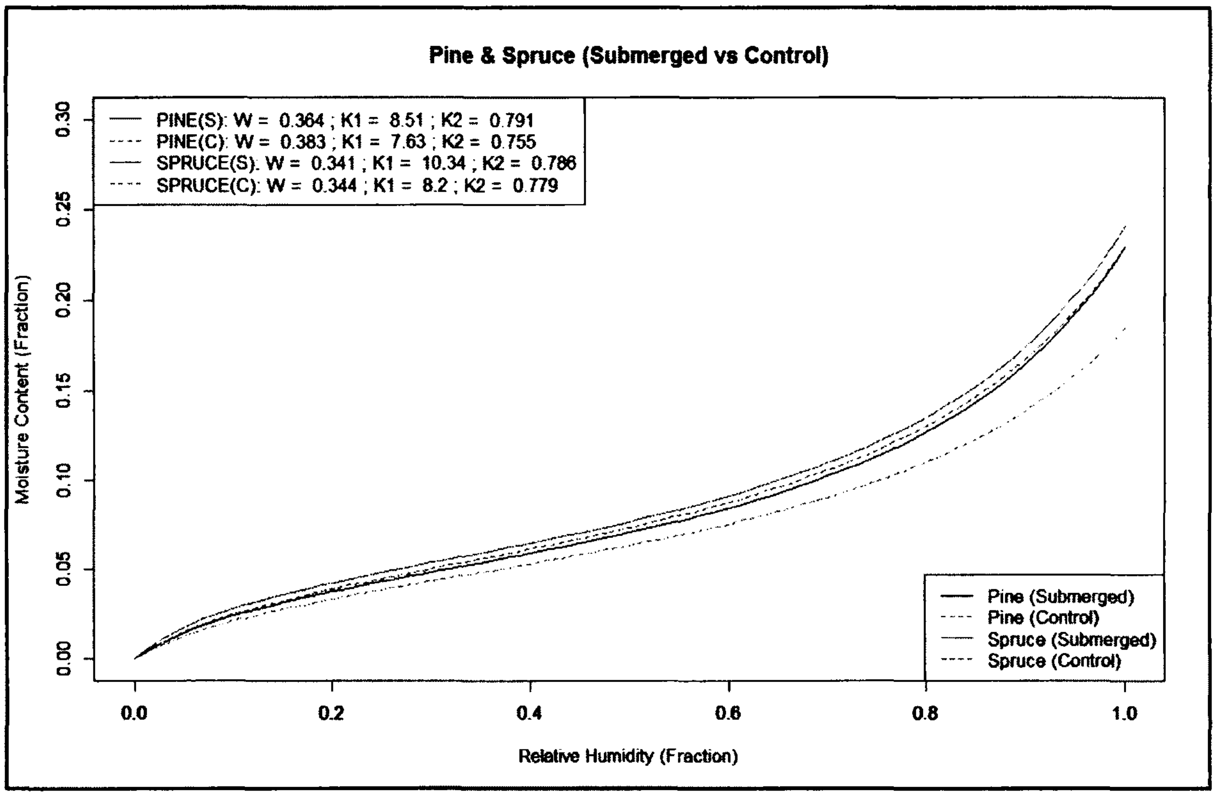

Figure 4.8 - Hailwood-Horrobin Adsorption Isotherm for Pine and Spruce

The unimolecular isotherm and dissolved water isotherms were compared based on the *W*, *K1* and *K2* coefficient from the modelled Hailwood-Horrobin isotherms (Figure 4.9 and Figure 4.10). Both the submerged and control wood samples had a higher unimolecular isotherm curve than the pine samples (Figure 4.9). The control samples for pine had a dissolved water sorption isotherm that was noticeably lower than the other samples and the control samples for spruce had a very similar isotherm to the submerged pine samples. The submerged samples for spruce had the highest isotherm curve for dissolved water.

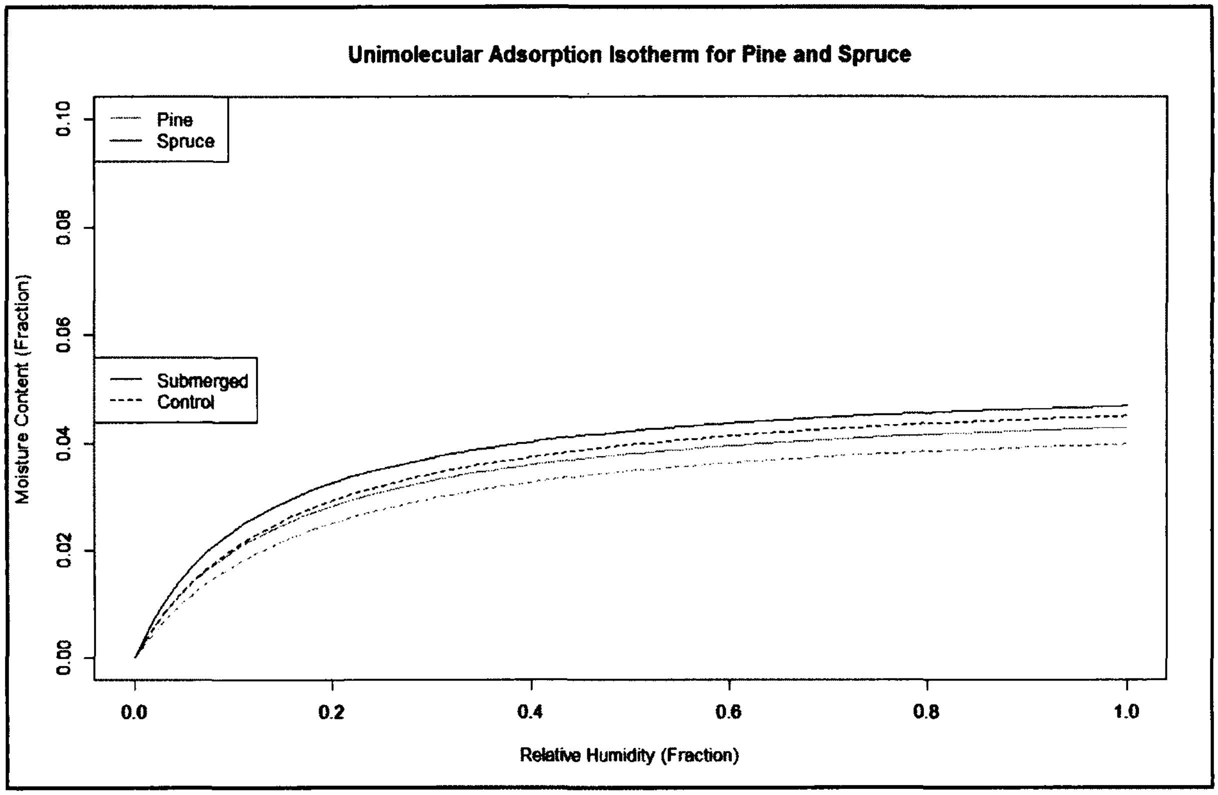

Figure 4.9 - M_h comparison for Pine and Spruce (Submerged and Control)

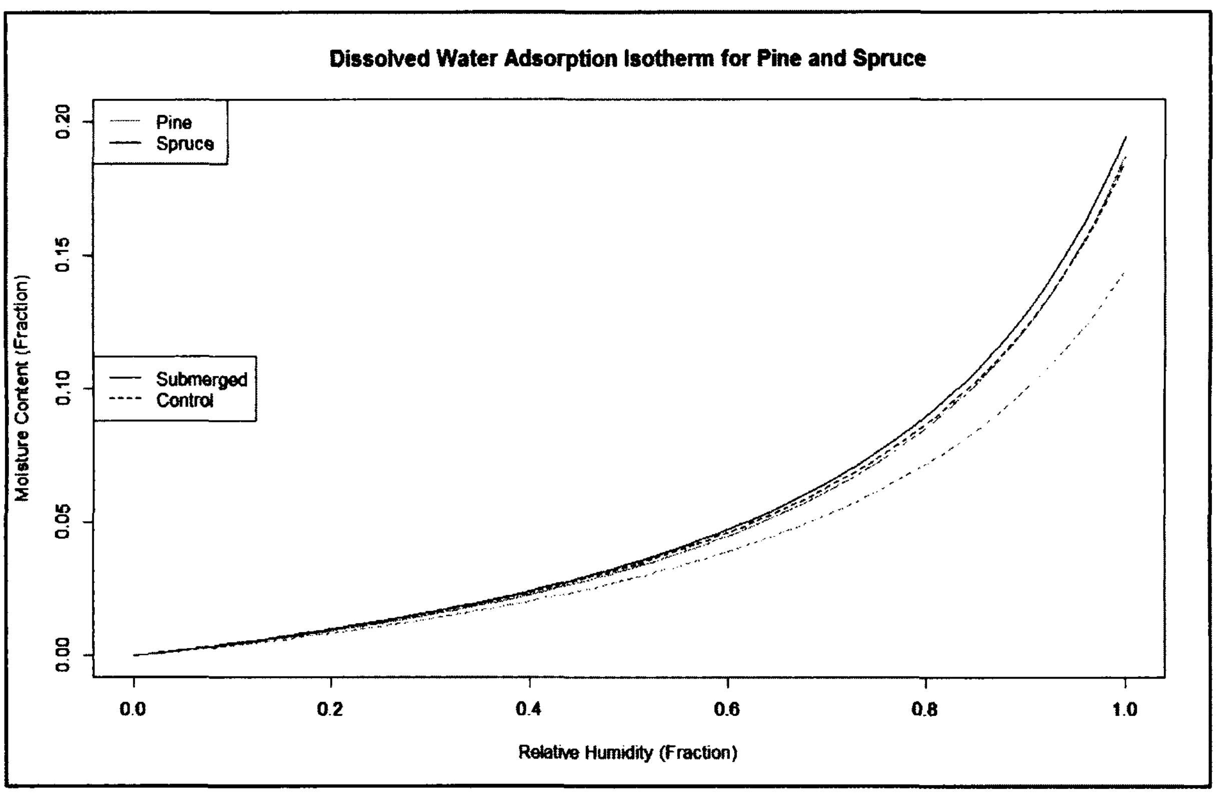

Figure 4.10 - M_s comparison for Pine and Spruce (Submerged and Control)

d. Comparison with other data

The equilibrium moisture content of Scots pine *(Pinus sylvestris)* was found for samples that had been used as lumber in a railway and submerged in water for 103 years [34], 205 year old wood that had been used in the construction of a house in Spain [36], 1170 year old wood that had been buried [35], and control samples [36] [34] (Table 4.17).

Table 4.17 - Data collected from other sources

Data from Other Studies					
	Moisture Content (At 35°C)				
RH	Submerged [34]	Buried [35]	Ancient [36]	Control 1 [34]	Control 2 [36]
(%)	(%)	(%)	(%)	(%)	(%)
11.17	3.42	2.62	2.44	1.51	1.40
21.37	4.48	4.58	3.64	2.89	2.92
32.00	6.09	5.48	4.97	3.21	3.27
42.55	7.83	7.10	6.07	4.29	4.34
49.72	8.84	7.93	7.21	4.84	4.90
66.08	12.39	10.78	9.87	6.42	6.55
75.11	14.98	12.22	11.56	7.98	7.99
82.95	17.73	15.55	13.77	9.52	9.62
89.40	22.20	17.69	16.43	12.74	13.06
96.71	28.67	22.25	-	16.18	-

i. Equilibrium Moisture Content comparison

The submerged wood from Esteban's study had a higher equilibrium moisture content than both the spruce and pine that had been submerged in Ootsa Lake as the relative humidity increased. The submerged wood from Ootsa Lake had moisture contents that were similar to the ancient wood and the buried wood supplied in other studies (Table 4.18).

Table 4.18 - Moisture Content Comparison (Pine and Spruce)

Comparison of Other Data with Pine						
	Moisture Content (At 35°C)			Current Data		
RH	Submerged [34]	Buried [35]	Ancient [36]	**RH**	Pine (S)	Spruce (S)
(%)	(%)	(%)	(%)	(%)	(%)	(%)
11.17	3.42	2.62	2.44	**11**	2.21±0.1	2.62±0.1
21.37	4.48	4.58	3.64	**20**	3.74±0.1	4.21±0.2
32.00	6.09	5.48	4.97	**32**	4.85±0.2	5.34±0.2
42.55	7.83	7.10	6.07	**43**	6.59±0.2	7.29±0.3
49.72	8.84	7.93	7.21	-	-	-
66.08	12.39	10.78	9.87	**66**	10.48±0.2	10.46±0.2
75.11	14.98	12.22	11.56	**79**	12.18±0.1	12.98±0.2
82.95	17.73	15.55	13.77	-	-	-
89.40	22.20	17.69	16.43	**93**	17.67±0.2	18.71±0.2
96.71	28.67	24.38	-	**100**	23.19±0.3	24.29±0.4

ii. Comparison of Hailwood-Horrobin Models

The equilibrium moisture contents for submerged, buried, ancient and control wood samples from previous studies were plotted against the respective relative humidity values (Figure 4.11). Using the R-statistical software package the Hailwood-Horrobin model was fit to these data points and the *W*, *K1* and *K2* coefficients were found (Table 4.19).

Table 4.19 - Comparison of Current Data with Previous Results

Comparison with past results, Temperature = 35°C								
Previous Data			Current Data					
			Pine			Spruce		
	Type	Modeled	Modeled	95% Conf. Interval Min	95% Conf. Interval Max	Modeled	95% Conf. Interval Min	95% Conf. Interval Max
W $\left(\frac{kg}{mol}\right)$	Submerged	0.293	0.364	0.354	0.374	0.342	0.332	0.352
	Buried	0.351						
	Ancient	0.333						
	Control	0.568						
K1	Submerged	7.53	8.51	7.43	9.58	10.34	8.89	11.78
	Buried	10.52						
	Ancient	5.90						
	Control	8.49						
K2	Submerged	0.820	0.791	0.785	0.797	0.786	0.780	0.793
	Buried	0.818						
	Ancient	0.772						
	Control	0.838						

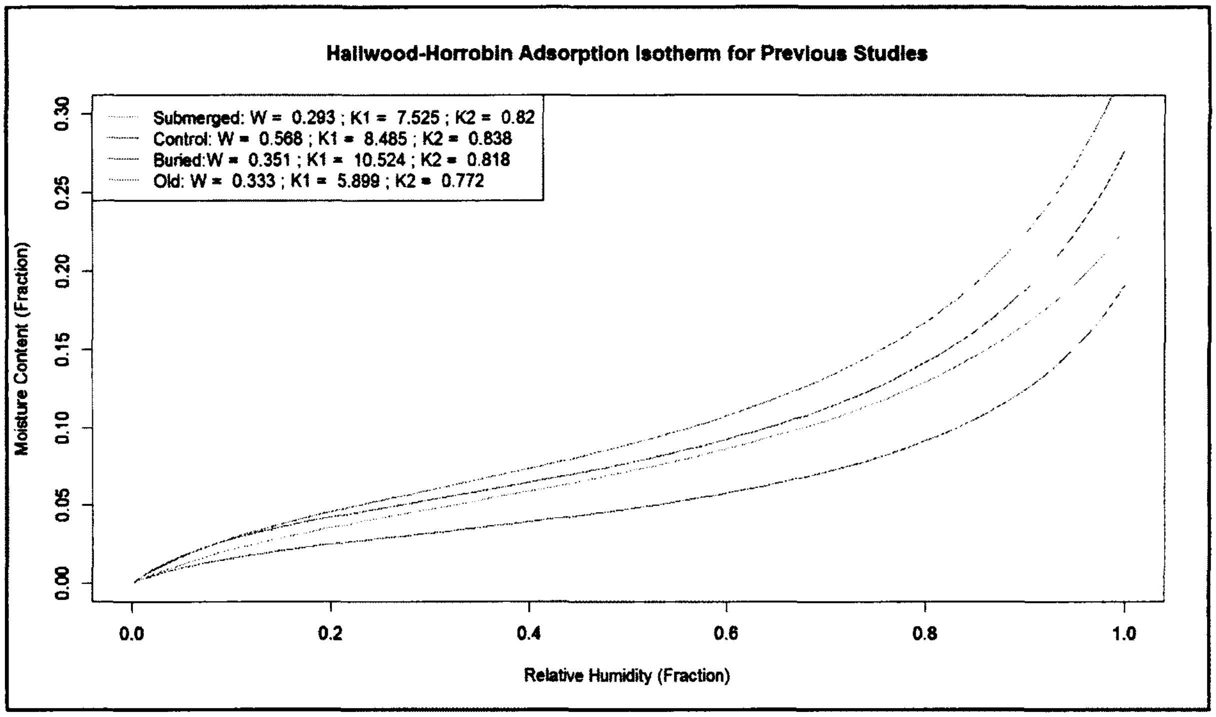

Figure 4.11 – Adsorption Isotherm for Previous Studies

The submerged pine had a larger W coefficient than all of the previous studies, excluding the control wood; the *W* coefficient for spruce was larger than that of previous submerged wood and ancient wood but was lower than both buried wood and control wood. None of the *W* coefficients from previous studies were within error of the pine samples while both the ancient and buried wood samples were within error of the spruce samples. The *K1* and *K2* coefficients modelled were found to not be within error of either the pine or spruce samples except for the submerged spruce samples and the *K1* for the control wood, and the spruce samples and *K1* for buried wood. None of the *K2* values were within error of either the pine or spruce samples (Table 4.19).

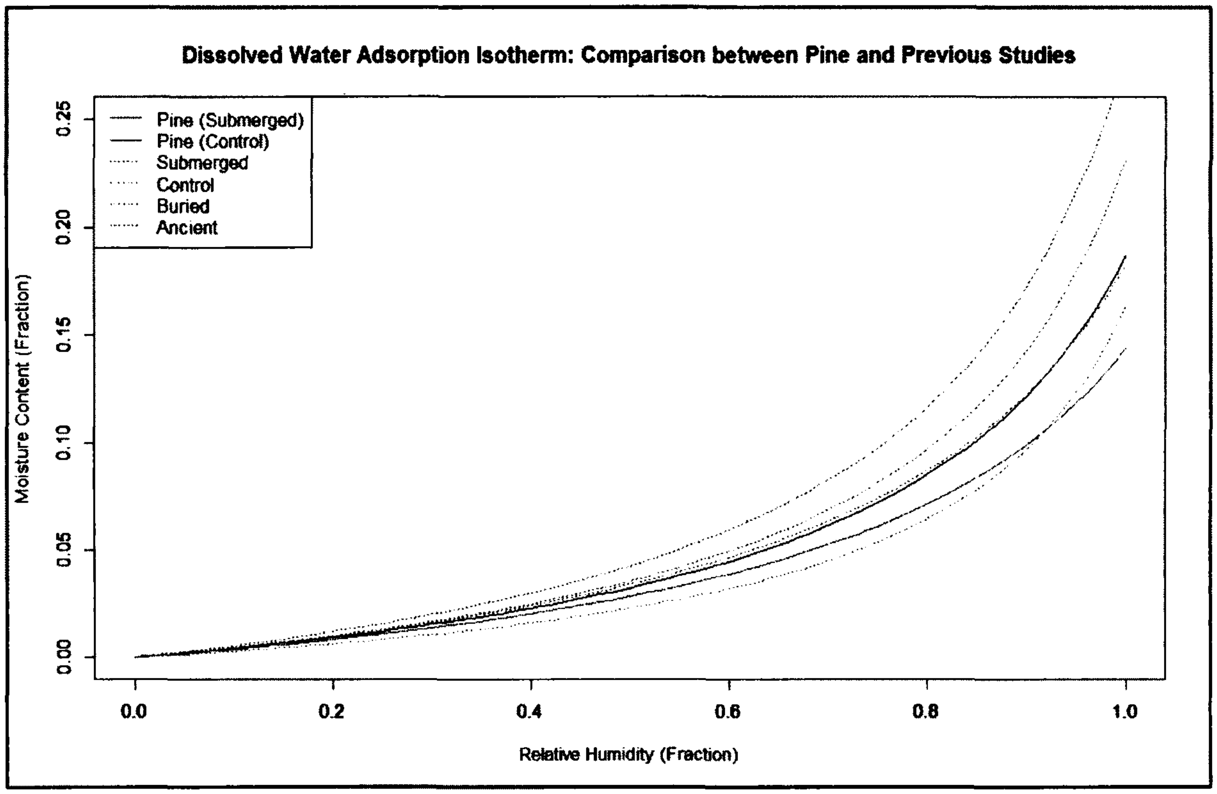

Figure 4.12 - Dissolved water Adsorption Isotherm Comparison for Pine

The unimolecular isotherm and dissolved water isotherm for pine is lower than the submerged water and buried water isotherms and is higher than the control sample. Compared to the ancient wood, the unimolecular isotherm is higher than the ancient wood below 60% and lower than the ancient above 60% (Figure 4.13). This trend is reversed in the free-water isotherm with the submerged pine being higher than the ancient wood until approximately 90% (Figure 4.12).

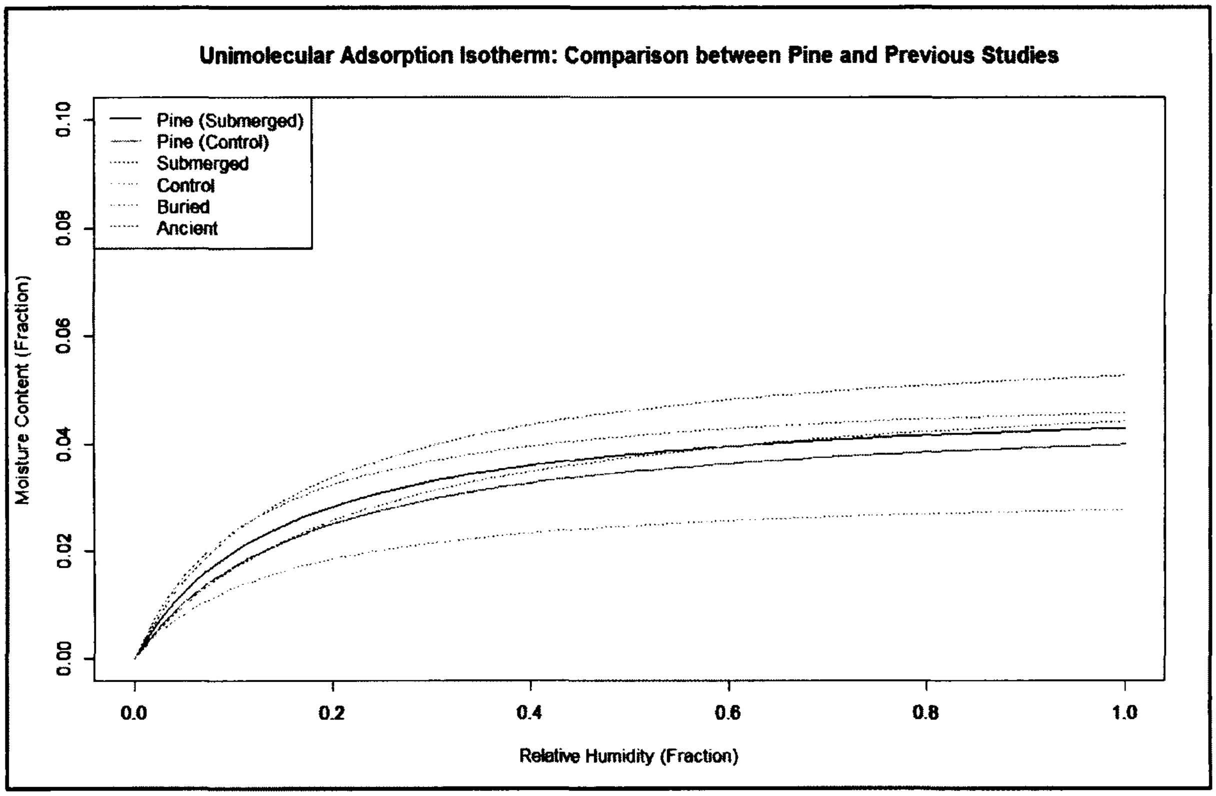

Figure 4.13 - Unimolecular Adsorption Isotherm Comparison for Pine

Like pine, the submerged spruce samples have a lower dissolved water adsorption isotherm than both the submerged wood samples and the buried wood samples, and a larger isotherm than the control samples and ancient wood samples from previous studies (Figure 4.14). For the unimolecular isotherms, though, the spruce samples were only lower than the submerged wood samples and was higher than all of the buried, ancient and control wood samples (Figure 4.15).

When the sorption isotherms from the Hailwood-Horrobin adsorption isotherm for the spruce, pine and previous studies were plotted (Figure 4.16) the submerged spruce samples were shown to be very similar to the buried wood until approximately 60% relative humidity and the submerged pine samples were similar to the old wood samples.

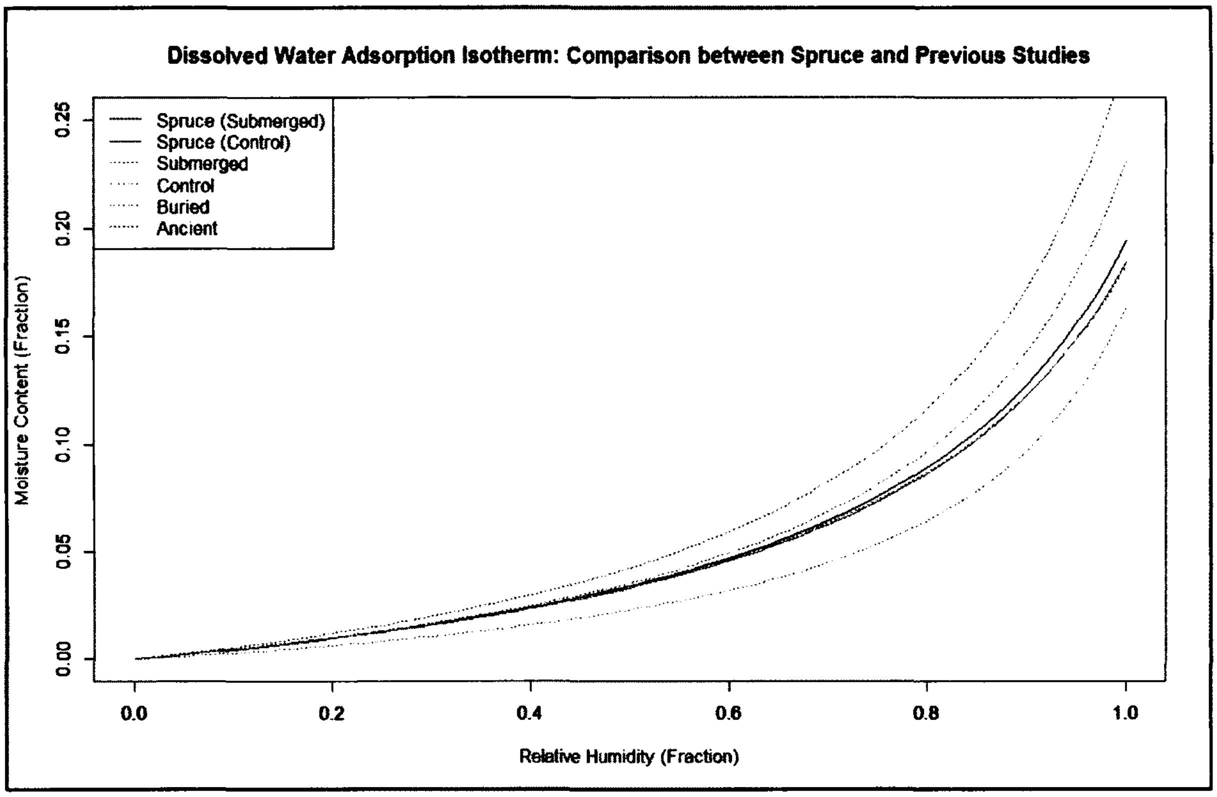

Figure 4.14 - Dissolved water Adsorption Isotherm Comparison for Spruce

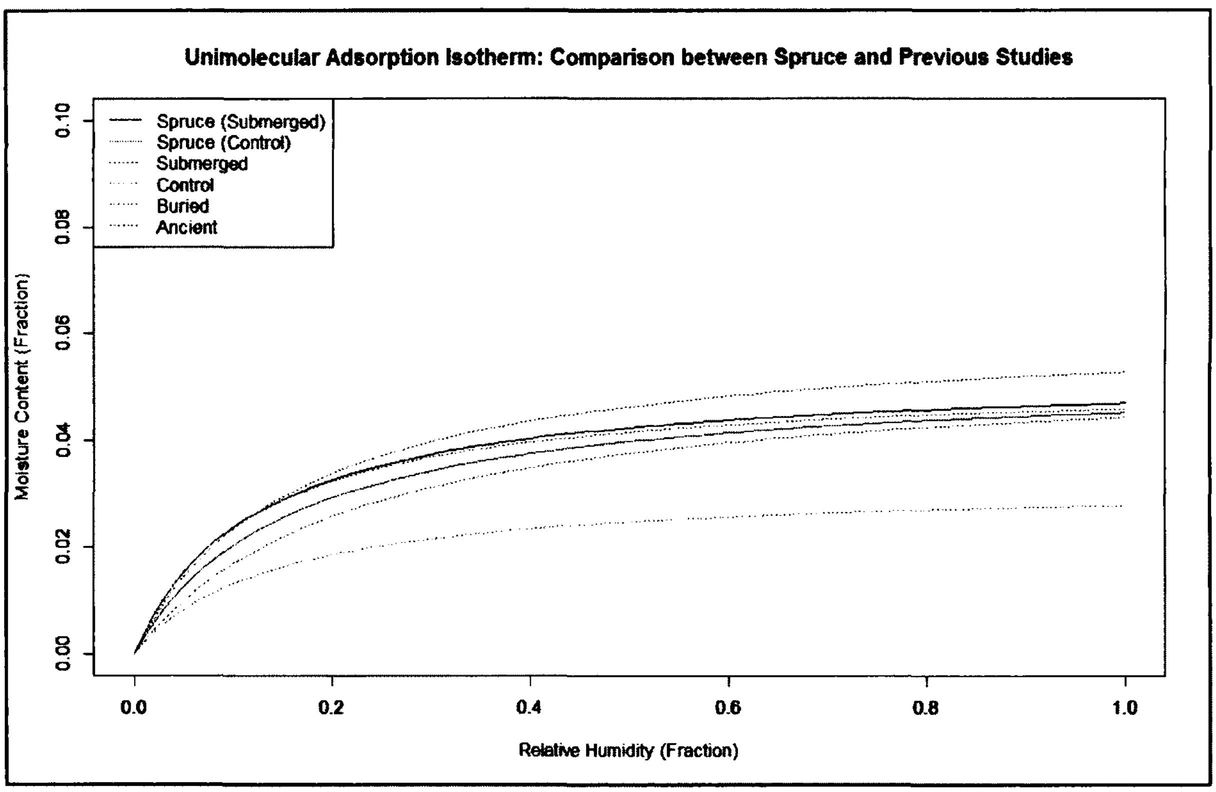

Figure 4.15 - Unimolecular Adsorption Isotherm Comparison for Spruce

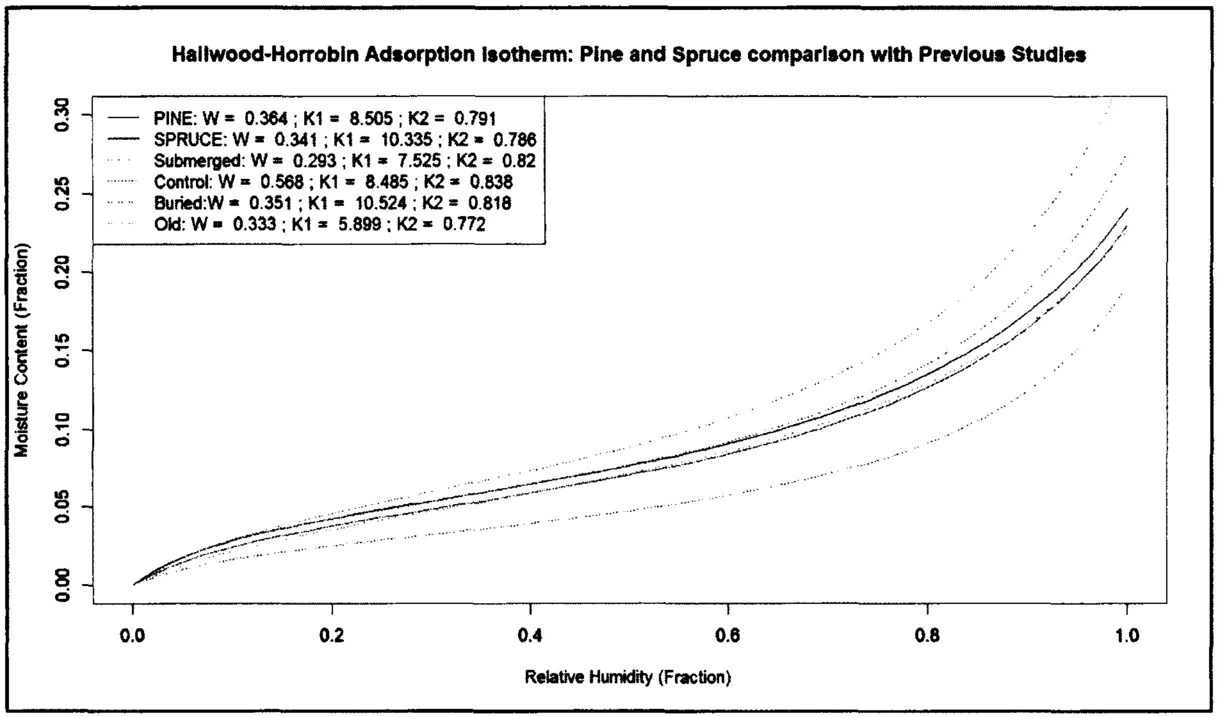

Figure 4.16 - Adsorption Isotherm Comparison for Spruce and Pine

E. Discussion

For both pine and spruce, the submerged wood had a higher mean moisture content than the control wood samples at each relative humidity level. These differences were statistically significant (Table 4.7 and Table 4.11). This implied that the submerged wood was able to adsorb more water than the control wood samples. This was also supported when the adsorption isotherm models were compared between the submerged and control samples (Figure 4.2 and Figure 4.5). In each case the adsorption isotherm for the submerged samples was higher than that of the control samples which implies that the submerged samples are able to adsorb more water.

It was expected that the W coefficient found when modelling the adsorption isotherms using the Hailwood-Horrobin model would be lower for the submerged. This expectation stems from the fact that a lower *W* would represent less crystalline areas within the wood [16] and that a higher ability to adsorb water is related to less crystallinity within the wood. It was found that W was lower for each of the submerged wood sets. However, the W coefficient for submerged spruce was not found to be different from the control wood.

The higher moisture content, adsorption isotherm and lower W coefficient found in the submerged wood agreed with the results of previous studies performed on submerged wood [34], wood that had been buried [35], and ancient wood [36] when they were compared with control wood samples (Table 4.18 and Table 4.19). The submerged spruce and pine wood was similar to that of buried and ancient wood but had lower adsorption isotherms, lower amounts of moisture content and higher W values than the submerged wood from the previous study. This is possibly due to the difference in the amount of years the wood was submerged in each case. For the current study, the wood was only submerged for approximately 53 years while the wood from the previous study was submerged for approximately 103 years. Additionally, the submerged wood from previous studies was also taken from a railway bridge where it had been submerged in a river. The submerged wood from the current study was taken from a lake where it had been submerged while still rooted into the ground. The combination of stress caused by trains using the bridge or from deterioration in the river could exacerbate the loss of crystallinity within the wood and cause the discrepancy seen.

Comparing the unimolecular adsorption isotherms, both the submerged sample sets were higher than their respective control sets implying that there was a higher level of available sorption sites for the control samples. Additionally, the submerged wood samples had a similar unimolecular adsorption isotherm to that of buried and ancient wood measured in previous studies. The unimolecular adsorption isotherm for the submerged wood in this study was not as high as that of submerged wood that had been submerged for 103 years. This could be explained by the fact that the 103 year old submerged wood was submerged for roughly twice as long and that it was used as lumber in a bridge for a railway as previously mentioned.

Larger unimolecular adsorption isotherms could be caused by a lower crystallinity leading to a larger amorphous area of wood for the submerged samples when compared to control data. In the previous studies it was shown that the submerged, ancient, and buried wood had a lower crystallinity index than that of the control wood. As the submerged wood from this study had similar unimolecular adsorption isotherms to that of the ancient and buried wood of previous studies this supported the theory that the submerged wood samples had lower crystallinity.

When comparing the dissolved water adsorption isotherm of the spruce and pine samples it was shown that the submerged pine was noticeably higher than the control pine. The submerged spruce was also higher than the control spruce although not by as large a margin. Additionally, the submerged pine, spruce and control spruce had similar dissolved water adsorption isotherms. This implied that there was a larger availability of wood to dissolved water for the submerged samples when compared to the pine control samples. The submerged wood samples, and control spruce samples, were comparable to the ancient wood samples from previous studies.

F. Summary

Pine and spruce samples that were submerged in Ootsa Lake, British Columbia, for 53 years were compared with control samples of the same species as well as to previous studies. It was believed that, due to submersion, the wood from Ootsa Lake would have a lower level of crystallinity.

It was found that the control samples had a higher equilibrium moisture content than the control samples. By modelling the adsorption isotherm of the control and submerged samples using the Hailwood-Horrobin adsorption isotherm theory it was shown that the adsorption isotherm for each submerged sample sets was higher than that of the corresponding control set. Additionally, the unimolecular adsorption isotherm was higher for the submerged species which implied that the wood was more amorphous compared to the control samples.

When compared to previous studies, the submerged wood was similar to ancient and buried wood samples that were shown to have a lower crystallinity index than the control samples from previous studies. This reinforced the belief that the submerged wood samples were less crystalline.

5. Comparison of Acoustic Measurements with Adsorption Measurements

A. Introduction

The ability of wood to transmit sound is directly related to the wood's cellular structure due to the strong dependence on density. The speed of sound through affected by the change in crystallinity of the wood as the crystallinity will affect the density of the wood [41]. The crystallinity is also connected to the amount of the wood that is available to water during adsorption. One such representation of the amount of wood available to water is the coefficient W from the Hailwood-Horrobin Adsorption Isotherm model [16].

In Chapter 3 it was shown that the acoustical properties of submerged wood were not suitable for use as musical instruments. This was primarily due to a lower speed of sound through the wood causing lowered acoustic constant and impedance values. In Chapter 4 it was shown that the submerged wood had a lower *W* coefficient than control samples for pine, and that it had a comparable W coefficient to that of buried and ancient wood from previous studies. As such, the wood was shown to have larger availability to water than both non-submerged pine samples and control samples from previous studies.

It was hypothesized that a correlation can be found between the acoustic properties of wood and the inaccessibility of the wood to water; specifically, that the speed of sound in wood could be related to the accessible fraction. As the accessible fraction is related to moisture content it was also hypothesized that a relationship between the speed of sound and moisture content as it varies with the accessible fraction could be obtained.

To explore this, the acoustic measurements calculated in Chapter 3 (Velocity, Density, Acoustic Constant and Characteristic Impedance) were compared with the inaccessible fraction found in Chapter 4. These results were then compared to a previously established model of the speed of sound as it varies with moisture content that was dependant on the temperature.

B. Results

a. Inaccessible Fraction

As stated in Hartley (1993) [16], the W from the Hailwood-Horrobin model, which represents the "polymer unit which contains one characteristic sorption site" can be compared to the polymer unit in cotton or wood, the glucose anhydrite unit; the glucose anhydrite unit has a value of 0.162 kg/mol. The amount of wood inaccessible to water, known as the inaccessible fraction (F_I) was found from Equation 5.1 where W has units of mol/kg.

$$F_I = \frac{(W - .162)}{W}$$

Equation 5.1

The calculated values for the submerged and control values of pine and spruce were compared with that of previous values in Table 5.1:

Table 5.1 - Fraction of wood inaccessible to water of samples

Inaccessible Fraction of Water in Wood			
Sample		W (kg/mol)	Inaccessible Fraction
Pine	Submerged	0.364	0.555
	Control	0.383	0.577
Spruce	Submerged	0.342	0.526
	Control	0.344	0.530
Previous Studies	Submerged	0.293	0.448
	Ancient	0.333	0.513
	Buried	0.351	0.539
	Control	0.568	0.715

The control samples for both pine and spruce as well as for the previous study had a lower inaccessible fraction and, therefore, more of the wood was accessible to water. The wood that had been submerged for 103 years had the highest amount of wood accessible to water. Both the control and submerged spruce samples from the current study were between the ancient and buried wood samples from previous studies. The only wood that was less accessible than the submerged pine samples were the control pine samples and the control samples from the previous study. The pine samples had, however, a much closer inaccessible fraction to that of the ancient and buried wood than to that of the submerged or control samples from the previous studies.

b. Inacessible Fraction Compared with Physical Acoustic Characteristics

Due to the relationship between the inaccessible fraction and crystallinity [16] as well as the relationship between the physical acoustic characteristics and crystallinity [41] the possible correlation between the inaccessible fraction and physical acoustic characteristics were explored further.

The inaccessible fraction was found for each individual sample used for the sorption measurement using Equation 5.1. These values, along with the *W* coefficients and the physical acoustic characteristics found in Chapter 3 for the samples, were provided in Table 5.2 and Table 5.3. The inaccessible fraction was plotted against the speed of sound, density, acoustic constant and characteristic impedance in Figure 5.1.

Table 5.2 - Acoustic Measurements and W Coefficient (Disk 2, Pine)

Disk 2, Pine								
#	c	ρ	AC	Z	W		Inaccessible Fraction	
					a	b	a	b
	ms^{-1}	*kgm^{-3}*	*$m^4kg^{-1}s^{-1}$*	*MPa•s/m*	*kg/mol*	*kg/mol*	*%*	*%*
1	2730	433	6.30	1.18	0.36	0.37	54.39	55.63
2	2930	472	6.20	1.38	0.37	0.36	55.77	55.50
3	2820	442	6.39	1.25	0.35	0.35	53.75	53.80
4	2540	435	5.83	1.11	0.35	0.34	53.93	52.60
5	2820	460	6.13	1.30	0.36	0.36	55.43	54.93
6	2760	426	6.48	1.18	0.36	0.35	55.58	54.02
7	2630	445	5.91	1.17	0.37	0.37	56.11	55.85
8	2880	417	6.91	1.20	0.37	0.36	55.97	55.23
9	2840	470	6.05	1.33	0.36	0.36	55.57	55.36
11	2360	418	5.66	0.99	0.35	0.36	53.79	55.08
12	2820	389	7.23	1.10	7.23	0.38	57.68	55.95
13	2980	459	6.50	1.37	6.50	0.39	58.58	55.78
14	2610	444	5.87	1.16	5.87	0.36	54.41	53.48
15	2540	353	7.21	0.90	7.21	0.36	54.64	53.95
16	2770	436	6.35	1.21	6.35	0.35	54.21	56.63
17	2680	489	5.47	1.31	5.47	0.37	56.42	58.16
18	2680	459	5.85	1.23	5.85	0.37	56.34	56.05
19	2730	455	6.00	1.24	6.00	0.37	56.18	57.24
20	2660	473	5.62	1.26	5.62	0.39	58.14	57.23
21	2480	482	5.15	1.20	5.15	0.36	54.85	55.51

Table 5.3 - Acoustic Measurements and W Coefficients (Disk 6, Spruce)

Disk 6, Spruce								
#	c	ρ	AC	z	W		Inaccessible Fraction	
					a	b	a	b
	m/s	*kg/m³*	*m⁴kg⁻¹s⁻¹*	*MPa•s/m*	*kg/mol*	*kg/mol*	*%*	*%*
1	2330	390	5.98	0.91	0.35	0.35	53.20	53.38
3	2420	394	6.16	0.95	0.35	0.35	53.69	53.85
4	2520	361	6.98	0.91	0.33	0.34	51.38	52.68
5	2210	382	5.79	0.85	0.34	0.36	52.65	54.76
6	2210	433	5.10	0.96	0.31	0.35	47.03	53.67
7	2030	392	5.18	0.80	0.31	0.35	48.07	54.03
8	2370	390	6.08	0.93	0.34	0.33	52.33	51.12
9	2240	439	5.10	0.98	0.36	0.35	54.66	53.26
11	2500	412	6.07	1.03	0.35	0.36	54.19	54.99
12	2340	379	6.16	0.89	0.33	0.33	50.73	50.41
13	2570	405	6.36	1.04	0.35	0.34	53.50	52.07
14	2670	379	7.05	1.01	0.35	0.35	54.16	53.59
15	2400	390	6.16	0.94	0.35	0.34	53.27	52.19
16	2750	383	7.19	1.05	0.35	0.34	53.27	52.32
17	2180	433	5.03	0.95	0.34	0.34	52.35	51.68
18	2310	366	6.33	0.85	0.33	0.32	51.04	49.19
19	2440	411	5.94	1.00	0.37	0.33	55.65	51.51
20	2380	388	6.13	0.92	0.35	0.32	54.19	48.78
21	2670	379	7.05	1.01	0.35	0.34	53.90	53.00
22	2580	360	7.17	0.93	0.34	0.34	51.85	52.43

Upon initial examination of Figure 5.1, the speed of sound and characteristic impedance seemed to have a larger connection with the inaccessible fraction. Density, also, appeared to have a connection but the acoustic constant did not appear to be strongly related with the inaccessible fraction based on the initial graphical observations.

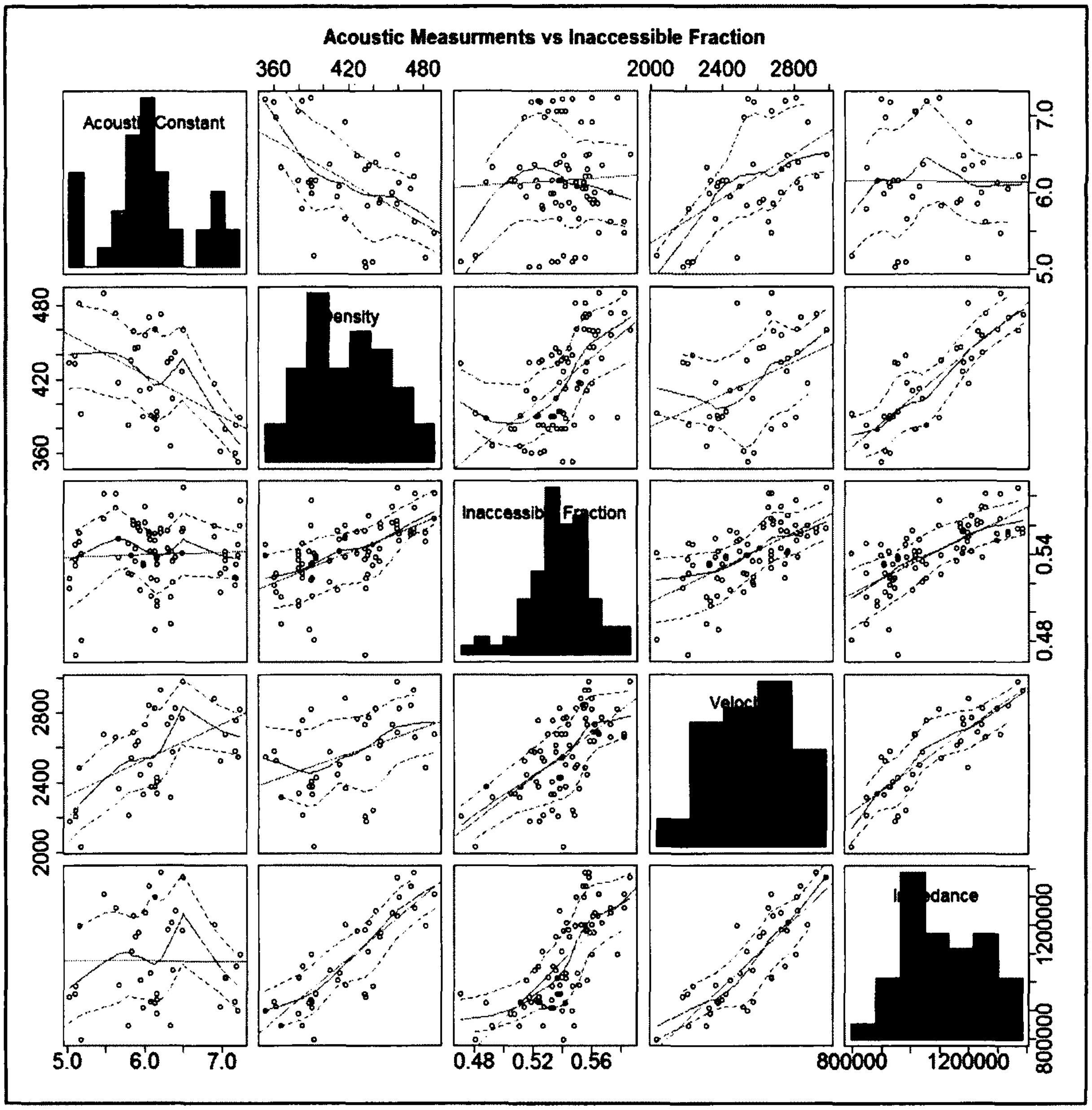

Figure 5.1 - Physical Acoustic Characteristics vs. Inaccessible Fraction

c. Comparison between the Speed of Sound and Accessible Fraction of Wood

To examine how the speed of sound through wood compared with the accessibility of water within wood, the speed of sound was plotted against the accessible fraction of water within wood. The accessible fraction, F_A, was found from the inaccessible fraction, F_I, using:

$$F_A = 1 - F_I$$

Equation 5.2

with both F_A and F_I expressed per cent. The speed of sound and accessible fraction were plotted in Figure 5.2.

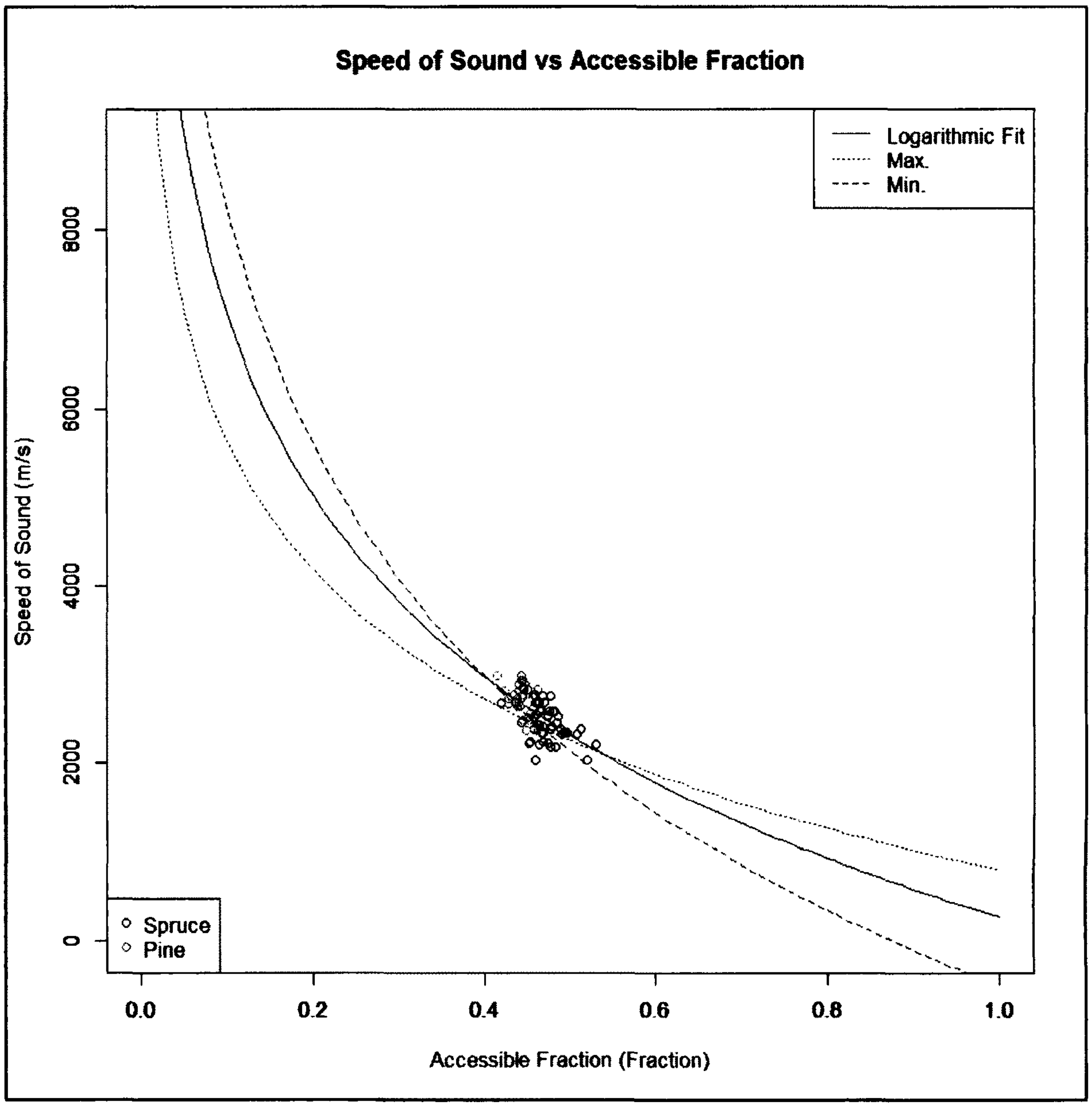

Figure 5.2 - Speed of Sound vs. Accessible Fraction Plot

To model the relationship between the speed of sound and accessible fraction, a logarithmic function was chosen. This was in an attempt to correlate the relationship between the speed and accessible fraction with a previously determined relationship between the speed of sound and moisture content [29]. In that study, the relationship between the speed of sound and moisture content was determined for temperatures above 0°C to be:

$$c_{ex}(M) = 6060.85\, m/s - 4.07\,°C^{-1} \cdot T - 652.75 m/s \cdot \ln M$$

Equation 5.3

where T is the temperature in °Celsius, M is the moisture content and c is the speed of sound through wood in m/s.

The model chosen, with coefficients of fit of A and B, was:

$$c = A \cdot \ln(B \cdot F_A)$$

Equation 5.4

where c is the speed of sound in m/s and F_A is the accessible fraction. The logarithmic model was fit and plotted with the data in Figure 5.2 and the coefficients were provided in Table 5.4. The R^2 value for the model was 38.1% (Table 5.5).

Table 5.4 - Speed of Sound vs. Accessible Fraction Coefficients (Logarithmic Fit)

c vs. F_A (Logarithmic Fit)							
	Estimate	Std. Error	t value	p-value	df	95% Confidence Interval	
						Min.	Max.
A (m/s)	-2952.8	425.9	-6.93	1.06E-09	78	-3804.6	-2101.0
B	0.91	0.11	7.98	1.02E-11	78	0.69	1.14

Table 5.5 - Goodness of Fit for Logarithmic Fit

Goodness of Fit		
RSS	SS	R^2
2.55E+06	4.13E+06	.381[1]

[1] Calculated with Equation 4.6

d. Relationship Between the Speed of Sound m_0

In order to verify the possible relationships between the Speed of Sound and Accessible Fraction of water within wood, the speed of sound was compared to the moisture content within the wood. Specifically, the relationship between the accessible fraction of water and the moisture content at which all of the available sorption sites in the wood are completely hydrated (m_0) [13] was used.

The Hailwood-Horrobin sorption isotherm, described previously, is:

$$M = m_0\left(\frac{K_1 \cdot K_2 \cdot h}{1 + K_1 \cdot K_2 \cdot h} + \frac{K_2 \cdot h}{1 - K_2 \cdot h}\right)$$

Equation 5.5

where $m_0 = \frac{0.018}{W}$.

The W coefficient and the inaccessible fraction (F_I) are related as described by Hartley [16]:

$$F_I = \frac{(W - .162)}{W}$$

Equation 5.6

Equation 5.6 can be re-arranged to solve for W:

$$F_I \cdot W = W - .162$$

$$F_I \cdot W - W = -.162$$

$$W \cdot (F_I - 1) = -.162$$

$$W = \frac{-.162}{F_I - 1}$$

$$W = \frac{.162}{1 - F_I}$$

Equation 5.7

Using the relationship between the accessible fraction (F_A) and the inaccessible fraction, $F_A = 1 - F_I$, Equation 5.7 can be re-written as:

$$W = \frac{.162}{F_A}$$

Equation 5.8

When Equation 5.8 is substituted in place of W, m_0 can be written as:

$$m_0 = \frac{F_A}{9} \leftrightarrow F_A = 9 \cdot m_0$$

Equation 5.9

Combining Equation 5.9 with Equation 5.4 provided a relationship between the speed of sound and m_0 using the logarithmic models:

$$c = A \cdot \ln(9B \cdot m_0)$$

Equation 5.10

Substituting in the A and B coefficients from Table 5.4 provided possible numerical relationship between the speed of sound and m_0:

$$c = (-2952.8 \pm 851.8\, m/s) \cdot \ln[9 \cdot (0.914 \pm 0.229) \cdot m_0]$$

Equation 5.11

Graphically, the relationship between m_0 and the speed of sound through wood was presented in Figure 5.3.

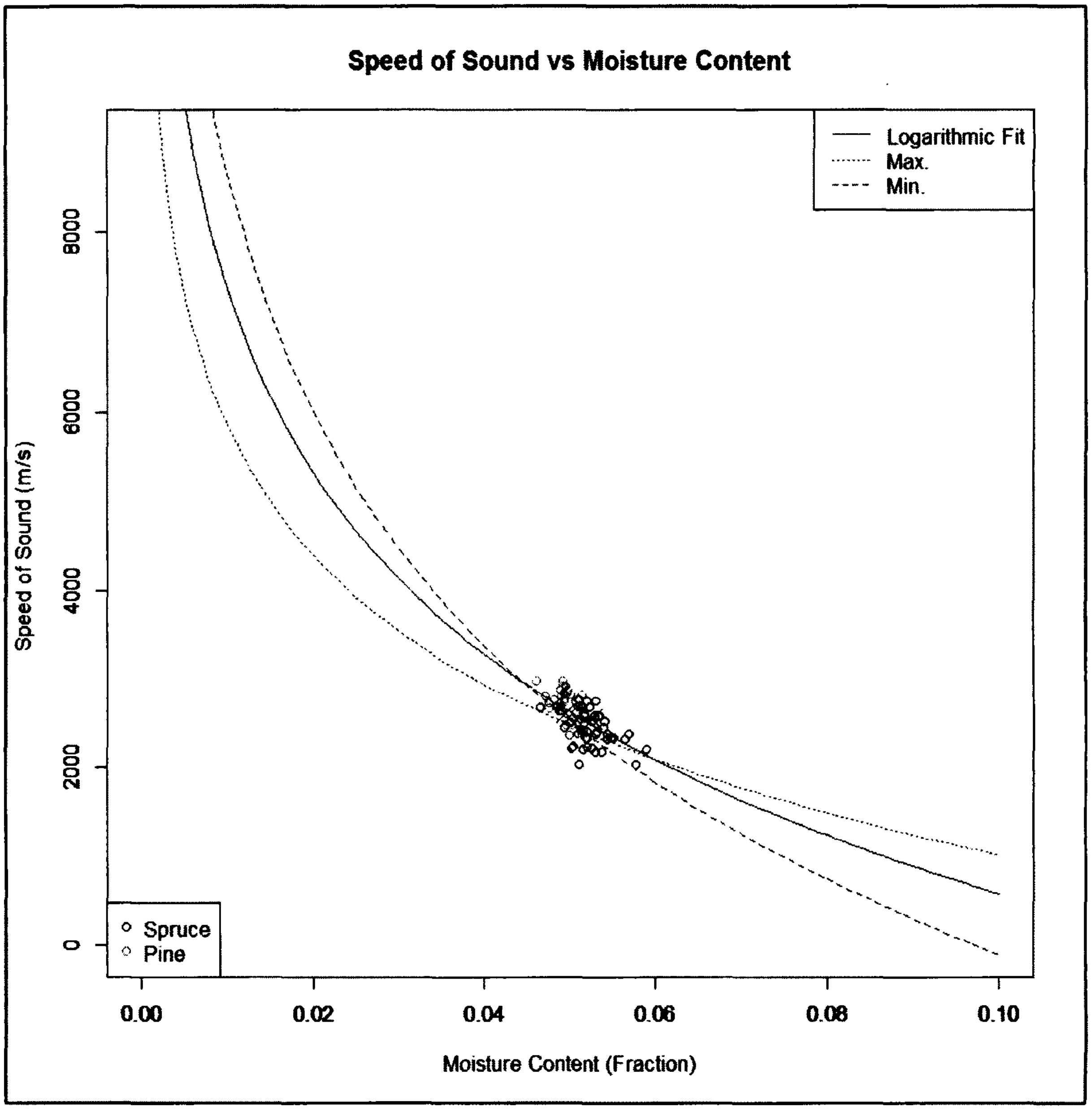

Figure 5.3 - Speed of Sound vs. m_0 (Logarithmic Fit)

e. Combination of Speed of Sound, m_0 and Moisture Content

A relationship between the moisture content and speed of sound though wood was presented by Chan [29] that described the decrease in speed as a logarithmic function of moisture content (Equation 5.3). As both Equation 5.3, and Equation 5.11 describe the speed of sound through wood as it is dependent on moisture content, it was proposed that, by comparing Equation 5.3 with the logarithmic model between the speed of sound and m_0, it would be possible to determine m_0 for the previous study.

Equation 5.3 was plotted along with Equation 5.11 in Figure 5.4 and the moisture content at which intersection occurs was determined using the R statistical software program and presented in Table 5.6.

Table 5.6 - m_0 determined from Logarithmic Model and Equation 5.3

		m_0 and $c_{ex}(m_0)$ (Theoretical)		
		Mean	Minimum	Maximum
m_0	(%)	1.85	0.93	2.34
$c_{ex}(m_0)$	(m/s)	5566.8	6016.6	5411.3

The m_0 values from the submerged pine and spruce were determined by converting the values of the inaccessible fraction in Table 5.1. This provided values of 4.95% and 5.26% for pine spruce, respectively. Comparing these values with the m_0 from Table 5.6 shows that the m_0 determined by intersecting Equation 5.3 with Equation 5.11 is a realistic value. It also implies that the moisture content at which all available sorption sites for the submerged wood was higher than that of the wood used by Chan [29], which indicates a larger availability to sorption sites in the submerged wood compared to non-submerged wood.

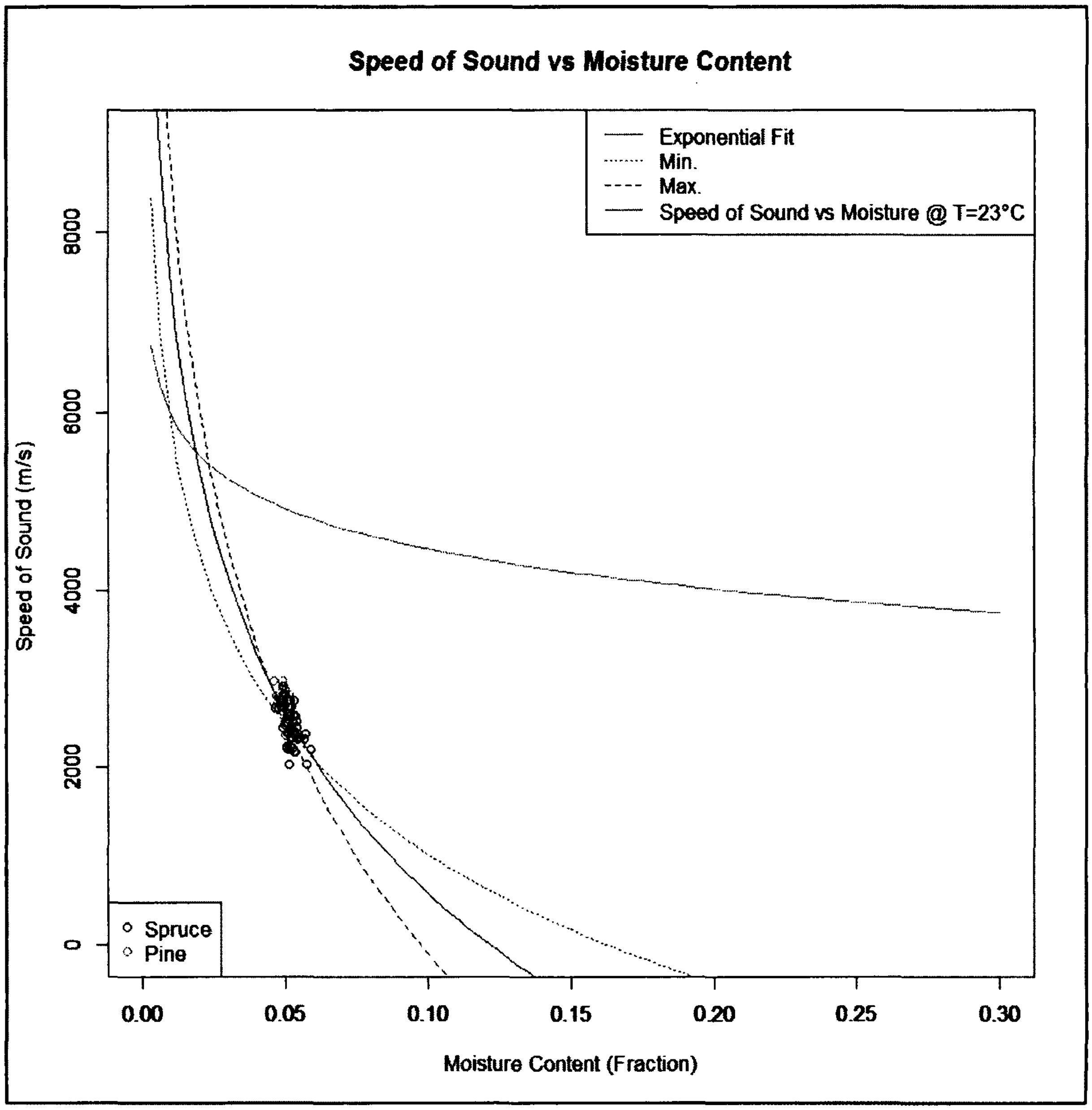

Figure 5.4 - Speed of Sound, Moisture Content and m0 (Logarithmic Fit)

f. Prediction of Speed of Sound vs. Moisture Content using m_0

By assuming that the relationship between the speed of sound through wood and the wood's moisture content would interact at m_0 the same way it was possible to translate Equation 5.3 for other wood samples. This was accomplished by translating Equation 5.3 with respect to Equation 5.11 depending on the value of m_0.

First, Equation 5.11 was rewritten as a function of the moisture content, *M*:

$$c_0(M) = (-2952.8 \pm 851.8\,m/s) \cdot \ln[9 \cdot (0.914 \pm 0.229) \cdot M]$$

Equation 5.12

Then, the translation was found using:

$$c_{th}(M) = c_{ex}(M - (m_2 - m_1)) + [c_0(m_2) - c_0(m_1)]$$

Equation 5.13

where $c_{th}(M)$ is the modified relationship for the speed of sound from Chan [29], $c_0(M)$ is the speed as a function of m_0, m_1 is m_0 found for the experimental model in Equation 5.3 (Table 5.6) and m_2 is the m_0 value for the wood samples that was being determined.

By using the m_0 values found for the submerged spruce and pine samples, determined using the W coefficient and $m_0 = \frac{.018}{W}$, the relationship between the speed of sound and moisture content for the submerged wood was determined using the mean (Figure 5.5), maximum (Figure 5.6), and minimum (Figure 5.7) coefficients for Equation 5.12. The general solutions for the mean, maximum and minimum coefficients at a constant temperature of 23°C were presented in Equation 5.14, Equation 5.15, and Equation 5.16.

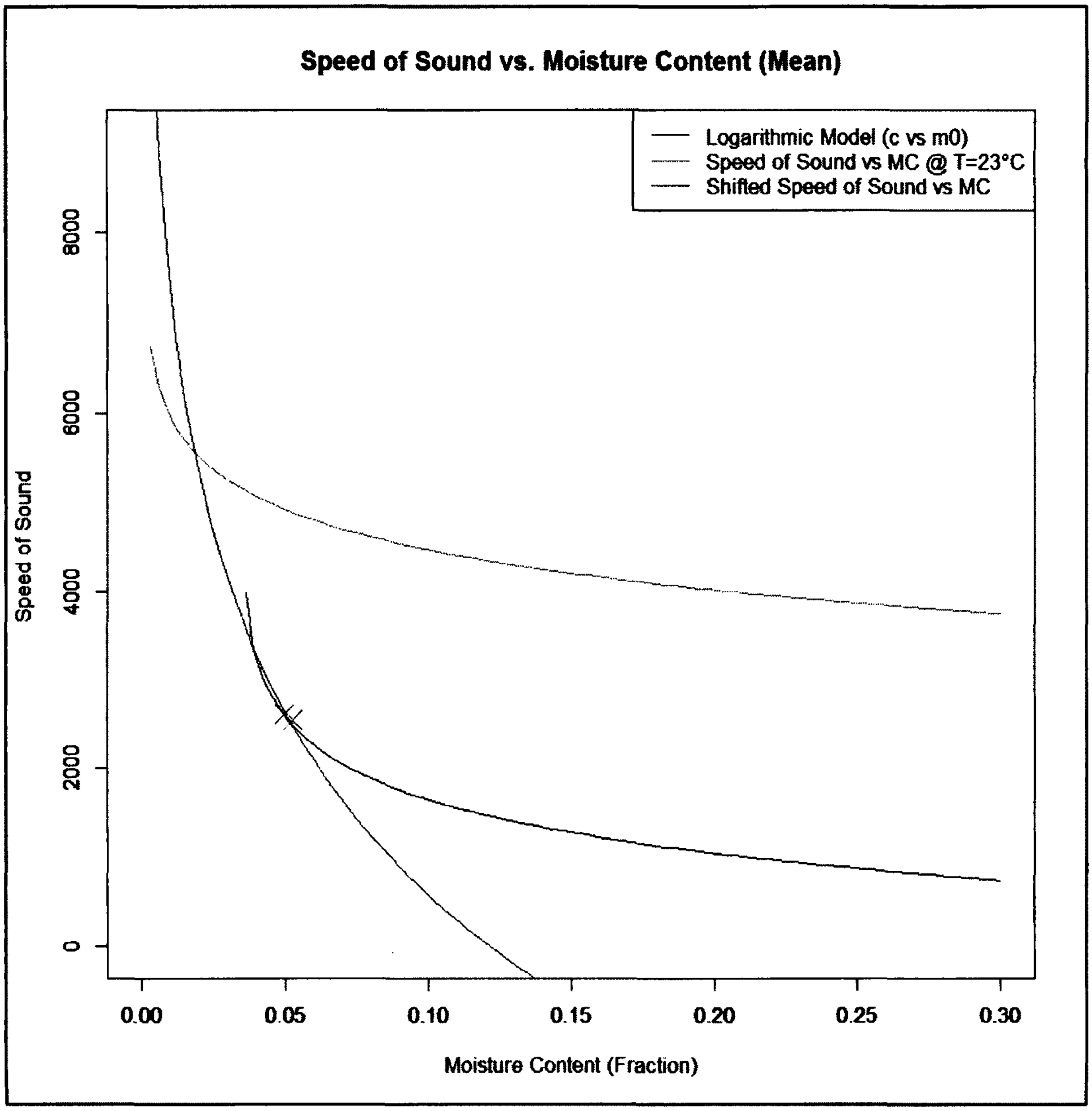

Figure 5.5 - Theoretical Speed of Sound vs. Moisture Content (Mean Logarithmic Fit)

$$c_{th}(M) = 404.2\,m/s - 652.75\,m/s \cdot \ln(M + .0185 - m_2) - 2952.8\,m/s \cdot \ln(8.23 \cdot m_2)$$

Equation 5.14

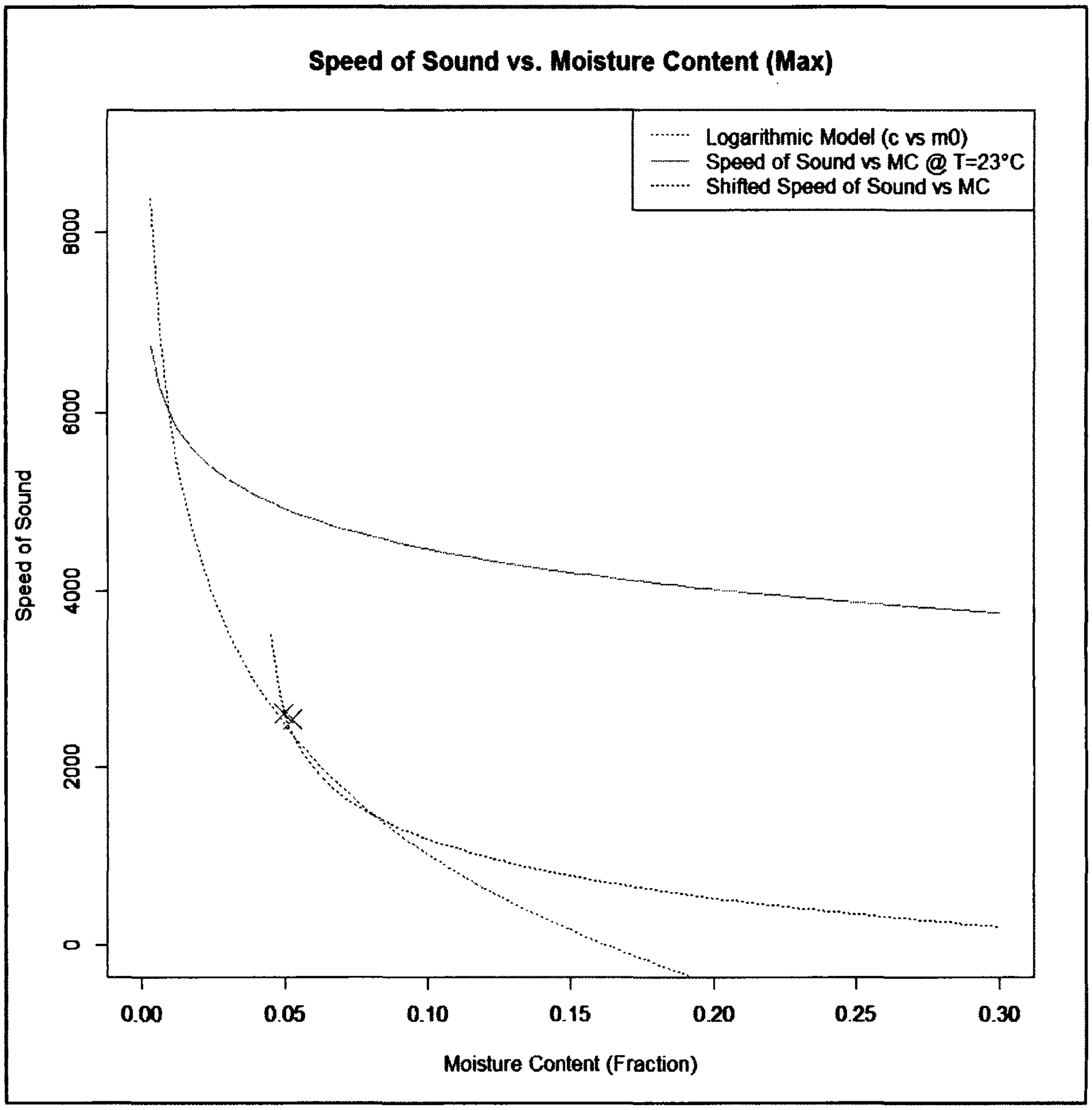

Figure 5.6 - Theoretical Speed of Sound vs. MC (Maximum Logarithmic Fit)

$$c_{th}(M) = -44.6\, m/s - 652.75\, m/s \cdot \ln(M + .009 - m_2) - 2100.9\, m/s \cdot \ln(6.17 \cdot m_2)$$

Equation 5.15

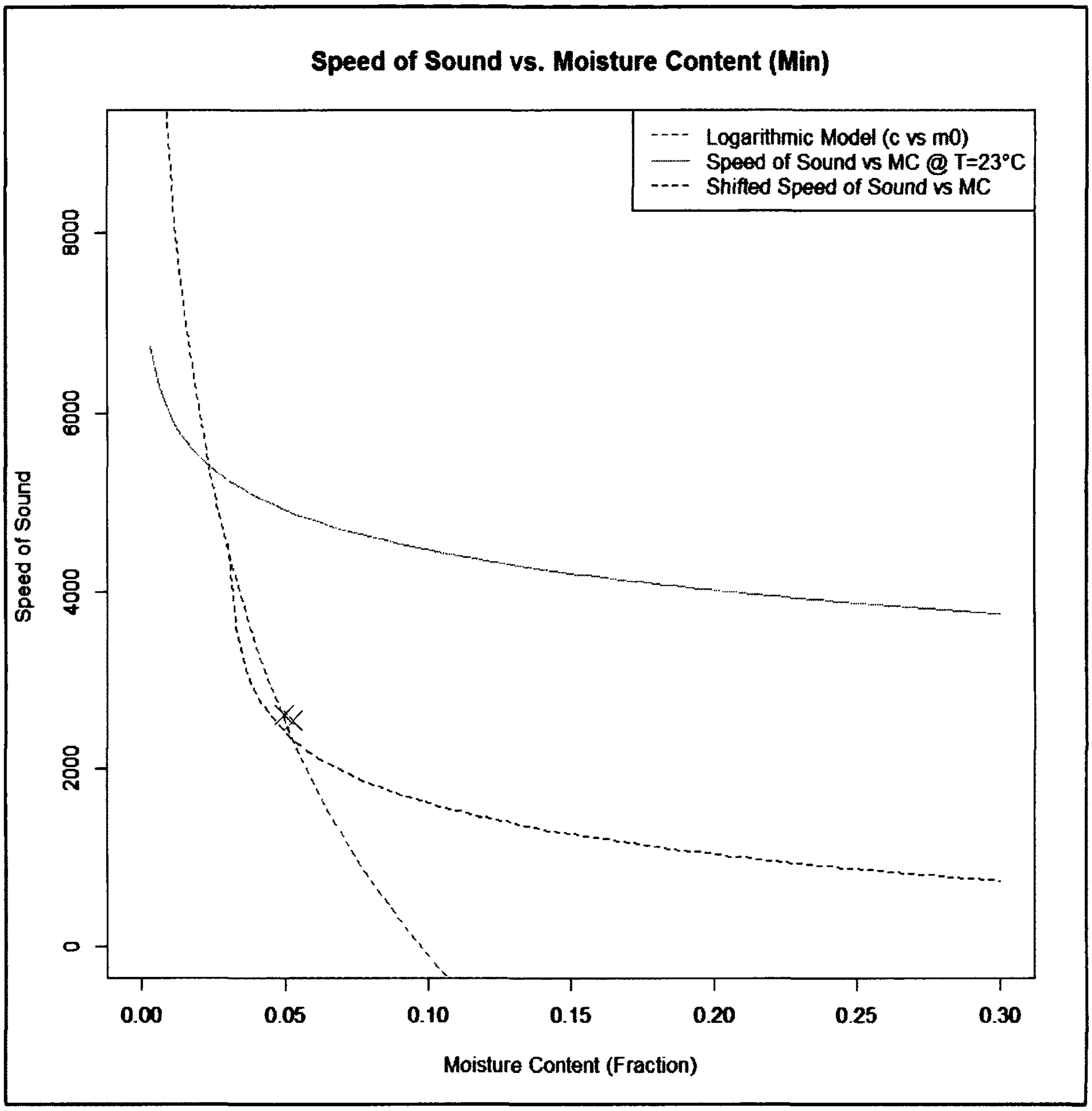

Figure 5.7 - Theoretical Speed of Sound vs. MC (Minimum Logarithmic Fit)

$$c_{th}(M) = 555.6\,m/s - 652.75\,m/s \cdot \ln(M + .023 - m_2) - 3804.6\,m/s \cdot \ln(10.29 \cdot m_2)$$

Equation 5.16

The general solution to Equation 5.13, including dependence on temperature, was:

$$c_{th}(M, T, m_0) = 6060.85\,m/s - 4.07°\mathrm{C}^{-1}T - 652.75\,m/s \ln(M + m_1 - m_0) + A \ln\left(\frac{m_0}{m_1}\right)$$

Equation 5.17

where the coefficients A, and Table 5.7.

Table 5.7 - Coefficients used in evaluation of Equation 5.17

Coefficients for General solution of c_{th}		
Fit	Coefficients	
	A	m_l
	(m/s)	-
Mean	-2952.8	1.85E-02
Max	-2100.9	9.27E-03
Min	-3804.6	2.34E-02

Similarly, using the coefficients from Table 5.7, Equation 5.17 could be rewritten with respect to the W coefficient or the accessible fraction of water within wood:

$$c_{th}(M,T,W) = 6060.85\,m/s - 4.07°\mathrm{C}^{-1}T - 652.75\,m/s\ln\left(M + m_1 - \frac{.018}{W}\right) + A\ln\left(\frac{.018}{Wm_1}\right)$$

Equation 5.18

$$c_{th}(M,T,F_A) = 6060.85\,m/s - 4.07°\mathrm{C}^{-1}T - 652.75\,m/s\ln\left(M + m_1 - \frac{F_A}{9}\right) + A\ln\left(\frac{F_A}{9m_1}\right)$$

Equation 5.19

C. Discussion

It was possible to use Equation 5.17, Equation 5.18, and Equation 5.19 to describe the relationship between speed of sound and moisture content as temperature, the W coefficient, the inaccessible fraction and the moisture content at which all available sorption sites in the wood were hydrated changed. The relationships are examined in Figure 5.8, Figure 5.9, Figure 5.10, and Figure 5.11.

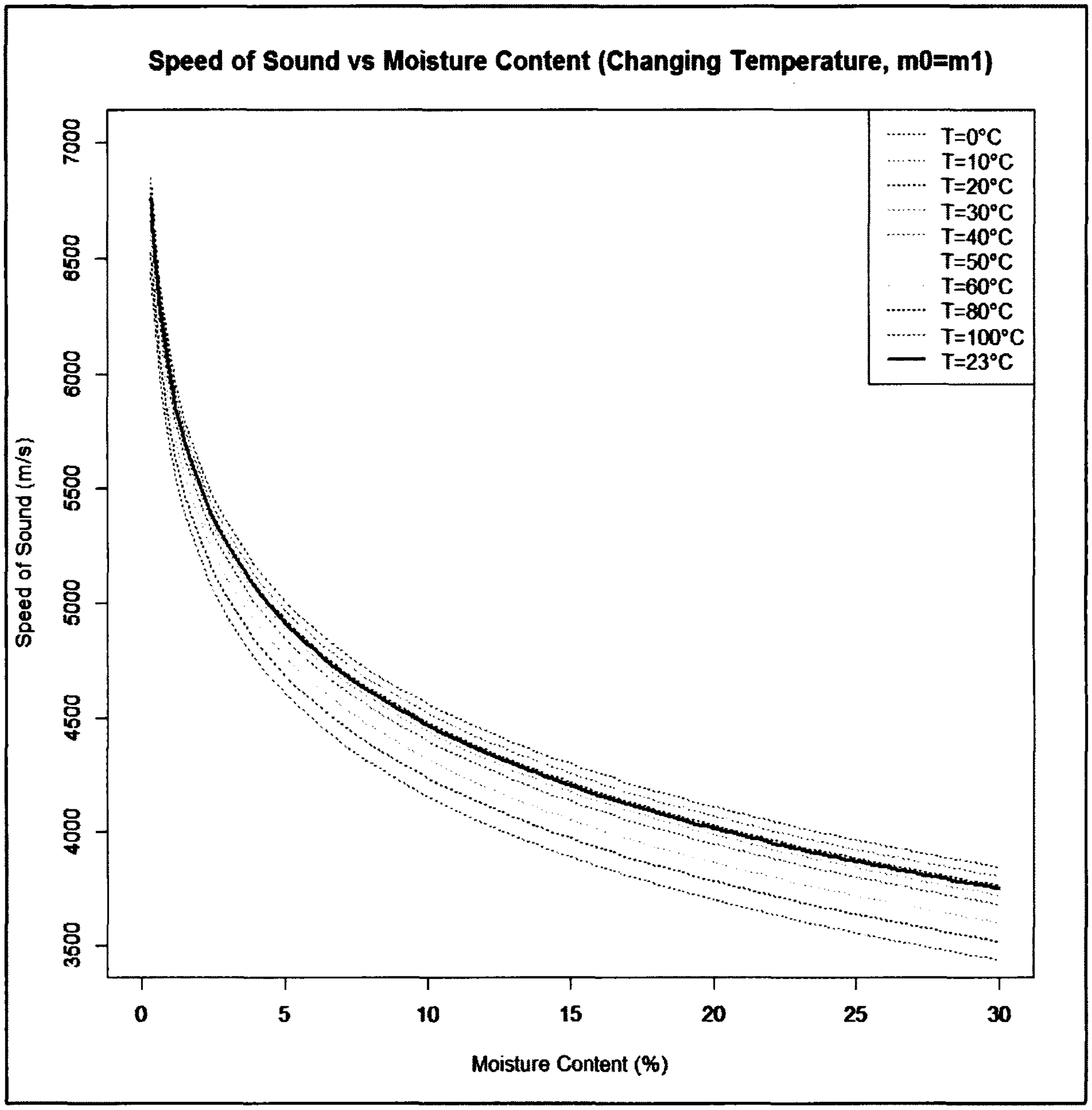

Figure 5.8 - Speed of Sound vs. MC (Changing T, Constant m_0) (Equation 5.17)

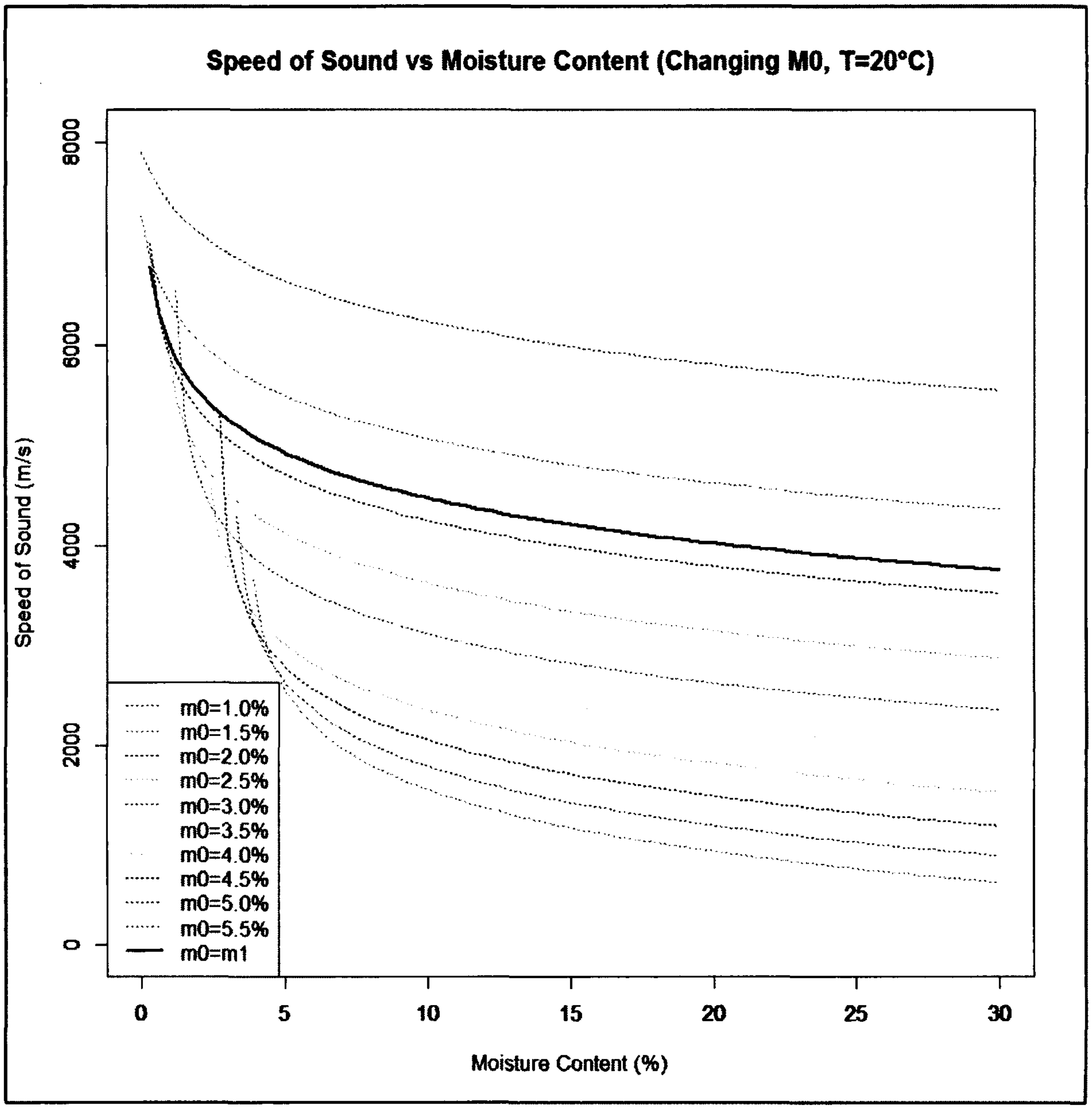

Figure 5.9 - Speed of Sound vs. MC (Changing m_0, Constant T) (Equation 5.17)

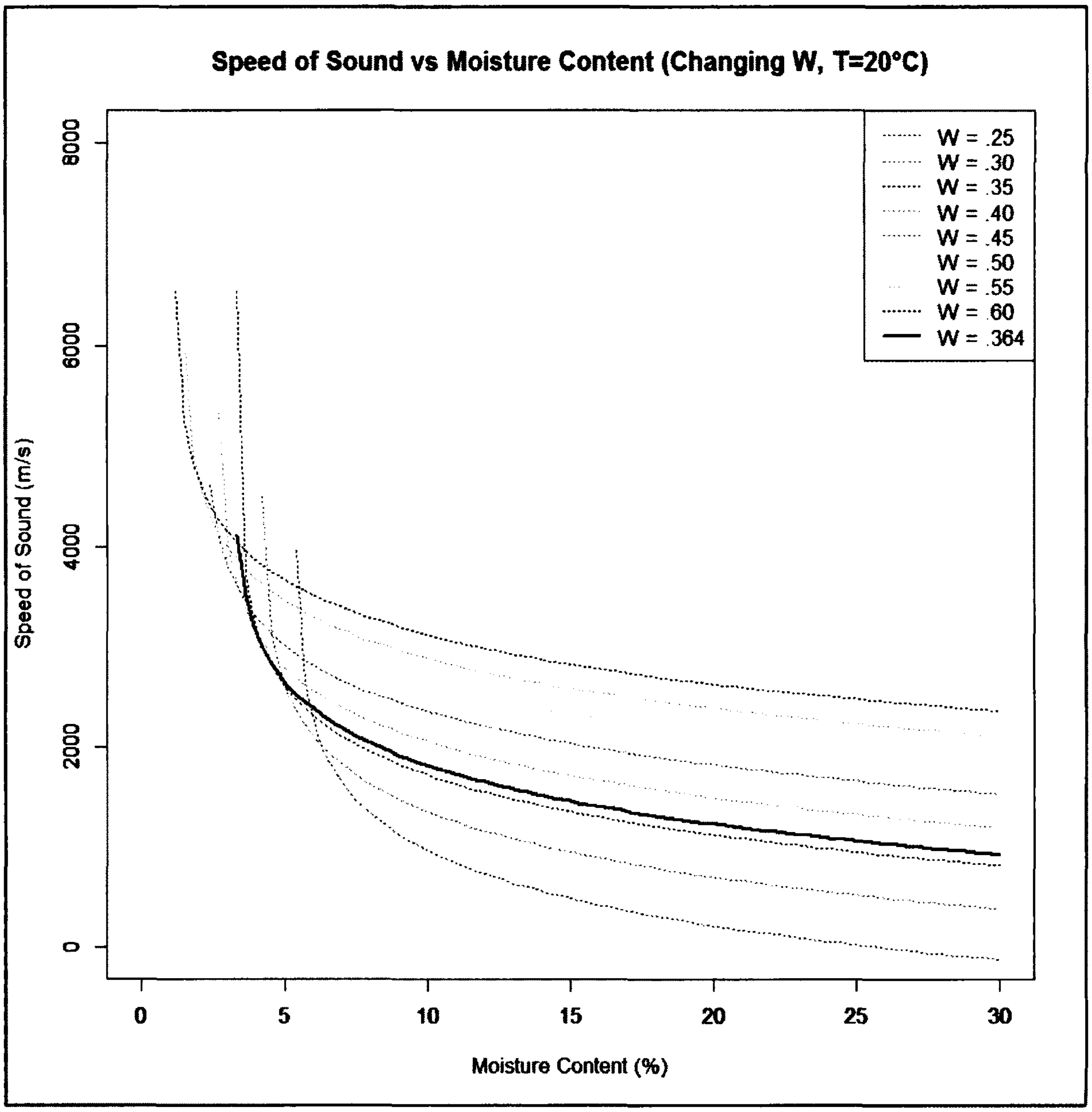

Figure 5.10 - Speed of Sound vs. MC (Changing W, Constant T) (Equation 5.18)

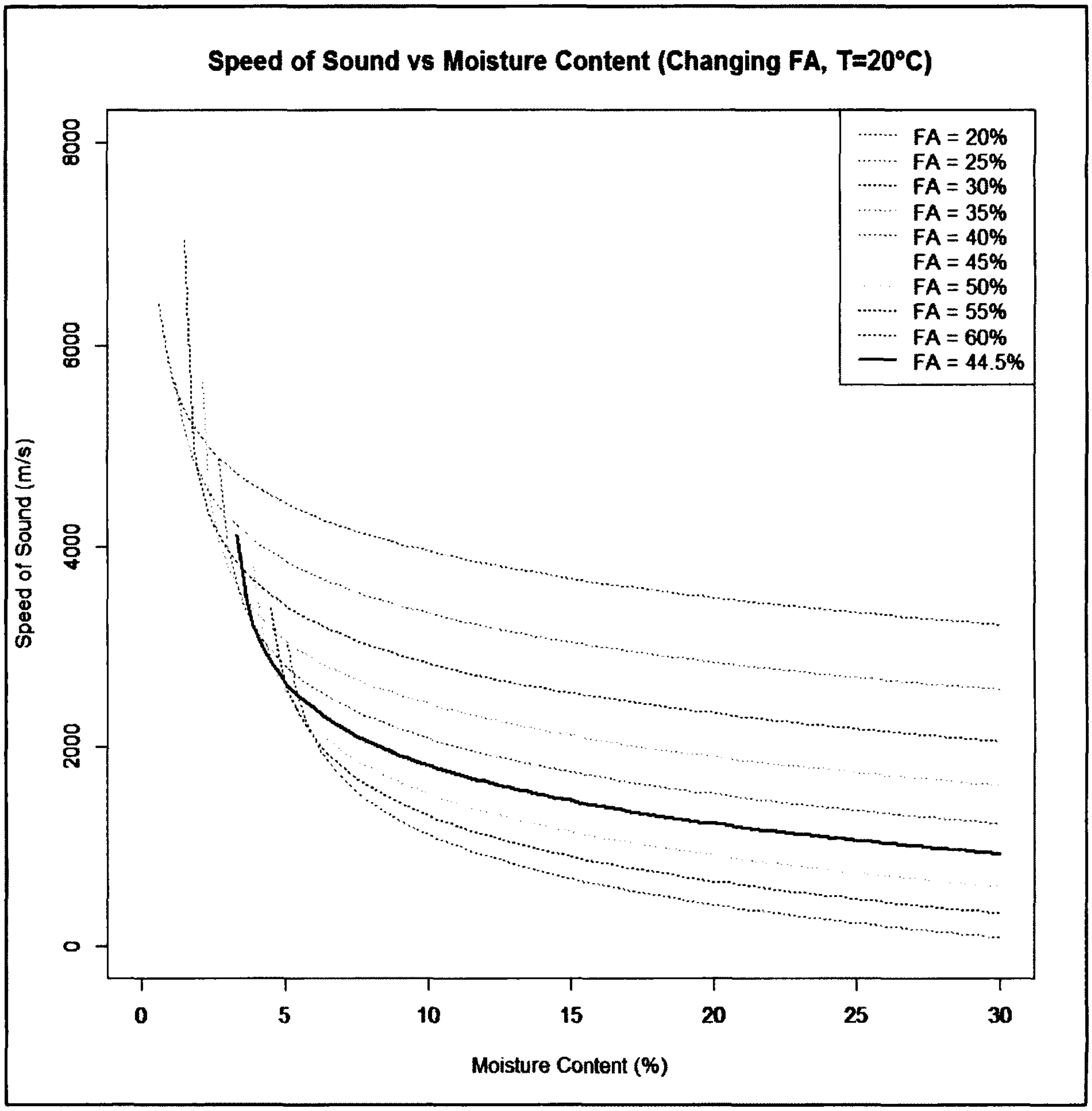

Figure 5.11 - Speed of Sound vs. MC (Changing F_A, Constant T) (Equation 5.19)

While the relationships provided did provide a method of describing the change in the speed of sound with respect to the moisture content, F_A, W and m_0, there is a heavy reliance upon the empirical relationship provided by Chan [29] to describe the general relationship. It was assumed that this relationship would describe the speed of sound through wood with the provided coefficients regardless of species and without taking into account defects in the wood. Additionally, the relationship used was not well defined below 10% moisture content and, as such, was not expected to accurately describe the speed of sound in this range. When examining the relationship between m_0 and the speed of sound, a logarithmic model was chosen (Equation 5.10). While this model provided a possible relationship it did have a large error range. Also, due to the limited range of data points with which to create the relationship between the speed of sound and inaccessible fraction, the coefficients chosen in the model had a large range of variability. Further research is recommended to refine both the equation describing the speed of sound and moisture content as well as the relationship between the speed of sound and m_0.

Regardless of the model chosen for either relationship, though, it was still believed that the relationship between the moisture content and speed of sound could be determined for varying temperature and m_0 by using equations of the form:

$$c_{th}(M, T, m_0) = c_{ex}(M - m_0, T) + c_0(m_0)$$

Equation 5.20

where T is the temperature, M is the moisture content, m_0 is the moisture content at which all sorption sites are hydrated, $c_{ex}(M)$ is the experimental relationship between speed of sound and moisture content proposed by Chan [29], and $c_0(m_0)$ is a relationship relating the speed of sound with m_0.

The accessible fraction, the W coefficient and m_0 are considered to be related with the crystallinity of the wood. Higher levels of crystallinity imply larger values for the W coefficient and lower values for both the accessible fraction and m_0. Higher crystallinity will also lead to higher values for the speed of sound through wood. As shown in Figure 5.9, Figure 5.10, and Figure 5.11, when W increased, the accessible fraction decreased or m_0

decreased, it lead to higher values for the speed of sound. As such, the proposed equations satisfy this relationship.

D. Summary

It was hypothesized that a correlation between the acoustic properties of wood, specifically the speed of sound, and the accessible fraction of moisture in wood could be determined. To examine this, the speed of sound was plotted against the accessible fraction and a logarithmic model was chosen to describe the relationship.

Using the relationship between the accessible fraction and the moisture content at which complete hydration of sorption sites within the wood occurs (m_0), the speed of sound was related to m_0 itself. Under the assumption that the speed of sound would react with wood in a similar way at m_0, independent of the wood species or sample, the relationship between the speed of sound and m_0 was extended to a previously obtained relationship between speed and moisture content. A relationship was then obtained that described the speed of sound through wood as a function of temperature, moisture content and m_0.

6. Conclusion

Wood submerged in water is currently being harvested for use in different wood products. One such usage of submerged wood is in the creation of musical instruments such as guitars or bagpipes. While wood is commonly used to create musical instruments due to its abundance, ease of crafting and resonate qualities, not all wood species are suitable for musical instruments. Submerged wood is believed, in general, to be at least adequate to create instruments.

To investigate the possible suitability of submerged wood from Ootsa Lake, British Columbia, an initial study was performed on the physical acoustic characteristics of pine and spruce wood samples. By measuring the speed of sound through wood and the density the acoustic constants for the submerged wood samples were found. It was determined that, although the density was within an appropriate range, both the speed of sound and acoustic constant of the pine and spruce samples were not high enough to be suitable for musical instruments.

At the time it was believed that the acoustic properties of the wood would improve if left to age untouched to become more resonant over time. To investigate this, the pine and spruce samples from Ootsa Lake were left to sit untouched for 3 years. The wood samples were then measured once more using the same equipment as before. The density and speed of sound were once again measured and from those the acoustic constant and characteristic impedance of the wood were determined.

When compared to the previous study, it was determined that both the density and the speed of sound had decreased; the speed of sound was found to be even further away from that of normal speed of sound values for soundboards and wood for other instruments such as xylophones and wind instruments. The density was found to be within the normal range for pine and spruce species as well as within the suitable range for wood used in soundboards. However, the density was not high enough for use as woodwind instruments or xylophones as both types of instruments require high density values.

As the acoustic constant is inversely proportional to the density, the lower density contributed positively to the acoustic constant. However, the speed of sound decreased by a larger magnitude than that of the density which caused the overall change in the acoustic constant to be a drop. Compared to resonant woods, the acoustic constant of the pine samples were not high enough to be considered for soundboards but were within appropriate ranges for wind instruments and other instruments such as xylophones. The highest range of acoustic constant values for spruce were found to just barely meet the minimum requirement for soundboards and also had values appropriate for other instruments.

The characteristic impedance of the wood is proportionally dependent on both the density and speed of sound. Because of the decrease in both density and speed of sound when compared to previous values this also led to a decrease in the characteristic impedance for both wood species. The pine samples had characteristic impedance values that were within the suitable range of values for that of soundboards but did not have values that were suitable for woodwind instruments other instruments such as xylophones. Spruce did not have appropriate characteristic impedance values for any instrument type.

From these results it was reaffirmed that the submerged wood samples removed from Ootsa Lake, British Columbia, were not suitable for use as musical instruments. Furthermore, the physical acoustic characteristics of the wood decreased after being let to sit, despite the hypothesis that there would be an increase.

After determining that the wood samples were not suitable for use as musical instruments due to lowered values of the speed of sound, it was hypothesized that the lowered value was due to a lower crystalline area within the wood, possibly due to having been submerged underwater. To examine this possibility, the equilibrium moisture content of the submerged wood samples was measured at increasing humidity levels. From the equilibrium moisture contents, and using the Hailwood-Horrobin Sorption Isotherm model, the adsorption isotherms were obtained along with the corresponding coefficients. Additionally, an equal amount of control pine and spruce samples were put through the same procedure.

When compared to the control samples it was determined that the equilibrium moisture content of the submerged wood was higher at every relative humidity level. Additionally, the adsorption isotherm, unimolecular isotherm and dissolved water isotherms were higher for the submerged samples when compared to their corresponding control samples. This indicated that the submerged wood was able to adsorb a higher amount of water and also that there was a higher amount of available sorption sites.

The submerged wood samples were also compared to buried, old and submerged wood from previous studies. It was discovered that the submerged wood from Ootsa Lake had similar adsorption isotherm, unimolecular isotherm, and dissolved water isotherm curves to that of the buried and old wood. Additionally, the isotherms were higher than the control wood used from the previous study.

Higher unimolecular adsorption isotherms imply a lower crystalline area within the wood. This supported the original hypothesis that the submerged wood had a lower crystalline area that possibly caused the lower speed of sound values that were previously determined.

To further investigate the relationship between the speed of sound and crystallinity of the wood, the speed of sound was compared with the availability of wood to water, represented by the accessible fraction. Three proposed models were created to describe the relationship between the speed of sound and accessible fraction: a) linear, b) exponential, and c) logarithmic. Using relationships between the accessible fraction, the W coefficient from the Hailwood-Horrobin Sorption theory which represents the apparent molecular weight of the wood of sorption sites, and m_0 which represents the moisture content at which all available sorption sites are filled provided a connection between m_0 and the speed of sound.

By using a relationship between the moisture content and the speed of sound empirically determined by Chan [29], and relating it to the relationship determined between the speed of sound and m_0, it was possible to describe the speed of sound through wood as a function of temperature, moisture content and m_0. Moreover, this relationship could be extended to replace m_0 with the measure of accessible fraction or the W coefficient.

By expressing the speed of sound as a function dependant on the accessible fraction of water within wood it is possible to describe how the speed of sound through wood changes as the amorphous area and, inversely, the crystalline area in the wood changes. The relationship provided predicts an increasing speed of sound with increasing degree of crystallinity. From this it was supported that the submerged wood from Ootsa Lake had a lower amount of crystalline areas within the wood which lead to a lower speed of sound through the wood.

There are many possibilities for future research that come from the studies and results provided. To further examine the acoustical properties of submerged wood from Ootsa Lake it is proposed that an instrument, such a guitar or violin, be crafted out of wood taken from the lake. It is also recommended that the crystallinity of the submerged wood be directly measured and compared with that of control wood samples. To create a more accurate model describing the relationship between the speed of sound, moisture content, accessible fraction and crystallinity of wood, it is necessary to refine both the model relating the speed of sound to moisture and temperature as well as the model relating the speed of sound to the accessible fraction. By varying the moisture content and velocity over a greater range and determining the speed of sound of samples with a larger variety of accessibility to water, it could be possible to determine a stronger empirical relationship between the variables.

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