Adhesive Bonding of Low Moisture Hickory Veneer with Soy-based Adhesive

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Abstract (Academic)

Low moisture veneer and regions of sapwood within hickory engineered wood flooring bonded with soy-flour adhesive are thought to be factors leading to potential performance deficiencies. The goal of this research was to gain a broader understanding of bonding low moisture hickory veneer with soy-based adhesive. Soyad® is of particular interest due to its novel cross-linking chemistry. Impacts of moisture content and wood region (heartwood versus sapwood) were analyzed with dry and wet shear bond strength tests, measurement of percent wood failure, lathe check characterization, and adhesive bondline thickness and penetration depth measurement. Impact of wood region and type (hickory versus red oak) was assessed by comparing wood buffering capacity and delamination following three-cycle water soaking.

Dry and wet shear strength values met expectations for engineered wood flooring yet percentage wood failure results were uniformly very low for all combinations of moisture levels and wood regions. In contrast, delamination following wet and dry cycling was minor and within minimum requirements for all specimens tested. The influence of moisture level, wood region and type were inconsistent; statistically significant relationships were not evident within the moisture range studied. However, different wood regions and types exhibited differing veneer buffering capacities that had potential to interfere with pH requirements of Soyad®. Additional study of buffering capacity and resin cure is recommended to determine the significance of the buffering capacity results found in this study.

Adhesive Bonding of Low Moisture Hickory Veneer with Soy-based Adhesive

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Abstract (General)

Performance issues including debonding and delamination have been reported for hickory engineered wood flooring products constructed using a soy-flour based adhesive. Sapwood regions within the composite and extremely low moisture veneer were provided by industry as possible factors that resulted in performance deficiencies. The goal of this research project was to gain a broader understanding of bonding low moisture hickory veneer with Soyad® adhesive. Soy-flour adhesive systems offer many environmental, health, and durability advantages. Soyad® is of particular interest due to its use of natural, renewable soy flour, a novel cross-linking resin, and no added formaldehyde. Test specimens were prepared using heartwood of hickory and red oak and sapwood of hickory. Analytical tests included determination of certain chemical properties of the adhesive and wood veneer, measurement of strength properties of the adhesive bond, and assessment of delamination tendencies of bonded panels following water soaking.

Results indicate that moisture levels and the different growth regions and wood type had an inconsistent impact on the bond strengths yet percent wood failure was uniformly low and considered unacceptable by industry. Although this research established a foundation of basic knowledge, more information about adhesive bonding of wood with the recently developed soy-based adhesives is needed to optimize the systems and provide technological advancements that lead to more efficient and safe utilization of woody materials from the forest.

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1. Introduction, Background, Literature Review

1.1. Introduction

Production of wood-based panel products has been growing in all regions globally and was reported to be at a record high in 2017 of 399 million m^3 (FAO 2017). Most of the adhesives used in these composite products are of synthetic origin, only partially biodegradable, formulated with added formaldehyde, and based on petroleum and natural gas feed stocks. Urea-formaldehyde and melamine urea-formaldehyde adhesives together were the leading product categories used for interior application wood composites, accounting for over 70% of the total volume in 2016 (Kutnar and Muthu 2016). Formaldehyde presents increasing health concerns and has been reclassified from a suspect carcinogen to a known carcinogen by the International Agency for Research on Cancer (IARC 2006).

Soy-flour adhesives that have no added formaldehyde are being developed for the wood-based composites industries for hardwood plywood interior applications. Although soy-flour adhesives have been around for many years, previous formulations often included formaldehyde and most exhibited very low resistance to delamination and high susceptibility to mold in the presence of moisture (Frihart et al. 2014). Performance problems such as debonding and delamination of hickory engineered wood flooring have been reported by consumers and are concerns within the wood-based composites industry. Preliminary, informal investigation has indicated that regions of sapwood and low moisture content veneer are possible factors.

Although, the natural, no-added formaldehyde soy adhesives being developed today offer many environmental, health, and durability advantages, research studies and performance data are scarce at this point for a variety of wood types, applications, and end use conditions (Frihart et al. 2014). More information about adhesive bonding of wood using soy-based adhesives is needed to optimize the systems and provide technological advancements that minimize performance problems.

The goal of this research was to gain a broader understanding of bonding low moisture hickory veneer with soy-based adhesives. The research in this study represents an industry /university cooperative research effort supported by the Wood-based Research Center to increase the fundamental understanding of bonding wood with soy-based adhesive systems. Soyad® adhesive is of particular interest due to its novel cross-linking resin system with no added formaldehyde.

1.2. Background and Literature Review

1.2.1. Soy-flour Adhesive

The largest use of adhesives globally is for wood-based composite products (Pizzi and Mittal 2011). Manufacture of the various wood composites consumes more than 65% of the volume of adhesives produced. Natural adhesives made with blood, casein, starch, plant proteins, and other natural materials have almost entirely been replaced in the current marketplace with synthetic adhesives based on petrochemicals. However, interest in bio-based adhesives for wood bonding has been re-energized in recent years due to increasing materials costs, sustainability, and concerns resulting from the reclassification of formaldehyde as carcinogenic to humans. Soy flour used in adhesives is deemed suitable for modern industrial use due to high production volumes, lower cost, ease of processing, and a reduced need for added formaldehyde (Frihart et al. 2014). However, different manufacturing processes such as higher hot pressing temperatures and longer press times have been required to achieve good bonding strengths and high water resistance (Li et al. 2014, Vnucec et al. 2016).

Achieving an adhesive that competes with the added formaldehyde adhesives that use petroleum and natural gas as feed stocks is a result of increased global regulatory pressure to reduce formaldehyde emissions from wood products. Soy-based adhesives are formulated with a natural soy-flour which is the by-product of soybean oil production and is a renewable adhesive feedstock with advantages and disadvantages relative to fossil fuel-based adhesives (Frihart et al. 2014). Proteins and polysaccharides within the soy flour give rise to an adhesive that is effective for engineered wood composites. Soy flours are used to create adhesives due to their high protein content compared to other vegetable proteins but as currently formulated, have low moisture resistance. Soy adhesives have a few configurations including defatted soy flour (DSF), soy protein isolate (SPI), and soy flour (SF). The most recent research has been completed with DSF and SF variants due to the high cost of SPI which is derived from DSF and contains 90 % crude soy protein (Chen et al. 2013 a, b). One major drawback for soy adhesives that has slowed application in certain products is low water resistant. Soy adhesive is also costlier than formaldehyde-based adhesives currently in the marketplace.

Research is investigating improvement of bond strength and water resistance through the addition of crosslinking agents. Crosslinking improves bonding properties and water resistance of soybean proteins by introducing a curing agent to crosslink the soybean protein molecules into an insoluble three-dimensional network (Fan et al. 2016, Li et al. 2019). Addition of lignin has been shown to improve water resistance through more crosslinking networks. (Xiao et al. 2013). Lignin-based resin combined with polyamidoamine-epichlorohydrin (PAE) was determined to form a more effective plywood adhesive (Luo et al. 2015). Wet and dry strength improved considerably because the lignin-based resin could penetrate into the wood for effective interlocking as well as forming a denser cross-linking network with the soy flour. Different crosslinking densities when crosslinked by epichlorohydrin-modified polyamide (EMPA) were found for three typical soybean meal products including low-temperature soybean flour (also known as defatted soybean flake), high-temperature soybean flour, and physical soybean flour by Li et al. (2019). The low-temperature soybean meal had the most promise due to a greater number of reactive groups, higher crosslinking densities, and superior bond strengths. Only the low-temperature adhesive exhibited the needed water resistance (> 0.8 MPa) (Li et al. 2019).

Polyamidoamine-epichlorohydrin (PAE) resins are thermosets that require a set minimum temperature to overcome the reactive energy barrier. For PAE to react, the azetidinium functional group must be opened so that the adhesive can combine with the adherend (Spayde 2013). More durable soy-flour adhesives are produced with added PAE resin as a curing agent (Li et al. 2014). It has also been found that the soy-flour and PAE adhesives do not need the highly alkaline conditions used with soybean adhesives and have good stability (Allen et al. 2010). The soy-flour PAE and no added formaldehyde adhesives have been reported to provide products with very low formaldehyde emission in standard laboratory tests (Birkeland et al. 2010) and at elevated temperature and humidity (Frihart et al. 2016). Sodium metabisulfite can be added to modify viscosity for tailoring to specific end products by breaking disulfide linkages in the tertiary structures of the protein itself and dispersing protein polymers (Spayde 2013).

The adhesive used in this research was Soyad® adhesive, a commercially available adhesive produced by Solenis. Soyad® is a patented, water-based, thermoset adhesive formulated with a proprietary cross-linking resin (a PAE polyamidoamine-epichlorohydrin) with a solids content of 45–60% and a pH value of 5.5 (Birkeland et al. 2010). Although PAE is a common wet-paper strength additive, its use as a wood adhesive system was considered very ground breaking when it was introduced in 2005. Soyad® is used to construct decorative plywood, particleboard, medium density fiberboard, and engineered wood flooring.

1.2.2. Wood Properties Impacting Adhesion

Wood is a complex, natural material resulting from growth in trees and consequently, variability in properties and processing of wood-based composites originates from numerous factors. A concise but comprehensive review showing the many variables that influence wood bonding has been provided by Frihart (2013). According to this review, factors associated with the wood component are numerous and include wood type, moisture content, density, plane of cut, heartwood versus sapwood, juvenile versus mature wood, earlywood versus latewood, reaction wood, grain angle, porosity, surface roughness, drying damage, machining damage, dirt and contaminants, extractives, pH, buffering capacity, and chemical nature of the surface. Several of the aspects of Frihart's (2013) review have been investigated but most have yet to be fully tested for soy-based adhesives applied to a variety of wood types.

1.2.2.1. Anatomical and Physical Properties

Hickory (*Carya* spp.) wood was used for this study due to the reported performance problems with hickory engineered wood flooring bonded with soy-flour adhesive. There are several species included in the *Carya* genus, common name hickory, including *C. ovata, C. laciniosa, c. glabra, and C. tomentosa*. Hickory is a ring porous hardwood with a volumetric anatomical composition shown in Table 1-1 (Panshin and deZeeuw 1980). Fiber tracheids range from thin- to-thick-walled. The sapwood of hickory is whitish to pale brown and the heartwood pale brown to brown or reddish brown which makes visual separation of heartwood and sapwood possible. Tyloses in hickory are moderately abundant. The low percentage of vessels accompanied with the high percentage of thick fiber cell walls and low lumen volume in hickory can make adhesive penetration difficult and this in turn, can further limit mechanical interlocking of adhesives to one or two cells deep. Higher density woods such as hickory exhibit large stresses as they change dimensions with changes in moisture content and the large stresses can also contribute to poor bond performance.

Although hickory was the primary focus of this research, red oak (*Quercus* spp.) wood was also used as face veneer to compare adhesion with hickory. Red oak is reported by industry to bond well with soy-flour adhesives (personal communication 2017, F. Carter, Columbia Forest Products). Several species are included in the *Quercus* genus, common name red oak: *Q. rubra, Q. velutina, Q. shumardii, Q. coccinea, Q. palustris, and Q. phellos.* Red oak is ring porous with an average volumetric anatomical composition shown in Table 1-1. Fiber tracheids and libriform fibers are medium-thick to thick-walled. The sapwood of red oak is whitish to grayish or pale reddish brown, heartwood pinkish to light reddish brown. Tyloses are absent or sparse.

Yellow-poplar (*Liriodendron tulipifera*) wood was used for the core of the three-ply plywood tested in this study. Engineered wood flooring is made with a lower density wood such as yellow-poplar or some type of particle of fiber composite. Yellow-poplar is a diffuse porous hardwood with a volumetric anatomical composition shown in Table 1-1 (Panshin and deZeeuw 1980). Fiber tracheids are thin- to moderately thick-walled. Sapwood of yellow-poplar is whitish, often variegated or striped; heartwood variable in color ranging from clear yellow to tan or greenish brown. Tyloses are absent or sparse.

Table 1-1: Anatomical and Physical Properties.

Wood Type	Anatomical Composition (% of total volume)[1]				Specific Gravity (ovendry basis)[1]	Average Shrinkage Green to Ovendry[2] (%)			Average Strength Properties[2] (MPa)	
	Vessels	Fibers	Rays	Axial Parenchyma		Radial	Tangential	Volumetric	Shear parallel to grain	Tension perpendicular to grain
Hickory	6.5	65.5	20.0	8.0	0.62 – 0.78	7.0	10.5	16.7	14.5	4.7
Red oak	19.5	41.3	31.4	23.4	0.62 – 0.76	4.4	10.8	14.7	13.3	6.0
Yellow-poplar	36.6	49.0	14.2	0.20	0.43	4.6	8.2	12.7	8.2	3.7

1 Panshin and deZeeuw 1980.
2 Wood Handbook 2010.

1.2.2.2. Chemical Properties

Physiological changes that occur during the sapwood to heartwood transition in tree stem wood create a group of organic chemical constituents called “extractives”. The extractives content of heartwood is important in adhesion for several reasons. When wood is subjected to high temperatures greater than 70°C, extractives can migrate to the surface and physically block adhesive contact. In addition, extractives are said to be a major cause for deactivation of a wood surface (Roffael 2016). Extractives have an impact on adhesive spread and penetration (Mirabile and Zink-Sharp 2017) and can impact the pH or buffering capacity which in turn affects bonding. Heartwood extractives can play a role in swelling and shrinkage that is caused by moisture change which creates high strain values within the bondline and the bond interface (Roffael 2016). Some extractives are hydrophobic, in which case these compounds can cause a detrimental influence on the bonding of a water-based adhesive. For example, research has found that for higher content of extractive waxes or long chain hydrocarbons, the less water the wood species will absorb from an adhesive (Jankowska et al. 2018).

Average extractives percentages of pignut and mockernut hickory stem wood have been reported to vary from 3.4 – 9.0% of the unextracted dry weight (Koch 1985a). Of this content, phenolics constituted more than 50%, carbohydrates about 33%, and resin extractives less than 1%. Red oak extractives exhibit similar chemical percentages where the average extractives content of stem wood varies from 4.3% – 6.0%. Of those, approximately 50% are phenolics, 48% are carbohydrates, and less than 1% resin extractives (Koch 1985a).

Acidity or alkalinity of a material is commonly assessed with pH which is defined as the logarithm of the reciprocal of the hydrogen ion concentration expressed in gram atoms per liter of solution (Skoog and West 2013). The pH of wood can have a large impact on adhesion because adhesives require particular acidic or alkaline conditions to properly function with the wood substrates (Johns and Niazi 1980, Wang et al. 2010). The pH of air dried heartwood and sapwood of several wood types was measured by Johns and Niazi (1980) using an aqueous wood extraction method and reported as shown Table 1-2 for the woods used in this study.

Table 1-2: pH of Air Dried Heartwood and Sapwood.[1]

	Sapwood	Heartwood
Hickory	4.97	5.63
Red oak	5.04	5.66
Yellow-poplar	4.75	4.79

1 Johns and Niazi 1980

Buffering capacity of a material is a measure of the ability to resist changes in pH (Skoog and West 2013). With wood materials, buffering capacity can have different variations across species and within the same tree, height in the tree, and age of the tree (Hernández 2013).

The effects of buffering capacity variations in wood have implications for curing and gelation times for adhesives (Wang et al. 2010). For example, a wood's buffering capacity can interfere with the pH requirements of wood adhesives, but generally only those operating in the acid range. pH and buffering capacity can change with storage conditions (Elias and Irle 1996).

1.2.2.3. Processing Parameters

The amount of moisture in wood can greatly influence the wetting, flow, penetration, and cure of aqueous wood adhesives (Kamke and Lee 2007, Dunky et al. 2002, Frihart and Beecher 2016). With low moisture content wood adherends, the dry wood can absorb water from the adhesive so quickly that adhesive flow and penetration into the bulk becomes inhibited due to an increase in solids content on the surface and reduction of solvent at the bonding interfaces (Frihart 2013). This situation is sometimes referred to as a "starved bondline".

Drying of wood veneer for use in plywood products is required to make the veneer suitable for adhesive bonding. Industrial practice is to remove the moisture in veneer as rapidly as possible using continuous-type, high-temperature (> 100° C) conveyer driers (Irle et al. 2013). Over drying can result in low moisture content wood and deactivation of the veneer surface. Deactivation of a wood surface can impair adhesive wetting and have negative effects on bondline performance. In general, hydrophobic extractives are the main cause of thermal deactivation; the extractives migrate to the wood surface in water and form what is a thin boundary layer (Gao 2010). With a deactivated surface, a water-based adhesive such as Soyad® might not readily penetrate the surface and this in turn might cause the bondline to have a slower cure due to the excessive water at the bondline. Over drying and overheating that occurs in the veneer dryers can create very low moisture content wood and cause extractives to come to the surface which modify surface characteristics.

Surface roughness of wood veneer is an important processing variable in wood bonding (Frihart 2013). For the ideal application of adhesives to wood surfaces, it is best to have the surface smooth, flat, free of machining marks, and surface irregularities (Irle et al. 2013). It has been well established that for high bonding quality, the adhesive must penetrate into the wood (Kamke and Lee 2007, Modzel et al. 2011) and form secure mechanical interlocks into the undamaged layer of wood (Frihart 2013). In addition, veneer processing can damage the wood surface and impact bulk materials properties by shredding and crushing the surface cells and creating lathe checks (Rohumaa et al. 2013). Checking and splitting of the wood can impact bond performance and cause premature adhesive joint failure if the adhesive does not adequately penetrate into the wood (Neese et al. 2004).

Rotary-cutting wood veneer for use in plywood produces cracks parallel to the wood grain called “lathe checks” on the knife side of the veneer. Lathe checks can be quite large and often deep as 70 -80 % of the veneer thickness (DeVallance et al. 2006, Rohumaa et al. 2013). The veneer surface next to the knife is called the loose side while the opposite side is called the tight side. The loose side is recommended to be one bonded and the tight side should be the finished side for hardwood plywood. This is done to make sure imperfections do not occur during finishing. The influence of lathe checks on bonding and product performance has been well researched and established over the past fifty years for a variety of wood types and processing parameters. Research efforts to measure lathe check characteristics in the last few years have focused on development of new and automated methods for measurement of lathe check size and distribution (Palubicki et al. 2010, Guan et al. 2014, Darmawan et al. 2015, Antikainen et al. 2015).

1.3. Summary and Research Goal

Wood surfaces present complicated environments for adhesive bonding. Factors associated with the wood component and the processing into composites are numerous and varied. Nevertheless, Pizzi and Mittal (2011) have stated that the chemistry of wood adhesives has been studied extensively and it is now known well enough to allow for prediction of the results of altering the chemistry. But this is not a universally held opinion within adhesive manufacturers. Preparation of wood surfaces has also been studied thoroughly and optimal conditions suggested. Bond durability has been examined for many adhesive and wood systems. However, Custodio et al. (2009) determined that no single joint configuration and testing procedure could provide all the information needed to provide a definite measure of bond performance. Although many factors related to adhesive bonding of wood have been investigated, most have yet to be fully tested for soy-based adhesives applied to a variety of wood types. Areas remaining less well understood are the adhesive interactions with wood surfaces, wood-adhesive interphase physical and mechanical properties, and failure zones for many wood bonds (Frihart 2013). Unlike the report by Pizzi and Mittal (2011), Frihart indicates that it is not yet possible to predict the performance of a new adhesive or the influence of a different wood species.

Due to concerns in bonding low moisture content wood with soy-flour adhesives, perceived performance deficiencies with hickory wood, and the lack of basic foundational knowledge, the goal for this research was to gain a broader understanding of bonding hickory heartwood and sapwood with a soy-flour adhesive. Specific objectives were to characterize and compare properties of low moisture hickory heartwood and hickory sapwood veneer bonded into plywood panels with Soyad® adhesive.

2. Materials and Methods

2.1. Materials

Soyad® adhesive was prepared and used to construct test specimens composed of hickory heartwood, hickory sapwood, or red oak heartwood face veneer and yellow-poplar core veneer sheets. Veneer sheets were moisture conditioned to the target final moisture content and hand sanded prior to further processing. Three-ply plywood panels were prepared for analysis as described in Section 2.2. Details of materials preparation are provided below.

2.1.1. Adhesive

Components to prepare Soyad® adhesive were provided by Solenis. The exact formulation is proprietary, but in general terms, the adhesive is made of soy flour, water, a proprietary cross-linking PAE resin, a defoaming agent, and a pH modifier. The adhesive was prepared by first mixing the water, PAE, and defoamer with a fan-blade mixer. Then one half of the soy flour was added followed by the pH modifier and then the other half of the soy flour. The components were mixed for 5 minutes with the fan blade at 1,000 rpm. The final step was to check the pH of the adhesive batch to ensure it matched the industry recommended pH of 5.5.

2.1.2. Wood Veneer

Hickory heartwood and sapwood, yellow-poplar, and red oak heartwood veneer was provided by Solenis and Columbia Forest Products. Hickory heartwood and sapwood sheets were visually separated based on color. Radial sheet average thickness of the hickory and red oak veneer was either 0.62 mm (hereafter referred to as “thin”) or 2.06 mm (“thick”). All yellow-poplar veneer averaged 2.06 mm thick.

2.1.3. Plywood

Veneer sheets were sized to 15.24 x 15.24 cm (6 x 6 in) and moisture conditioned to 2 %, 4 %, 6 %, or 8 % moisture content using a Russells Technical Products GD-8-105 moisture and humidity chamber prior to further processing. This range of moisture contents approximates the range wood veneers obtain upon exit from the veneer dryers. After complete equilibration at the respective moisture contents, a few sheets were subjected to oven drying at 103°C for 24 hours for moisture content determination.

Just prior to adhesive application, veneer sheets were hand sanded using 220 grit sand paper with three passes forward and three passes back until the full veneer face was sanded. Saw dust particles were blown from the surfaces with compressed nitrogen gas. Without an extensive chemical pretreatment of the veneer, better bonding conditions were not possible. The best method for preparing wood surfaces for adhesive bonding is to use sharp planer blades. However, hand sanding is reported "acceptable" in the absence of sharp planer blades because it causes less damage to the cells at and near the surfaces (Frihart 2013). Since the thermal history of the veneer provided to us by industry was unavailable, and, it was not practical to plane the surfaces due to the thickness of the veneer, bonding surfaces were hand sanded just prior to adhesive application to achieve the best possible bonding.

Three-ply plywood panels were prepared with veneer sheets conditioned to the respective moisture contents. Face plys were hickory heartwood, hickory sapwood, or red oak heartwood. All core plys were yellow-poplar. The plywood was prepared according to specifications provided by Solenis for the Soyad® adhesive. The adhesive was applied to one side using a soft rubber roller at the rate of 0.02 g/cm^2 per veneer face for a three ply lay-up. After the adhesive was applied, the panel was put under a 1,981g weight for 10 minutes for stand time. The panels were then taken to a cold press for five minutes and 690 KPa pressure. Panels were then weighed and evaluated for cold press tack as described in Section 2.2.1.3 below. Panels were then placed in the laboratory Carver press for three minutes at 116°C and 1,034 KPa. Upon removal from the press, the panels were weighed again and thickness measurements taken on each of the four panel sides. Panels designated for the dry shear test were conditioned to 9% moisture content and those designated for the wet shear test and the water cycling tests were conditioned to 6% moisture content according to the standards specifications.

2.2. Analytical Methods

Methods used for characterization and comparison of bonding low moisture hickory heartwood and sapwood were grouped into three categories: (a) those related to the adhesive, adhesion, or veneer properties, (b) assessment of bond shear strength, and (c) measurement of bond durability. The overall analytical structure is shown below in Table 2-1.

Table 2-1. Analytical Methods Matrix*.

Test Completed	Technique	Materials Used	# of Tests or Specimens
Adhesive, Adhesion, and Veneer Properties			
Adhesive Viscosity	Parallel plate rheology; varying shear rates	Mixed adhesive	35 data points for each up and each down ramp, 5 samples
Veneer Buffering Capacity	Titration with added acid or base	Veneer ground into wood powder	2 per wood type (HS, HH, & ROH)
Cold Press Tack	Visual assessment, 0 - 5 scale, 0 = little contact; 5 = held together, no visible gaps	Plywood veneer layers evaluated after cold pressing	8 HS and HH at 2% and 4% MC; 8 HH 6% and 8% MC; 8 ROH at 6% MC
Lathe Check Length	Optical Stereo Microscopy; line trace along check until termination	Specimens cut from plywood panels	160 HS, 160 HH at each MC
Lathe Check Depth	Optical Stereo Microscopy; perpendicular termination distance from bonded surface	Specimens cut from plywood panels	160 HS, 160 HH at each MC
Adhesive Penetration	Epifluorescence microscopy; maximum depth method	Specimens cut from plywood panels	150 HS, 150 HH at each MC
Bondline Thickness	Epifluorescence microscopy; width cured adhesive between two wood substrates	Specimens cut from plywood panels	150 HS, 150 HH at each MC
Bond Shear Strength			
Dry Strength	ASTM D906-98(2017)	Specimens cut from plywood panels and notched	15 - 23 per HSO, HSC, HHO, and HHC at each MC
Wet Strength	EN 314-1:2004	Specimens cut from plywood panels and notched	18 HSO, 18 HSC, 18 HHO, 18 HHC; 6% MC
Percent Wood Failure	ASTM D5266-13(2013)	Uses ASTM D906-98 and EN 314-1 specimens	15 - 23 per HSO, HSC, HHO, and HHC at each MC
Bond Durability			
Delamination	ANSI/HPVA HP-1-2004 (Three-cycle soak test)	Specimens cut from plywood panels	18 HH; 18 HS; 18 ROH
Thickness Swell	Caliper measurement of ANSI specimen thickness, 12 points	Used ANSI three-cycle soak specimens	18 HH; 18 HS; 18 ROH

*HH = hickory heartwood; HS = hickory sapwood; ROH = red oak heartwood; O = lathe check pulled open; C = lathe check pulled closed; MC = moisture content

2.2.1. Adhesive, Adhesion, and Veneer Properties

2.2.1.1. Viscosity

Viscosity of the adhesive was assessed using a TA Instruments Advanced Rheometer AR-2000. For parallel plate rheology the 25 mm steel plate was used with a gap of 1,000 µm. The process involved a ramp up in shear rate followed by a ramp down from 0.005 1/s to 500 1/s. Thirty-five points were taken for each up and down cycle for a total of 70 data points for one sample. This process was repeated for 5 different adhesive samples.

2.2.1.2. Buffering Capacity

Buffering capacity of the woods was determined using a Metrohm 905 Titrando instrument. The wood veneers were ground into powders using the laboratory Wiley mill and a mesh unit size of 60 to get the materials to less than 0.25 mm. The materials were put into vials with covers that had small holes to retain the contents once they were placed into a desiccator. The desiccator was put under vacuum for 10 minutes followed by nitrogen for 1 minute and allowed to stand for 30 minutes. This process was repeated three times. The materials were left unmodified overnight. The next day materials were weighed again and the desiccator process repeated to compare final weights to previous weights. After obtaining a consistent weight, the samples were evaluated with the 905 Titrando set to measure pH and assess buffering capacity. A sample of approximately 0.5 grams was placed into a four-neck, round-bottom flask to which 5 ml of 0.06 M NaCl and 300 ml of distilled water were added. The mixture was stirred and the flask was then purged with nitrogen. The instrument was set to measure pH followed by completion of the titration. Titration was accomplished using HCl for acid and NaOH for base. The acid or base was added at 0.02 mL every 2 seconds until the desired pH was reached for assessment of the buffering capacity. Two specimens were tested for each wood studied.

2.2.1.3. Cold Press Tack

Tack is “the property of an adhesive that enables it to form a bond of measurable strength immediately after the adhesive and adherend are brought into contact under low pressure” (Frihart 2013). Tack is not just a material property of the adhesive, it also depends on the adherend properties and the processing conditions. With wood-based composites, assessment is usually performed following cold pressing which is then referred to as “cold press tack”. Currently there are no universal standards for evaluation of tack in wood-based composite products and mature cold press tack tests for liquid resins are rare (Himsel et al. 2015). The system developed in this study was to evaluate cold press tack after the 5-minute cold press phase of plywood preparation. The veneer stack was visually evaluated after being removed from the cold press frame. If there was little contact or the layers were not held together at all, a 0 was assigned, values of 1 – 4 were assigned based on the amount of intermediate contact and how well the layers held together, and a 5 was assigned if the layers were held together completely without any visible gaps. Eight specimens were evaluated at the moisture conditions and wood region and type (heartwood or sapwood; hickory or red oak).

2.2.1.4. Lathe Check Length and Depth

Depth and length of lathe checks of the hickory face veneer were measured using a Nikon SMZ1500 stereomicroscope equipped with a Nikon DS-Fi1 camera and the NIS-Elements BR software. Small samples (6 mm x 10 mm x 10 mm) were cut from the bonded panels and microtomed with a GSL-1 sliding microtome after a very brief soak in water. Check length was measured as the trace of the check from initiation at the veneer surface in contact with the adhesive to termination in the wood veneer, check depth was measured as the perpendicular distance from the wood ply face to the check termination (see example in Figure 2-1). Measurements were made for hickory heartwood and sapwood panels at each moisture content being evaluated in this study. An average of 320 measurements were made at each moisture content and heartwood or sapwood specimen for a total of 1280 data points.

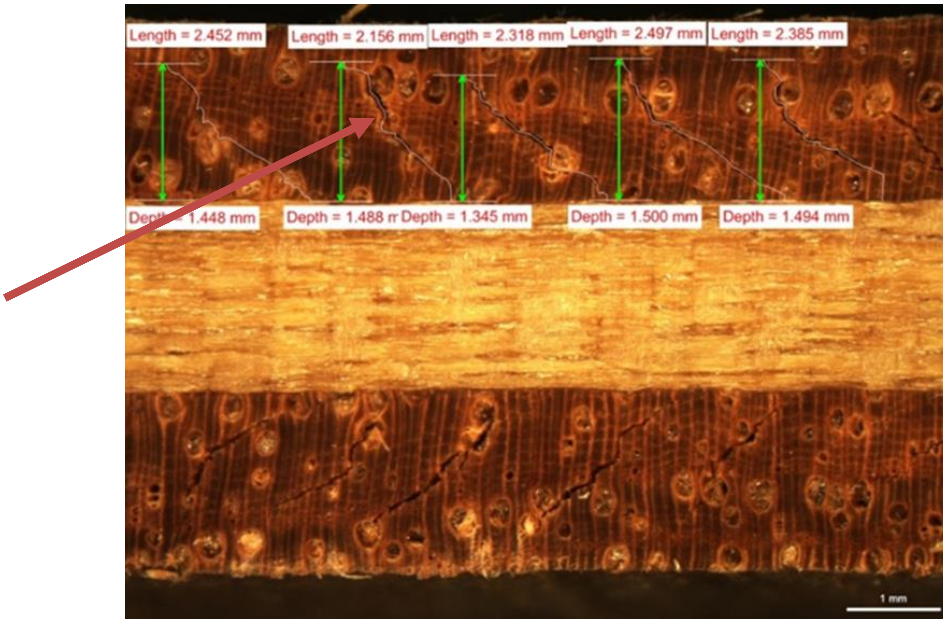

Figure 2-1: Example Illustrating Measurement Scheme for Lathe Check Length and Depth. Micrograph by Dylan Harris.

2.2.1.5. Adhesive Penetration Depth and Bondline Thickness

Measurements of penetration of the adhesive into the hickory wood veneer and the bondline thickness were made using epifluorescence light microscopy and image analysis software techniques. Microscope slides were prepared from small blocks cut from the bonded wood panels. Small blocks (6 mm x 8 mm x 20 mm) were soaked for 5 minutes in water to soften the surfaces for microtoming. A GSL-1 sliding microtome, WSL Swiss Federal Institute for Forest, Snow, and Landscape Research, Birmensdorf, Switzerland, was used to cut 30 μm thick sections. The sections were stained for 2 minutes in a 0.8% aqueous solution of Safranin O stain. Excess stain was washed from the sections with distilled water and the sections were mounted on glass slides with glycerin mounting medium. Slides were examined with a Nikon Eclipse LV 100 light microscope equipped with a Nikon DS-Fi1 camera and the Nikon B GFP/D epifluorescence filter cube set. NIS-Elements BR software was used for the measurements.

Adhesive penetration depth was measured using the maximum depth approach as fully described in (Sernek et al. 1999) and adapted for this research. In sum total, 1200 measurements of penetration depth were made across the moisture content range for hickory heartwood and sapwood blocks. Bondline thickness was measured on the same microscope slides as the penetration depth study (Figure 2-2). Thickness of the bulk cured adhesive between the face and core veneer was measured at ten locations in three microscope sections for each of the moisture contents and heartwood and sapwood specimens for a total of 1200 data points.

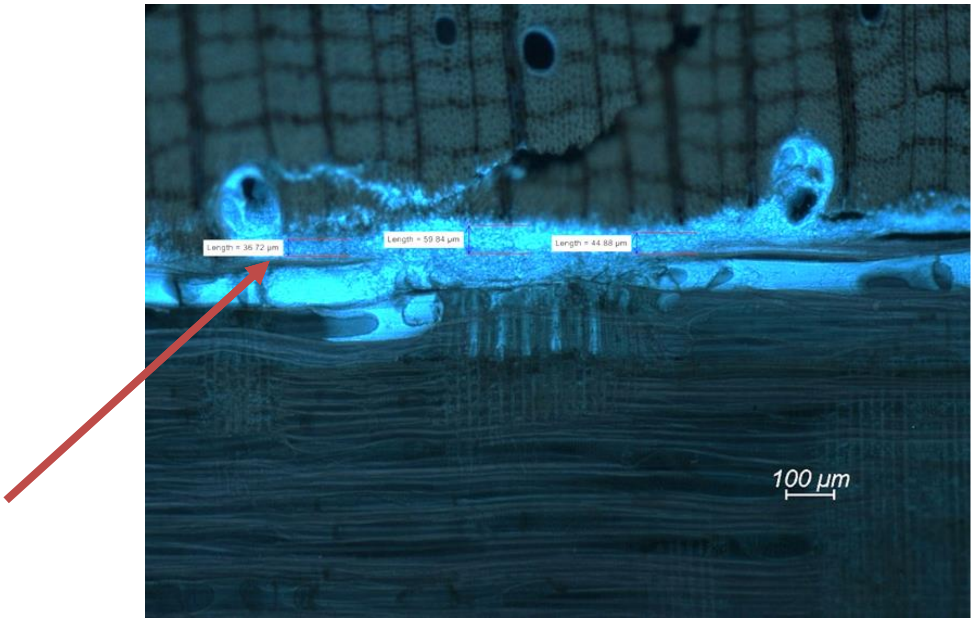

Figure 2-2. Example Measurement of Bondline Thickness. Micrograph by Pabitra Aryal.

2.2.2. Bond Shear Strength Assessment

2.2.2.1.ASTM D906-98 (reapproved 2017) Dry Shear Strength Test

Test specimens were cut from the plywood panels into 82.6 mm-long by 25.4 mm-inch wide strips with cut inlays being 2/3 through the core layer which created a shear area of 25.4 mm by 25.4 mm. Specimen configurations are shown in Figure 2-3. The bond shear strength tests were conducted by following the standard ASTM D906-98 (ASTM 2017) using a MTS Sintech10GL Machine, with a cross head speed of 0.508 mm/min. The maximum shear stress was recorded. An average of 70 specimens per veneer moisture content were tested, 15 – 22 at each moisture content and as described in the standards specifications.

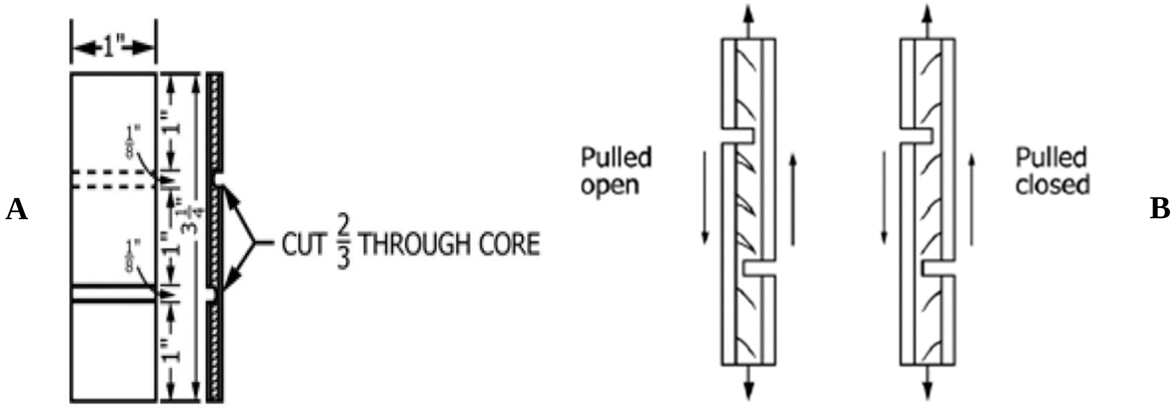

Figure 2-3: Specimen Configurations for ASTM D906-98 and EN 314-1. A: Form and Dimension (U.S. Customary Units are shown in the Standard rather than S.I.). B: Lathe and Notch Orientations (ASTM D906-98 2017).

2.2.2.2.EN 314-1 Wet Shear Strength Test

Test specimens were cut from the plywood panels into 82.6 mm-long by 25.4 mm-inch wide strips with cut inlays being 2/3 through the core layer which created a shear area of 25.4 mm by 25.4 mm. Specimens for this test are configured the same as the D906-98 specimens as shown in Figure 2-3. For the wet shear test, specimens were placed into a water-bath at 20 ± 3 °C for 24 hours. After soaking, the specimens were left to dry at room temperature for 48 hours. The specimens were then tested according to EN 314-1 (BSI 2004) using the MTS Sintech10GL test frame with a cross head speed of 0.508 mm/min. The maximum shear stress of the specimens was recorded. Figure 2-4 illustrates a test specimen in the test frame fixture. Eighteen specimens were tested at 6% veneer and panel moisture content for each wood growth region and lathe check configuration as described in the standards specifications.

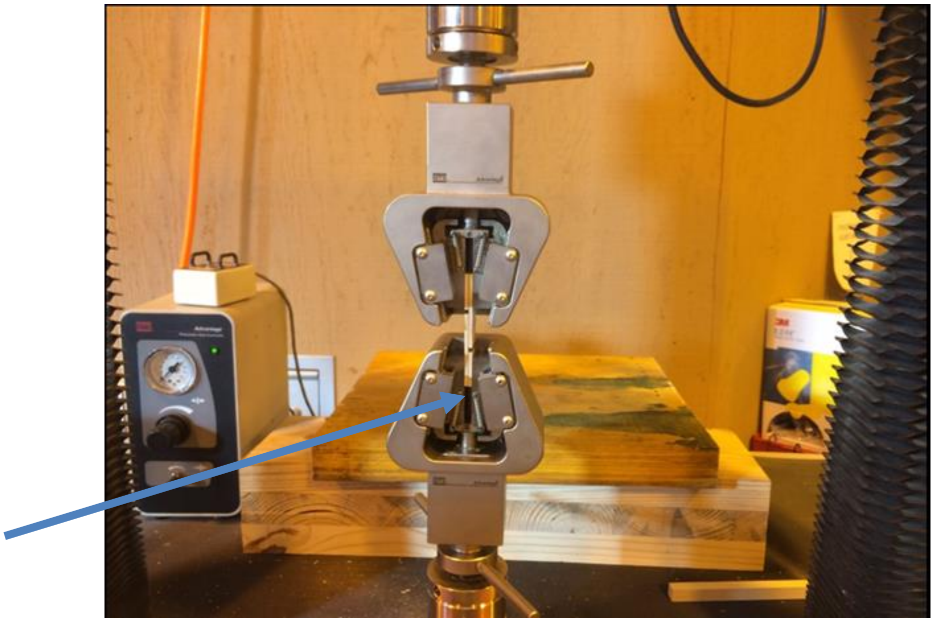

Figure 2-4: EN 314-1 Test Specimen (arrow) in the Test Frame Fixture.

2.2.2.3.ASTM D5266-13 Percent Wood Failure

This process involves a visual approximation of the amount of wood remaining on the bondline of the failed dry and wet shear test specimens according to ASTM D5266-13 specifications (ASTM 2013). Specimen surfaces were viewed with a magnification lens of 10x connected to a lamp with a 60W bulb for clear and consistent lighting. A 25.4 mm by 25.4 mm grid system printed on a copier transparency film was manually placed on the surface of the failed test samples. The grid system had lines that divided the grid area into 25 equal size squares and completely covered the entire area of delamination. Figure 2-5 illustrates the grid positioned on a failed test specimen as viewed through the lighted magnifying lens. Each blocked square within the grid was given a rough visual percentage of the amount of wood failure within the squares and then all measurements were combined for a final calculation of the percentage wood failure for each specimen. Number of specimens evaluated ranged from 15 – 22 depending on the original test configuration of D906-98 or EN 314-1 specifications.

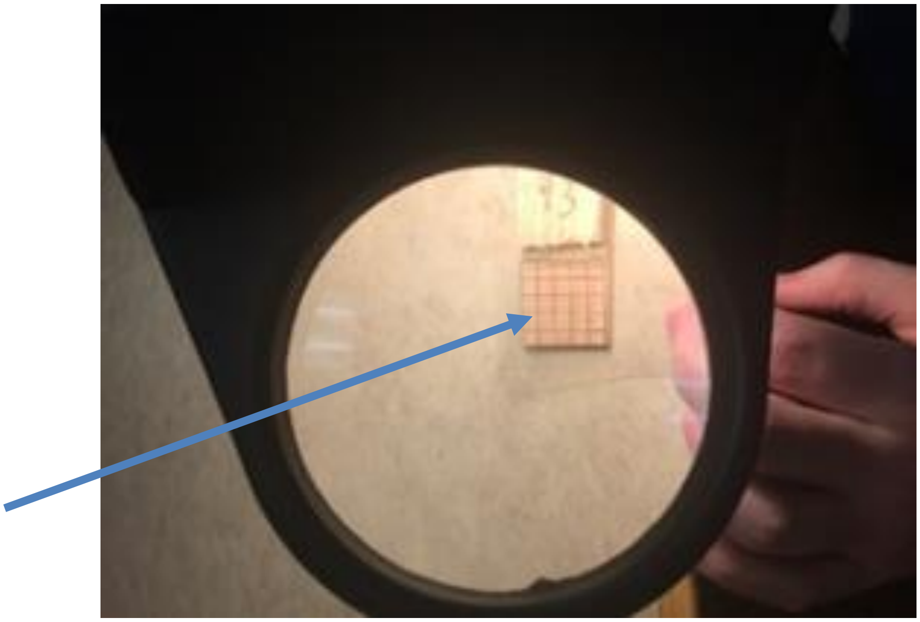

Figure 2-5: Example of Grid (at arrow) Positioned on Failed D906-98 Test Specimen viewed with Magnifying Lamp.

2.2.3. Bond Durability

2.2.3.1. ANSI Type II Three-cycle Soak Test

Test specimens for the ANSI Three-cycle Soak Test (ANSI 2004) were cut from the panels to 12.7 cm (parallel to the grain of the face veneers) by 5.08 cm without any cut inlays made. Figure 2-6 illustrates specimen dimensions. The prepared test specimens were submerged in water which was 24 ± 3°C and held there for 4 hours. Specimens were then immediately dried in an oven at a temperature of 50°C for 19 hours. This was repeated for a total of three cycles with all testing groups. At the end of the third cycle, delamination was evaluated using a feeler gage that was 0.08 in width and 12.7 mm in length. According to the standard specifications, specimen was labeled as failed when delamination between two plies was greater than 50.8 mm in length and over 6.4 mm in depth, and 0.08 mm in width as stated by the standard. All specimens were recorded as either passing or failing. Eighteen specimens of hickory heartwood, hickory sapwood, and red oak heartwood were evaluated according to the standard.

2.2.3.2. Thickness Swell Measurement

Measurements of thickness swell were taken after each water soak during the ANSI three-cycle soak test. Thickness was measured at the locations illustrated in Figure 2-6. Each location was measured three times using a caliper with a resolution of 0.01 mm.

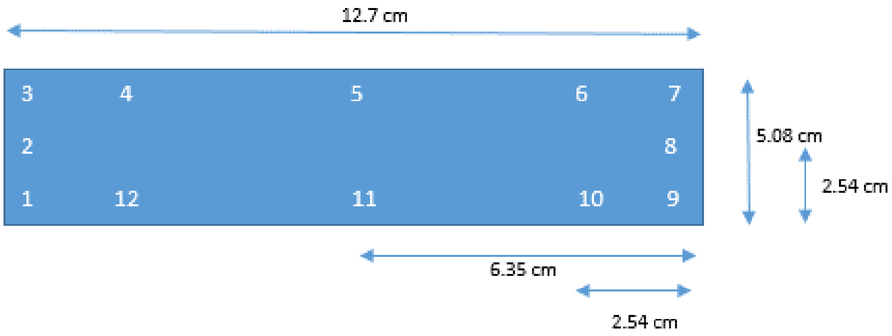

Figure 2-6: Location of Measurement Points used for Thickness Swell.

2.2.4. Statistical Methods

Results for veneer moisture content, heartwood and sapwood, and wood type were evaluated using a one-way ANOVA comparison and a Tukey's honestly significant difference test $\alpha = 0.05$ for comparisons between each moisture content and heartwood versus sapwood. JMP software was used. Statistical analyses were completed within moisture contents and according to heartwood or sapwood to determine significant differences. Detailed information including p values and other statistical data are provided in Appendix A.

3. Results and Discussion

3.1. Adhesive, Adhesion, and Veneer Properties

3.1.1. Viscosity

Determination of adhesive viscosity is an assessment of the resistance to flow and is a standard step in adhesion studies. Characterization of Soyad® viscosity was completed to provide a description of the mixture's flow characteristics. Viscosity and the relationships between shear stress and shear rate are shown in Figures 3-1 and 3-2 for five samples. Similarity in the up and down ramp traces in Figure 3-1 is indicated, however on the ramp down after a high shear rate, a slight decrease in viscosity is noted. The decrease shows that the liquid structures in the adhesive have changed. Viscosity measurements shown in Figure 3-1 show classic non-Newtonian fluid behavior that exhibits shear-thinning due to the reorganization of components as the shear rate increased. This behavior was as expected for the Soyad® adhesive.

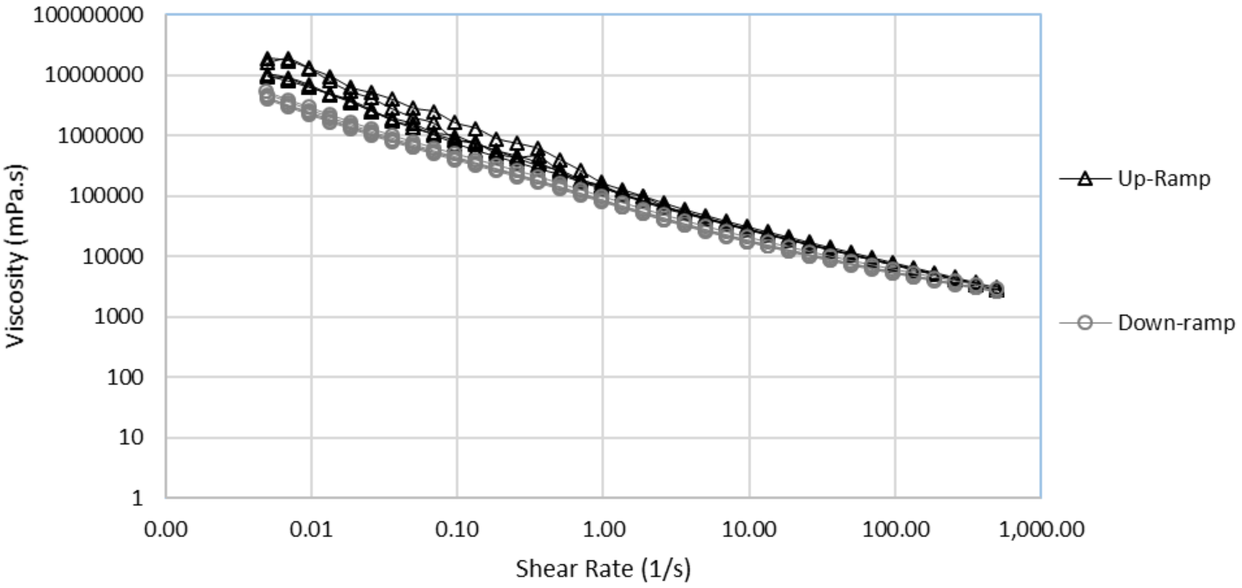

Figure 3-1: Steady-state Flow Curves for Soyad® Adhesive.

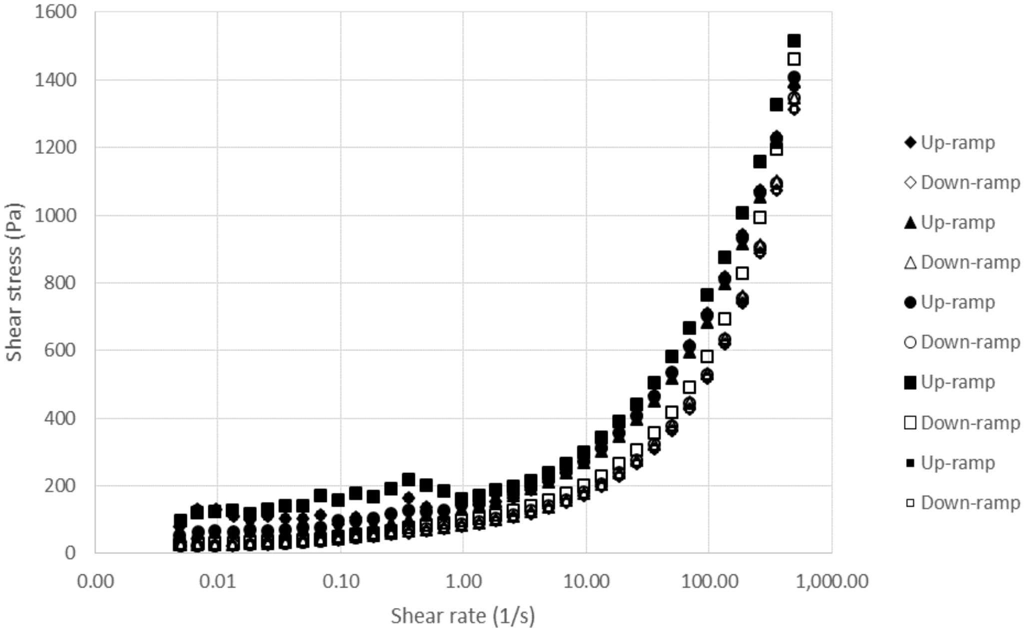

Figure 3-2: Shear Stress versus Shear Rate for Soyad® Adhesive.

The relationship between shear stress and shear rate through several up and down ramps is illustrated in Figure 3-2. A change in the shear stress behavior at around 10 cycles per second shear rate is another indicator that the liquid structures in the adhesive have changed at higher shear rates which further illustrates the importance of characterization of the adhesive properties.

Adhesive viscosity has been shown to be a key factor during application, open time, closed time, and pressing (Frihart 2013). The viscosity also changes after application by the amount of adhesive spread, wood species, moisture content, temperature of wood, temperature and humidity of surrounding air, and evaporation and absorption of solvent. The typical soy adhesive viscosity range is between 2,000 to 75,000 mPa.s with the lower end for spray applications and the upper end for roll coaters (Frihart et al. 2014). Solenis recommends a viscosity of 35,000 mPa.s for Soyad® used in engineered wood flooring. The viscosity of the mixture used in this study was checked and found to match Solenis recommendations.

3.1.2. Buffering Capacity

Buffering capacity of a material is the resistance to changes in pH. When an acid or base is added to a slurry or wood flour, the impact on pH change can be large or small, depending on the initial pH and the capacity of the wood materials to resist change in pH (pH is measured on a logarithmic scale). A titration method was used in this study in which a known volume and concentration of a base or an acid was added to the ground wood being assessed. An example titration curve for hickory heartwood is shown in Figure 3-3. Buffering capacities obtained for the hickory and red oak materials are shown in Table 3-1. Standard deviations in parentheses.

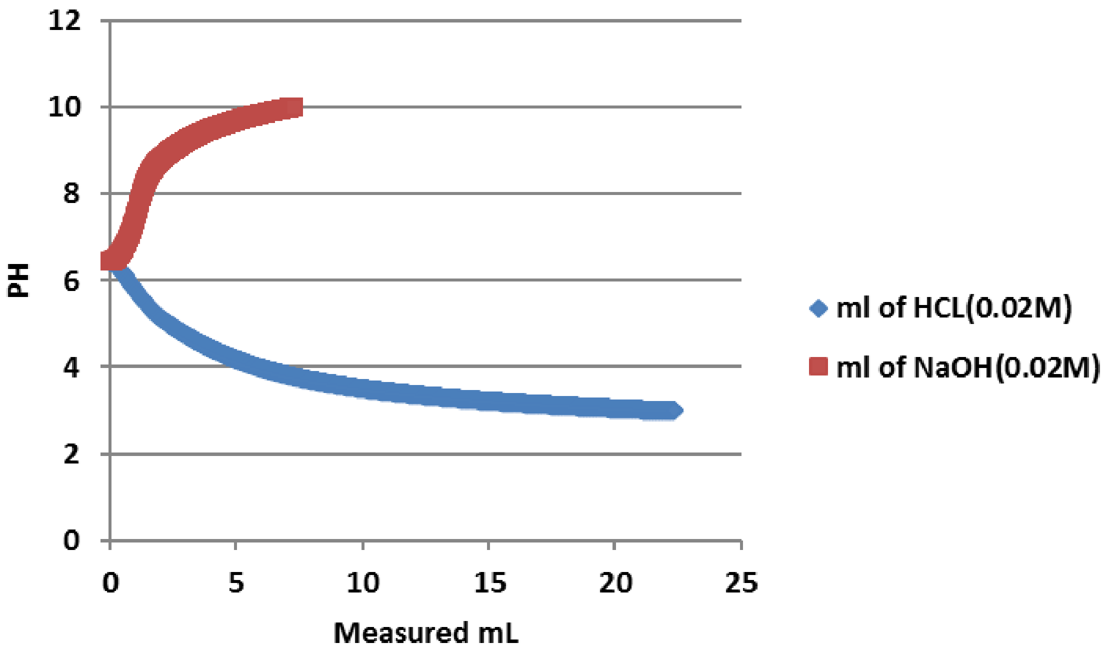

Figure 3-3: Example Titration Curve for Hickory Heartwood.

Table 3-1: Buffering Capacity Assessment. Standard Deviation in Parentheses.

	Hickory Sapwood		Hickory Heartwood		Red Oak Heartwood	
	Alkaline Buffering Capacity (ml of 0.02 Normal HCl)	Acid Buffering Capacity (ml of 0.02 Normal NaOH)	Alkaline Buffering Capacity (ml of 0.02 Normal HCl)	Acid Buffering Capacity (ml of 0.02 Normal NaOH)	Alkaline Buffering Capacity (ml of 0.02 Normal HCl)	Acid Buffering Capacity (ml of 0.02 Normal NaOH)
Initial pH average	6.17 (0.01)	6.18 (0.00)	6.41 (0.01)	6.49 (0.03)	5.96 (0.00)	5.94 (0.02)
Average ml required to reach 3 (acid) or 10 (base) pH	20.17 (0.53)	6.93 (0.76)	22.1 (0.59)	7.1 (0.69)	18.77 (0.46)	6.90 (0.86)
Count	2	2	2	2	2	2

In Table 3-1 the alkaline buffering capacity refers to the volume of acid added and the acid buffering capacity refers to the amount of base added. Differences were found in the buffering capacities for the wood studied. The alkaline buffering capacity of hickory heartwood was greater than that of hickory sapwood and red oak heartwood. The acid buffering capacity is of less importance since Soyad® functions in the acid range.

Quantification of buffering capacity is very important because adhesives have narrow pH ranges in which they function effectively. A buffer resists changes in pH due to the addition of an acid or base though reaction with the buffer. As long as the buffer is not completely reacted, the pH will not change drastically. However, the pH change will increase (or decrease) more drastically as the buffer is depleted. If the buffering capacities of the woods studied were too small or outside the required range, this may have caused interference with adhesion due to altering the adhesive outside the preferred pH range.

3.1.3. Cold Press Tack

Tack is commonly defined as the ability to bond immediately upon contact (Frihart 2013). Soy-flour adhesives do not usually exhibit sticky tack properties seen with other wood-bonding adhesives but resemble wet plaster or cement in their flow characteristics (Koch 1985b). However, evaluating cold press tack was of interest in this study to comply with the industry partner's standard plywood procedures but also as an additional evaluation of hickory compared to red oak at several moisture content levels. Cold press tack was assessed using visual evaluation of the immediate or instantaneous sticking together of the veneer stacks on the 0 – 5 scale developed for this study. A value of 0 was given if there was relatively little sticking or bonding between the veneer sheets and the sheets were not held together. A value of 5 was assigned if the panel showed no visible separation between veneer layers and the layers held together prior to being placed in the hot press. Intermediate bond development was assigned values from 1 – 4 depending on level of tack developed.

Cold press tack is important in plywood production so that the veneers hold together during processing and transporting into the hot press (Hogger et al. 2018). Averages for cold press tack shown in Table 3-2 indicate that there was very little immediate or instantaneous bonding during the stand time or the cold press for any of the wood types studied. These results confirmed initial expectations for cold press tact of Soyad®. Red oak average was slightly greater than 1.00, but this is still considered lacking in immediate tack. Standard deviations are quite high for all wood types which indicates a high degree of variability in either making the measurements or in the plywood panels themselves.

Table 3-2: Average Cold Press Tack. Standard deviation in parentheses.
0 = slight sticky and not holding together, 5 = no visible gaps, panel holds together well.

Moisture Content	Hickory Sapwood	Hickory Heartwood	Red Oak Heartwood
2% MC	1.00 (0.76)	0.50 (0.76)	NA
4%MC	0.88 (0.83)	0.75 (0.89)	NA
6% MC	NA	0.75 (0.89)	1.11 (0.60)
8% MC	NA	0.43 (0.53)	NA
Count	8	8	8

3.1.4. Lathe Check Measurements

Lathe checks occurring in the hickory face veneer were measured on specimens taken from the prepared plywood panels. Length was measured as the line trace of the visible split and depth was the extent into the body of the veneer in the radial direction. Results are summarized for lathe check length in Table 3-3 and for depth in Table 3-4. Figure 3-4 indicates check length and Figure 3-5 shows check depth. Identical capital letters indicate no statistically significant differences were found, different capital letters indicate there were statistically significant differences using Tukey's ANOVA, α = 0.05. Error bars indicate ±1 standard deviation.

Table 3-3: Face Veneer Lathe Check Length (mm) Results.

	2 %		4%		6%		8%	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	2.19	2.23	2.28	2.42	1.94	1.98	1.99	2.16
S.D.	0.52	0.50	0.48	0.46	0.48	0.52	0.48	0.49
Min	1.13	1.15	1.09	1.08	0.62	0.33	0.58	0.69
Max	4.38	3.55	3.85	3.39	2.98	3.13	3.04	3.45
Count	160	160	160	160	160	160	160	160

Table 3-4: Face Veneer Lathe Check Depth (mm) Results.

	2 %		4%		6%		8%	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	1.41	1.52	1.44	1.58	1.22	1.49	1.22	1.36
S.D.	0.29	0.29	0.23	0.31	0.30	0.22	0.30	0.26
Min	0.75	0.82	0.76	0.82	0.44	0.39	0.38	0.48
Max	1.05	2.06	1.90	2.06	1.86	1.98	1.97	1.81
Count	158	176	113	128	157	292	156	165

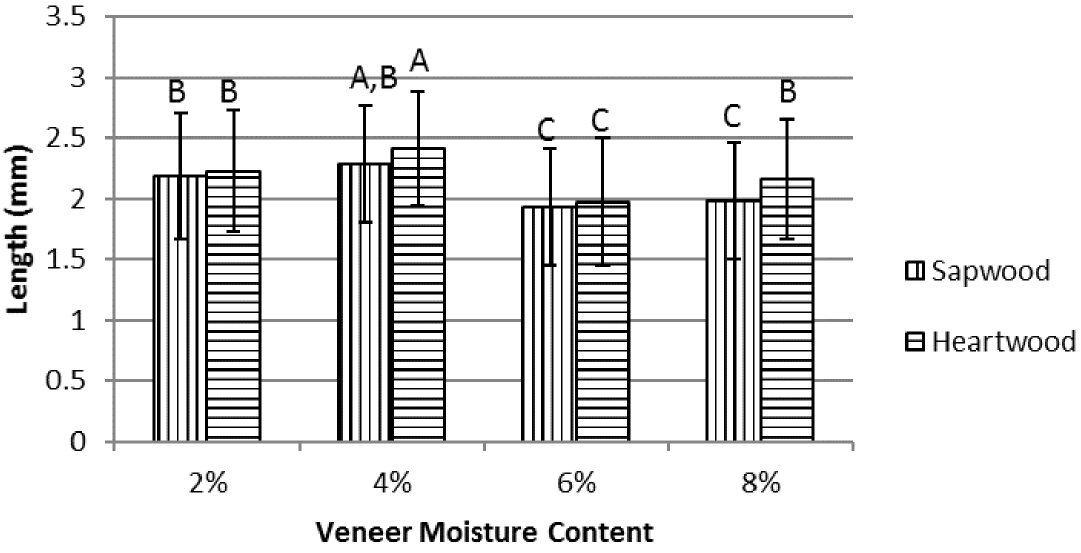

Figure 3-4: Face Veneer Lathe Check Length as a Function of Moisture Content.

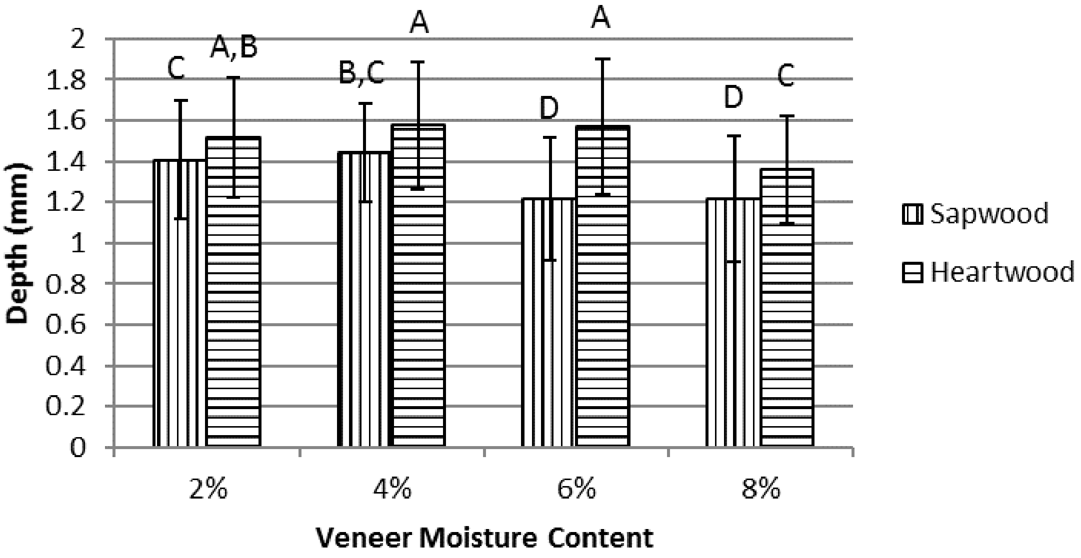

Figure 3-5: Face Veneer Lathe Check Depth as a Function of Moisture Content.

Characteristics of the lathe checks measured in this study (Figures 3-4 and 3-5) indicate that both average length (diagonal trace) and depth (extension radially) could be considered large because results show checks sometimes extended beyond 50% of the veneer thickness (2.06 mm) for all moisture content conditions and wood regions. Lengths of the checks were statistically different for each moisture content and likewise, sapwood and heartwood were statistically dissimilar. The highest average value for length was found in heartwood at 4% and the lowest in sapwood at 6%. These statistically significant results at 4% heartwood and 6% sapwood are isolated and not considered conclusive for the influence of moisture content or wood region, but they do indicate that there are interactions taking place beyond the scope of the factors studied.

Depths of the checks also exhibited statistical dissimilarities within and across the moisture content range and wood region. Lathe check depth might be envisioned as how close to the opposite surface the check terminated or extended. For example, depths in the 6% and 8% veneer frequently extended almost from one surface to the other. Figure 3-6 illustrates an example of adhesive flow into lathe checks observed with epifluorescence microscopy. In this particular case, the lathe check extended almost to the surface of the face veneer and adhesive appears to travel from the bondline to the outer surface.

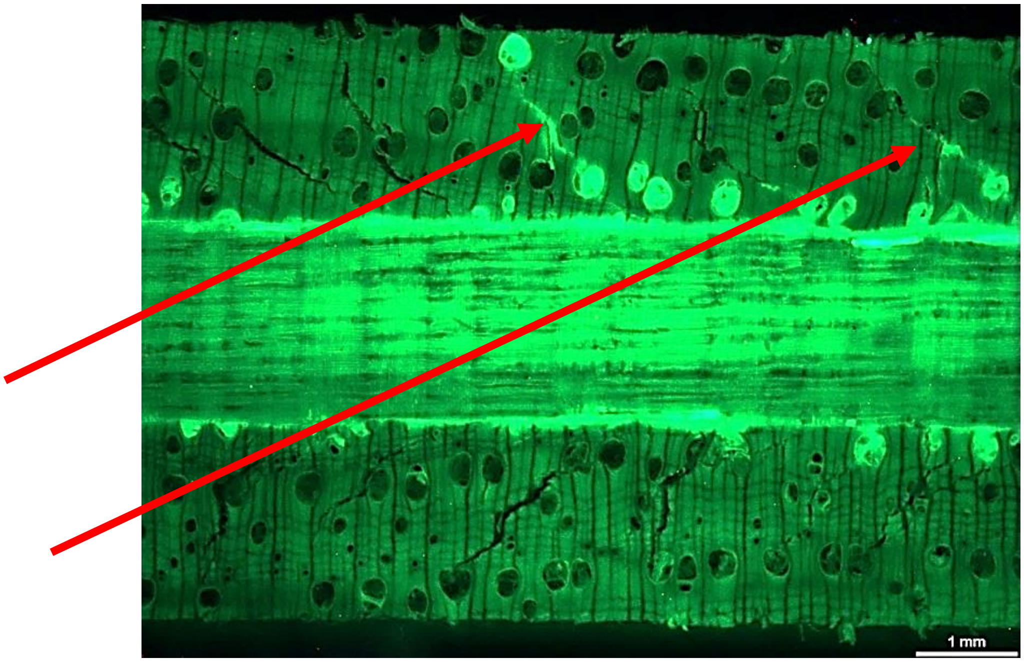

Figure 3-6: Example of Adhesive Flow into Face Veneer Lathe Checks (arrows) Observed with Epifluorescence Microscopy. Micrograph by Dylan Harris.

Surface quality of the veneer sheets requires significant consideration in wood bonding. Wood surfaces need to be smooth, flat, and free of machine marks and other surface irregularities (Hass et al. 2014). Lathe checks created during rotary peeling of logs pose a potential problem for adhesion because they create cracks and roughness in the surface which can result in low surface quality and excessive adhesive consumption (Darmawan et al. 2015). Lathe checks can also have an impact on plywood strength properties and durability (DeVallance et al. 2006, Antikainen et al. 2015).

The size and frequencies of lathe checks are dependent upon many factors including veneer thickness, wood type, and processing parameters. Frequency of lathe checks has been reported to correlate well with lathe check length (Antikainen et al. 2015) Lathe checks serve as channels into which adhesives can flow. However, over penetration of adhesive into lathe checks is usually not a problem in industrial applications if the adhesive spread rate has been adjusted correctly. This in turn requires knowledge of lathe check sizes and frequencies. Numerous and large lathe checks are very common in certain types of veneer at low moisture content and were certainly evident in the hickory veneer used in this study.

Lathe check size and frequency in the yellow-poplar core veneer was not a primary consideration, however a limited study of the failed D 906 specimens observed in side view with optical reflected light microscopy was completed. Figure 3-7 illustrates several examples of failed specimens. Lathe checks in the yellow-poplar core were frequently the location of deep wood pullout zones (e.g., image 3) however other surfaces indicate very low wood failure and pullout (e.g., image 5). Percentage of wood failure (Section 3.2.3) exhibited a wide range of values and correspondingly high standard deviations. The high degree of variability is also visible in the images of Figure 3-7.

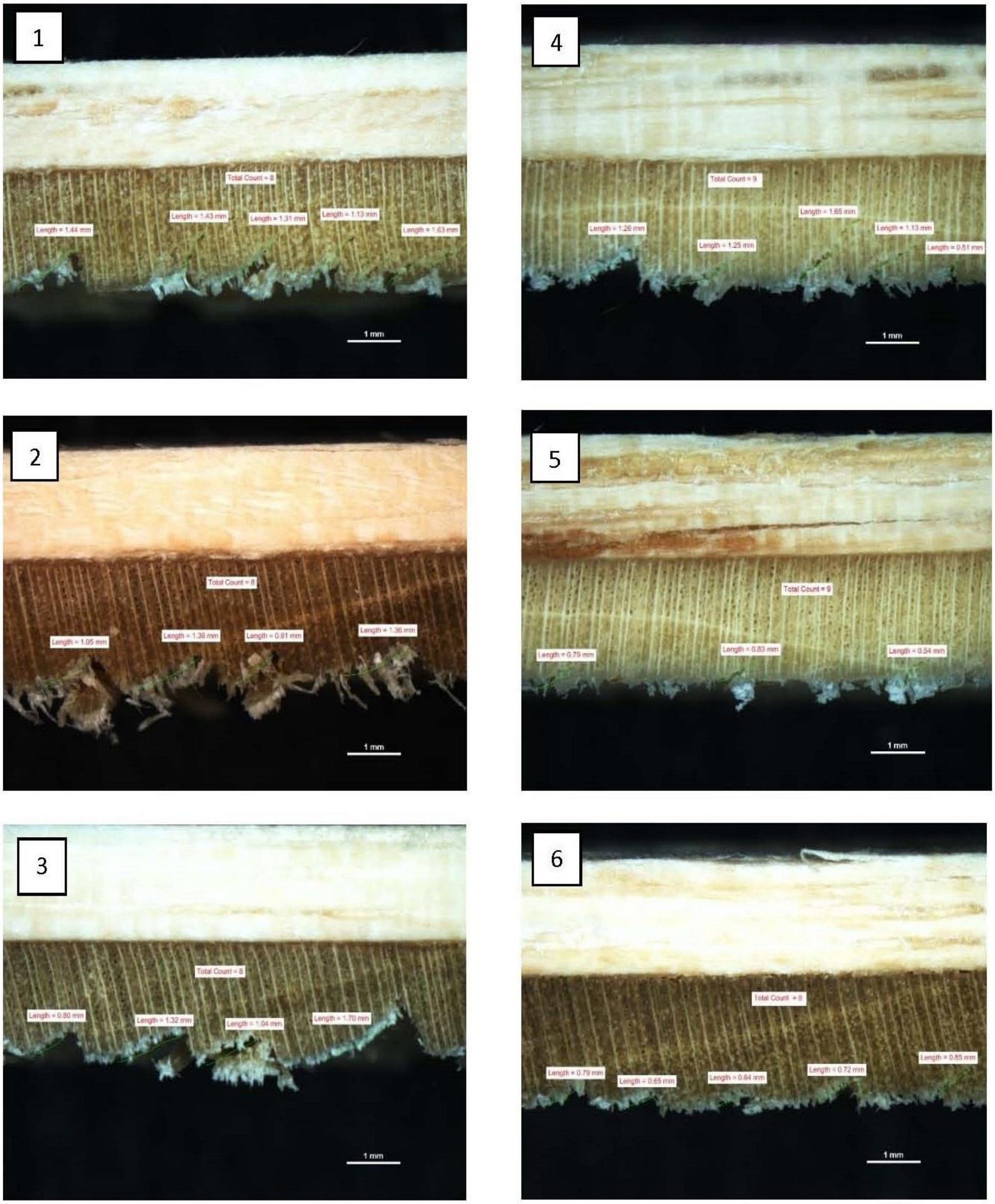

Figure 3-7: Example Reflected Light Micrographs of Core Lathe Checks and Wood Pull Out.

3.1.5. Adhesive Penetration and Bondline Thickness

Results are summarized for adhesive penetration depth in Table 3-5 and for bondline thickness in Table 3-6. Penetration depths of the adhesive at each of the moisture conditions studies are illustrated in Figure 3-8. Average bondline thickness is shown for each moisture content in Figure 3-9. Identical capital letters indicate no statistically significant differences were found, different capital letters indicate there were statistically significant differences using Tukey's ANOVA, α = 0.05. Error bars indicate ±1 standard deviation.

Bondline thickness and degree of adhesive penetration into the cell structure have a direct impact on bond performance (Kamke and Lee 2007, Paris et al. 2014, Stables 2017). For example, bondline thickness can be influential in joint strength, stress transfer, and resistance to shrinkage and swelling. Adhesive penetration depth is associated with the amount of surface contact at the cellular level between the adhesive and wood and the potential for mechanical interlocking formation and the development of secondary and covalent bonding.

Table 3-5: Adhesive Penetration Depth (μm) Results.

	2 % MC		4% MC		6% MC		8% MC	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	145.1	156.0	123.4	105.8	216.8	199.1	122.9	128.3
S.D.	100.49	40.07	53.74	58.71	43.59	109.65	43.52	55.04
Min	0	0	0	0	0	0	0	0
Max	808.1	825.9	530.4	531.8	725.6	781.9	703.6	527.7
Count	150	150	150	150	150	150	150	150

Table 3-6: Bondline Thickness (μm) Results.

	2 %		4%		6%		8%	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	25.37	27.39	45.62	50.43	31.60	31.70	28.94	33.78
S.D.	2.23	2.81	16.61	10.17	4.97	4.66	4.87	3.46
Min	13.6	14.96	0	0	14.96	0	0	19.04
Max	40.8	43.52	183.6	136.0	55.76	55.76	55.76	58.48
Count	150	150	150	150	150	150	150	150

Factors present within an adhesive bondline coupled with those of the surrounding bond interphase have been found to strongly influence wood composite performance (Modzel et al. 2011, Pizzi and Mittal 2011). Of the many factors, permeability and surface energy are particularly important for adhesive bonding and penetration into the wood cellular structure (Kamke and Lee 2007). Permeability of a material influences bondline thickness and adhesive penetration depth, and, unfortunately, is one of the most highly variable properties with wood substrates. Adhesives do not penetrate readily into high density woods such as hickory due to the high percentage of longitudinal fiber tracheids and libriform fibers with thick cell walls and small lumina. Furthermore, moderate-to-abundant tyloses in hickory can hinder adhesive flow.

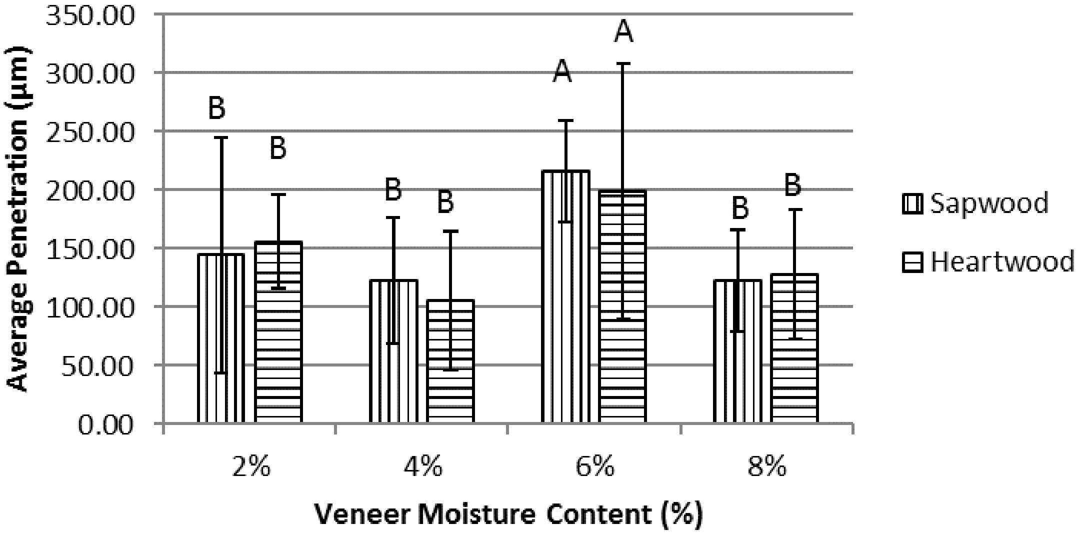

Figure 3-8: Adhesive Penetration as a Function of Moisture Content.

Adhesive penetration depths for the hickory face veneer provided in Figure 3-8 were similar across the moisture levels with the exception of those measured at 6% veneer moisture content. Results indicate that the correlation between penetration and moisture content was not impacted consistently by the moisture content of the veneer nor the heartwood versus sapwood. However, variability in penetration was high which makes analyses across the variables difficult.

The most favorable degree of adhesive penetration will depend on the composite type and the adhesive and substrate properties. There are no set levels for optimal penetration depth for each adhesive and wood combination. Though, it is known that adequate penetration can be linked to optimal composite performance. In general, it is common for adhesive penetration to average from 150 µm to above 400 µm depending on method, adhesive, and wood type. Greater penetration can be associated with more cellular level surface contact between the wood and adhesive which increases the potential for secondary bonding forces and development of covalent bonding. Penetration depths averaged 150 µm for all specimens as a group in this study which is on the lower end of the recommended range, but proved to create adequate bonding with all wood and moisture content combinations.

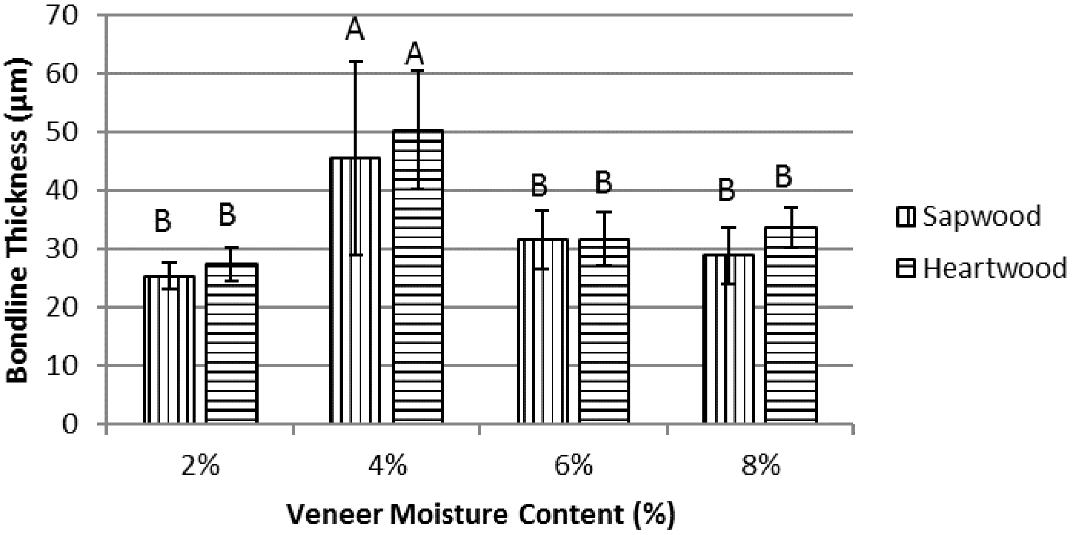

Figure 3-9: Bondline Thickness as a Function of Moisture Content.

Bondline thickness results shown in Figure 3-9 were similar within the moisture content range and wood region. Highest average bondline thickness is noted at 4% veneer. Averages for all other moisture contents were not found to be statistically significantly different. Bondlines that have shown to withstand the highest mechanical loading and dimensional change are reported to average between 0.076 to 0.152 mm depending on the type of composite and adhesive (Wood Handbook 2010, Scott et al. 2005). In this study, bondline thicknesses ranged from 0.02 to 0.05 mm which might be considered too thin to effectively transfer stresses from one adherend to another for certain composite applications. Yet adequate dry and wet shear strength was developed in all combinations as described in the following section.

Statistically significant differences in penetration at 4% and bondline thickness at 6% indicate that there are interactions among the variable but not on a consistent basis. It would be expected that a thicker bondline (4%) would be accompanied by lower penetration depth which is confirmed by the low values reported for 4% MC. However for the highest penetration depths (6%), there is no accompanying low value for bondline thickness. Further, the lowest moisture content (2%) should have exhibited the most pronounced differences since the aqueous adhesive was applied to a very low moisture level wood substrate and adhesive viscosity should have gone up and influenced penetration and bondline thickness. Reasons for the lack of correlation are unknown.

3.2. Bond Shear Strength Assessment

3.2.1. ASTM D906-98 Dry Shear Strength

Shear strength of the bonding with veneer at several low moisture contents and wood regions was evaluated using shear by tension loading in accordance with ASTM D906-98 (ASTM 2017). Table 3-7 provides a summary of results for this test. Figures 3-10 and 3-11 indicate average bond strength at each of the moisture contents studied. No statistical differences were observed within this moisture content range or for wood region. Identical capital letters indicate no statistically significant differences were found, different capital letters indicate there were statistically significant differences using Tukey’s ANOVA, α = 0.05.

Table 3-7: Dry Shear Strength Averages (KPa) at each Moisture Content.

Open								
	2% MC		4% MC		6% MC		8% MC	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	1571	1738	1699	1815	1848	1794	1744	1828
S.D.	447	394	288	236	349	518	283	241
Min	1082	996	1187	1421	1020	665	1319	1326
Max	2670	2501	2475	2214	2441	2992	2451	2380
Count	16	20	17	15	18	22	20	20
Closed								
	2% MC		4% MC		6% MC		8% MC	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	2204	2557	1929	2440	2461	2485	2238	2379
S.D.	426	460	645	574	418	494	212	337
Min	1274	1693	452	1576	1615	1598	1912	1891
Max	3002	3546	2983	3302	3230	3437	2676	3074
Count	18	14	18	20	19	19	23	22

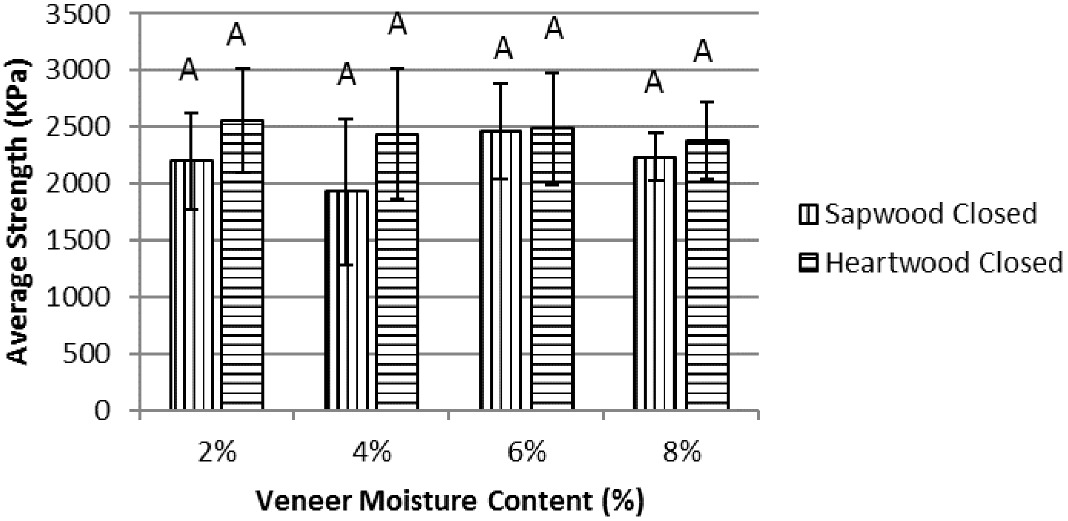

Figure 3-10: Average Shear Strength, Core Lathe Check Closed Orientation.

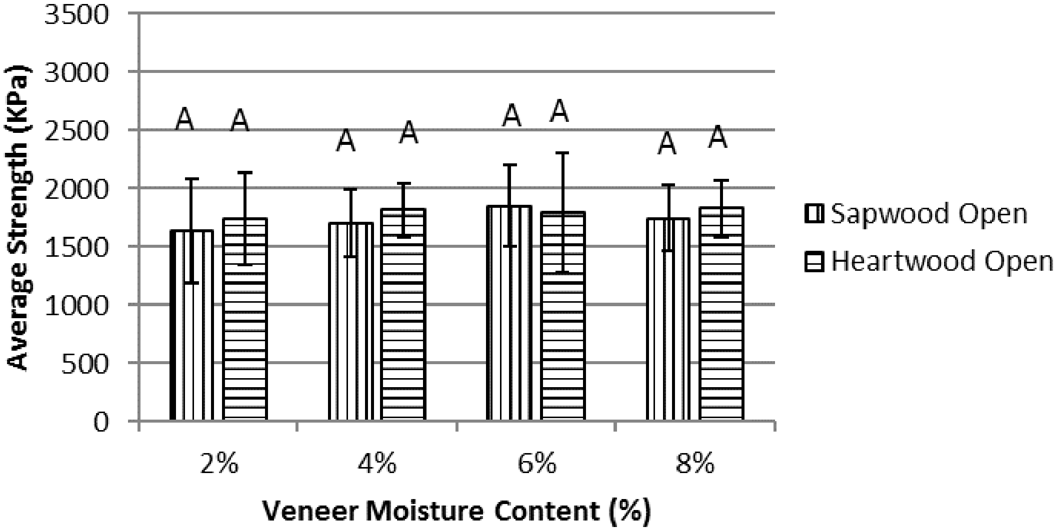

Figure 3-11: Average Shear Strength, Core Lathe Check Open Orientation.

Combining all dry shear strength data in Figure 3-12 shows that specimens in which the lathe checks are being pulled closed (in compression) uniformly have higher values that those in which the checks are being pulled open. This result is not unexpected but it does underscore the need to know and understand the implications of the lathe check orientation and loading configuration when analyzing rotary peeled veneer sheets incorporated into plywood products.

Dry shear bond strength values indicate that Soyad® bonding with low moisture hickory sapwood and heartwood develops reasonable dry shear strength levels for use in hardwood and decorative plywood (ANSI 2004). There were no statistically significant differences found for moisture content within the range studied. The results could imply that any interactions taking place were consistent across this moisture range, however this is conjecture at this point.

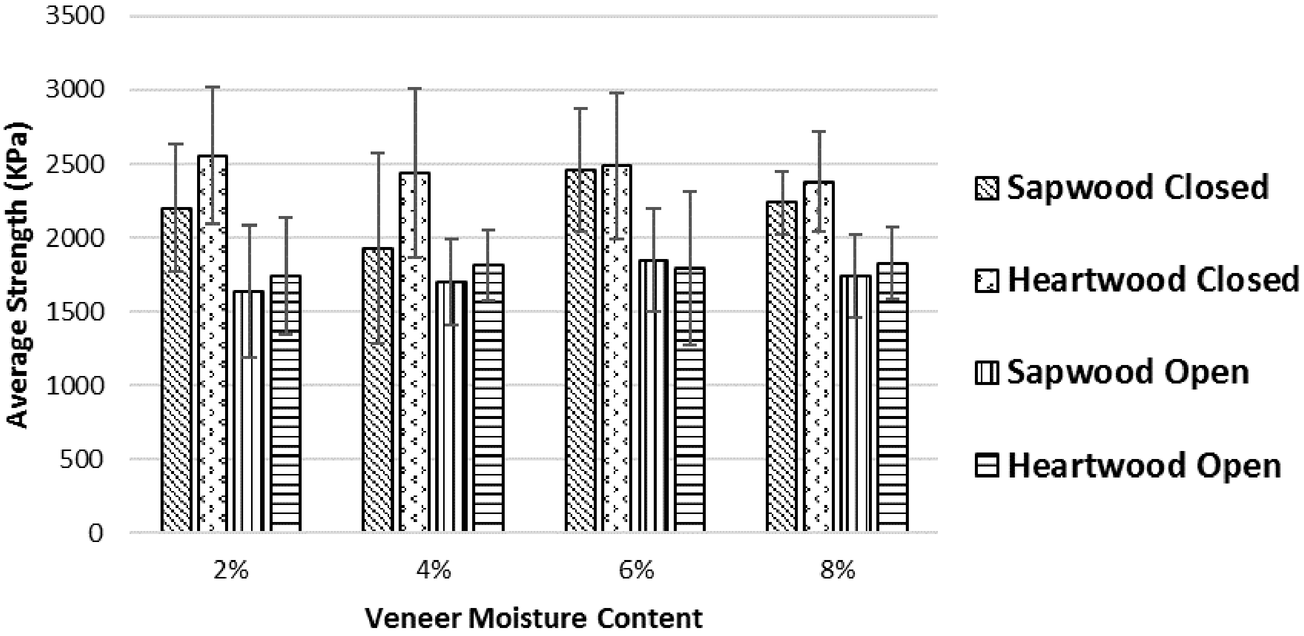

Figure 3-12: All Shear Strength Data at each Moisture Content.

3.2.2. EN 314-1 Wet Shear Strength

Bond strengths for specimens with veneer conditioned to 6% and later subjected to water treatment are shown in Figure 3-13. Table 3-8 provides a summary of results from the wet shear strength testing. A comparison between the dry and wet shear results at 6% is provided in Figure 3-14. Because initial tests for the influence of moisture content in dry shear strength were neither conclusive nor consistent, it was determined with input from industry partners that the best use of resources was to investigate the wet shear strength at one moisture content (6%) rather than across a range shown to not have a consistent or conclusive impact. Six percent was chosen to correlate to the standards specifications.

Table 3-8: Wet Shear Strength Results
for 6% Moisture Content. KPa.

	Sapwood		Heartwood	
	Open	Closed	Open	Closed
Mean	998	1593	1260	1851
S.D.	483	635	304	806
Min	1	273	826	290
Max	1769	2513	1653	2915
Count	16	14	15	14

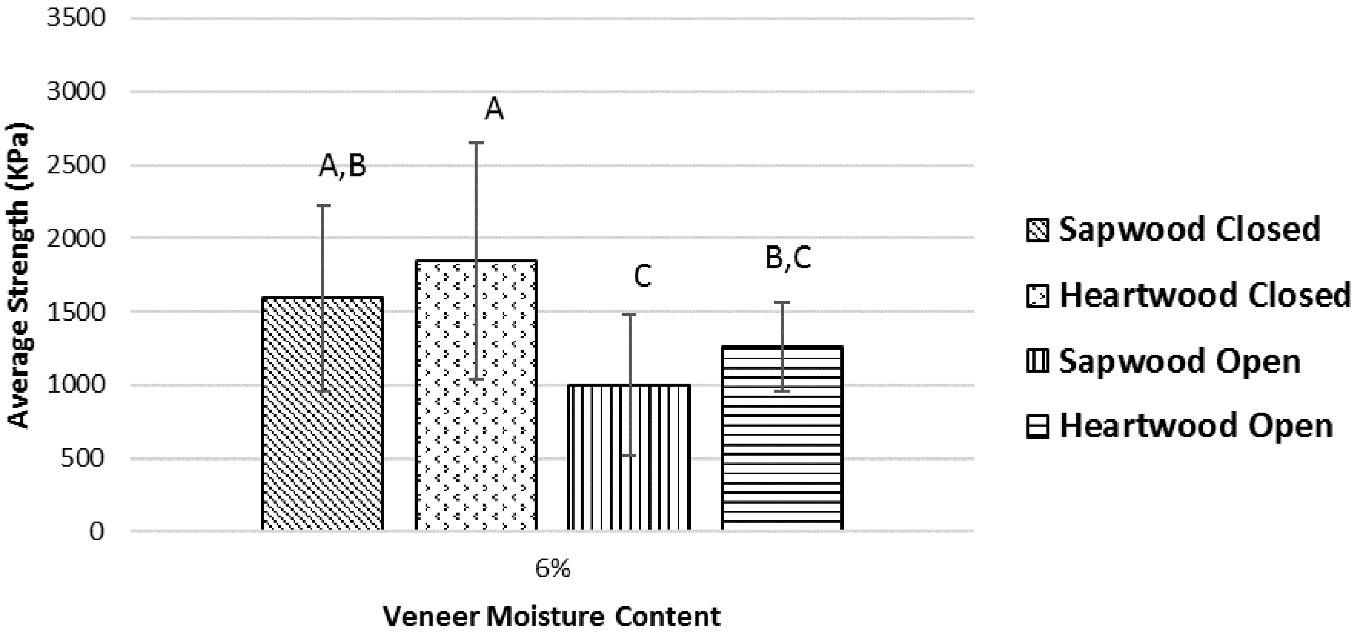

Figure 3-13: Wet Shear Strength for Specimens Conditioned to 6% Moisture Content.

Figure 3-14 shows that statistically significant variation occurred when comparing sapwood and heartwood and likewise between closed compared to open lathe check orientations. Error bars indicate ±1 standard deviation. For the closed lathe check specimens there were no differences found in sapwood compared to heartwood and likewise the open configurations were similar in strength. However statistical difference are noted when comparing closed configuration specimens with open. This is the same finding as the dry shear specimen results in which closed lathe check configurations produced higher strength values.

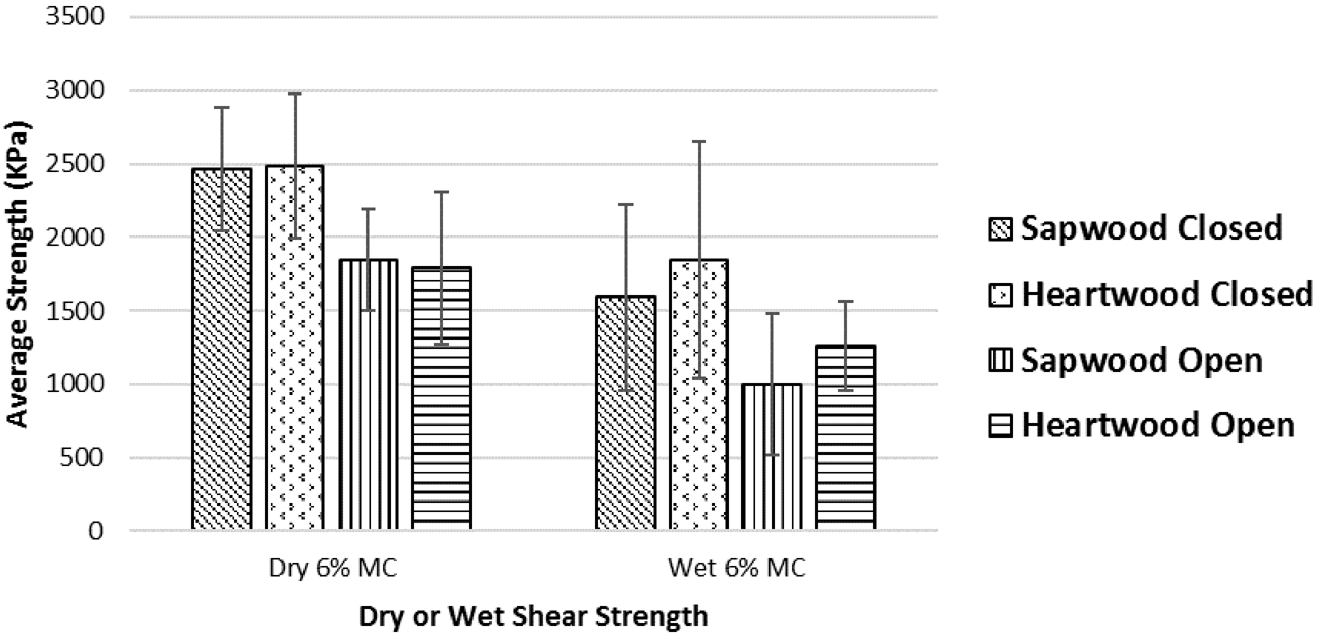

Figure 3-14: Comparison of Dry and Wet Shear Strength Results.

Results provided in Figure 3-14 show that as expected, wet shear strengths were less than dry but it is interesting to note that heartwood closed results for dry and wet shear tests are comparable when taking data variability into account. Although the wet shear strength results are lower than dry strength, the magnitude of the values indicate that sufficient wet strengths had been developed that could withstand the intensive water soaking treatment.

3.2.3. ASTM D5266-13 Percent Wood Failure

Percent wood failure is the percentage of wood area remaining on the adherend in the fractured surface test area (ANSI 2004). This measure is used in industrial research and practice as an estimate of bond quality. ASTM D5266 is currently accomplished through a visual assessment by a trained technician, however digital and automated systems have been investigated (Zink and Kartanova 1998, Scott et al. 2005, Yang et al. 2008, Daoui et al. 2011, Kariz and Sernek 2014, Lin et al. 2015).

High strength and durable bonds are said to correlate well with high wood failure percentages and, correspondingly, if wood failure is shallow and sparse, bond strength and durability are said to be lacking. Standards establish minimum acceptable values for percent wood failure from 75% in some standards to above 85% in others depending on the product type bond line requirements (ANSI 2004, BSI 1993).

Table 3-9 lists the average percent wood failure values for each moisture content, wood region, and lathe check configuration from the D906 dry shear strength test specimens and Table 3-10 shows the values from the EN 314-1 wet shear strength test specimens at 6% moisture content.

Table 3-9: Average Percent Wood Failure Values, Dry Shear Strength Specimens.

	Open							
	2% MC		4% MC		6% MC		8% MC	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	24	20	35	19	20	33	22	24
S.D.	18	15	24	12	15	19	23	19
Min	4	5	6	6	3	4	0	1
Max	72	72	84	44	60	70	88	70
Count	16	20	17	15	18	22	20	20

	Closed							
	2% MC		4% MC		6% MC		8% MC	
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood
Mean	40	44	39	44	18	38	18	20
S.D.	43	29	26	27	24	29	22	23
Min	1	0	1	0	1	2	0	0
Max	92	96	80	90	84	80	76	84
Count	18	14	18	20	19	19	23	22

Table 3-10: Average Percent Wood Failure Values,
6% Veneer,
Wet Shear Strength Specimens.

	Sapwood		Heartwood	
	Open	Closed	Open	Closed
Mean	11	27	11	23
S.D.	10	25	15	29
Min	0	0	0	0
Max	36	80	48	88
Count	16	14	15	14

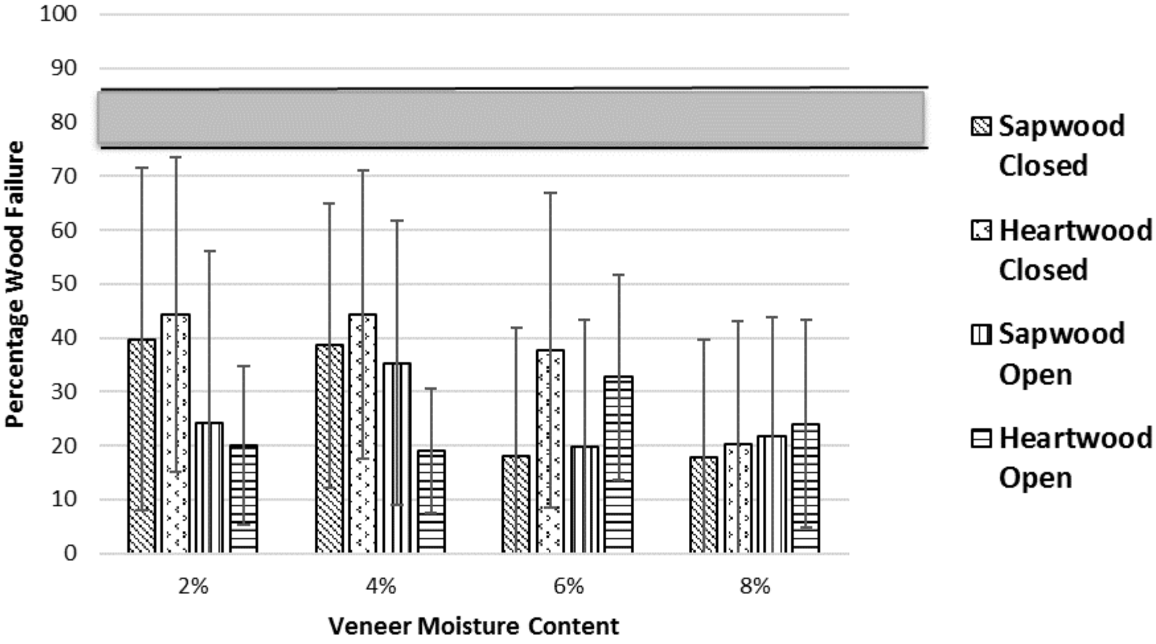

Figure 3-15: Percentage Wood Failure, Dry Shear Strength Test Specimens.

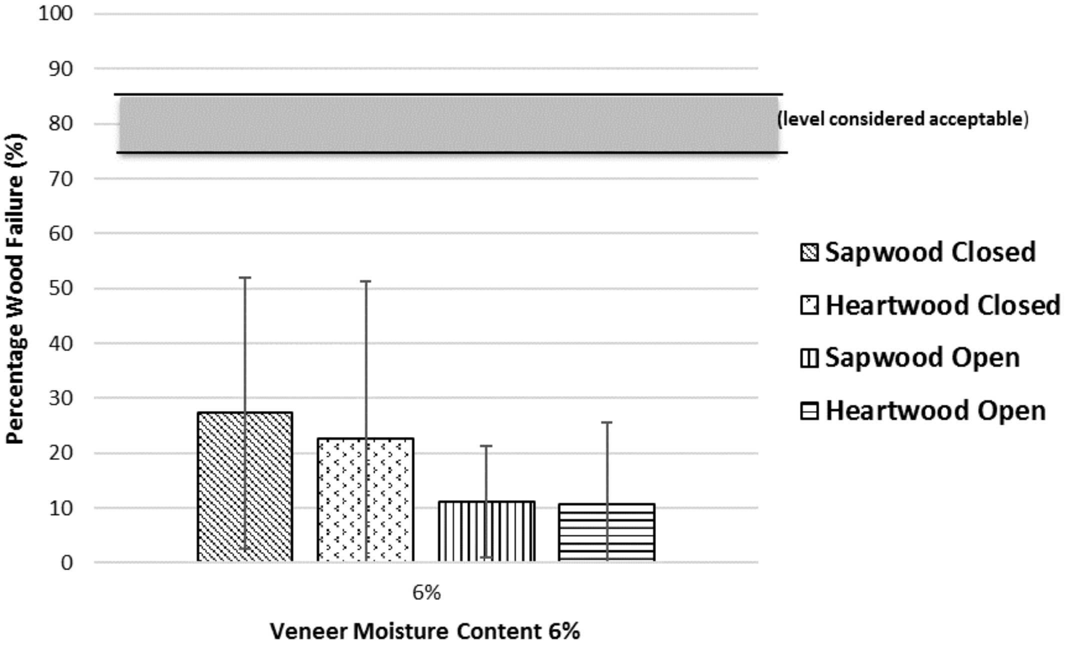

Figure 3-16: Percentage Wood Failure, Wet Shear Test Specimens.

It can be seen in Figures 3-15 and 3-16 that specimens in which the core lathe checks were being pulled closed exhibited higher percentages of wood failure at the lower moisture contents but limited differences within the 8% level (see Figure 3-15). Other research on the impact of lathe check orientations in shear strength testing have found similar trends where percent wood failure is higher when checks are pulled closed (Rohumaa et al. 2017). It was found that when checks were pulled open, the failure zone moved closer to the bondline and only a small amount of wood was present on the failed surfaces. When specimen lathe checks were pulled closed, the failure was mainly along a line demarcated by the crack tips of the lathe checks and the failure zone was further from the bondline which was thought to result in higher percentage wood failure.

Data variability is quite high in this test as a result of subjective decisions being required and difficulty in visual assessment of contrast differences between the nearly transparent soy-flour adhesive and the wood background. In some cases, the magnitude of the standard deviations would indicate negative percent wood failure values which are not possible and therefore were not shown beneath the zero line in Figures 3-15 and 3-16. Due to the high variability, differences within and across the moisture contents and heart/sapwood are not clear.

An expectation in industrial settings is for an adhesive bond to be as strong as or stronger than the wood itself. To create this type of wood and adhesive failure situation, mechanical interlocking of the adhesive within the wood cells is key; this is when the adhesive penetrates into sound wood two to six cells deep creating an interlocking network within the porous woods (Wood Handbook 2010). High percentages of wood failure in test specimens can indicate substrate failure rather than cohesive failure within the bulk of the adhesive. Interphase failure is much more complicated to evaluate.

The percent wood failure results do not appear to be reflecting the trends found for the adhesive penetration depth maximum at 4% and bondline thickness maximum at 6% results. This may be due to the high data variability which is masking any trends. It can be noted in Figure 3-15 that percentage wood failure results at 6% and 8% do not mirror results at the other moisture contents. At 6% moisture content, both sapwood closed and open results are noticeably lower than heartwood averages and at 8% moisture content, the values are similar within that moisture level.

In general, it is thought that percent wood failure is a good estimate of the bond strength and durability of a bonded joint. However, in this study, none of the wood combinations achieved the wood failure percentages considered acceptable yet adequate dry and wet bond strength values were produced. The results indicate that bond strengths were not reflected well in the wood failure percentages. Shallow and highly variable adhesive penetration, questionably thin bondlines, and low moisture veneer that might have drawn water from the adhesive into the wood bulk may together have led to the uniformly low percentages of wood failure.

3.3. Bond Durability

3.3.1. ANSI Type II Three-cycle Soak Test

An ANSI three-cycle soak test (ANSI 2004) was performed using red oak and hickory veneer and two different veneer thicknesses, 2.06 mm (labeled “thick” in Table 3-11) and 0.62 mm (labeled “thin”). This test subjects the bonded specimens to water soaking and drying to assess resistance to delamination during moisture exposure. A test specimen is classified as failed if delamination between two plies is greater than 50.8 mm in length, over 6.4 mm in depth, and 0.08 mm in width. As seen in Table 3-11, all wood combinations passed the delamination criterion set in the standard. Although hickory heartwood thick specimens showed a lower pass rate than did all other combinations, the aggregated values passed the standard. These delamination results indicate that durable bonds that withstood stresses created during water cycling were developed with all combinations of wood regions and types. It can be said that these wood and adhesive combination levels are sufficient for interior plywood because all specimens passed the water soak tests.

Table 3-11: Percentage of Specimens with Delamination Passing Three-cycle Soak Tests. n = 18

	Thick Veneer (avg. 2.06 mm)			Thin Veneer (avg. 0.62 mm)		
Cycle	Hickory Sapwood	Hickory Heartwood	Red Oak Heartwood	Hickory Sapwood	Hickory Heartwood	Red Oak Heartwood
1st Soak	100%	89%	100%	100%	100%	100%
2nd Soak	100%	89%	100%	100%	100%	100%
3rd Soak	100%	83%	100%	100%	100%	100%

3.3.2. Thickness Swell Measurement

Dimensional change due to swelling was assessed by measuring the thickness of the specimens after each soaking phase of the ANSI Three-cycle Soak Test (ANSI 2004). Measurement of thickness is not part of the ANSI standard but was completed in this study to provide additional comparison of heartwood versus sapwood and hickory to red oak. Table 3-12 shows thickness swell following each soak cycle as a percentage of the original thickness, standard deviations in parentheses. Thicker veneer exhibited greater percent thickness swell and red oak heartwood values are the lowest on average. However, standard deviation is quite high which makes comparisons and determination of relationships difficult. Although care was taken to extend the caliper fully and evenly across the specimen width, edge effects due to high swelling along the surfaces had potential to impact some measurements.

Table 3-12: Percent Thickness Swell During ANSI Three-cycle Soak Tests. Standard Deviations in Parentheses. n = 18

	Thick Veneer (avg. 2.06 mm)			Thin Veneer (avg. 0.62 mm)		
Cycle	Hickory Sapwood	Hickory Heartwood	Red Oak Heartwood	Hickory Sapwood	Hickory Heartwood	Red Oak Heartwood
1st Soak	1.57	2.34	1.35	1.21	0.91	0.88
	(1.57)	(1.95)	(1.16)	(0.91)	(0.60)	(0.59)
2nd Soak	1.57	1.56	1.16	0.60	0.60	0.29
	(1.37)	(1.75)	(1.35)	(0.91)	(0.60)	(0.59)
3rd Soak	3.14	3.71	2.70	1.81	1.21	1.17
	(1.96)	(2.34)	(1.54)	(0.91)	(0.91)	(0.88)

There are various important factors involved when evaluating wood bonding for creation of a water resistant, durable composite. Factors that have been found to have the most significant impart are the wood’s ability to distribute stresses away from the bondline and the chemical and physical properties of the adhesive (Frihart 2009). Adhesives can be separated into two groups: *in-situ* polymerized and pre-polymerized (Frihart 2009) based on the way the adhesive interacts with the cell wall and the adhesive chemistry. The *in-situ* adhesives such as Soyad® help distribute stress away from the bondline, whereas pre-polymerized adhesives have longer polymer chains and allow more flexibility at the bondline. The longer polymer chains with more flexibility allow for the stress from warping in the wood structure due to moisture change to be distributed through the adhesive rather than the adhesive wood interphase. Delamination and thickness swell results show that Soyad® adhesive developed sufficiently durable bonds with low moisture content veneer of both hickory heartwood and sapwood as well as red oak heartwood.

4. Summary and Recommendations for Further Study

4.1. Summary

Adhesive, adhesion, and veneer property analyses provided the following information:

- Viscosity: Soyad® as prepared was confirmed to be a non-Newtonian fluid
- Buffering capacity: hickory heartwood exhibited the highest values followed by hickory sapwood and red oak heartwood
- Cold press tack: little to none was exhibited by any combination, as expected
- Lathe check length: highest at 4% moisture content and lowest at 6%; no differences for heartwood versus sapwood
- Lathe check depth: no consistent trends found across moisture content range; data variability very high; heartwood checks extended deeper than sapwood checks
- Adhesive penetration depth: lowest at 4% and highest at 6%, values at 2% were statistically similar to those at 8%; no differences for heartwood versus sapwood
- Bondline thickness: highest at 4%, 2, 6, and 8% statistically similar; no differences for heartwood versus sapwood

Bond shear strength assessment results are as follows:

- Dry shear strength: no statistically significant differences found for the moisture content range studied; no differences found for heartwood versus sapwood; lathe check configuration pulled closed statistically higher than open configuration
- Wet shear strength (only done at 6% veneer moisture content): results less than dry shear strength values; no differences found for heartwood versus sapwood; lathe check configuration pulled closed statistically higher than open configuration
- Percentage wood failure: all results lower than industry accepted values for all wood combinations; data variability very high; values at 2 and 4% greater than 6 and 8%; no differences found for heartwood versus sapwood except 6% sapwood

values notably lower than all others; lathe check configuration pulled closed higher than open configuration; values for all combinations at 8% were very similar

Bond durability as measured with delamination and thickness swell results are as follows:

- All combinations exhibited delaminations that were within acceptable values as established by the standard.
- Thickness swell was greater for the thicker veneer but data variability was very high for all combinations

Based on the findings from the study it can be said that moisture content within the range studied was not a clear factor leading to poor bonding as tested with the ASTM D906 dry shear test. Likewise, for the EN 314 wet shear tests, moisture content of the veneer did not have a consistent or negative impact that could be said to be conclusive. All EN 314 wet shear strength values were considerably lower than dry shear strengths, but still within acceptable levels for hardwood and decorative plywood. Results for percentage wood failure indicated that averages were below industrial acceptability levels for all moisture contents studied. Statistically significant but inconsistent differences were found when analyzing the impact of moisture content on adhesive penetration and bondline thickness. Adhesive penetration depth at 4% and bondline thickness at 6% were statistically different when compared to measurements at the other moisture contents. Adhesive penetration depth and bondline thickness appears to correlate to the lathe check features at the same moisture contents but the importance of this finding needs further study. It would seem that impactful interactions occurred but not on a consistent basis or were clearly identifiable.

Heartwood and sapwood chemical differences are known to have strong impacts in adhesive bonding of wood, but in this study no robust or consistent trends emerged for the hickory heartwood or sapwood strength, percentage wood failure, or delamination tests. The most pronounced differences for hickory heartwood and sapwood occurred in buffering capacity and lathe check features. The significance of differing buffering capacity was not immediately clear, but buffering capacity of wood materials can interfere with resin cure. Lathe checks in heartwood were longer and deeper than sapwood on average but, when data variability was taken into account, the values were found to be statistically similar.

Comparison of hickory to red oak revealed differences in buffering capacities between the two wood types that may provide some insight into why red oak is said to bond well with Soyad® but this must be further explored. No other pronounced differences between the two woods were found with the tests conducted. Delamination measurements of water soaked and cycled hickory heartwood, hickory sapwood, and red oak heartwood specimens did not show any differences in performance. Averages for specimens exhibited delaminations that successfully passed the standards expectations. None of the wood combinations fell below standards for delamination. Thickness swell tendencies were also similar between the hickory and red oak wood.

The most intriguing findings from this research were (1) the contrast between shear strength levels that met expectations for hardwood and decorative plywood, delamination averages that were also within acceptable levels, yet percentages of wood failure below standards levels, (2) lathe check and adhesive bondline features showing statistically significant differences but only for isolated moisture contents, and (3) differences in buffering capacity found for hickory heartwood, hickory sapwood, and red oak heartwood.

Impact of bonding low moisture content hickory heartwood and sapwood with a soy-flour adhesive was neither consistent nor conclusive for any of the wood combinations studied. However, results have provided a broader understanding of adhesive bonding of hickory when veneer moisture contents were within the range of 2 to 8%. Expectations that low moisture levels might provide less favorable bonding of hickory and experience problems with sapwood were not confirmed with the combinations of variables and analytical methods used in this study.

The research conducted in this study was intended to provide basic foundational information about bonding hickory veneer with a soy-flour adhesive rather than replicate industrial processing parameters or in-service conditions. Specific objectives were to characterize and compare properties of low moisture hickory heartwood and hickory sapwood veneer bonded into plywood panels with Soyad® adhesive. Although this research established a foundation of basic knowledge, more information about adhesive bonding of wood with the recently developed soy-based adhesives is needed to optimize the systems and provide technological advancements that lead to more efficient and safe utilization of woody materials from the forest.

4.2. Recommendations for Further Study

Numerous factors are involved with adhesive bonding of wood but one of the most promising avenues in this study is results from the buffering capacity tests. Adhesives are sensitive to a buffer effect and the adhesive cure must have certain pH requirements with which wood may interfere. This study determined differences in buffering capacity found for the hickory heartwood, hickory sapwood, and red oak heartwood that could be quite important. It is fairly common in the literature to attribute variations of buffering capacity to the presence of extractives in heartwood (Roffael 2016). However, the results of Hernandez (2013) using just sapwood specimens (and the methods of Johns and Niazi (1981)) indicate measurable differences in pH and buffering capacity that could not simply be attributed to the presence of extractives since there are none or only a limited quantity in sapwood. Results from others and those found here indicate buffering capacity of hickory heartwood and sapwood is a very encouraging area to explore more fully. Ways to test determine if buffering capacity has an impact would be to analyze resin cure as a function of wood exposure. Some examples are to mix and cure the adhesive with the wood flour of interest or to mix the adhesive using water that is a water extract from the woods in addition to traditional methods used to determine if adhesive cure is affected by exposure to the wood flour/extract.

Exploring the mechanics of shrinkage and swelling of the plywood would also provide additional information about the relationships between veneer material properties and any veneer thickness effect. In plywood, maximum stiffness occurs in the longitudinal direction of the face veneers which also has minimal linear expansion. Even though the veneers are restrained due to the adhesive bondline, they still expand when exposed to water or humidity even though there is partial restraint created by bonding and cross lamination.

An equation used for partial restraint is $\Delta D_{res} = \frac{\frac{E_1\, x\, T_1\ x\, \Delta D_1}{1-\Delta D_1}+\frac{E_2\, x\, T_2\, x\, \Delta D_2}{1-\Delta D_2}}{\frac{E_1\, x\, T_1}{1-\Delta D_1}+\frac{E_2\, x\, T_2}{1-\Delta D_2}}$

(Suchsland 2004)

In this equation, the free expansion is D_1 and D_2 for individual layers and the resultant expansion is ΔD_{res} .The equation also includes E which is the modulus of elasticity for a desired moisture content: E_1 is for the core and E_2 is for the face veneer. T_1 and T_2 are the thicknesses of the core and the face veneer. Using this equation, researchers can test variables to determine where there might be deviations from what would be expected and to evaluate the best possible results for the veneer in terms of shrinkage and swelling of the plywood.

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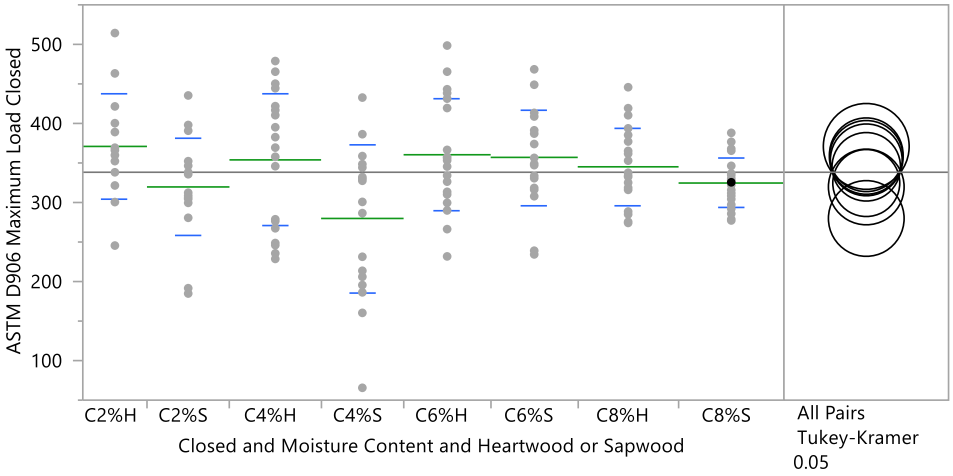
Appendix A: Statistical Analyses.

Oneway Analysis of ASTM D906 Maximum Load By Closed and Moisture Content and Heartwood or Sapwood



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD Confidence Quantile

q*	Alpha
3.07570	0.05

HSD Threshold Matrix

Abs(Dif)-HSD

	C2%H	C6%H	C6%S	C4%H	C8%H	C8%S	C2%S	C4%S
C2%H	-76.801	-61.022	-57.691	-53.766	-43.688	-22.552	-21.141	18.727
C6%H	-61.022	-65.925	-62.594	-58.603	-48.405	-27.214	-26.115	13.753
C6%S	-57.691	-62.594	-65.925	-61.935	-51.736	-30.546	-29.446	10.421
C4%H	-53.766	-58.603	-61.935	-64.256	-54.038	-32.838	-31.790	8.078
C8%H	-43.688	-48.405	-51.736	-54.038	-61.266	-40.050	-39.093	0.775
C8%S	-22.552	-27.214	-30.546	-32.838	-40.050	-59.919	-59.005	-19.137
C2%S	-21.141	-26.115	-29.446	-31.790	-39.093	-59.005	-67.732	-27.864
C4%S	18.727	13.753	10.421	8.078	0.775	-19.137	-27.864	-67.732

Positive values show pairs of means that are significantly different.

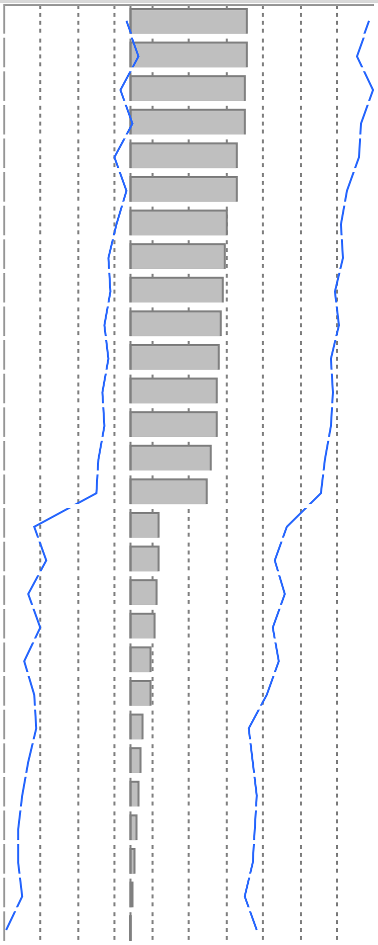
Connecting Letters Report

Level			Mean
C2%H	A		370.91518
C6%H	A		360.36781
C6%S	A		357.03612
C4%H	A		353.87498
C8%H	A		345.13440
C8%S	A	B	324.58809
C2%S	A	B	319.64778
C4%S		B	279.78010

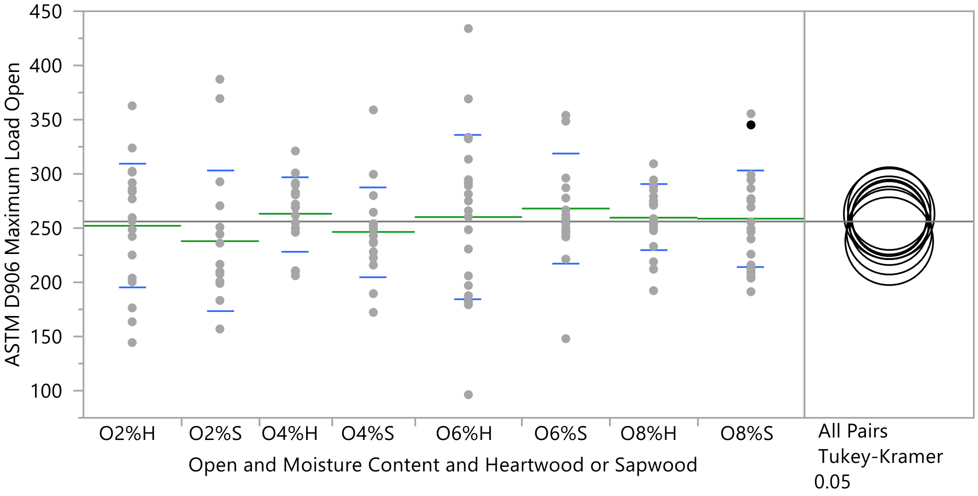
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
C2%H	C8%S	26.54658	8.923460	-0.8993	53.99246	0.0658
C4%H	C8%S	26.51087	8.048513	1.7561	51.26568	0.0266*
C2%H	C6%S	26.12782	9.272065	-2.3903	54.64591	0.0986
C4%H	C6%S	26.09211	8.433364	0.1536	52.03060	0.0475*
C2%H	C8%H	24.01299	8.999870	-3.6679	51.69388	0.1410
C4%H	C8%H	23.97727	8.133147	-1.0378	48.99239	0.0706
C2%S	C8%S	21.98309	8.284229	-3.4967	47.46289	0.1458
C2%S	C6%S	21.56433	8.658609	-5.0670	48.19561	0.2079
C4%S	C8%S	20.81643	8.284229	-4.6634	46.29622	0.1985
C4%S	C6%S	20.39766	8.658609	-6.2336	47.02894	0.2714
C6%H	C8%S	19.94508	8.161017	-5.1558	45.04591	0.2286
C6%H	C6%S	19.52632	8.540800	-6.7426	45.79525	0.3084
C2%S	C8%H	19.44949	8.366479	-6.2833	45.18227	0.2876
C4%S	C8%H	18.28283	8.366479	-7.4499	44.01560	0.3668
C6%H	C8%H	17.41148	8.244496	-7.9461	42.76907	0.4123
C2%H	C6%H	6.60150	9.272065	-21.9166	35.11959	0.9965
C4%H	C6%H	6.56579	8.433364	-19.3727	32.50428	0.9940
C2%H	C4%S	5.73016	9.380696	-23.1220	34.58236	0.9987
C4%H	C4%S	5.69444	8.552654	-20.6109	31.99984	0.9977
C2%H	C2%S	4.56349	9.380696	-24.2887	33.41569	0.9997
C4%H	C2%S	4.52778	8.552654	-21.7776	30.83317	0.9995
C8%H	C8%S	2.53360	7.850392	-21.6118	26.67904	1.0000
C8%H	C6%S	2.11483	8.244496	-23.2428	27.47242	1.0000
C2%S	C6%H	2.03801	8.658609	-24.5933	28.66929	1.0000
C2%S	C4%S	1.16667	8.774837	-25.8221	28.15543	1.0000
C4%S	C6%H	0.87135	8.658609	-25.7599	27.50262	1.0000
C6%S	C8%S	0.41876	8.161017	-24.6821	25.51960	1.0000
C2%H	C4%H	0.03571	9.173198	-28.1783	28.24971	1.0000



Oneway Analysis of ASTM D906 Maximum Load By Open and Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.07731	0.05

HSD Threshold Matrix

Abs(Dif)-HSD

	O6%S	O4%H	O6%H	O8%H	O8%S	O2%H	O4%S	O2%S
O6%S	-54.006	-51.828	-43.661	-45.563	-42.155	-36.744	-33.206	-25.593
O4%H	-51.828	-59.161	-51.234	-53.014	-49.728	-44.260	-40.621	-32.968
O6%H	-43.661	-51.234	-48.851	-50.882	-47.345	-41.994	-38.563	-30.990
O8%H	-45.563	-53.014	-50.882	-54.006	-50.598	-45.187	-41.649	-34.036
O8%S	-42.155	-49.728	-47.345	-50.598	-48.851	-43.500	-40.069	-32.496
O2%H	-36.744	-44.260	-41.994	-45.187	-43.500	-51.235	-47.754	-40.162
O4%S	-33.206	-40.621	-38.563	-41.649	-40.069	-47.754	-55.572	-47.946
O2%S	-25.593	-32.968	-30.990	-34.036	-32.496	-40.162	-47.946	-57.283

Positive values show pairs of means that are significantly different.

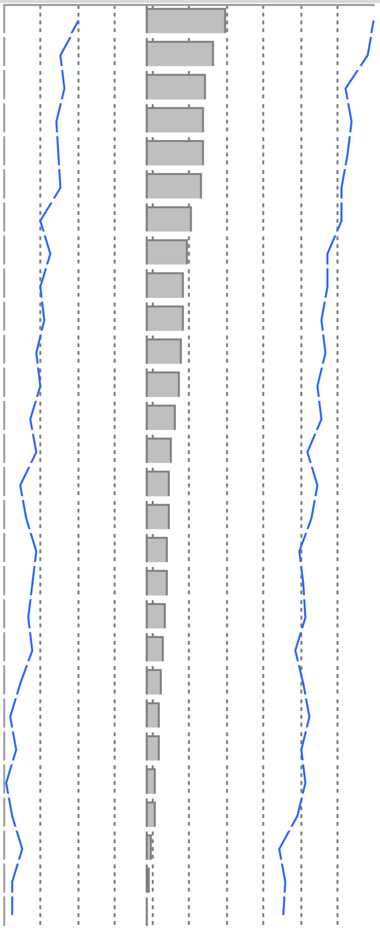
Connecting Letters Report

Level		Mean
O6%S	A	268.00732
O4%H	A	263.19247
O6%H	A	260.17529
O8%H	A	259.56413
O8%S	A	258.66918
O2%H	A	252.11255
O4%S	A	246.41863
O2%S	A	237.93124

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
O6%S	O2%S	30.07609	18.09001	-25.5925	85.74470	0.7111
O4%H	O2%S	25.26123	18.92216	-32.9682	83.49064	0.8839
O6%H	O2%S	22.24405	17.29880	-30.9898	75.47787	0.9027
O8%H	O2%S	21.63290	18.09001	-34.0357	77.30151	0.9319
O6%S	O4%S	21.58869	17.80610	-33.2063	76.38363	0.9270
O8%S	O2%S	20.73794	17.29880	-32.4959	73.97176	0.9311
O4%H	O4%S	16.77383	18.65093	-40.6209	74.16857	0.9857
O6%S	O2%H	15.89477	17.10551	-36.7442	68.53378	0.9827
O2%H	O2%S	14.18132	17.65923	-40.1617	68.52430	0.9927
O6%H	O4%S	13.75665	17.00169	-38.5629	66.07616	0.9924
O8%H	O4%S	13.14550	17.80610	-41.6494	67.94044	0.9957
O8%S	O4%S	12.25055	17.00169	-40.0690	64.57006	0.9963
O4%H	O2%H	11.07991	17.98328	-44.2603	66.42009	0.9986
O6%S	O8%S	9.33814	16.73316	-42.1550	60.83131	0.9993
O4%S	O2%S	8.48740	18.33868	-47.9465	64.92125	0.9998
O6%S	O8%H	8.44319	17.54989	-45.5633	62.44968	0.9997
O6%H	O2%H	8.06273	16.26649	-41.9943	58.11981	0.9997
O6%S	O6%H	7.83204	16.73316	-43.6611	59.32520	0.9998
O8%H	O2%H	7.45158	17.10551	-45.1874	60.09059	0.9999
O8%S	O2%H	6.55663	16.26649	-43.5004	56.61370	0.9999
O2%H	O4%S	5.69392	17.36829	-47.7537	59.14157	1.0000
O6%S	O4%H	4.81486	18.40648	-51.8276	61.45734	1.0000
O4%H	O8%S	4.52328	17.62948	-49.7281	58.77470	1.0000
O4%H	O8%H	3.62833	18.40648	-53.0141	60.27081	1.0000
O4%H	O6%H	3.01718	17.62948	-51.2342	57.26859	1.0000
O6%H	O8%S	1.50611	15.87447	-47.3446	50.35681	1.0000
O8%H	O8%S	0.89495	16.73316	-50.5982	52.38812	1.0000
O6%H	O8%H	0.61115	16.73316	-50.8820	52.10432	1.0000



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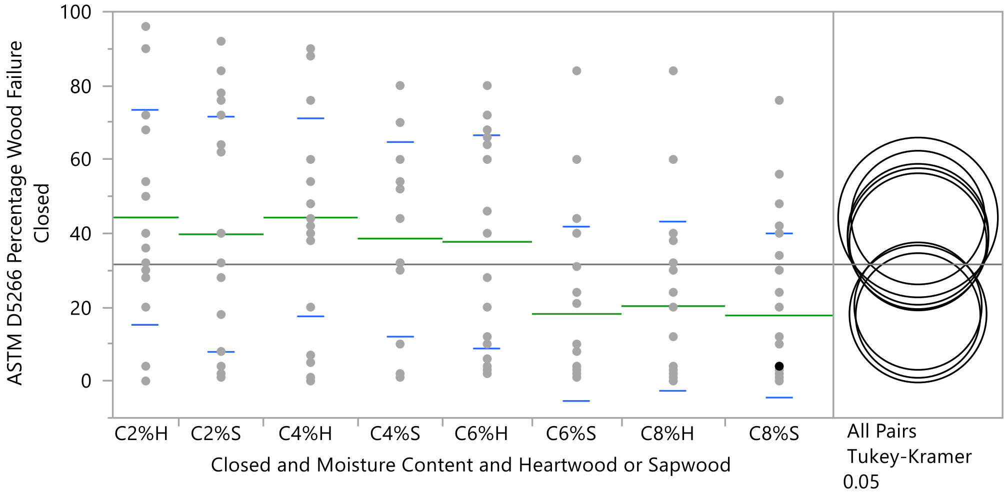
Oneway Analysis of ASTM D5266 Percentage Wood Failure By Closed and Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.07570	0.05

HSD Threshold Matrix
Abs(Dif)-HSD

	C2%H	C4%H	C2%S	C4%S	C6%H	C8%H	C6%S	C8%S
C2%H	-30.602	-28.178	-24.289	-23.122	-21.917	-3.668	-2.390	-0.899
C4%H	-28.178	-25.604	-21.778	-20.611	-19.373	-1.038	0.154	1.756
C2%S	-24.289	-21.778	-26.989	-25.822	-24.593	-6.283	-5.067	-3.497
C4%S	-23.122	-20.611	-25.822	-26.989	-25.760	-7.450	-6.234	-4.663
C6%H	-21.917	-19.373	-24.593	-25.760	-26.269	-7.946	-6.743	-5.156
C8%H	-3.668	-1.038	-6.283	-7.450	-7.946	-24.412	-23.243	-21.612
C6%S	-2.390	0.154	-5.067	-6.234	-6.743	-23.243	-26.269	-24.682
C8%S	-0.899	1.756	-3.497	-4.663	-5.156	-21.612	-24.682	-23.876

Positive values show pairs of means that are significantly different.

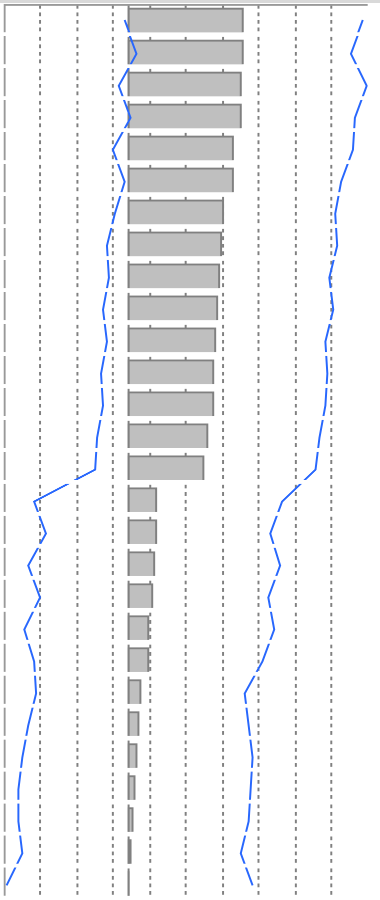
Connecting Letters Report

Level			Mean
C2%H	A	B	44.285714
C4%H	A		44.250000
C2%S	A	B	39.722222
C4%S	A	B	38.555556
C6%H	A	B	37.684211
C8%H	A	B	20.272727
C6%S		B	18.157895
C8%S		B	17.739130

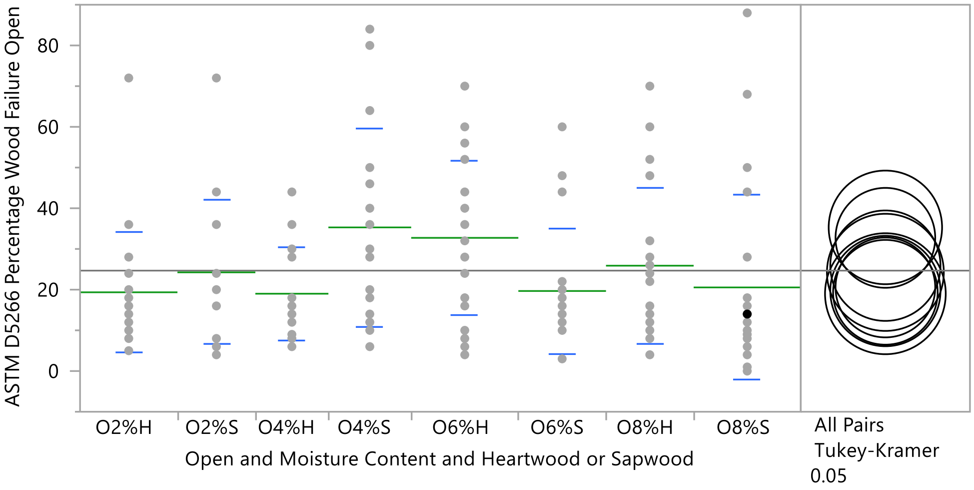
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
C2%H	C8%S	26.54658	8.923460	-0.8993	53.99246	0.0658
C4%H	C8%S	26.51087	8.048513	1.7561	51.26568	0.0266*
C2%H	C6%S	26.12782	9.272065	-2.3903	54.64591	0.0986
C4%H	C6%S	26.09211	8.433364	0.1536	52.03060	0.0475*
C2%H	C8%H	24.01299	8.999870	-3.6679	51.69388	0.1410
C4%H	C8%H	23.97727	8.133147	-1.0378	48.99239	0.0706
C2%S	C8%S	21.98309	8.284229	-3.4967	47.46289	0.1458
C2%S	C6%S	21.56433	8.658609	-5.0670	48.19561	0.2079
C4%S	C8%S	20.81643	8.284229	-4.6634	46.29622	0.1985
C4%S	C6%S	20.39766	8.658609	-6.2336	47.02894	0.2714
C6%H	C8%S	19.94508	8.161017	-5.1558	45.04591	0.2286
C6%H	C6%S	19.52632	8.540800	-6.7426	45.79525	0.3084
C2%S	C8%H	19.44949	8.366479	-6.2833	45.18227	0.2876
C4%S	C8%H	18.28283	8.366479	-7.4499	44.01560	0.3668
C6%H	C8%H	17.41148	8.244496	-7.9461	42.76907	0.4123
C2%H	C6%H	6.60150	9.272065	-21.9166	35.11959	0.9965
C4%H	C6%H	6.56579	8.433364	-19.3727	32.50428	0.9940
C2%H	C4%S	5.73016	9.380696	-23.1220	34.58236	0.9987
C4%H	C4%S	5.69444	8.552654	-20.6109	31.99984	0.9977
C2%H	C2%S	4.56349	9.380696	-24.2887	33.41569	0.9997
C4%H	C2%S	4.52778	8.552654	-21.7776	30.83317	0.9995
C8%H	C8%S	2.53360	7.850392	-21.6118	26.67904	1.0000
C8%H	C6%S	2.11483	8.244496	-23.2428	27.47242	1.0000
C2%S	C6%H	2.03801	8.658609	-24.5933	28.66929	1.0000
C2%S	C4%S	1.16667	8.774837	-25.8221	28.15543	1.0000
C4%S	C6%H	0.87135	8.658609	-25.7599	27.50262	1.0000
C6%S	C8%S	0.41876	8.161017	-24.6821	25.51960	1.0000
C2%H	C4%H	0.03571	9.173198	-28.1783	28.24971	1.0000



Oneway Analysis of ASTM D5266 Percentage Wood Failure By Open and Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.07731	0.05

HSD Threshold Matrix
Abs(Dif)-HSD

	O4%S	O6%H	O8%H	O2%S	O8%S	O6%S	O2%H	O4%H
O4%S	-19.746	-16.023	-10.065	-9.008	-3.842	-3.842	-3.047	-4.100
O6%H	-16.023	-17.358	-11.458	-10.438	-5.176	-5.236	-4.409	-5.550
O8%H	-10.065	-11.458	-19.190	-18.141	-12.953	-12.968	-12.165	-13.238
O2%S	-9.008	-10.438	-18.141	-20.354	-15.211	-15.197	-14.409	-15.440
O8%S	-3.842	-5.176	-12.953	-15.211	-17.358	-17.418	-16.591	-17.731
O6%S	-3.842	-5.236	-12.968	-15.197	-17.418	-19.190	-18.387	-19.460
O2%H	-3.047	-4.409	-12.165	-14.409	-16.591	-18.387	-18.205	-19.314
O4%H	-4.100	-5.550	-13.238	-15.440	-17.731	-19.460	-19.314	-21.021

Positive values show pairs of means that are significantly different.

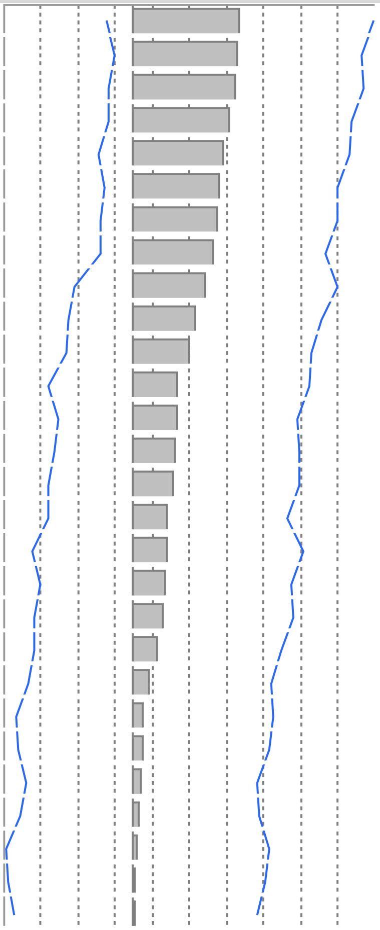
Connecting Letters Report

Level		Mean
O4%S	A	35.294118
O6%H	A	32.727273
O8%H	A	25.888889
O2%S	A	24.250000
O8%S	A	20.545455
O6%S	A	19.666667
O2%H	A	19.350000
O4%H	A	19.000000

Levels not connected by same letter are significantly different.

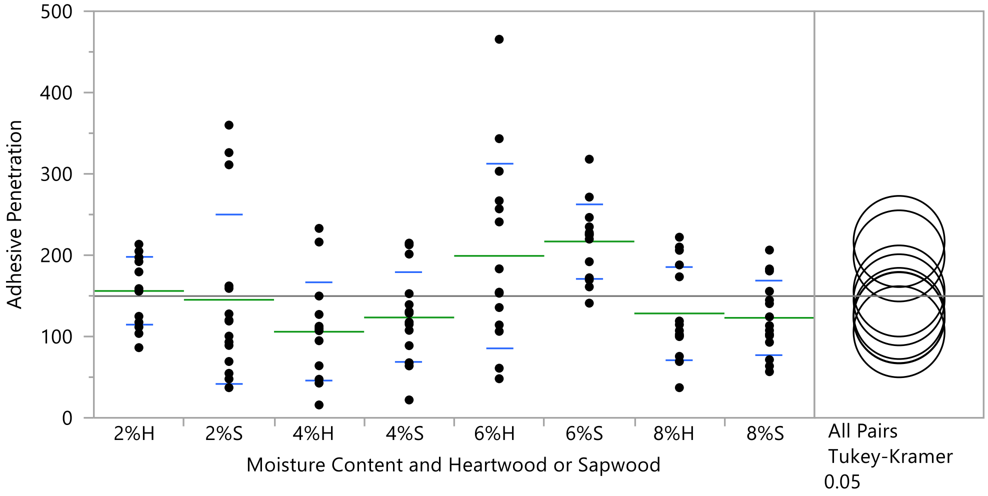
Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
O4%S	O4%H	16.29412	6.627110	-4.0996	36.68781	0.2222
O4%S	O2%H	15.94412	6.171357	-3.0471	34.93531	0.1708
O4%S	O6%S	15.62745	6.326924	-3.8425	35.09737	0.2171
O4%S	O8%S	14.74866	6.041097	-3.8417	33.33900	0.2300
O6%H	O4%H	13.72727	6.264165	-5.5495	33.00406	0.3633
O6%H	O2%H	13.37727	5.779864	-4.4092	31.16372	0.2933
O6%H	O6%S	13.06061	5.945682	-5.2361	31.35733	0.3602
O6%H	O8%S	12.18182	5.640569	-5.1760	29.53961	0.3826
O4%S	O2%S	11.04412	6.516161	-9.0081	31.09638	0.6906
O4%S	O8%H	9.40523	6.326924	-10.0647	28.87515	0.8134
O6%H	O2%S	8.47727	6.146668	-10.4379	27.39249	0.8653
O8%H	O4%H	6.88889	6.540250	-13.2375	27.01528	0.9651
O6%H	O8%H	6.83838	5.945682	-11.4583	25.13510	0.9442
O8%H	O2%H	6.53889	6.077988	-12.1650	25.24276	0.9608
O8%H	O6%S	6.22222	6.235884	-12.9675	25.41199	0.9741
O8%H	O8%S	5.34343	5.945682	-12.9533	23.64016	0.9858
O2%S	O4%H	5.25000	6.723486	-15.4403	25.94027	0.9939
O2%S	O2%H	4.90000	6.274737	-14.4093	24.20933	0.9939
O2%S	O6%S	4.58333	6.427802	-15.1970	24.36369	0.9965
O2%S	O8%S	3.70455	6.146668	-15.2107	22.61976	0.9988
O4%S	O6%H	2.56684	6.041097	-16.0235	21.15719	0.9999
O8%H	O2%S	1.63889	6.427802	-18.1415	21.41924	1.0000
O8%S	O4%H	1.54545	6.264165	-17.7313	20.82225	1.0000
O8%S	O2%H	1.19545	5.779864	-16.5910	18.98190	1.0000
O8%S	O6%S	0.87879	5.945682	-17.4179	19.17551	1.0000
O6%S	O4%H	0.66667	6.540250	-19.4597	20.79306	1.0000
O2%H	O4%H	0.35000	6.389880	-19.3137	20.01366	1.0000
O6%S	O2%H	0.31667	6.077988	-18.3872	19.02053	1.0000



Missing Rows5

Oneway Analysis of Adhesive Penetration By Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.08903	0.05

HSD Threshold Matrix
Abs(Dif)-HSD

	6%S	6%H	2%H	2%S	8%H	4%S	8%S	4%H
6%S	-79.279	-61.557	-18.423	-7.557	9.217	14.183	14.634	31.720
6%H	-61.557	-79.279	-36.145	-25.279	-8.504	-3.538	-3.087	13.999
2%H	-18.423	-36.145	-79.279	-68.413	-51.638	-46.672	-46.221	-29.135
2%S	-7.557	-25.279	-68.413	-79.279	-62.504	-57.538	-57.087	-40.001
8%H	9.217	-8.504	-51.638	-62.504	-79.279	-74.313	-73.862	-56.776
4%S	14.183	-3.538	-46.672	-57.538	-74.313	-79.279	-78.828	-61.742
8%S	14.634	-3.087	-46.221	-57.087	-73.862	-78.828	-79.279	-62.193
4%H	31.720	13.999	-29.135	-40.001	-56.776	-61.742	-62.193	-79.279

Positive values show pairs of means that are significantly different.

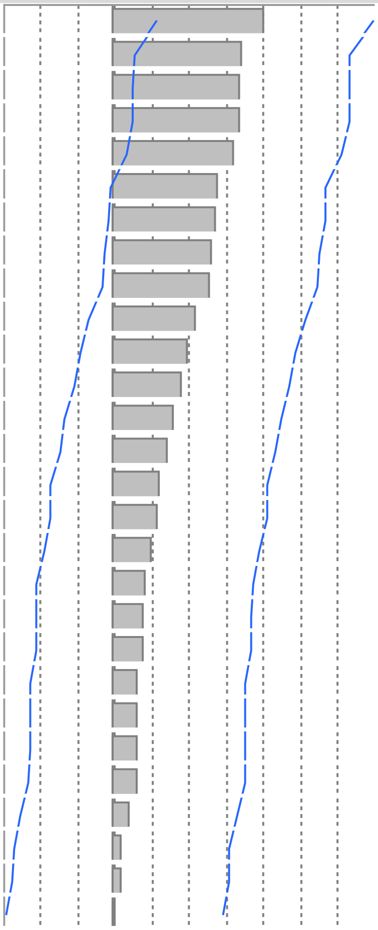
Connecting Letters Report

Level				Mean
6%S	A			216.85867
6%H	A	B		199.13733
2%H	A	B	C	156.00333
2%S	A	B	C	145.13733
8%H		B	C	128.36267
4%S		B	C	123.39667
8%S		B	C	122.94600
4%H			C	105.86000

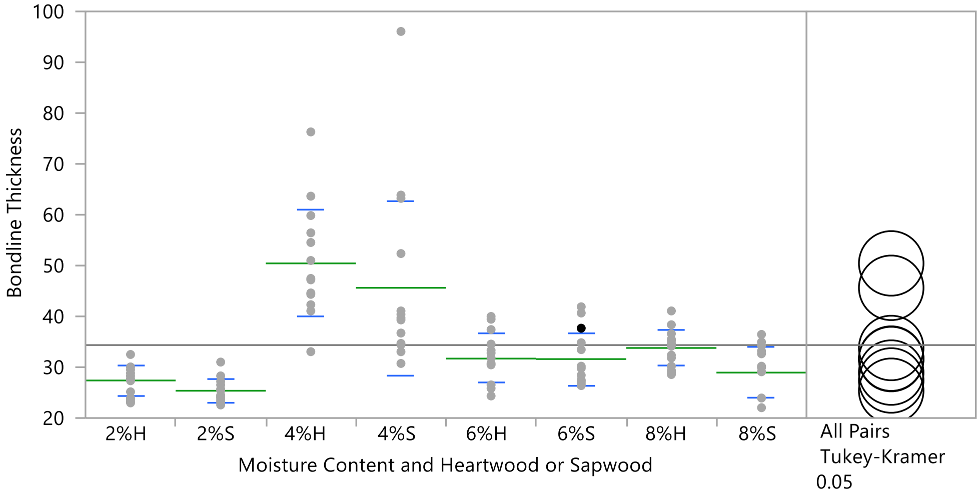
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
6%S	4%H	110.9987	25.66453	31.7201	190.2772	0.0008*
6%S	8%S	93.9127	25.66453	14.6341	173.1912	0.0090*
6%S	4%S	93.4620	25.66453	14.1835	172.7405	0.0095*
6%H	4%H	93.2773	25.66453	13.9988	172.5559	0.0097*
6%S	8%H	88.4960	25.66453	9.2175	167.7745	0.0175*
6%H	8%S	76.1913	25.66453	-3.0872	155.4699	0.0690
6%H	4%S	75.7407	25.66453	-3.5379	155.0192	0.0722
6%S	2%S	71.7213	25.66453	-7.5572	150.9999	0.1068
6%H	8%H	70.7747	25.66453	-8.5039	150.0532	0.1166
6%S	2%H	60.8553	25.66453	-18.4232	140.1339	0.2658
6%H	2%S	54.0000	25.66453	-25.2785	133.2785	0.4188
2%H	4%H	50.1433	25.66453	-29.1352	129.4219	0.5175
6%H	2%H	43.1340	25.66453	-36.1445	122.4125	0.6996
2%S	4%H	39.2773	25.66453	-40.0012	118.5559	0.7894
2%H	8%S	33.0573	25.66453	-46.2212	112.3359	0.9015
2%H	4%S	32.6067	25.66453	-46.6719	111.8852	0.9078
2%H	8%H	27.6407	25.66453	-51.6379	106.9192	0.9603
8%H	4%H	22.5027	25.66453	-56.7759	101.7812	0.9876
2%S	8%S	22.1913	25.66453	-57.0872	101.4699	0.9885
2%S	4%S	21.7407	25.66453	-57.5379	101.0192	0.9899
6%S	6%H	17.7213	25.66453	-61.5572	96.9999	0.9971
4%S	4%H	17.5367	25.66453	-61.7419	96.8152	0.9973
8%S	4%H	17.0860	25.66453	-62.1925	96.3645	0.9977
2%S	8%H	16.7747	25.66453	-62.5039	96.0532	0.9980
2%H	2%S	10.8660	25.66453	-68.4125	90.1445	0.9999
8%H	8%S	5.4167	25.66453	-73.8619	84.6952	1.0000
8%H	4%S	4.9660	25.66453	-74.3125	84.2445	1.0000
4%S	8%S	0.4507	25.66453	-78.8279	79.7292	1.0000



Oneway Analysis of Bondline Thickness By Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.08903	0.05

HSD Threshold Matrix
Abs(Dif)-HSD

	4%H	4%S	8%H	6%H	6%S	8%S	2%H	2%S
4%H	-8.988	-4.180	7.658	9.743	9.843	12.499	14.050	16.072
4%S	-4.180	-8.988	2.850	4.935	5.035	7.691	9.242	11.264
8%H	7.658	2.850	-8.988	-6.903	-6.803	-4.147	-2.596	-0.575
6%H	9.743	4.935	-6.903	-8.988	-8.889	-6.232	-4.682	-2.660
6%S	9.843	5.035	-6.803	-8.889	-8.988	-6.332	-4.782	-2.760
8%S	12.499	7.691	-4.147	-6.232	-6.332	-8.988	-7.438	-5.416
2%H	14.050	9.242	-2.596	-4.682	-4.782	-7.438	-8.988	-6.967
2%S	16.072	11.264	-0.575	-2.660	-2.760	-5.416	-6.967	-8.988

Positive values show pairs of means that are significantly different.

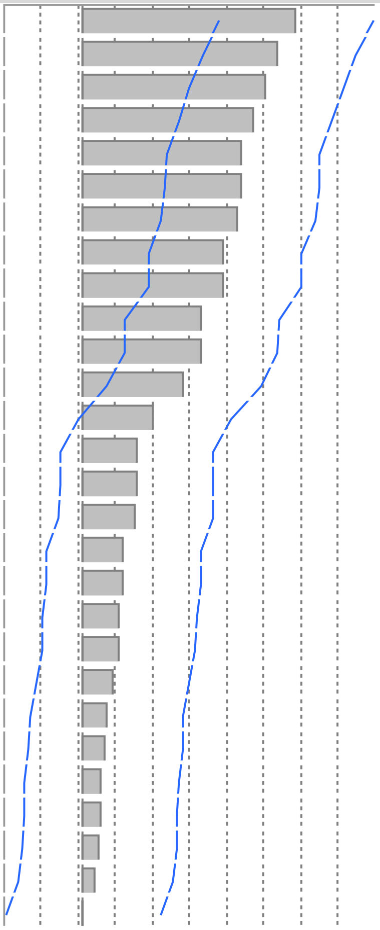
Connecting Letters Report

Level			Mean
4%H	A		50.428667
4%S	A		45.620673
8%H		B	33.782400
6%H		B	31.697067
6%S		B	31.597333
8%S		B	28.940800
2%H		B	27.390400
2%S		B	25.368533

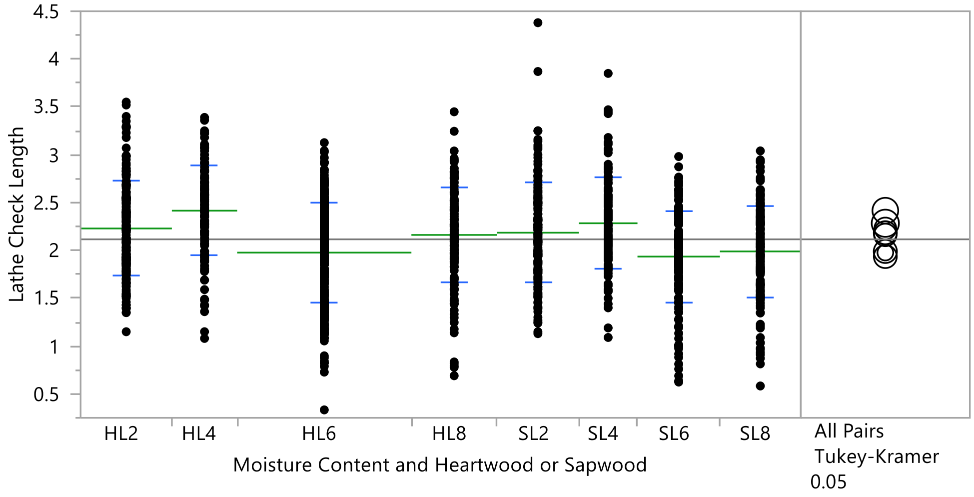
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
4%H	2%S	25.06013	2.909794	16.0717	34.04858	<.0001*
4%H	2%H	23.03827	2.909794	14.0498	32.02671	<.0001*
4%H	8%S	21.48787	2.909794	12.4994	30.47631	<.0001*
4%S	2%S	20.25214	2.909794	11.2637	29.24058	<.0001*
4%H	6%S	18.83133	2.909794	9.8429	27.81978	<.0001*
4%H	6%H	18.73160	2.909794	9.7432	27.72005	<.0001*
4%S	2%H	18.23027	2.909794	9.2418	27.21872	<.0001*
4%S	8%S	16.67987	2.909794	7.6914	25.66832	<.0001*
4%H	8%H	16.64627	2.909794	7.6578	25.63471	<.0001*
4%S	6%S	14.02334	2.909794	5.0349	23.01178	0.0001*
4%S	6%H	13.92361	2.909794	4.9352	22.91205	0.0001*
4%S	8%H	11.83827	2.909794	2.8498	20.82672	0.0022*
8%H	2%S	8.41387	2.909794	-0.5746	17.40231	0.0841
8%H	2%H	6.39200	2.909794	-2.5964	15.38045	0.3617
6%H	2%S	6.32853	2.909794	-2.6599	15.31698	0.3748
6%S	2%S	6.22880	2.909794	-2.7596	15.21725	0.3958
8%H	8%S	4.84160	2.909794	-4.1468	13.83005	0.7102
4%H	4%S	4.80799	2.909794	-4.1805	13.79644	0.7174
6%H	2%H	4.30667	2.909794	-4.6818	13.29511	0.8164
6%S	2%H	4.20693	2.909794	-4.7815	13.19538	0.8337
8%S	2%S	3.57227	2.909794	-5.4162	12.56071	0.9220
6%H	8%S	2.75627	2.909794	-6.2322	11.74471	0.9805
6%S	8%S	2.65653	2.909794	-6.3319	11.64498	0.9843
8%H	6%S	2.18507	2.909794	-6.8034	11.17351	0.9951
8%H	6%H	2.08533	2.909794	-6.9031	11.07378	0.9963
2%H	2%S	2.02187	2.909794	-6.9666	11.01031	0.9970
8%S	2%H	1.55040	2.909794	-7.4380	10.53885	0.9995
6%H	6%S	0.09973	2.909794	-8.8887	9.08818	1.0000



Oneway Analysis of Lathe Check Length By Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.03556	0.05

HSD Threshold Matrix

Abs(Dif)-HSD

	HL4	SL4	HL2	SL2	HL8	SL8	HL6	SL6
HL4	-0.19072	-0.06478	0.00930	0.04935	0.07435	0.24445	0.28001	0.29923
SL4	-0.06478	-0.20139	-0.12788	-0.08770	-0.06275	0.10742	0.14217	0.16217
HL2	0.00930	-0.12788	-0.16137	-0.12170	-0.09654	0.07336	0.11134	0.12820
SL2	0.04935	-0.08770	-0.12170	-0.17032	-0.14521	0.02475	0.06196	0.07957
HL8	0.07435	-0.06275	-0.09654	-0.14521	-0.16666	0.00327	0.04079	0.05810
SL8	0.24445	0.10742	0.07336	0.02475	0.00327	-0.17140	-0.13429	-0.11659
HL6	0.28001	0.14217	0.11134	0.06196	0.04079	-0.13429	-0.11679	-0.10408
SL6	0.29923	0.16217	0.12820	0.07957	0.05810	-0.11659	-0.10408	-0.16978

Positive values show pairs of means that are significantly different.

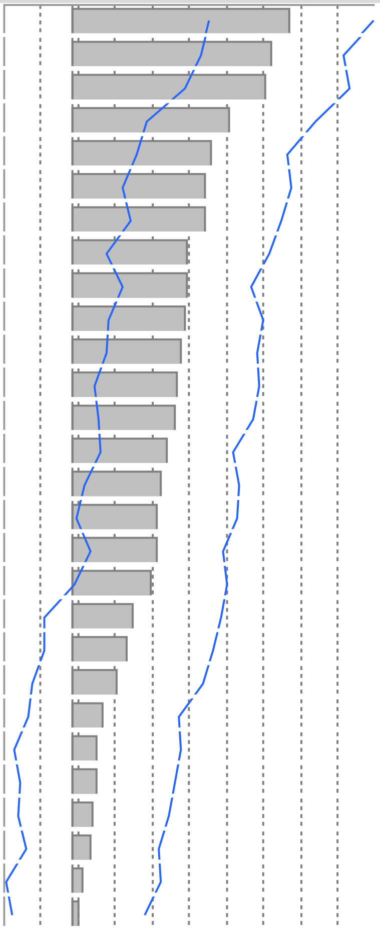
Connecting Letters Report

Level				Mean
HL4	A			2.4151587
SL4	A	B		2.2838053
HL2		B		2.2292045
SL2		B		2.1850000
HL8		B		2.1617091
SL8			C	1.9893846
HL6			C	1.9770119
SL6			C	1.9353774

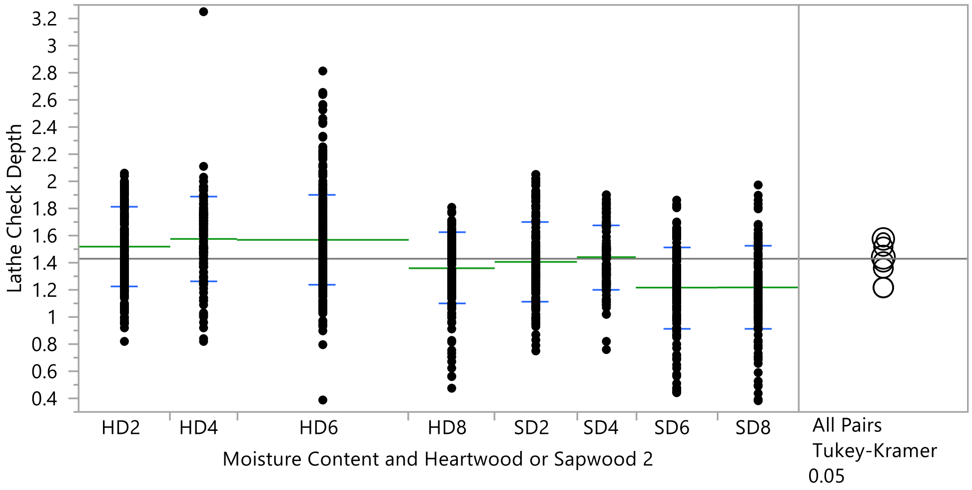
Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
HL4	SL6	0.4797814	0.0594799	0.299227	0.6603361	<.0001*
HL4	HL6	0.4381468	0.0520952	0.280009	0.5962849	<.0001*
HL4	SL8	0.4257741	0.0597322	0.244453	0.6070948	<.0001*
SL4	SL6	0.3484280	0.0613590	0.162169	0.5346868	<.0001*
SL4	HL6	0.3067934	0.0542308	0.142173	0.4714142	<.0001*
SL4	SL8	0.2944207	0.0616036	0.107419	0.4814221	<.0001*
HL2	SL6	0.2938272	0.0545631	0.128198	0.4594567	<.0001*
HL4	HL8	0.2534496	0.0589998	0.074352	0.4325472	0.0005*
HL2	HL6	0.2521926	0.0464024	0.111335	0.3930499	<.0001*
SL2	SL6	0.2496226	0.0560188	0.079574	0.4196712	0.0002*
HL2	SL8	0.2398199	0.0548380	0.073356	0.4062841	0.0004*
HL4	SL2	0.2301587	0.0595630	0.049352	0.4109659	0.0029*
HL8	SL6	0.2263317	0.0554196	0.058102	0.3945613	0.0012*
SL2	HL6	0.2079881	0.0481057	0.061960	0.3540159	0.0004*
SL2	SL8	0.1956154	0.0562866	0.024754	0.3664769	0.0123*
HL4	HL2	0.1859542	0.0581960	0.009297	0.3626117	0.0309*
HL8	HL6	0.1846972	0.0474066	0.040792	0.3286028	0.0026*
HL8	SL8	0.1723245	0.0556903	0.003273	0.3413758	0.0420*
HL4	SL4	0.1313534	0.0646109	-0.064777	0.3274838	0.4598
SL4	HL8	0.1220962	0.0608937	-0.062750	0.3069428	0.4787
SL4	SL2	0.0988053	0.0614396	-0.087698	0.2853089	0.7455
HL2	HL8	0.0674955	0.0540394	-0.096544	0.2315352	0.9169
SL4	HL2	0.0546008	0.0601153	-0.127883	0.2370843	0.9853
SL8	SL6	0.0540073	0.0561986	-0.116587	0.2246016	0.9797
HL2	SL2	0.0442045	0.0546537	-0.121700	0.2101092	0.9927
HL6	SL6	0.0416345	0.0480027	-0.104081	0.1873497	0.9888
SL2	HL8	0.0232909	0.0555088	-0.145210	0.1917914	0.9999
SL8	HL6	0.0123727	0.0483150	-0.134290	0.1590358	1.0000



Oneway Analysis of Lathe Check Depth By Moisture Content and Heartwood or Sapwood



Means Comparisons
Comparisons for all pairs using Tukey-Kramer HSD
Confidence Quantile

q*	Alpha
3.03558	0.05

HSD Threshold Matrix

Abs(Dif)-HSD

	HD4	HD6	HD2	SD4	SD2	HD8	SD8	SD6
HD4	-0.11353	-0.08776	-0.04866	0.01719	0.06123	0.10901	0.24935	0.25071
HD6	-0.08776	-0.07071	-0.03474	0.02862	0.07456	0.12257	0.26261	0.26400
HD2	-0.04866	-0.03474	-0.09682	-0.03190	0.01285	0.06072	0.20095	0.20231
SD4	0.01719	0.02862	-0.03190	-0.12083	-0.07709	-0.02935	0.11105	0.11239
SD2	0.06123	0.07456	0.01285	-0.07709	-0.10219	-0.05435	0.08592	0.08728
HD8	0.10901	0.12257	0.06072	-0.02935	-0.05435	-0.09999	0.04026	0.04162
SD8	0.24935	0.26261	0.20095	0.11105	0.08592	0.04026	-0.10284	-0.10148
SD6	0.25071	0.26400	0.20231	0.11239	0.08728	0.04162	-0.10148	-0.10251

Positive values show pairs of means that are significantly different.

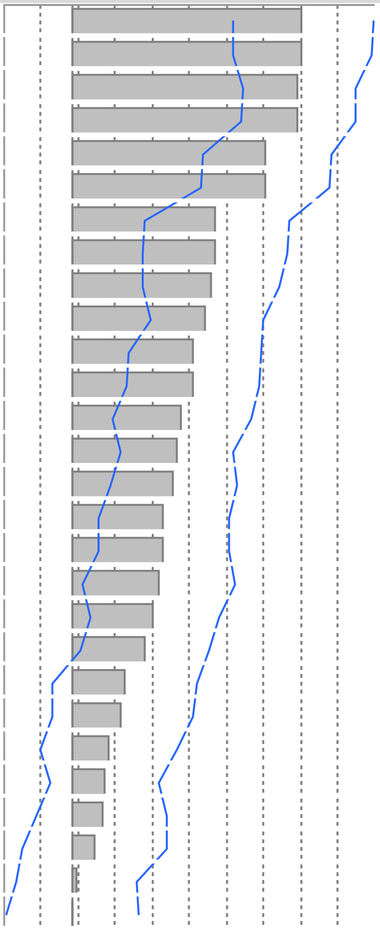
Connecting Letters Report

Level					Mean
HD4	A				1.5753125
HD6	A				1.5685000
HD2	A	B			1.5184659
SD4		B	C		1.4408850
SD2			C		1.4060759
HD8			C		1.3593273
SD8				D	1.2176410
SD6				D	1.2164459

Levels not connected by same letter are significantly different.

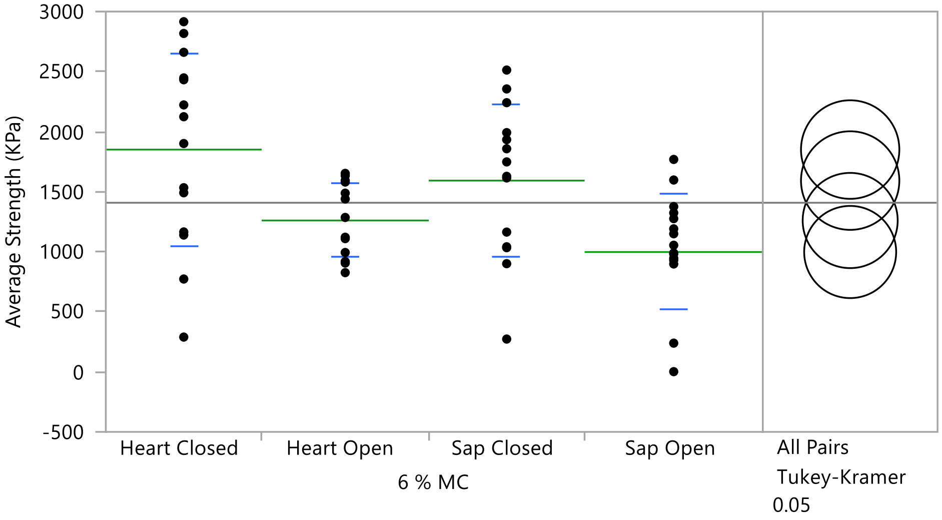
Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
HD4	SD6	0.3588666	0.0356312	0.250705	0.4670281	<.0001*
HD4	SD8	0.3576715	0.0356825	0.249354	0.4659885	<.0001*
HD6	SD6	0.3520541	0.0290082	0.263997	0.4401109	<.0001*
HD6	SD8	0.3508590	0.0290711	0.262611	0.4391068	<.0001*
HD2	SD6	0.3020200	0.0328457	0.202314	0.4017260	<.0001*
HD2	SD8	0.3008249	0.0329013	0.200950	0.4006996	<.0001*
SD4	SD6	0.2244391	0.0369110	0.112393	0.3364855	<.0001*
SD4	SD8	0.2232439	0.0369605	0.111047	0.3354405	<.0001*
HD4	HD8	0.2159852	0.0352411	0.109008	0.3229626	<.0001*
HD6	HD8	0.2091727	0.0285277	0.122575	0.2957709	<.0001*
SD2	SD6	0.1896301	0.0337163	0.087281	0.2919787	<.0001*
SD2	SD8	0.1884349	0.0337705	0.085922	0.2909479	<.0001*
HD4	SD2	0.1692366	0.0355805	0.061229	0.2772442	<.0001*
HD6	SD2	0.1624241	0.0289459	0.074556	0.2502918	<.0001*
HD2	HD8	0.1591386	0.0324222	0.060719	0.2575588	<.0001*
HD8	SD6	0.1428814	0.0333579	0.041621	0.2441422	0.0005*
HD8	SD8	0.1416862	0.0334127	0.040259	0.2431132	0.0006*
HD4	SD4	0.1344275	0.0386214	0.017189	0.2516658	0.0121*
HD6	SD4	0.1276150	0.0326114	0.028621	0.2266095	0.0024*
HD2	SD2	0.1123900	0.0327908	0.012851	0.2119290	0.0145*
SD4	HD8	0.0815577	0.0365346	-0.029346	0.1924614	0.3329
HD2	SD4	0.0775810	0.0360675	-0.031905	0.1870669	0.3826
HD4	HD2	0.0568466	0.0347567	-0.048660	0.1623534	0.7286
HD6	HD2	0.0500341	0.0279271	-0.034741	0.1348089	0.6259
SD2	HD8	0.0467487	0.0333038	-0.054348	0.1478451	0.8558
SD4	SD2	0.0348090	0.0368621	-0.077089	0.1467069	0.9816
HD4	HD6	0.0068125	0.0311554	-0.087762	0.1013874	1.0000
SD8	SD6	0.0011952	0.0338239	-0.101480	0.1038703	1.0000



Missing Rows6

Oneway Analysis of Average EN 314-1 Wet Strength (KPa) By 6 % MC



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Confidence Quantile

q*	Alpha
2.64937	0.05

HSD Threshold Matrix

Abs(Dif)-HSD

	Heart Closed	Sap Closed	Heart Open	Sap Open
Heart Closed	-580.37	-322.09	20.03	291.09
Sap Closed	-322.09	-580.37	-238.25	32.81
Heart Open	20.03	-238.25	-560.69	-289.47
Sap Open	291.09	32.81	-289.47	-542.88

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level				Mean
Heart Closed	A			1850.8395
Sap Closed	A	B		1592.5586
Heart Open		B	C	1260.1978
Sap Open			C	997.8127

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Heart Closed	Sap Open	853.0268	212.1026	291.089	1414.964	0.0010*
Sap Closed	Sap Open	594.7459	212.1026	32.808	1156.683	0.0341*
Heart Closed	Heart Open	590.6417	215.3767	20.030	1161.254	0.0398*
Sap Closed	Heart Open	332.3608	215.3767	-238.251	902.973	0.4193
Heart Open	Sap Open	262.3851	208.2978	-289.472	814.242	0.5921
Heart Closed	Sap Closed	258.2809	219.0586	-322.086	838.648	0.6425