

AN ABSTRACT OF THE THESIS OF

Dylan Willard for the degree of Master of Science in Wood Science presented on July 21, 2021.

Title: Analysis of Adhesive Atomization on Composite Bond Performance

Abstract approved:

Fredrick A. Kamke

Spraying of liquid adhesive onto wood surfaces has shown to be a highly effective and efficient method of application across many different wood-based composite industries. However, the dynamics of spraying are extremely variable and distribution can be affected by liquid properties (rheology, molecular weight distribution, and temperature), application parameters (disk atomizers, spray nozzles, air-less, mixing, air pressure), and manufacturing equipment (blender design, nozzle configuration). There is a need for more insight into what defines an optimal droplet size, or size distribution, for a given product. The goal of this project was to establish guidelines for the atomization of resin for OSB manufacture. Phenol-formaldehyde resin distribution was studied to identify relationships between wood species, resin spot size, resin molecular weight, resin viscosity, and atomizer control. Atomization was created using a spinning disk system, where disk speed was a test parameter. Lap-shear and internal bond tests were used as a metric for the effectiveness of different resin distribution patterns created by the independent variables of resin molecular weight and disk speed. Aspen and southern pine strands were used. Digital image analysis and a

scanning laser microscope were used to measure resin distribution parameters of spot size and surface coverage.

In the process of making strand board using a spinning disk atomizer, resin distribution on strands is impacted by the disk speed of the atomizer and resin viscosity. In this study it was found that increasing atomizer speed decreases the size of resin spots detected on the strand surface. Furthermore, increasing viscosity by advancing polymerization increased resin spot size. Overall, smaller resin spot size, increased area coverage, and a continuous resin spot size distribution led to increased bondline performance.

©Copyright by Dylan Willard

July 21, 2021

All Rights Reserved

Analysis of Adhesive Atomization on Composite Bond Performance

by

Dylan Willard

A THESIS

submitted to

Oregon State University

in partial fulfillment of the
requirements for the
degree of

Master of Science

Presented July 21, 2021

Commencement June 2022

Master of Science thesis of Dylan Willard presented on July 21, 2021.

APPROVED:

Major Professor, representing Wood Science

Head of the Department of Wood Science & Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Dylan Willard, Author

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Fred Kamke allowing me the opportunity to take part in this project which taught me many valuable skills and lessons I will take with me for the rest of my life.

I would also like to thank the rest of my committee members for their support:
Dr. John Nairn, Dr. Jason Ideker, and Dr. Matthew Powers

Thank you to Tomáš Pipíška for helping to set up the project and your guidance whenever I first arrived at OSU.

Financial support for this project was provided by the Wood Based Composite Center and a special thank you goes out to my technical committee members:

Jesse Pairs, Sudip Choudhury, Christa Stables, and Jim Ni

Thank you to all of the wonderful WSE staff who have helped me along my way especially:

Milo Clausen, Tyler DeBoodt, Scott Leavengood, John Simonsen, Laurence Schimleck, Jessica King, and Angela Haney

Finally, I would like to thank all of my friends from WSE:

Ryan Longman, Matthias Wind, Micah Sutfin, Luis Molina, Ian Morrell, Maria Munoz, Kenneth Udele, Sujit Bhandari, Mohit Srivastava, and Talbot Rueppel

TABLE OF CONTENTS

	<u>Page</u>
1. Introduction.....	1
1.1 Background.....	1
1.2 Goals and Objectives	1
1.3 Project Overview	2
2. Literature Review.....	3
2.1 Oriented Strand Board (OSB).....	3
2.2 Phenol-formaldehyde Resin.....	11
2.3 Isocyanate Resin	15
2.4 Spinning Disk Resin Atomizer	17
2.5 Resin Atomization	19
2.6 Influence of Resin Distribution on Bond Performance.....	23
3. Materials and Methods.....	29
3.1 Phenol-formaldehyde Resin Characterization	29
3.1.1 Resin Molecular Weight	29
3.1.2 Influence of Temperature on Viscosity.....	30
3.1.3 Influence of Temperature on Surface Tension.....	30
3.2 Lap-Shear Specimen Preparation and Testing.....	31
3.3 Panel Manufacture and Testing	40
3.4 Resin Distribution Analysis	43
3.5 Statistical Analysis.....	48
4. Results and Discussion	49
4.1 Resin Characterization.....	49

TABLE OF CONTENTS (Continued)

	<u>Page</u>
4.1.1 Resin Molecular Weight	49
4.1.2 Influence of Temperature on Viscosity.....	49
4.1.3 Influence of Temperature on Surface Tension.....	50
4.2 Lap-Shear Testing	52
4.3 Panel Testing.....	54
4.3.1 Internal Bond	54
4.3.2 Medium Viscosity Resin Internal Bond.....	57
4.3.3 Three Point Bending	60
4.4 Resin Distribution	63
4.4.1 Blender Strand Image Analysis	64
4.4.2 Lap-Shear Strand Image Analysis	72
4.4.3 Blender Strand Resin Area Coverage	80
4.4.4 Observations and Comparisons from Image Analysis.....	84
5. Conclusion	87
6. Bibliography	90
7. Appendix.....	94

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 2-1, Knife-ring log strander (left) and knife-ring strand cutting detail (right) (Kadant Inc. , n.d.).	4
Figure 2-2, OSB Strand Dryer (Siempelkamp, 2020).	5
Figure 2-3, Coil OSB Blender (NDI, Inc., 2020).	6
Figure 2-4, OSB Forming Line (Siempelkamp, 2020)	7
Figure 2-5, Siempelkamp Gmbh ContiRoll continuous press, and Dieffenbacher Gmbh CPS+ continuous press system concept (Siempelkamp, 2020).	8
Figure 2-6, OSB Continuous Hot Press Model (Pereira, Carvalho, & Costa, 2004).	8
Figure 2-7, Dieffenbacher multi-opening press (Left) and Siemplekamp multi-opening press (Right) (Siempelkamp LP, 2004).	9
Figure 2-8, OSB Manufacturing Schematic (Longwood, 1997).	10
Figure 2-9, Experimental plots of viscosity η_a vs. molecular weight (M): (A) polydimethyl siloxane, (B) polyisobutylene, (c) polyethylene, (D) polybutadiene, (E) polytetramethyl p-sulphen1 siloxane, (F) poly(methyl methacrylate), (G) poly(ethylene glycol), (H) poly(vinyl acetate), and (I) polystyrene. (Painter & Coleman, 2009).	15
Figure 2-10, PMDI Synthesis (Conner, 2001)	16
Figure 2-11, Concept of spinning disk atomization showing liquid application to spinning disk (right) and creation of ligaments, and ultimately, droplets of liquid (left) (Graco, 1995)	18
Figure 2-12, Coil spinning disk atomizer (Coil Manufacturing, 2020)	19
Figure 2-13, NDI spinning disk atomizer (NDI, Inc., 2020)	19

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 2-14, Centrifugal atomization of liquids: (A) Direct droplet formation, can result from a high atomizer RPM and a low resin flow rate. (B) Direct droplet and ligament formation, can result from a high atomizer RPM or a low resin flow rate. (C) Ligament formation, can result from balanced atomizer RPM and resin flow rate. (D) Film or sheet formation, can result from a low atomizer RPM and a high liquid flow rate. (Zhang, Muszynski, & Gardner, 2008).....	22
Figure 2-15, Images of resin spots on wood surface. (A) Before hot pressing, (B) after hot pressing.	26
Figure 2-16, Fracture toughness (G_{Ic}) as a function of resin area coverage, showing 95% confidence interval bars. The curves are least-square fits of a square root relationship. S represents spacing between droplets. (Conrad, Smith, & Fernlund, 2003)	27
Figure 3-1, Biolin Scientific Theta Lite tensiometer connected to Julabo circulating water bath.....	31
Figure 3-2, Rotating Drum Blender	33
Figure 3-3, Custom OSB blender door with pneumatic slide used for strand insertion.	34
Figure 3-4, Pneumatic slide as viewed on inside of OSB blender door, with slide open.	34
Figure 3-5, Pneumatic slide as viewed on inside of OSB blender door, with slide closed.	35

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 3-6, Custom strands on OSB blender door pneumatic slide.....	36
Figure 3-7, Front side of the spinning disk atomizer. Atomizer cone, resin well exit holes, and drive shaft are depicted in image.	37
Figure 3-8 Side view section of blender with lap-shear strand insertion device.	38
Figure 3-9, Drawing of lap-shear specimen without spacers (dimension in inches) ..	39
Figure 3-10, Lap-shear specimen without spacers.....	39
Figure 3-11, Drawing of lap-shear specimen with spacers (dimension in inches)	40
Figure 3-12, Lap-shear specimen with spacers.....	40
Figure 3-13, Strand board cutting diagram	43
Figure 3-14, Cropped image imported into ImageJ	45
Figure 3-15, Image in 8-bit grey scale	46
Figure 3-16, Grey scale histogram, manual section of threshold.	47
Figure 4-1, Influence of temperature on viscosity experiment.	50
Figure 4-2, Box plot of aspen lap-shear specific failure stress for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	52
Figure 4-3, Box plot of southern pine lap-shear specific failure stress for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	53
Figure 4-4, Box Plot of aspen internal bond strength for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	55
Figure 4-5, Box Plot of southern pine internal bond strength for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	56

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 4-6, Plot of medium viscosity resin aspen internal bond strength as a function of density, with atomizer speeds: 7,000 RPM (Red), 10,000 RPM (Green), and 13,000 RPM (Blue).....	58
Figure 4-7, Plot of medium viscosity resin southern pine internal bond strength as a function of density, with atomizer speeds: 7,000 RPM (Red), 10,000 RPM (Green), and 13,000 RPM (Blue).....	59
Figure 4-8, Box plot of aspen strand board MOR for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	61
Figure 4-9, Box plot for southern pine MOR for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.....	62
Figure 4-10, Cumulative fraction of area coverage up to 25% for aspen blender strands.	65
Figure 4-11, Cumulative fraction of area coverage up to 50% for aspen blender strands.	66
Figure 4-12, Cumulative fraction of area coverage up to 75% for aspen blender strands.	67
Figure 4-13, Cumulative fraction of area coverage for aspen blender strands.	68
Figure 4-14, Cumulative fraction of area coverage up to 25% for southern pine blender strands.	69
Figure 4-15, Cumulative fraction of area coverage up to 50% for southern pine blender strands.	70

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 4-16, Cumulative fraction of area coverage up to 75% for southern pine blender strands.	71
Figure 4-17, Cumulative fraction of area coverage for southern pine blender strands.	72
Figure 4-18, Cumulative fraction of area coverage up to 25% for aspen lap-shear strands.	73
Figure 4-19, Cumulative fraction of area coverage up to 50% for aspen lap-shear strands.	74
Figure 4-20, Cumulative fraction of area coverage up to 75% for aspen lap-shear strands.	75
Figure 4-21, Cumulative fraction of area coverage for aspen lap-shear strands.	76
Figure 4-22, Cumulative fraction of area coverage up to 25% for southern pine lap-shear strands.	77
Figure 4-23, Cumulative fraction of area coverage up to 50% for southern pine lap-shear strands.	78
Figure 4-24, Cumulative fraction of area coverage up to 75% for southern pine lap-shear strands.	79
Figure 4-25, Cumulative fraction of area coverage for southern pine lap-shear strands.	80
Figure 4-26, Percent area coverage for aspen blender strands.	81
Figure 4-27, Percent area coverage for SYP blender strands	82

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 4-26, Resin spot size count for aspen lap-shear strands sprayed at 7,000 RPM in increments of 0.001 mm ²	85
Figure 4-27, Resin spot size count for aspen lap-shear strands sprayed at 7,000 RPM in increments of 0.001 mm ² with the vertical axis expanded	85
Figure 7-1, Aspen blender strand LV resin 7,000 RPM	94
Figure 7-2, Aspen blender strand LV resin 10,000 RPM	95
Figure 7-3, Aspen blender strand LV resin 13,000 RPM	96
Figure 7-4, Aspen blender strand MV resin 7,000 RPM	97
Figure 7-5, Aspen blender strand MV resin 10,000 RPM	98
Figure 7-6, Aspen blender strand MV resin 13,000 RPM	99
Figure 7-7, Aspen blender strand HV resin 7,000 RPM	100
Figure 7-8, Aspen blender strand HV resin 10,000 RPM	101
Figure 7-9, Aspen blender strand HV resin 13,000 RPM	102
Figure 7-10, Southern pine blender strand LV resin 7,000 RPM	103
Figure 7-11, Southern pine blender strand LV resin 10,000 RPM	104
Figure 7-12, Southern pine blender strand LV resin 13,000 RPM	105
Figure 7-13, Southern pine blender strand MV resin 7,000 RPM	106
Figure 7-14, Southern pine blender strand MV resin 10,000 RPM	107
Figure 7-15, Southern pine blender strand MV resin 13,000 RPM	108
Figure 7-16, Southern pine blender strand HV resin 7,000 RPM	109
Figure 7-17, Southern pine blender strand HV resin 10,000 RPM	110

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
Figure 7-18, Southern pine blender strand HV resin 13,000 RPM.....	111
Figure 7-19, Aspen lap-shear strand LV resin 7,000 RPM.....	112
Figure 7-20, Aspen lap-shear strand LV resin 10,000 RPM.....	113
Figure 7-21, Aspen lap-shear strand LV resin 13,000 RPM.....	114
Figure 7-22, Aspen lap-shear strand MV resin 7,000 RPM	115
Figure 7-23, Aspen lap-shear strand MV resin 10,000 RPM	116
Figure 7-24, Aspen lap-shear strand MV resin 13,000 RPM	117
Figure 7-25, Aspen lap-shear strand HV resin 7,000 RPM	118
Figure 7-26, Aspen lap-shear strand HV resin 10,000 RPM	119
Figure 7-27, Aspen lap-shear strand HV resin 13,000 RPM	120
Figure 7-28, Southern pine lap-shear strand LV resin 7,000 RPM	121
Figure 7-29, Southern pine lap-shear strand LV resin 10,000 RPM	122
Figure 7-30, Southern pine lap-shear strand LV resin 13,000 RPM	123
Figure 7-31, Southern pine lap-shear strand MV resin 7,000 RPM	124
Figure 7-32, Southern pine lap-shear strand MV resin 10,000 RPM	125
Figure 7-33, Southern pine lap-shear strand MV resin 13,000 RPM	126
Figure 7-34, Southern pine lap-shear strand HV resin 7,000 RPM	127
Figure 7-35, Southern pine lap-shear strand HV resin 10,000 RPM	128
Figure 7-36, Southern pine lap-shear strand HV resin 13,000 RPM	129

LIST OF TABLES

<u>Table</u>	<u>Page</u>
Table 3-1. Resin viscosity on the day of lap-shear specimen fabrication.....	37
Table 3-2. Resin viscosities on the day of strand board fabrication.	41
Table 3-3. Strand board specifications.....	41
Table 3-4. Pressing schedule.....	42
Table 4-1, Molecular weight and polydispersity index in grams per mole for PF adhesives used in the experiment. Number average (Mn), weight average (Mw), Z average (Mz).	49
Table 4-2, Influence of temperature on surface tension for three different tests on one resin. Viscosity was also measured at the time of each surface tension test.	51
Table 4-3, Aspen lap-shear two-way ANOVA.....	53
Table 4-4, Southern pine lap-shear two-way ANOVA.....	54
Table 4-5. Aspen internal bond ANOVA	56
Table 4-6, Southern pine internal bond ANOVA	57
Table 4-7, Aspen medium viscosity resin internal bond ANOVA	60
Table 4-8, Southern pine medium viscosity resin internal bond ANOVA	60
Table 4-9, Aspen strand board MOR ANOVA	62
Table 4-10, Southern pine strand board MOR ANOVA	62
Table 4-11, Resin spot size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of aspen blender strands in mm ²	64

LIST OF TABLES (Continued)

<u>Table</u>	<u>Page</u>
Table 4-12, Resin spot size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of southern pine blender strands in mm ²	68
Table 4-13, Droplet size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of southern pine lap-shear strands in mm ²	76
Table 4-14, Percent of strand area coverage of resin on blender strands.	82
Table 4-15, Percent of strand area coverage of resin on aspen strands ANOVA.....	83
Table 4-16, Percent of strand area coverage on southern pine strands ANOVA	83
Table 7-1, Estimated mass of resin on Aspen lap-shear strands in grams.....	129
Table 7-2, Estimated mass of resin on SYP lap-shear strands in grams.....	131

1. Introduction

1.1 Background

Oriented strand board (OSB) is a common engineered wood product used in the construction industry as a sheathing material. OSB is made up of wood strands that are cut using a ring log strander. Phenolic and or isocyanate adhesives, depending on the manufacturer, are used for bonding the strands in OSB. Adhesive is applied to the OSB strands using a spinning disk atomizer inside of a rotating drum. A spinning disk atomizer operates by using centrifugal force to atomize liquids that are dispensed onto the inside of a conical disk spinning at RPM's of up to 18,000 RPM.

To ensure the quality and bondline performance of OSB it is important to understand the factors that influence resin distribution. Methods of adhesive application have a direct influence on resin distribution. This project analyzes the effect of altering atomizer RPM and resin molecular weight and their impact on bondline performance, strand board properties, and resin distribution. Three different atomizer RPM's and three different resin molecular weights were used in combination in this study.

1.2 Goals and Objectives

The goal of this project is to establish guidelines for the atomization of resin for a wood strand composite. Specific objectives are to:

- 1) Determine if the same distribution of spot size of phenol-formaldehyde resin will provide equal performance for bonding aspen and southern pine strands.
- 2) Characterize the effect of phenol-formaldehyde resin viscosity on spot size distribution and coverage.
- 3) Determine if spinning disk speed of the atomizer changes phenol-formaldehyde spot size distribution or surface coverage.

These objectives were achieved by characterizing each of the three resins used in this project, performing mechanical testing on strand board and isolated adhesive

bonds, and measurement of resin distribution using microscopy and digital image analysis.

1.3 Project Overview

To characterize the phenol-formaldehyde resin (PF) used in this project, tests were performed to understand the impact of temperature on viscosity and impact of temperature on surface tension of resins with varying molecular weights. Temperature, surface tension, and viscosity have a direct influence on the characteristics of PF, therefore understanding these properties provide an effective way to maintain or manipulate the atomizer spray pattern. Because two of the three resins used in this project had their molecular weight advanced, an analysis of average molecular weight and molecular weight distribution was conducted to further characterize the resin.

To determine the effect of adhesive molecular weight and spray distribution patterns on individual bondlines, custom strands were crafted and sprayed with resin under specific constraints. These specimens were tested in shear according to ASTM D-2339 (ASTM, 2021). An estimation of the mass of adhesive on each strand was also measured. Along with strands for shear testing, strands were also sprayed for image analysis of resin distribution.

To determine the effect of adhesive molecular weight and spray distribution patterns on strand board bondlines, strand boards were manufactured. Internal bond testing and three-point bending tests were conducted according to ASTM D-1037 (ASTM, 2020). Individual strands from the furnish were also randomly selected for resin distribution analysis.

Using samples taken throughout the project, image analysis was conducted to determine the variation in resin spot size and percentage of resin coverage on the wood strands caused by various atomizer speeds and resin molecular weights. Digital images of strands were obtained using a laser scanning microscope in focus variation mode. These images were then analyzed using software to determine the percentage of resin coverage and the distribution of resin spot size.

2. Literature Review

2.1 Oriented Strand Board (OSB)

Oriented Strand Board (OSB) is an engineered wood product commonly used in the construction industry as a sheathing material for roofing, walls, and floors. OSB panels are made from layers of thin wood strands with common grain directions that are bound by water resistant adhesives. As layers of wood strands are stacked, they are given alternating grain directions in three layers, which run perpendicular to one another. The layers are commonly called “face” and “core”. Alternating the grain direction creates a final product with increased dimensional stability, as opposed to a wood strand product with no grain orientation, like waferboard. Panels can be treated with moisture resistant sealant and textured to provide a more abrasive surface for workers walking on them (The Engineered Wood Association, 2017). In 1965 OSB was patented by Armin Elmendorf as waferboard. It wasn’t until the late 1970’s OSB was distinguishable from waferboard. Much more time, research and development was required to make it the structural product that it is today (Zerbe, Cai, & Harpole, 2015).

Waferboard was the first engineered wood product made entirely from wood strands. Prior to the invention of waferboard, there was chipboard, which was often confused with waferboard. While waferboard and chipboard may have similar external appearances, chipboard has a core made of fine ground wood fibers that are overlaid with wood strands. Waferboard and OSB have a very similar manufacturing process. The defining characteristics between waferboard and OSB are the strands used and the mat forming process. Compared to waferboard, OSB uses longer narrow strands, which are laid into mats with oriented grain directions. Waferboard does not have a common direction in which the strands lie (Stark, Cai, & Carll, 2010).

The manufacturing process for OSB begins with the debarking of a log. Trimmed trees arrive at a mill where they are cut into 8, 16, or 24 feet in length and immediately have their bark removed. Once debarked, logs are either sent to a soaking pond to heat or directly to a strander (Stark, Cai, & Carll, 2010). Soaking logs in hot water decreases the strength of the lignin bonds between the cellulosic fibers. This

allows the fibers to separate with ease and ultimately causes less damage to the fibers than stranding dry logs (Youngquist, 1999).

After soaking, logs are sent through a strander (*Error! Reference source not found.*). The most common type of strander is a long-log ring strander (Stark, Cai, & Carll, 2010). A ring strander operates by rotating a drum around a fixed log. Within the rotating drum, there are multiple cutting apparatus which shave strands off the log (USA Patent No. US 7,938,155 B2, 2008). The typical strand dimensions for OSB are 0.5 inches in width, 4.5-6 inches in length, and 0.023-0.027 inches in thickness (Stark, Cai, & Carll, 2010). Actual strand dimensions are controlled to the manufacturer's specifications. As illustrated in *Figure 2-2*, strand length corresponds to the longitudinal direction, whereas width and thickness is somewhat randomly distributed between radial and tangential directions. Both heartwood and sapwood are included. Since logs tend to be small diameter, most of the strands are cut from juvenile wood. Once cut, strands are sent to a rotating drum dryer where their moisture content is brought down to 3-7%. Moisture content of the wood strands is dependent on the type of adhesive being used and where the strands are to be used in the panel.

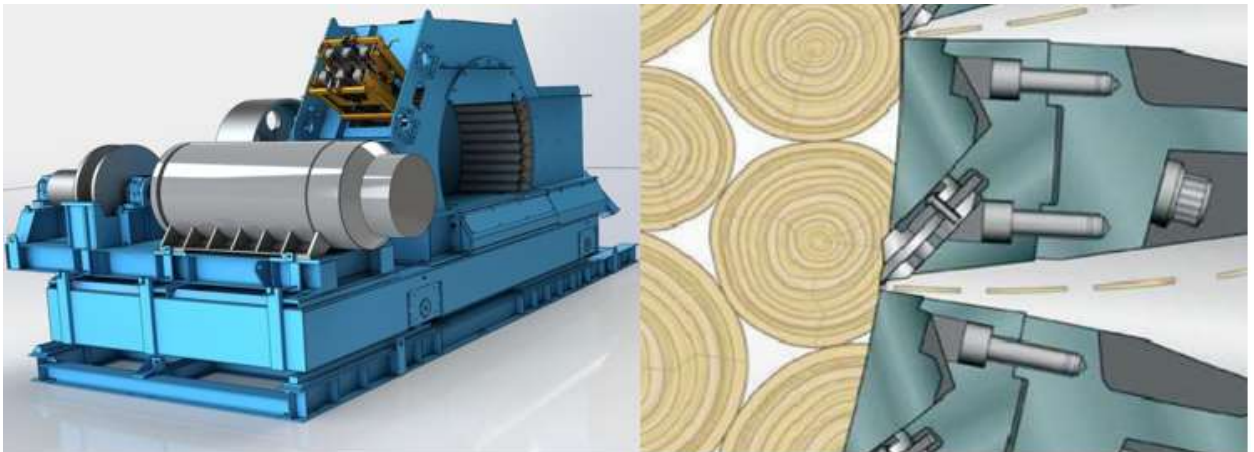


Figure 2-1, Knife-ring log strander (left) and knife-ring strand cutting detail (right) (Kadant Inc. , n.d.).



Figure 2-2, OSB Strand Dryer (Siempelkamp, 2020)

To prepare for mat formation, dry strands are then sent into a rotating blender to have adhesive and wax applied (*Figure 2-3*). The rotating drum is configured with a fixed incline of approximately 3 to 5 degrees to facilitate material flow toward the outlet (Smith, 2005). As the drum rotates, the strands tumble through the cross-section of the drum. Residence time in the blender depends on the rate of rotation and the slope of the drum. Inside the blender, mounted on a stationary shaft, there are a series of spinning disk atomizers, which atomize adhesive for application on to the strands as the drum rotates. This results in tiny droplets of adhesive on the surface of the strands. Strands make several passes through the atomized resin before exiting the drum. In addition, it is believed that resin is transferred from strand to strand due to mixing.

Phenolic and isocyanate resins are commonly used in OSB. Types of resin used in OSB can be contingent on the location of the strand within the panel, the species of wood being used, or the manufacturer's preference. When using a combination of adhesives, liquid or powder phenolic resins can be used for face strands, while isocyanate resins are used for the core. This is because isocyanate adhesives cure at lower temperature than phenolic adhesives. In a hot press, face strands of an OSB panel will be exposed to direct heat and higher temperature, therefore curing the resin in the face layers faster than the resin in the core layer. Having an adhesive in the core, which

cures at a lower temperature, cuts down on time that the mat spends in a hot press (Stark, Cai, & Carll, 2010). In addition, isocyanate adhesive tends to stick to the metal platens of the hot-press, so phenolic adhesive is often preferred for the face layers. OSB can be made entirely with isocyanate adhesive, but then a release agent must be added to metal surfaces in contact with the mat. Once the strands are coated with adhesive, they are then sent to forming lines to be formed into mats.



Figure 2-3, Coil OSB Blender (NDI, Inc., 2020)

In a forming line, strands fall through a series of parallel, vertical spinning disks on to a conveyer belt as seen in *Figure 2-4*. The purpose of the disk apparatus is to orient the strands. As the strands fall through the disk apparatus, they land in a parallel orientation to one another. Strands can also be aligned using electrostatic technology. Orientation of the strands is changed twice to create two face layers and a core layer. The grain orientation of the core layer is perpendicular to that of the face layers (Stark, Cai, & Carll, 2010).



Figure 2-4, OSB Forming Line (Siempelkamp, 2020)

A hot press is used to cure the adhesive and bond the wood strands to one another. The hot press can either be continuous or batch. In a continuous hot press, mats of strands are sent between a set of rollers, press plates and twin steel belts, heated, and then cut to size after pressing (*Figure 2-6*) (Stark, Cai, & Carll, 2010). Continuous hot pressing is a more recent technological development in OSB manufacturing. With a multi-opening, batch hot press, up to 16 mats can be pressed at once with dimensions as large as 12 x 24 feet. Once the mats are in the press, and a platen temperature of 350-400°F has been reached, the adhesive only takes two to five minutes to cure depending on the adhesive type and mat thickness (Longwood, 1997).

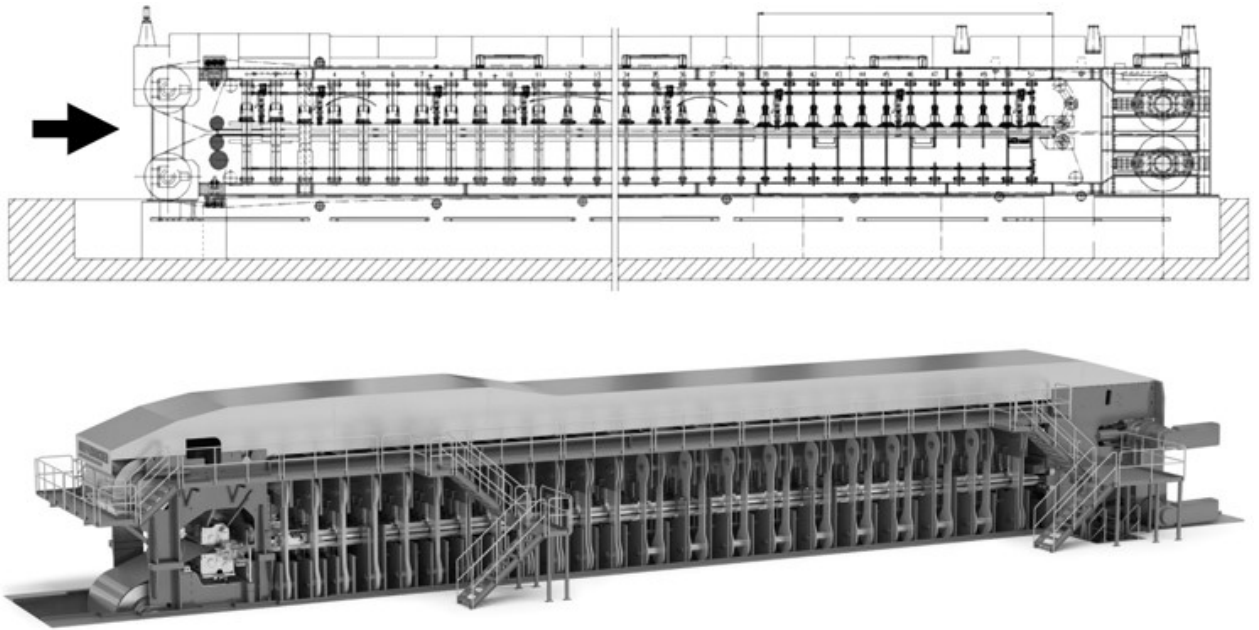


Figure 2-5, Siempelkamp Gmbh ContiRoll continuous press, and Dieffenbacher Gmbh CPS+ continuous press system concept (Siempelkamp, 2020).

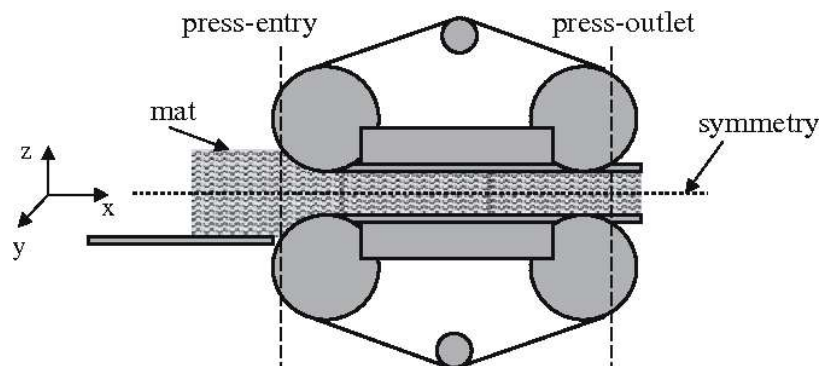


Figure 2-6, OSB Continuous Hot Press Model (Pereira, Carvalho, & Costa, 2004).

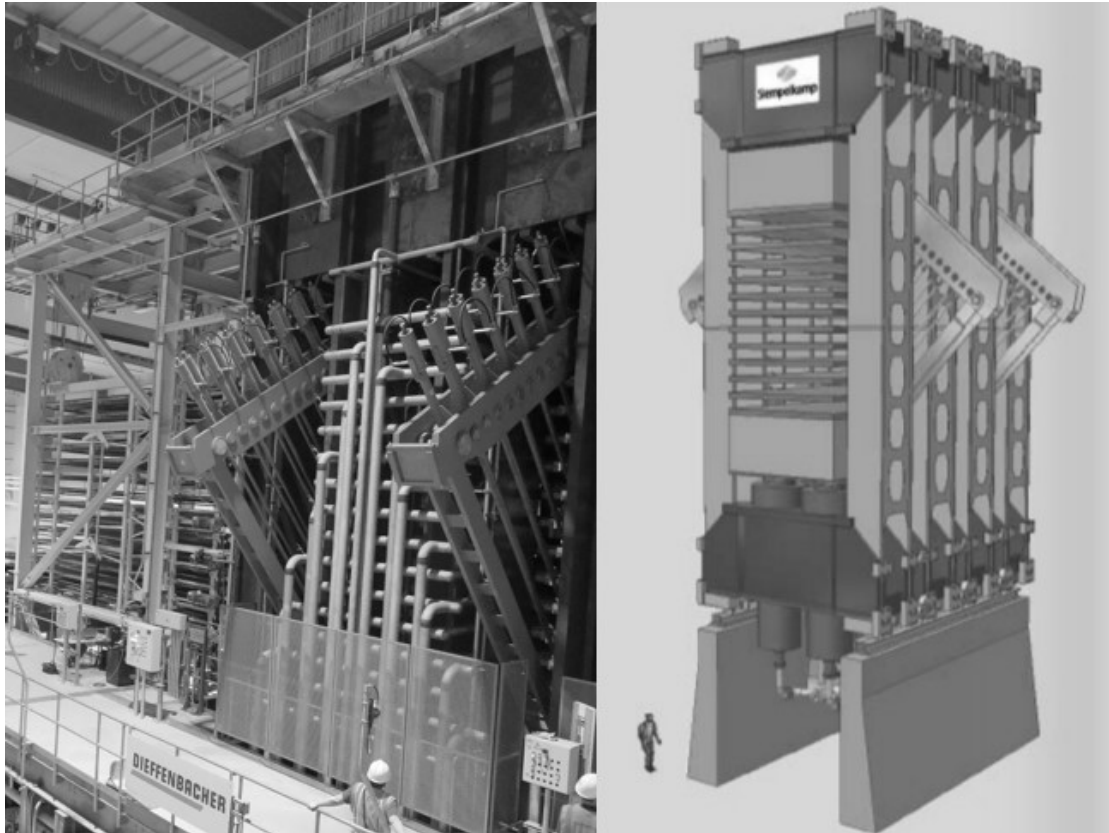


Figure 2-7, Dieffenbacher multi-opening press (Left) and Siempelkamp multi-opening press (Right) (Siempelkamp LP, 2004).

Mats are pressed to various thicknesses. Common sizes of OSB sheathing include 3/8 inch, 7/16 inch, 15/32 inch, 1/2 inch, 19/32 inch, 5/8 inch, 23/32 inch, and 3/4 inch (The Engineered Wood Association, 2017). OSB mats are typically hot-pressed with a wire mesh on the bottom, which facilitates the release steam from the interior of the mat. The impression created by the wire mesh on one side of the panel creates a slip-resistant surface for workers (Longwood, 1997). Once out of the press, panels are ready for finishing.

To finish, OSB panels are first cut with a large master saw into four-foot by eight-foot panels, which can be sanded or profiled, for sheathing grade applications. Specialty dimensions are also manufactured to meet customer demand. OSB panels are inspected by ultrasonic devices to detect for internal defects. After passing inspection, panels are given their grade stamp while hot and stacked to rest for 12 to 48 hours to complete the curing process. After stacking and labeling, the edges of the panels are

sprayed with a moisture resistant coating for protection (Longwood, 1997). A schematic of the OSB manufacturing process can be seen in *Figure 2-8*.

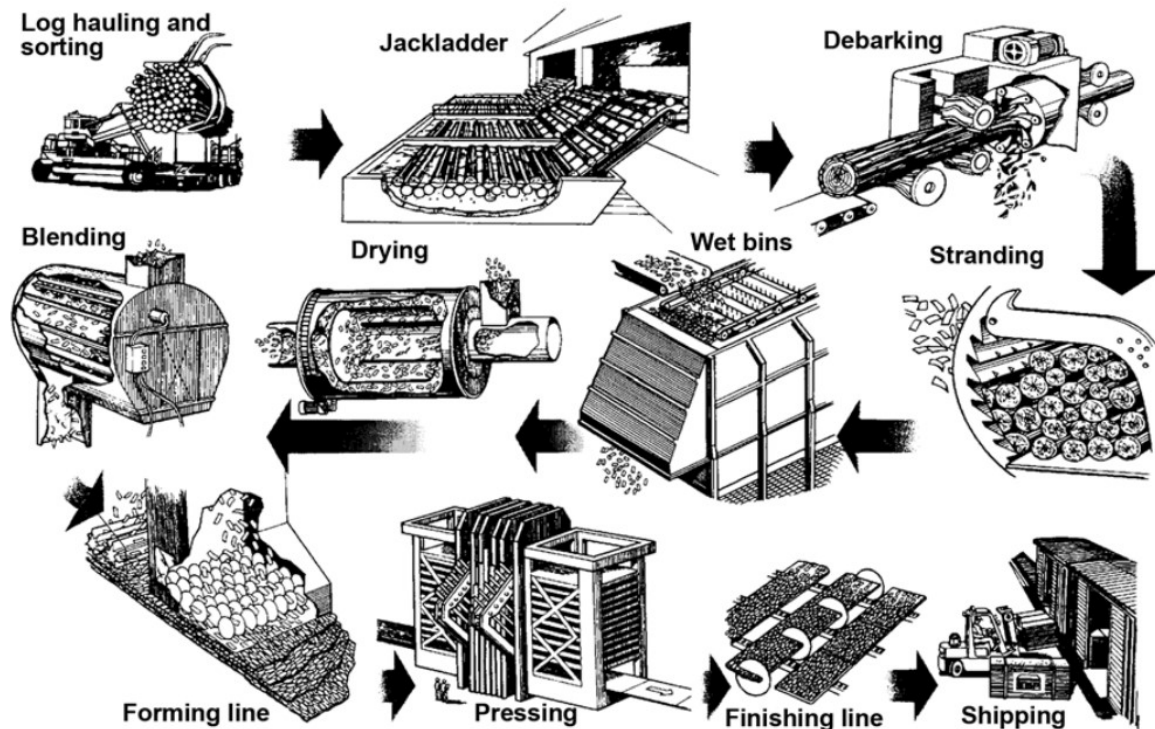


Figure 2-8, OSB Manufacturing Schematic (Longwood, 1997).

In the engineered wood products market, the primary competitor of OSB is plywood. Similar to OSB, plywood has increased dimensional stability, strength, and stiffness because of its alternating grain orientations between veneers. Plywood is manufactured using thin layers of veneer which have been peeled from a log using a lathe. These layers are then glued together with alternating grain orientations. A hot press is used to cure the adhesive and bond the veneers (The Engineered Wood Association, 2011). Plywood can often be an inefficient use of material because the log has to be peeled. Veneer cannot be peeled from the outer edge of the log if it is tapered because it will not yield full sheets, nor the center of the log because the veneer can check due to the geometry of how its cut. By using strands, as opposed to veneer, OSB has a much higher yield of useable material. APA - The Engineered Wood Association has found that 85-90 percent of the log can be used when making strands for OSB, so

in some cases producing OSB is a much more economical choice than plywood (The Engineered Wood Association, 2017).

2.2 Phenol-formaldehyde Resin

Phenol-formaldehyde resin (PF) is an adhesive commonly used in the forest products industry to create engineered wood products such as plywood, OSB, and glulam. Compared to other resins, such as urea formaldehyde (UF), PF resin creates more durable bonds, which are more effective at higher temperatures and in the presence of moisture. PF resin can be created through two different methods to make two types of PF resin, resol and novolac (Pizzi, et al., 1983).

An anonymous survey from a resin manufacturing company claimed their PF resin used for the manufacturing OSB has a number average molecular weight (M_n) of 1500-2000, a pH of 9.5-11, a viscosity of 100-300 mPa.s. and a 48-55% solids content. The anonymous resin manufacturer also makes PF adhesives for structural products such as parallel strand lumber (PSL) and laminated veneer lumber (LVL). Specifications for their PSL resin include a M_n of 2200-3000, a pH of 11-12, 500-900 cps, and a solids content of 45-55%. Specifications for their LVL resin include a M_n of 2400-3400, a pH of 11-12, a viscosity of 500-900 cps (2200-3600 cps with additives), and a solids content of 41-45% (44-46% dry solids with additives) (Anonymous, 2020).

Resol PF resin is created by reacting phenol with an excess of formaldehyde (molar ratio range 1.8-2.2 : 1.0). An alkali catalyst is used in the reaction between phenol and formaldehyde and an excess of alkali can be used to help stabilize the reaction. The resol PF resin is cured by exposing the adhesive to high temperatures in the presence of a catalyst to create a thermosetting resin. Resol PF resin is most commonly used in plywood, LVL, particleboard, OSB, and glulam manufacturing either as a liquid or sprayable dry powder (Stark, Cai, & Carll, 2010) (Pizzi, et al., 1983).

Novolac PF resin is created by reacting an excess of phenol with formaldehyde (molar ratio range 0.8-1.0 : 1.0), in the presence of an acid catalyst, commonly hydrochloric acid (HCl). Post reaction, the novolac PF resin is ground to a fine powder and then mixed with about 15% hexamethylenetetramine. When curing novolac resin,

heat is used to break down the hexamethylenetetramine creating ammonia and formaldehyde. Ammonia reacts with the liquified novolac resin making it thermosetting. Novolac resins are more stable than resol resins, but must be kept completely dry (Pizzi, et al., 1983). Novolac resins are commonly used for molding compounds, electrical insulations, and high temperature laminates.

PF resin synthesizes through a process of methylation and condensation between ionized phenol and unionized formaldehyde. The methylation process is exothermic combining the phenol and formaldehyde compounds and releasing a hydroxide. The molecule will then condensate producing PF and a molecule of water. It is also possible for hydrogen to bond to a hydroxyl hydrogen on the molecule of a different methylol group. This will result in a dibenzyl ether bridge, which can release a bound formaldehyde and a water molecule (Gollob, 1982). Illustrations of the methylation and condensation process can be seen in *Figure 7* and *Figure 8*.

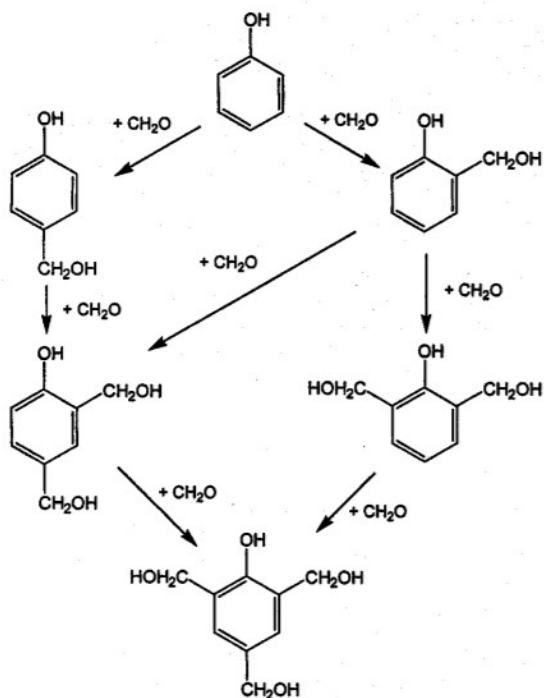


Figure 7. Possible pathways for methylation of phenol with formaldehyde (Conner, 2001)

There is a direct relationship between apparent viscosity (η_a) and molecular weight (M) of a polymer. As molecular weight increases so will viscosity, but this relationship is not always linear. On a logarithmic scale, low molecular weight polymers will have a linear increase in viscosity based on molecular weight, but once a certain degree of polymerization (DP) is achieved the viscosity increases at a higher rate as seen in *Figure 2-9* (Painter & Coleman, 2009). The relationship to viscosity of low molecular weight polymers can be defined by the equation:

$$\eta_a = K_L(DP)^{1.0} \quad \text{Eq. 1}$$

K_L is a constant

High molecular weight polymers are defined by a similar equation but after a certain degree of polymerization is achieved, there will be an effect on viscosity:

$$\eta_a = K_H(DP)^{3.4} \quad \text{Eq. 2}$$

K_H is a constant

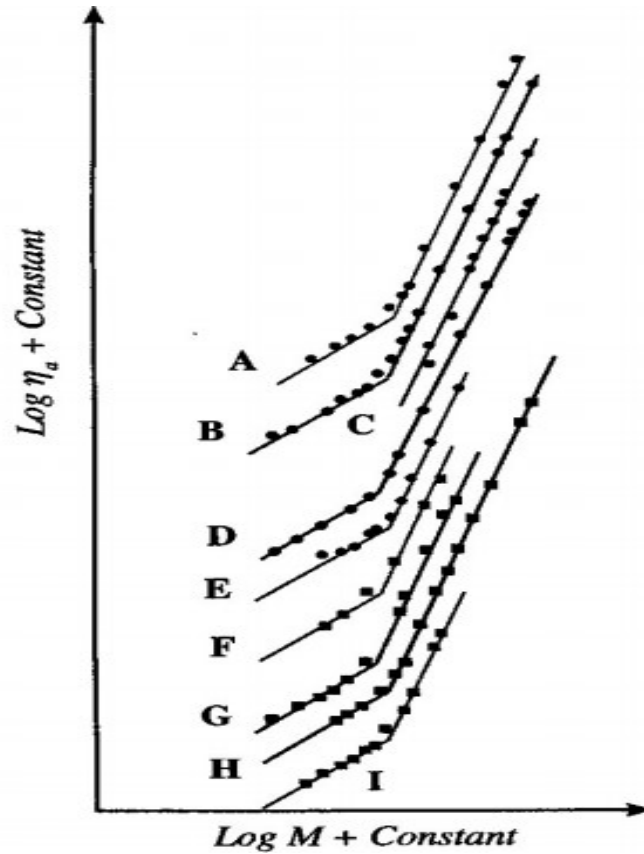


Figure 2-9, Experimental plots of viscosity η_a vs. molecular weight (M): (A) polydimethyl siloxane, (B) polyisobutylene, (c) polyethylene, (D) polybutadiene, (E) polytetramethyl p-sulphen1 siloxane, (F) poly(methyl methacrylate), (G) poly(ethylene glycol), (H) poly(vinyl acetate), and (I) polystyrene. (Painter & Coleman, 2009)

Thickeners can be added to increase the viscosity of phenolic resins without effecting the molecular weight. This is important for adhesives that do not have enough tack prior to pre-pressing or pressing, depending on the wood composite being manufactured (Pizzi, et al., 1983).

Different solids contents of PF resin can be desirable depending on the application; thus, it is important to maintain the ability to alter the solids content of PF resin for its intended purpose. One way to increase the solids content of PF resin during the manufacturing process is to acidify it (USA Patent No. US 6,730,770 B2 , 2002). When manufacturing PF, after creating an aqueous mixture of phenol and formaldehyde, a basic polymerization catalyst is added and then maintained at a constant temperature. Once a desirable amount of free formaldehyde has evaporated from the mixture, it can be cooled and acidified. Using sulfuric acid, the PF resin mixture is brought down to a pH of 2-3. This in return can increase the solids content of PF resin (USA Patent No. US 6,730,770 B2 , 2002). A study by Hu et al. examined the effects of altering formaldehyde/phenol (F:P) ratios when synthesizing PF at room temperature. In this study it was determined that increasing the amount of formaldehyde in the mixture increases the viscosity and solids content of the resin (Hu, Zhao, & Cheng, 2015).

2.3 Isocyanate Resin

Another common type of adhesive used in OSB manufacturing is based on isocyanate chemistry. Isocyanate adhesives are a petroleum derived material, which typically have a higher cost than phenolic resin, but have shown to have improved technical performance in some bonding aspects (Pizzi, et al., 1983), and may have a lower overall cost to manufacturing OSB (Broline & Adams, 2006).

A common type of isocyanate adhesive used in the wood products industry is polymeric diphenylmethane diisocyanate (PMDI). PMDI is synthesized by the condensation of aniline in formaldehyde, as seen in *Figure 2-10*. PMDI reacts with compounds which have active hydrogen and also can create covalent bonds between hydroxyl bonds in cellulose and isocyanate, making it an excellent adhesive for wood (Conner, 2001).

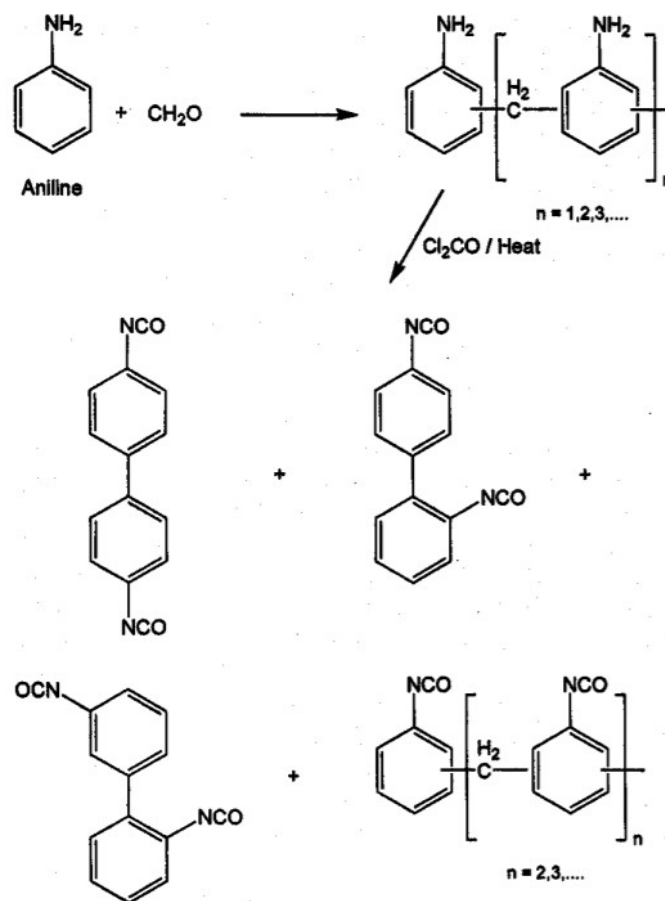


Figure 2-10, PMDI Synthesis (Conner, 2001)

Common PMDI used in an industrial setting as a one-component adhesive contains about 50% MDI, while the other 50% consists of higher order isocyanate oligomers. This industrial PMDI has a viscosity of approximately 200 mPa at 25°C and an NCO value of 30-33%, although other formulations are possible (Gurke, 2002).

One of the advantages to PMDI is that water is used to form the urea linkages that comprise the primary polymerization reaction. PMDI is also 100% polymer in

liquid form. This means that PMDI can be used on wood strands with higher moisture contents, which in turn cuts down on time spent in the strand dryer. Another advantage to PMDI is that, due to greater reactivity, it can cure at lower temperatures than other thermosetting adhesives. Both of these advantages not only save energy, but cut down on time in the manufacturing process of OSB (Conner, 2001).

2.4 Spinning Disk Resin Atomizer

The unique characteristic of OSB that separates it from other structural engineered wood products is that it utilizes wood strands as opposed to solid-sawn lumber or veneer. Having a wood strand-based product provides many benefits, such as increased raw material yield and cost savings, but also has its difficulties. Uniformity is incredibly important in OSB, because it is made up of a non-uniform material. It is also very important that the strands are properly adhered to one another. Unlike other wood products, strands cannot simply pass under a roll-coater for adhesive application, because this would be inefficient, excessive, and lack control. Instead, adhesive is applied to wood strands through atomization in a rotary blending process.

A spinning disk resin atomizer is used to apply liquid adhesive to wood strands during the manufacturing process of OSB. This is accomplished by spraying a fine mist of adhesive using a conical centrifugal atomizer within a contained, rotating drum to coat wood strands. Within the drum there are fins lining the wall protruding inward, so as the drum rotates strands are pushed towards the center. Momentarily the strands are suspended in air allowing the atomizer to evenly coat them (USA Patent No. US 2003/0230639 A1, 2002).

Centrifugal atomization is utilized by a spinning disk atomizer (USA Patent No. US 2003/0230639 A1, 2002). In centrifugal atomization liquid is introduced to a rotating surface, in this case a cone, where centrifugal force sends the liquid across the cone's surface to the edge where it is spun off. The cone shape of the atomizer is designed to propel the spray forward. Droplet size can vary by the liquid flow rate on to the rotating surface, as well as the rotational speed. Certain parameters can be altered to change the size and distribution of resin droplets. Higher liquid flow rates have a direct correlation to droplet size, and rotational speed has a direct correlation to droplet

distribution. An example of a centrifugal atomizer can be seen in *Figure 2-11* (Graco, 1995).

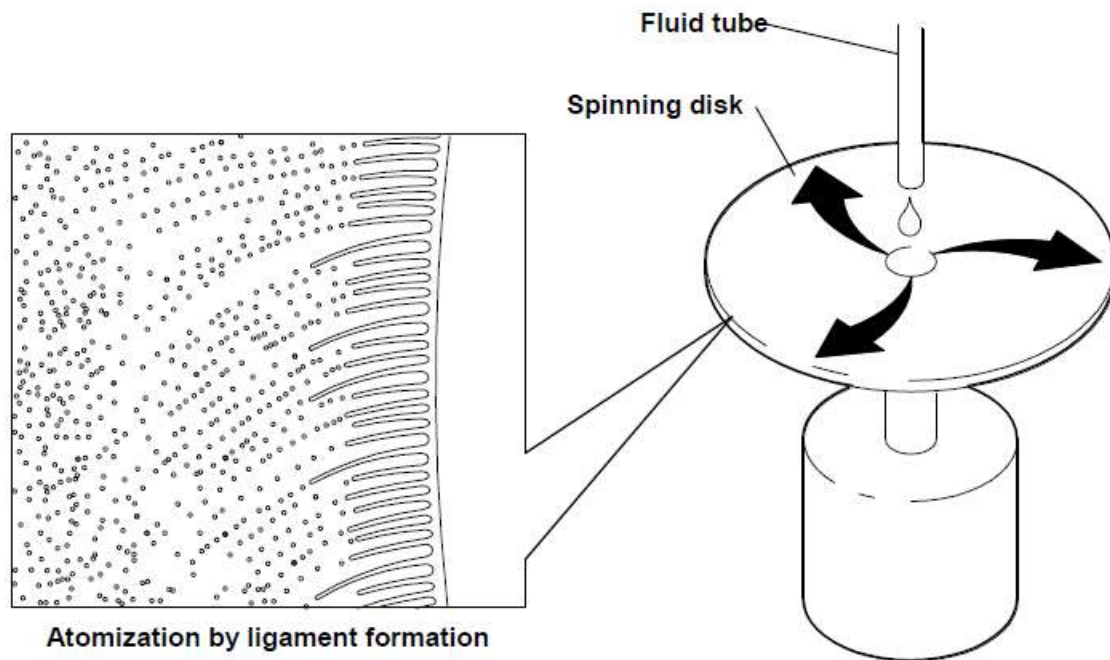


Figure 2-11, Concept of spinning disk atomization showing liquid application to spinning disk (right) and creation of ligaments, and ultimately, droplets of liquid (left) (Graco, 1995)

In the OSB industry there are two primary manufacturers of spinning disk atomizers, Coil and NDI. Both of these manufactures make a very similar product. These atomizers have adjustable RPM, and cone shape may be customized to accommodate for the type of adhesive being atomized. Images of these atomizers can be seen below in *Figure 2-12* and *Figure 2-13*.



Figure 2-12, Coil spinning disk atomizer (Coil Manufacturing, 2020)



Figure 2-13, NDI spinning disk atomizer (NDI, Inc., 2020)

2.5 Resin Atomization

Atomization is the process of turning large quantities of liquid into droplets. Atomization occurs naturally and can easily be recreated in a manufacturing setting through a variety of methods. Once a large quantity of liquid is atomized it creates a collection of droplets commonly known as a spray. A liquid is considered a droplet once it almost represents a perfect spherical shape. The near perfect spherical shape is created by the liquid's surface tension, which causes the droplet to resist deformation, minimize surface area, and increases stabilization. The point in which a droplet forms is contingent on the type of liquid being atomized. Liquids with stronger surface tension will form large droplets while liquids with weaker surface tension will create a finer

particle (Graco, 1995). A liquid's Weber number can be used to characterize the importance of surface tension in relation to inertia. The Weber number is important for characterizing high speed microfluidic microdroplet applications and can also be commonly found in model equations for atomization (Zhang, Day, & Manz, 2012). The Weber number can be applied to liquid streams, or secondary break-up of liquid drops, in liquid-gas systems. A higher Weber number indicates less stability of the liquid stream or drop and the onset, or extent, of atomization.

$$We = (\rho u^2 L) / \sigma \quad \text{Eq. 3}$$

We = Weber Number

ρ = gas density (kg/m³)

u = liquid velocity relative to gas (m/s)

L = droplet or stream diameter (m)

σ = surface tension (N/m)

Another factor that affects the characteristic of a liquid's atomization is viscosity. In a study done by Tanasawa et al. it has been found that increasing viscosity of a liquid will result in a larger mean droplet diameter (Lefebvre, 2011). Viscosity is an indication of how well a liquid resists agitation. If the force from an atomizer is not powerful enough, the liquid being sprayed may never form droplets but rather a small mass of liquid (Graco, 1995).

Density can affect the atomization process due to the liquid's resistance to acceleration. Liquids with higher densities will be more likely to resist acceleration, and without enough inertia from the force of the atomizer, larger droplets may be formed (Graco, 1995).

It has been found that droplet size and distribution of adhesives play a large role in affecting the performance of engineered wood products. Finer droplets have been shown to enhance strength properties (Zhang, Muszynski, & Gardner, 2008).

If the same adhesive is being atomized in an OSB manufacturing setting, surface tension, viscosity, and density will remain constant. Therefore, the only variables that can be altered to affect the droplet size would be rotary speed and flow rate of resin to the atomizer. Three types of sprays can generally be seen from variable flow rates with consistent rotational disk speed. At the lowest of flow rates droplets are

directly formed from the edge of the spinning disk with nearly uniform sizes. As the flow rate is increased, ligaments begin to form. Ligaments occur when the flow rate is high enough that the resin does not form into droplets before the edge of the spinning disk. Individual streams will flow off the disk's edge in the shape of tails before the centrifugal force breaks the liquid into droplets. Droplets formed from ligaments tend to be larger than droplets which are associated with those formed directly off the edge of the disk at lower flow rates. There is a wide range of ligament size and frequency. There can also be an intermediate state between droplets directly forming from the edge of the disk and ligament formation. This can cause a wide range of droplet sizes, with largest droplets forming from the end of the ligament followed by smaller satellite droplets directly formed off the edge of the disk. As the flow rate continues to increase, a condition is reached where ligaments are no longer formed and a continuous sheet or film of liquid protrudes from the disk. The formation of a film causes a high variability of droplet sizes, which can affect the consistency of resin distribution. It has been found that the ideal liquid spray is when ligaments are formed without droplets coming directly off the disk. This is because ligaments provide the most consistent droplet formations with a narrow range of droplet diameters (Zhang, Muszynski, & Gardner, 2008).

Different types of sprays can be seen in *Figure 2-14*:

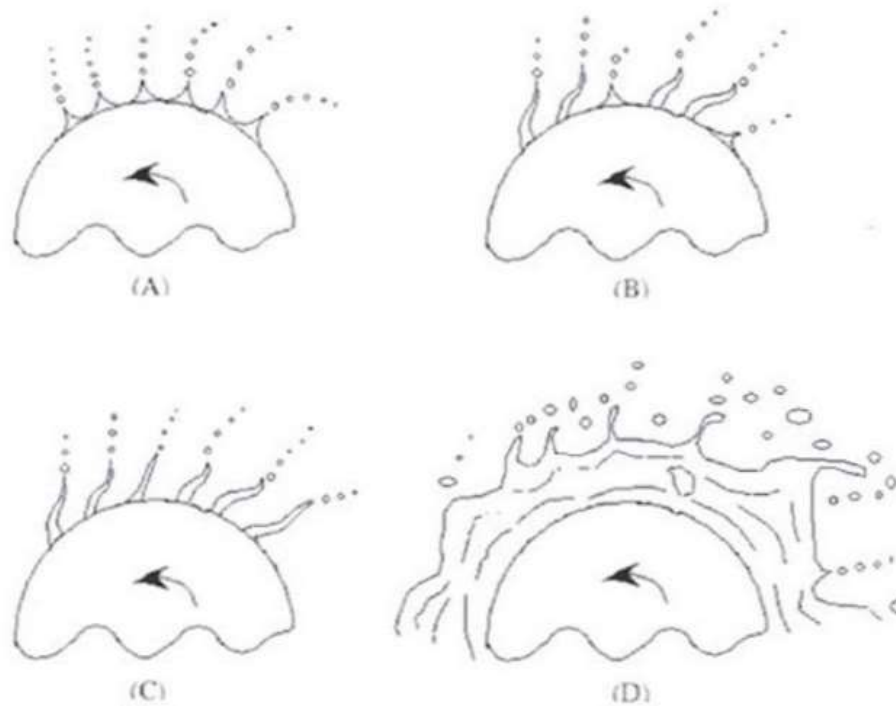


Figure 2-14, Centrifugal atomization of liquids: (A) Direct droplet formation, can result from a high atomizer RPM and a low resin flow rate. (B) Direct droplet and ligament formation, can result from a high atomizer RPM or a low resin flow rate. (C) Ligament formation, can result from balanced atomizer RPM and resin flow rate. (D) Film or sheet formation, can result from a low atomizer RPM and a high liquid flow rate. (Zhang, Muszynski, & Gardner, 2008)

As previously discussed, to achieve ligament formation, parameters of a spinning disk atomizer must be in cooperation with the chosen resin. Assuming all variables of the resin remain constant, atomizer speed and flow rate of resin on to the cone can be altered to achieve ligament formation. Diameter of resin droplet size during ligament formation can be estimated according to the following equation:

$$D_{10} = \left[0.77 \frac{V_L}{\omega_{rps} d} \left(\frac{\rho_L \omega_{rps}^2 d^3}{\sigma} \right)^{-5/12} \left(\frac{\rho_L \sigma d}{\mu_L^2} \right)^{-1/16} \right]^{0.5} \quad \text{Eq. 4}$$

D_{10} = Diameter (m)

V_L = Liquid flow rate (ml/min)

σ = Surface tension (N/m)

μ_L = Viscosity (Pa·s)

ω_{rps} = Rotary speed (revolutions per second)

ρ_L = Liquid density (kg/m^3)

d = Disk diameter (mm)

(Liu, 2000)

2.6 Influence of Resin Distribution on Bond Performance

Adhesive distribution has a direct influence on composite performance. Unlike some wood products, OSB has discontinuous bondlines because the adhesive is sprayed on. The distribution and droplet size of adhesive on each strand will influence the bondline properties, where each localized droplet will have its own mechanical properties. While optimum droplet size is unknown, smaller droplets increase the probability of adhesive coverage on all strands from a fixed amount of adhesive. If the droplets are too small, the adhesive can be excessively absorbed by the wood or lost in the cell lumens on the strand surface. It has also been found that decreasing adhesive droplet size can increase bending strength, internal bond strength, and dimensional stability (Kamke, Kultikova, & Lenth, 1996).

OSB is a product based around efficiency. In comparison to its main competitor, plywood, OSB is able to use more material per log. This is one of the factors that is able to significantly drive cost down. OSB manufacturing requires more adhesive than plywood manufacturing. One study comparing life cycle assessment of plywood and OSB found plywood to use 11.7 kg of PF resin per cubic meter and OSB to use 12.1 kg per cubic meter (Kaestner, 2015). Unlike OSB, plywood has continuous bondlines. During plywood manufacturing veneers pass through a roll-coater allowing them to have 100% adhesive coverage. Even though OSB uses more adhesive than plywood, strands do not achieve 100% coverage during the blending process. Because OSB is made up of individual strands, there is much more surface area for the adhesive to cover, hence the reason more adhesive is used for OSB than plywood (Kaestner, 2015).

To achieve optimum performance of OSB, 100% adhesive coverage is not necessary. One study done by Le examined how adhesive distribution on individual wood strands affected bond strength (Le, 2010). This was done by using a stamp to apply PF resin and PVA adhesive to individual strands and test them in tension with a double-sided lap-shear test to measure interfacial stiffness per area. Le found a direct

correlation to increased stiffness property as percent coverage increased. This was of no surprise, but an interesting finding was that with 100% coverage the adhesive stiffness was greater than the wood (Le, 2010).

This conclusion by Le, that 100% adhesive coverage on wood strands creates a bondline that is stiffer than the wood itself, supports the notion that there is an optimal amount of adhesive distribution that would make the discontinuous bondline equal to the stiffness of the wood strand and that amount of coverage is less than 100%.

A study by Dai et al. theoretically modeled resin distribution and compared their model to actual resin distribution from a spinning disk atomizer (Dai, Yu, Groves, & Lohrasebi, 2007). In this study it was found that computer modeling can serve as a useful tool to help predict resin coverages (including area coverage and mass coverage), resin content has an effect on the variability of resin coverage, strand thickness and density affect resin coverage, and many other factors influence resin distribution on strands. When comparing estimates of resin coverage that were simulated to experimental evaluations, they were found to be quite similar (Dai, Yu, Groves, & Lohrasebi, 2007). Some important equations used to model resin distribution include: the average number of resin coverage, resin area coverage, and resin mass coverage.

The equation for calculating the average number of resin coverage (n_r) is an equation that can be used regardless of resin distribution patterns. This equation was important to the Dai et al. experiment to later find the maximum possible resin coverage under ideal conditions. Both the equations for resin area coverage (R_a) and mass coverage (R_m) are also helpful for determining resin distribution characteristics and are later used in the study to build more complex equations. Resin area coverage is the amount of surface area taken up on a wood strand by resin while the resin mass coverage is the weight of resin solids on a strand (Dai, Yu, Groves, & Lohrasebi, 2007). Average number of resin coverage (n_r), as defined by Dai et al., is the probability of a single resin spot landing on a strand multiplied by the total number of resin spots on the strand. When one considers the total number of resin spots and strands in a blender, and the relative size of resin spots compared to strand surface area, the following average number of resin coverage was defined by Dai et al.:

$$n_r = \frac{\tau \rho_s R_c}{2(1+MC)\tau_r \rho_r R_{solids}} \quad \text{Eq. 5}$$

Resin area coverage:

$$R_a = 1 - e^{-n_r} \quad \text{Eq.6}$$

Resin mass coverage:

$$R_m = \frac{\pi d^2 \tau_r \rho_r N_{r,s}}{4 \lambda \omega R_{solids}} \quad \text{Eq. 7}$$

τ = thickness of wood strand

ρ_s = density of wood strand

R_c = resin content fraction on oven dry weight basis

MC = moisture content fraction of wood strands, oven dry weight basis

τ_r = thickness of resin spot

ρ_r = density of resin mix

R_{solids} = solids content fraction in resin

d = resin spot diameter

$N_{r,s}$ = total number of resin spots

λ = strand length

ω = strand width

(Dai, Yu, Groves, & Lohrasebi, 2007)

After completing the experimental evaluation in the study, Dai et al. observed significantly more variation than anticipated. This was alluded to earlier in the article when discussing the Poisson resin coverage distribution and the tendency of droplets to overlap due to random distribution. Through the experiment, significant variations in spot diameter for all resin content variations were found with coefficients of variation's (COV) between 260-290% (Dai, Yu, Groves, & Lohrasebi, 2007). This shows the lack of uniformity in resin coverage on strands that can be expected when atomizing resin in a blender.

Studying wood strands that have had adhesive sprayed on them is a good way to study distribution patterns and can help to find correlation of what provides a superior bondline, but it does not show the exact distribution of the adhesive because that changes during hot-pressing.

In another later study by Dai et al. resin distributions on wood strands were examined after hot pressing (Dai, He, & Jin, 2010). This was done by placing a sheet of Teflon between two wood strands during pressing so they would not adhere to each other. To keep the distribution patterns consistent a stamp was used to distribute resin across the strand surface. Before and after pictures from pressing can be seen in *Figure 2-15*. As seen in *Figure 2-15* post pressing the adhesive has significantly spread out and penetrated into the wood. The adhesive also appears to travel further vertically along the wood grain than it does tangentially. This further spread of adhesive is a result of heat and pressure from the hot press (Dai, He, & Jin, 2010).

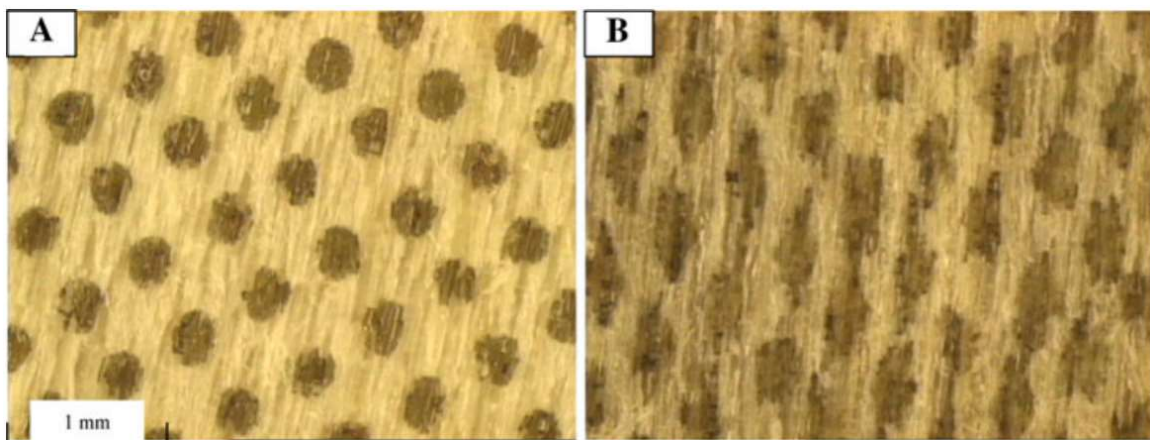


Figure 2-15, Images of resin spots on wood surface. (A) Before hot pressing, (B) after hot pressing.

In a paper by Conrad et al. the fracture toughness of a Douglas-fir substrate bound with phenol-formaldehyde resin was measured (Conrad, Smith, & Fernlund, 2003). The objective of the paper was to analyze how adhesive droplet size and distribution impacted the strength of the bond. In a similar method to the previous study mentioned by Dai et al. (Dai, He, & Jin, 2010), a flexographic printing technique was used to apply uniform droplets to the wood substrate. Eight different printing patterns were used in this study, based on droplet spacing (S) and area coverage (A). Droplet spacing in this study refers to the distance between the center of a droplet to another and the coverage has a relationship to the actual droplet diameter (D) (Conrad, Smith, & Fernlund, 2003). Conrad et al. created an equation to estimate theoretical droplet diameter based on droplet spacing and area coverage:

$$D = \frac{S}{5} \sqrt{\frac{A}{\pi}}$$

(Conrad, Smith, & Fernlund, 2003)

For the eight different types of printing patterns there were two droplet spacings (0.5 mm – 1.0 mm) and four different resin area coverages (6%, 12%, 25%, 50%). Once the resin was stamped on to the wood substrate, they were then pressed and cured to another substrate. A double cantilever beam test was used to analyze the fracture toughness, which would cause failure by cleavage (Conrad, Smith, & Fernlund, 2003).

An important finding in this paper that there is a minimum droplet diameter for the bond to become load bearing. Conrad et al. found it to be 110-140 micrometers for a droplet spacing of 0.5 mm and 340-490 micrometers for a droplet spacing of 1.0 mm. They also found that the fracture toughness increased linearly with droplet diameter (Conrad, Smith, & Fernlund, 2003). A relationship of the bond strength to area coverage can be seen in *Figure 2-16*.

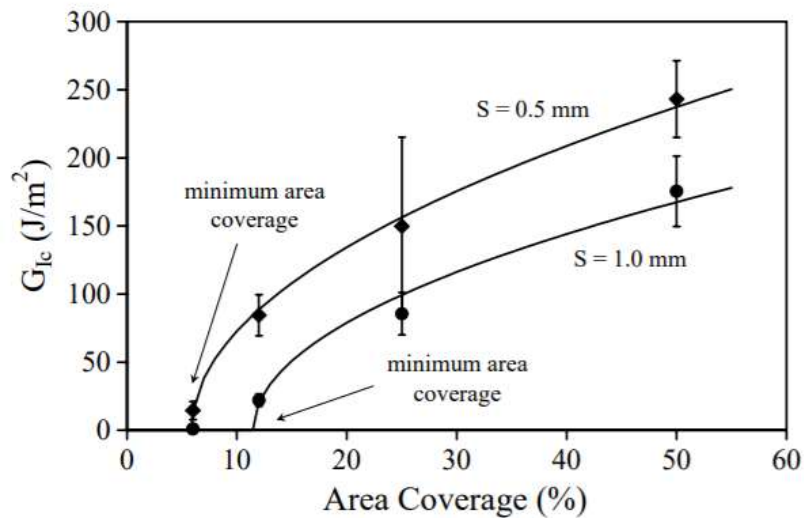


Figure 2-16, Fracture toughness (G_{Ic}) as a function of resin area coverage, showing 95% confidence interval bars. The curves are least-square fits of a square root relationship. S represents spacing between droplets. (Conrad, Smith, & Fernlund, 2003)

The literature review indicates the characteristics of resin spray by spinning disk atomization can be manipulated by resin viscosity. In addition, disk speed and flow rate

influence resin droplet diameter. Resin spray produced by spinning disk atomization is represented by a broad distribution of droplet diameters. The size of the resin spots, and surface area covered, will influence bond performance. There is some evidence that resin distribution and coverage affect mechanical properties of aspen strand board. What is lacking in the literature is experimental evidence of the relation between resin viscosity and resin distribution; spinning disk speed and resin distribution; and if these factors have a significant influence on bond performance.

3. Materials and Methods

3.1 Phenol-formaldehyde Resin Characterization

The PF resin used in this project was supplied courtesy of Arclin (Springfield, Oregon). The initial viscosity of the resin, as reported by Arclin, was 149 cP at 25°C and the non-volatile content was 60%.

One of the objectives of this project was to determine the effect of resin viscosity on atomization. This was accomplished by testing resins with identical formulation but different molecular weights. One large batch of resin was acquired, divided into thirds, then using time and temperature, two of the three resin batches were advanced to a desired viscosity. The target viscosities were the initial viscosity from the manufacturer (measured at approximately 170 cP), 500 cP, and 1,000 cP. These resins are designated based on their viscosity. Low viscosity resin (LV) is the resin with the viscosity as it came from the manufacturer, which was approximately 170 cP. Medium viscosity resin (MV) is the resin that had a target viscosity of 500 cP, and high viscosity resin (HV) is the resin that had a target viscosity of 1,000 cP.

3.1.1 Resin Molecular Weight

Advancing the PF resin to greater viscosity means polymerization was advanced to achieve three molecular weight distributions (designated LV, MV, and HV). The molecular weight of the MV and HV PF resin in this project was advanced by elevating the temperature of the resin over time in a water bath. The PF resin was separated into containers and placed in the water bath. The containers were sealed to prevent evaporation. Temperature of the water bath was brought up to 50°C. During the heating of the resin, containers were shaken every 30 minutes to mix up the resin and help ensure an even distribution of heat. Each time after heating the resin, the temperature was brought back down to 25°C and the viscosity was measured using Brookfield digital viscometer with a LV62 spindle (AMETEK Brookfield, Middleton, MA). Advancing the resin took many hours so this was done over the course of multiple days until the target viscosity was achieved. Once the target viscosity of the resin was

achieved, resin was removed from the water bath and put into a cold room (5°C) until needed.

Molecular weight of each resin was measured by the manufacturer using gel permeation chromatography (GPC). Two samples were taken from each batch of resin.

3.1.2 Influence of Temperature on Viscosity

For each resin, viscosity was measured over a range of temperatures from 10°C to 40°C in five-degree increments. Resin temperature was controlled using a circulating water bath (AMETEK Brookfield TC-550, Middleton, MA). This water bath was chosen because it has the ability to heat and cool allowing for a very fine control over the temperature of the water. A sample of resin was placed in the water bath until its temperature reached the desired point. Viscosity was then measured using a Brookfield digital viscometer with a LV62 spindle (AMETEK Brookfield, Middleton, MA).

3.1.3 Influence of Temperature on Surface Tension

Surface tension of the resin samples was measured using an optical pendant drop tensiometer (Biolin Scientific Theta Lite, Gothenburg, Sweden) over a temperature range of 10°C to 40°C in five-degree increments. The density of the PF resin used for testing was estimated to be 1.3 g/mL. The pendant drop test was conducted by suspending a 10 µL droplet from a pipet, which was dispensed at a rate of 1 µL per second. Once the tensiometer recognizes that the volume of the droplet is stable at 10 µL, it proceeds to measure the surface tension of the droplet for 10 seconds.

To control the temperature of the resin, the resin was first heated to a desired temperature in a circulating water bath (Julabo CD 200-F, Seelbach, Germany). The resin was then transferred into a pipet, and the tip of the pipet was placed inside the temperature-controlled chamber of the tensiometer. The same circulating water bath controlled the temperature of the chamber (Figure 3-1).

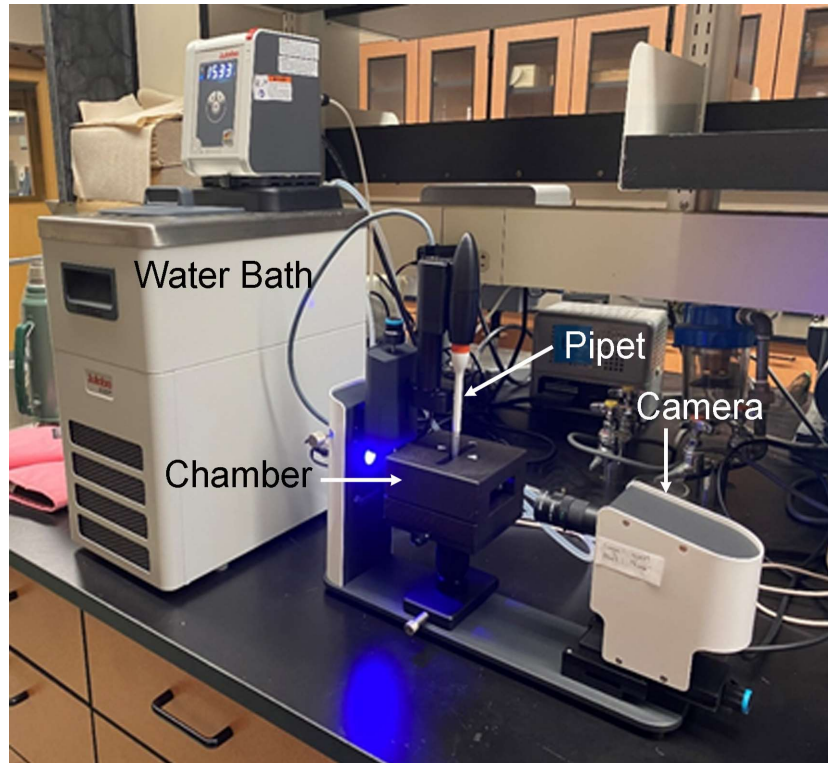


Figure 3-1, Biolin Scientific Theta Lite tensiometer connected to Julabo circulating water bath.

A single sample of resin was used for this test and was tested on three separate occasions. After the first and second test, the resin was given some time to advance to increase viscosity and molecular weight. The three resins (LV, MV, and HV) that were used for all other tests in this project were not used for surface tension analysis, because the elevated viscosity of the HV resin was much too high for the tensiometer to pump in and out of the pipet.

3.2 Lap-Shear Specimen Preparation and Testing

Custom wood strands were sprayed with resin and tested in shear to determine the effects of spray patterns on individual bondlines. Three resins LV, MV, and HV were used in conjunction with three atomizer speeds 7,000, 10,000, and 13,000 RPM's.

Because of the variation in strands used to make OSB, custom strands were fabricated for lap-shear testing. Southern yellow pine (*Pinus sp.*) and aspen (*Populus tremuloides*) logs were acquired for making custom strands. The logs for this project

were sourced from a mill in Sagola, Michigan and southern pine logs were sourced from a mill in Carthage, Texas.

The process for creating custom strands started by cutting the logs into one-foot segments using a circular saw and then quartering them with a band saw. Quartered logs were then soaked in warm water to soften the wood before slicing. After soaking for over 24 hours, the quartered logs were cut into 1/8-inch thick sheets using a veneer slicer. Wet veneers were then oven-dried with a mesh sheet and weight on top of them to avoid warping during the drying process. Once the veneers had dried, the surfaces were smoothed using a hand planer and metal scraper. Smoothing the veneers helped to eliminate variation in the surface quality and provided a flat surface for bonding. Using a table saw, the sheets of veneer were cut into one by two-inch sections. After cutting to final size, the strands are evaluated for surface quality. Any strands with defects, such as knots, voids, crooked grain pattern, etc. were eliminated.

A rotating drum blender was used as a controlled environment to apply adhesive to the individual wood strands. For the lap-shear specimen creation, the blender remained stationary. The blender drum has a diameter of six feet and depth of three feet (Figure 3-2).



Figure 3-2, Rotating Drum Blender

A custom door was made for the OSB blender (Figure 3-3). This blender door has a pneumatic slide which can open and expose strands to the spray of the atomizer for a controlled period of time (Figure 3-4 & Figure 3-5). The pneumatic slide has four one-inch by one-inch openings, allowing the user the ability to spray up to four strands at a time (Figure 3-6).



Figure 3-3, Custom OSB blender door with pneumatic slide used for strand insertion.



Figure 3-4, Pneumatic slide as viewed on inside of OSB blender door, with slide open.



Figure 3-5, Pneumatic slide as viewed on inside of OSB blender door, with slide closed.



Figure 3-6, Custom strands on OSB blender door pneumatic slide.

In the four slots of the pneumatic slide, three strands of wood and one piece of aluminum foil were attached to the slide using tape on the back side. Two of the wood strands were used for the lap-shear test, one of the wood strands was saved for resin distribution image analysis, and the piece of aluminum foil was used to determine the estimated mass of resin on each strand.

Determining the mass of resin on each strand was important for analyzing the effectiveness of the lap-shear bondline. The mass of resin cannot accurately be estimated through image analysis and cannot be measured by weighing the strands before and after resin application. As previously stated, the wood strands are secured to the pneumatic sliding door using tape. When removed from the door after resin application, pulling the tape off of the wood strands can cause some loss of fiber. The amount of fiber loss was found to be significant, and in many cases, greater than the mass of resin on the strand. In addition, a change of moisture content of the strand would cause significant error of the weight measurement. This makes it difficult to accurately measure the mass of resin on the strand itself. The aluminum foil provided a consistent substrate with no loss of moisture or substrate as a result of the test procedure.

The atomizer used for this research project was a spinning disk atomizer (Coil Manufacturing, Surry, British Columbia, Canada). The Coil atomizer is powered using an electric motor. The electric motor in the atomizer powers a drive shaft (Figure 3-7) that spins the cone. The cone of the atomizer is responsible for distributing adhesive down and away from the atomizer to effectively cover wood strands. The downward facing angle of the atomizer also helps to prevent adhesive build up on the atomizer itself.

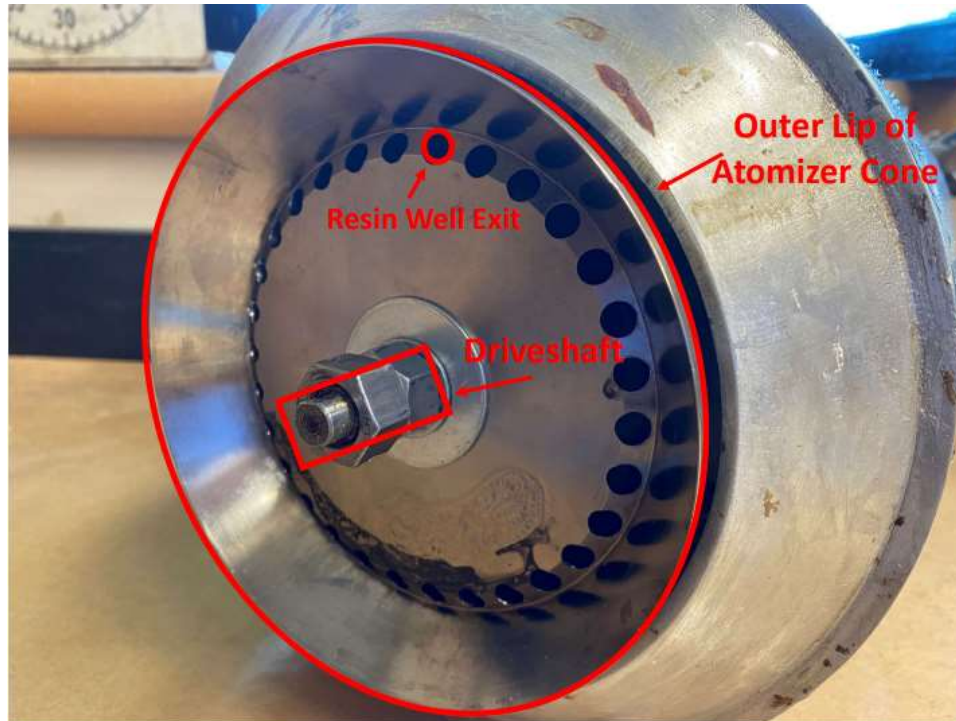


Figure 3-7, Front side of the spinning disk atomizer. Atomizer cone, resin well exit holes, and drive shaft are depicted in image.

To prepare for spraying resin on the strands, resin was acquired from the cold (5°C) storage, a circulating water bath was used to bring the resin temperature up to 25°C. Three molecular weights of PF resin were used in this experiment. The viscosity of each resin was measured on the day of fabrication and can be seen in Table 3-1.

Table 3-1. Resin viscosity on the day of lap-shear specimen fabrication

Resin Viscosity 25°C (cP)	
LV	176
MV	548
HV	1215

Resin was pumped into the atomizer using a peristaltic pump (Cole-Parmer Industrial model No. 07559-00/77900-60) at a rate of 180 g/min. Constant flow rate required adjustment of the pump-head speed due to viscosity differences. A preliminary experiment established the appropriate pump-head speed for each resin.

Once resin is pumped into the atomizer it is deposited on to the backside of the atomizer cone. The resin will then pool up in the resin well. The resin well is machined into the back side of the atomizer cone. This resin well helps to ensure that resin is evenly distributed on to the cone. As the atomizer spins, resin exits the resin well through a series of holes in the cone and slides along the surface of the cone by centrifugal force toward the outer rim (*Figure 3-7*). The objective of the atomizer's speed is to have the resin break down into very fine particles at the rim of the cone. This creates a very fine 360-degree spray pattern, which then impacts the wood strands in the blender (USA Patent No. US 2003/0230639 A1, 2002).

Lap-shear strands were exposed to resin spray for 10 seconds inside the blender (Figure 3-8). Before opening the pneumatic slide and exposing the strands, the atomizer was started and brought up to constant speed. Then the resin pump was turned on allowing the feed line to be filled with resin and eliminate any air pockets. Bringing the atomizer up to speed and pumping the resin before exposing the strands allowed for a consistent spray pattern during the time of exposure. Strands were sprayed at atomizer speeds of 7,000 RPM, 10,000 RPM, and 13,000 RPM.

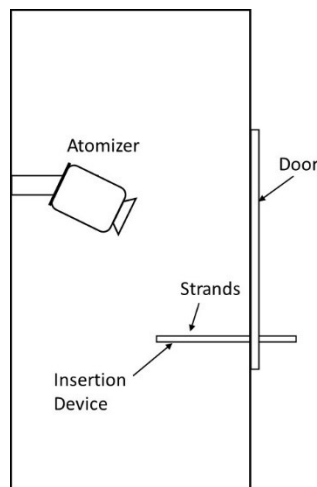


Figure 3-8 Side view section of blender with lap-shear strand insertion device.

Lap-shear test specimens were made in accordance with ASTM D2339. Two strands were overlapped with the one- by one-inch area that was sprayed with the atomizer. Once overlapped, lap-shear specimens were put into a hot press for two minutes at 200°C and 50 psi. Before pressing, spacers were added to the end of the

specimens to center the bondline in the grips of the test machine (*Figure 3-9, Figure 3-10, Figure 3-11, & Figure 3-12*). Without the spacers, the bondline would be off center during testing and promote additional peel force.

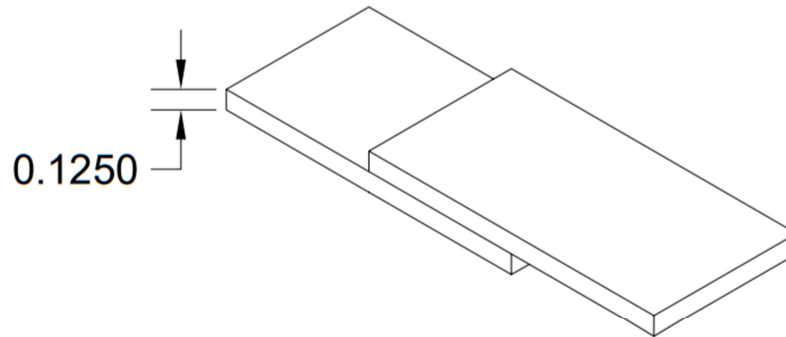


Figure 3-9, Drawing of lap-shear specimen without spacers (dimension in inches)

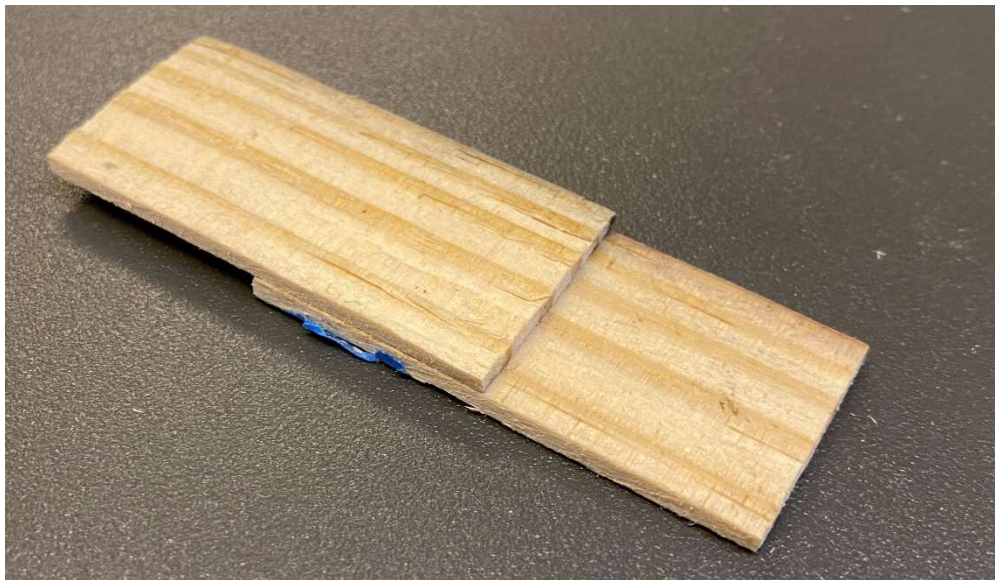


Figure 3-10, Lap-shear specimen without spacers.

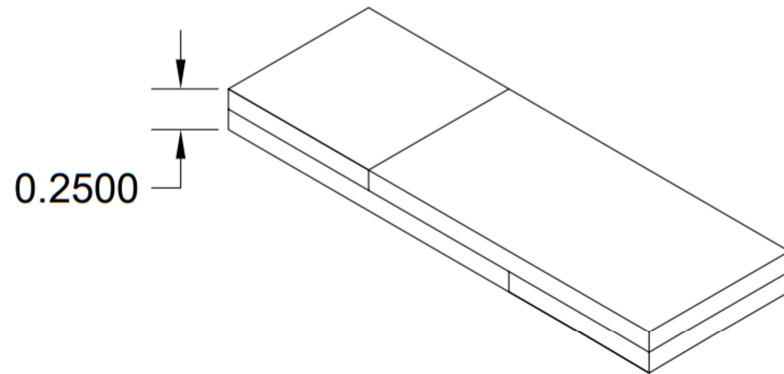


Figure 3-11, Drawing of lap-shear specimen with spacers (dimension in inches)

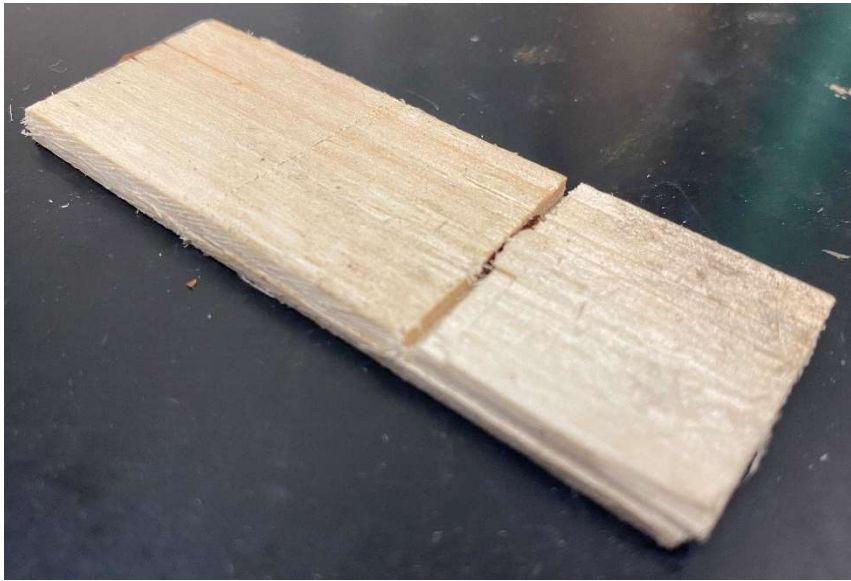


Figure 3-12, Lap-shear specimen with spacers

Five strands were manufactured and tested for each treatment. Lap-shear specimens were tested to failure using an Instron testing machine with a 10kN load cell for the lap-shear test of Resin LV and Resin HV, and a 100kN load cell for the lap-shear test of Resin MV. Strands were tested at a rate of 0.3 mm/min Maximum load from each test was recorded.

3.3 Panel Manufacture and Testing

Two species of wood strands were used for this project: aspen (*Populus tremuloides*), and southern pine (*Pinus sp.*). These strands were sourced from the same

LP mills as the logs used for specimen creation in the lap-shear section of the project. All strands were commercially dried and intended for the surface layer in OSB. Wood strands for this project were conditioned to 3% moisture content using an environmental chamber. After conditioning, strands were double wrapped in polyethylene bags until the day of panel fabrication.

Three molecular weights of PF resin were used for this experiment. The viscosities of each molecular weight of resin that were measured on the day of fabrication can be seen in Table 3-2

Table 3-2. Resin viscosities on the day of strand board fabrication.

Resin Viscosity @25°C (cP)	
LV	175.8
MV	523.5
HV	1086

Target specifications for each laboratory-manufactured strand board were the same (Table 3-3). No wax was added to omit any interference of wax with adhesion. The strands were not oriented.

Table 3-3. Strand board specifications.

Strand Board Furnish	
Target density (lb/ft ³)	40.6
Thickness (in)	0.51
Length (in)	16
Width (in)	16
Wood MC %	3
Resin solids loading %	6.5
Wax solids loading %	0
Mat MC %	10

A Coil spinning disk atomizer was used to apply resin to the strands. Atomizer speeds of 7,000 RPM, 10,000 RPM, and 13,000 RPM were used. Strands and resin were blended together in a rotating drum, which was six-feet in diameter and three-feet in depth, at 6.7 RPM. The peristaltic pump delivered resin at a rate of 180 g/min, which was calibrated for each resin on the day of fabrication.

Mats were formed in a 16 by 16-inch box on top of a 1/8-inch-thick aluminum caul plate. Once the box was removed a wire mesh was placed on top of the mat. The same wire mesh design is used for the manufacture of commercial OSB, and is intended to help steam escape from the panel during hot-pressing. After forming, the mat was then moved into a hot-press and pressed to 0.5-inch thickness at 200°C platen temperature for 420 sec total time. Steel bars were used to control the target thickness. The hot-press schedule can be seen in Table 3-4. Pressing schedule. Three replicate panels were made for each formulation of strand board.

Table 3-4. Pressing schedule.

Press Schedule		
<i>Step</i>	<i>Distance between platens (mm)</i>	<i>Time (sec)</i>
Hold	100	0
Close	100-19	0-30
Hold	19	30-390
Vent	19-23	390-420
Open	23-100	420

After pressing, panels were cut into internal bond (IB) specimens (2-inch x 2-inch), and static bending specimens (3-inch x 14-inch), following the cutting diagram shown in Figure 3-13. Three panels were made for each treatment, creating 30 IB specimens and nine three-point bending specimens per treatment. Panels then underwent internal bond testing and three-point bending testing according to ASTM D-1037. Mass of the IB specimens for the MV resin were measured for density correction.

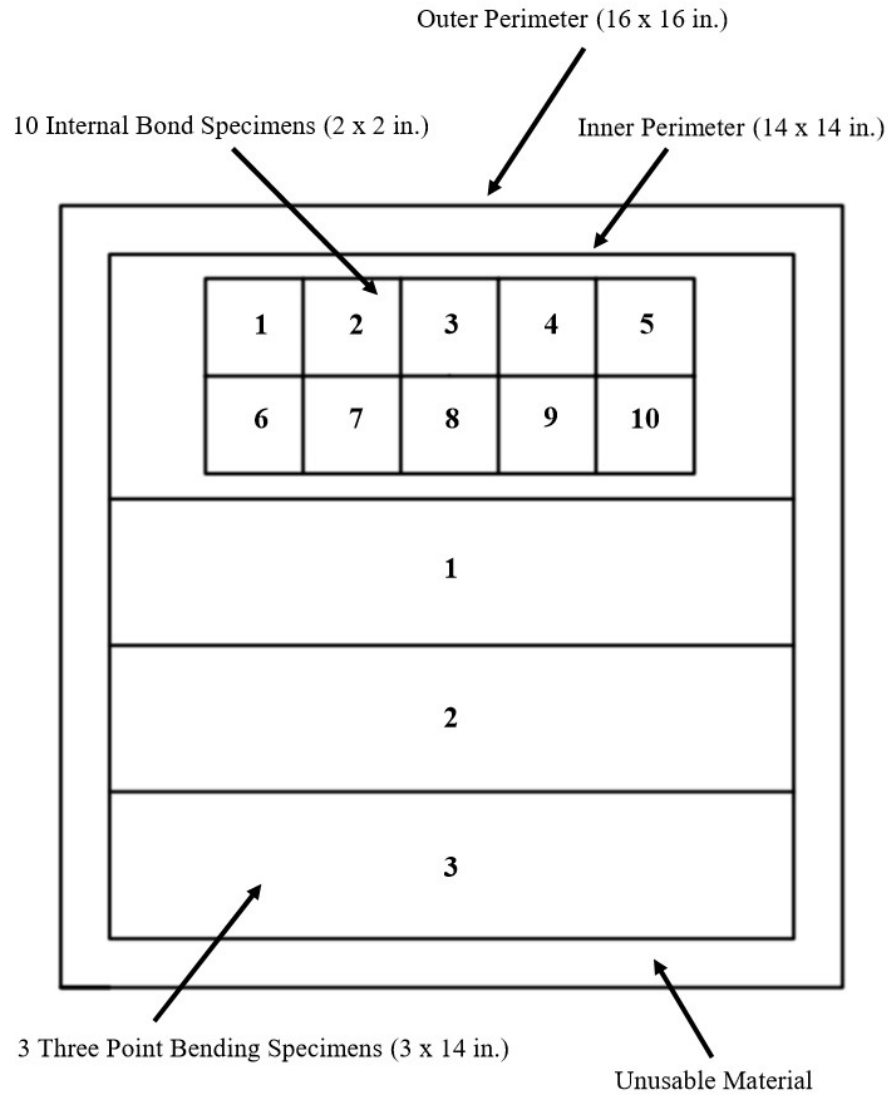


Figure 3-13, Strand board cutting diagram

3.4 Resin Distribution Analysis

As mentioned in the methods for preparing lap-shear and strand board specimens, samples of wood strands with adhesive spray were saved for image analysis. From the lap-shear test, there was a corresponding strand for each lap-shear specimen, for a total of 90 strands for resin distribution analysis. For the manufacture of strand board, strands were randomly pulled from each batch of furnish; 5 strands each from blender runs for Resins LV and HV, and 15 strands from blender runs for

Resin MV. Each strand from the strand board furnish was analyzed on both sides, thus providing 390 images for resin distribution analysis.

Resinated strands were put in an oven at 103°C for over 24 hours to cure the adhesive. Curing the resin creates a much darker color, which provides better color contrast against the wood during image analysis.

The strands with the cured resin were examined to measure the projected two-dimensional size and shape of resin droplets and surface area coverage by resin. Image capture was performed using a laser scanning microscope (LSM) with a focus variation option (Keyence, model VK-X1050, Osaka Japan). The focus variation option uses coaxial and ring LED white light illumination. Since a large field of view was desired, the 2.5x objective lens was selected, which provided sufficient magnification to clearly observe the smallest resin droplets. The field of view for the 2.5x objective lens was 7.4 x 5.5 mm. The LSM has an automatic x-y-z stage. Focus variation utilizes a color camera and z-direction objective lens control to capture sequential images at increments of focal distance within the range of the lowest focal point to the highest focal point (maximum 7 mm). The images are then combined to omit out-of-focus regions, based on brightness variation between adjacent pixels, to yield a sharp image and three-dimensional data (Keyence, 2019). In focus variation mode, the LSM utilizes a 16-bit CMOS camera with x-y image size of 5.6 megapixels and z-direction resolution of 5nm. Using a scanning microscope allowed the capture of a much larger image without sacrificing image resolution. The automated stage allows for multiple images to be captured and then stitched together. Thirty images for blender strands and thirty-six images for lap-shear strands were stitched for data collection to yield an effective field of view of approximately 650 mm² for blender strands and 760 mm² for lap-shear strands. Each pixel was equivalent to 32.06 µm². The images were automatically calibrated based on the selected objective lens and z-direction motion in focus variation mode. The calibration factor was later used for calculation of resin spot size on the strand surface, as well as percent of surface area coverage.

2D optical images were exported as tif format files and imported into ImageJ (Rueden, 2017) for image analysis. Images were cropped to omit edges or splits in the strands (Figure 3-14). Images were converted into 8-bit gray-scale format Figure 3-15.

Because of the distinct dark color of PF resin, it had a much lower gray-scale value (darker) in comparison to the wood. A gray-scale threshold can then be set, which transforms the image to binary (black and white). When creating the threshold, ImageJ creates a histogram of gray-scale values from 0 to 255 for the 8-bit image. Selection of the threshold was done manually based on shape of the histogram and observation of the objects of interest (resin spots). On the histogram there will usually be a minima signifying the change in gray-scale from wood to resin Figure 3-16. This point can be useful to decide where to place the threshold on the image. There was not one standard threshold value that could be set for each image, because each image has variation in wood and resin color. Therefore, the threshold of each individual image was a subjective decision.

After establishing a threshold, the objects of interest (resin spots) on the image were analyzed. Object measurements included area, circularity, and percent area of field of view. Some software filters were applied to promote consistency and omit objects that were clearly not resin. Software filters were minimum object size of 25 pixels ($802 \mu\text{m}^2$) and circularity 0.001-1.00.



Figure 3-14, Cropped image imported into ImageJ

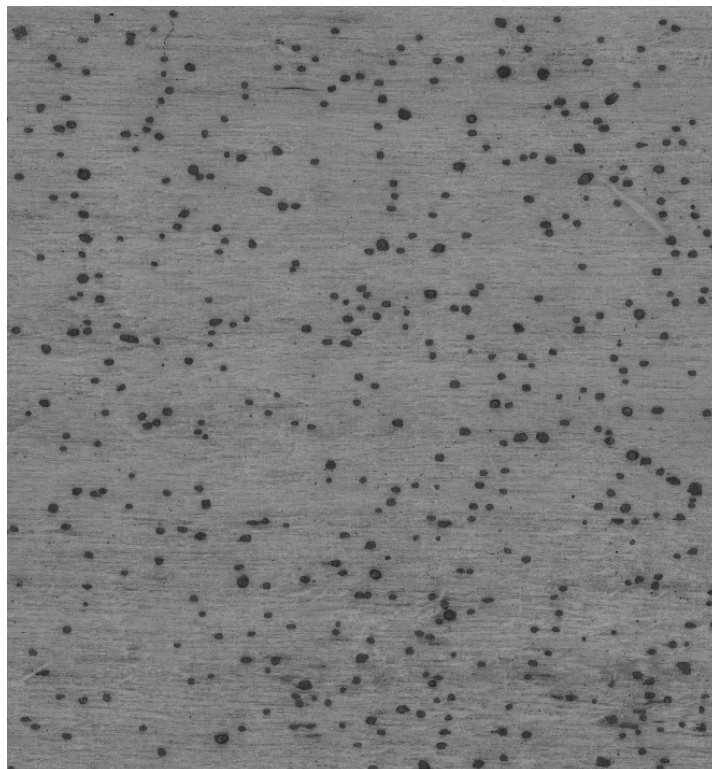


Figure 3-15, Image in 8-bit grey scale

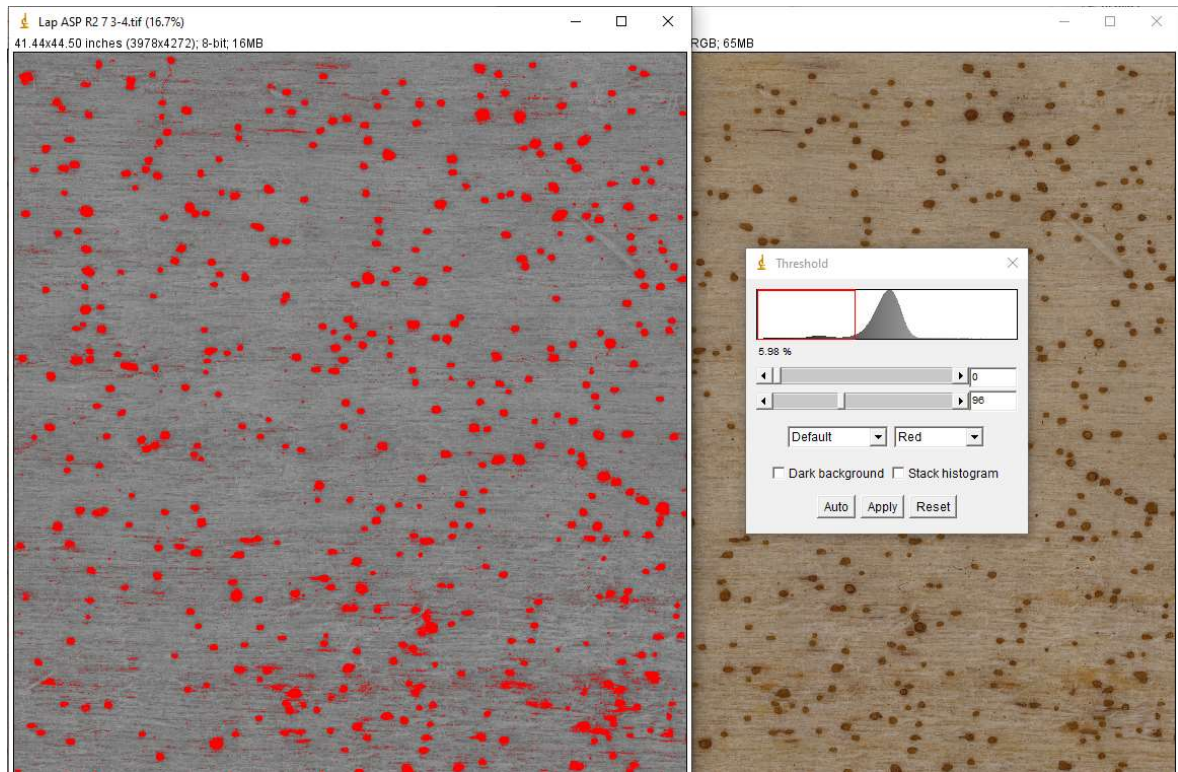


Figure 3-16, Grey scale histogram, manual section of threshold.

In some scenarios it was necessary to crop the photos because of defects in the wood strand, such as a large crack or void. When analyzing images, it is important to choose a uniform surface. Analyzing an area with a void could give an inaccurate analysis of the percent of resin area coverage.

To reduce the effect of noise and non-resin objects from the analysis, a minimum spot size filter was implemented. The minimum was selected to be 25 pixels ($32.06 \mu\text{m}^2$) based of visual observation. Implementing a minimum spot size had almost no effect on the area coverage of the strand, but did significantly reduce the number of spots that were recorded in the image.

Circularity constraints can also be useful for eliminating dark colored cracks that are picked up in the threshold. Circularity is calculated by comparing the object area to its perimeter. By having a circularity that between 0.001-1, unusually long objects that are obviously not resin were excluded from the image analysis.

3.5 Statistical Analysis

R Studio and Microsoft Excel were used for the statistical analysis of this project.

The lap-shear test in this project were analyzed using a two-way analysis of variance (ANOVA) test where the null hypothesis states that neither atomizer RPM, resin viscosity, or an interaction of the two have an effect on bondline performance. The raw data was represented using a boxplot. Once the model of the data was made it was found the residuals vs. fitted plot resembled a horn shape and the normality plot exhibited heavy tails. This was an indication that the data needed a log transformation, so a natural log was applied to the continuous variable of the lap-shear data.

The internal bond and three-point bending test in this project were also analyzed using a two-way analysis of variance (ANOVA) test where the null hypothesis states that neither atomizer RPM, resin viscosity, or an interaction of the two have an effect on tension strength for internal bond or MOR for three-point bending. The raw data was represented using a boxplot.

The MV Resin internal bond test in this project was analyzed using an analysis of covariance (ANCOVA) where the null hypothesis states that neither atomizer RPM or resin viscosity has an effect on bondline performance. The raw data was represented using a boxplot.

4. Results and Discussion

4.1 Resin Characterization

4.1.1 Resin Molecular Weight

Molecular weight of resins LV, MV, and HV was analyzed by Arclin. Results of each resin's molecular weight GPC test can be seen in Table 4-1.

Table 4-1, Molecular weight and polydispersity index in grams per mole for PF adhesives used in the experiment. Number average (Mn), weight average (Mw), Z average (Mz).

Sample	Mn (g/mol)	Mw (g/mol)	Mz (g/mol)
LV Sample 1	1920	3410	4770
LV Sample 2	2170	3220	4330
MV Sample 1	4090	7210	12650
MV Sample 2	2940	6880	12490
HV Sample 1	4090	10510	19570
HV Sample 2	4060	10750	19130

From the GPC results it can be seen that there was a correlation of increasing viscosity with increase in molecular weight.

4.1.2 Influence of Temperature on Viscosity

Results from the viscosity temperature effect on viscosity test can be seen in Figure 4-1. Each batch of resin was tested from 10°C to 40°C in 5-degree increments. At 25°C, the target viscosity for each resin was: 175 cP, 500 cP, and 1,000 cP for the low, medium, and high viscosity levels, respectively.

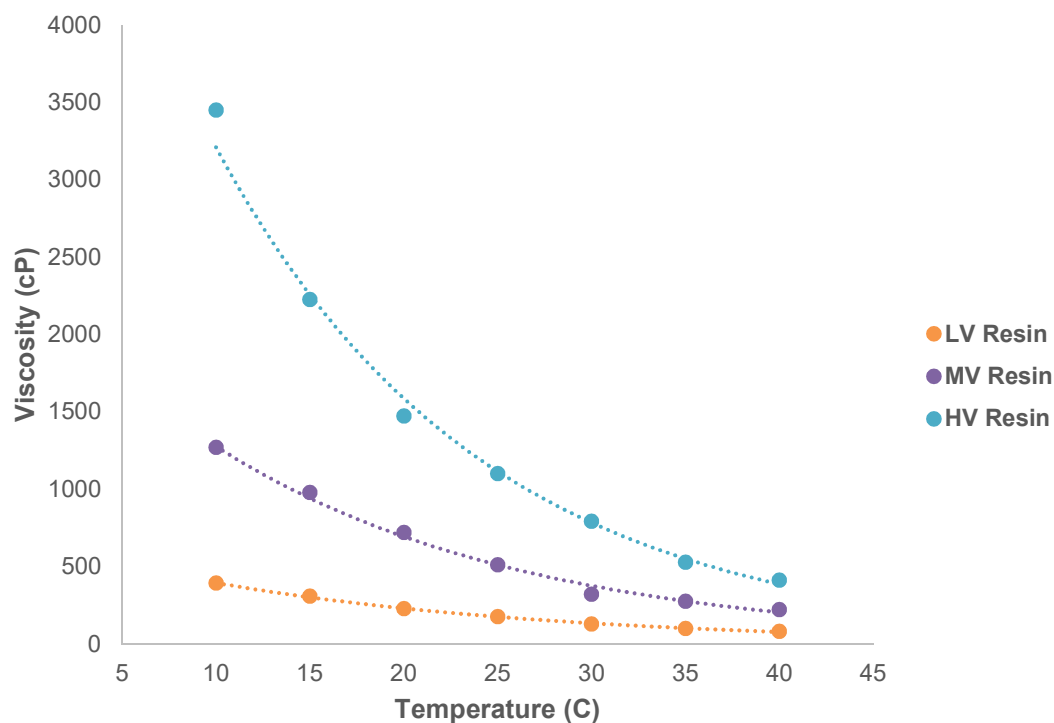


Figure 4-1, Influence of temperature on viscosity experiment.

Resin 3		
Temperature (C)	Viscosity (cP)	Surface Tension (mN/m)
10	525	69.62
15	420.6	69.84
20	292.8	69.45
25	222	69.39
30	172.5	69.19
35	130.8	69.42
40	105.6	68.99

As seen from the test results, decreasing temperature causes an exponential increase in viscosity. Resin LV, which had the lowest observed molecular weight, appears to be the least sensitive to temperature changes, while Resin HV, which had the highest observed molecular weight, appeared to be the most sensitive.

4.1.3 Influence of Temperature on Surface Tension

Results from the influence of temperature on surface tension test results can be seen in Table 4-2. Three resin samples were evaluated. LV resin is labeled Sample 1, while samples 2 and 3 were slightly advanced. Viscosity at 25°C ranged from 177 to

222 cP. Temperature, or the small increase in molecular weight, did not appear to have any significant effect on the surface tension of the resin. The results for surface tension as a function of temperature followed no trend within the range of 10 to 40°C. Overall, surface tension was in the range of 68.1 to 71.2 for all samples and temperatures. These results are similar to PF surface tension values reported by others at 25°C (). No previous reports could be found for the influence of temperature on surface tension of PF. Although, water and some polymer liquids have been shown to decrease surface tension with increasing temperature over the range used in this experiment (). The lack of a clear temperature dependence may be due to temperature instability of the pendant drop inside the chamber, since there was no way to directly measure temperature of the drop, and constant temperature from the water bath to the pipet tip was assumed. In addition, it has been observed that skin formation on a PF resin drop during contact angle measurement, via the sessile drop method, can cause errors (). The surface tension of MV and HV resins were not evaluated due to an inability of the pendant drop apparatus to handle a drop on the pipet tip.

Table 4-2, Influence of temperature on surface tension for three different tests on one resin. Viscosity was also measured at the time of each surface tension test.

Sample 1			Sample 2			Sample 3		
Temp (°C)	Viscosity (cP)	Surface Tension (mN/m)	Temp (°C)	Viscosity (cP)	Surface Tension (mN/m)	Temp (°C)	Viscosity (cP)	Surface Tension (mN/m)
10	388	71.2	10	474	70.8	10	525	69.6
15	322	70.5	15	354	68.2	15	421	69.8
20	233	70.6	20	264	71.0	20	293	69.5
25	177	68.1	25	197	70.5	25	222	69.4
30	135	70.4	30	150	71.2	30	173	69.2
35	107	68.7	35	117	70.8	35	131	69.4
40	85	69.0	40	92	69.2	40	106	69.0

4.2 Lap-Shear Testing

Lap-shear specimens were tested to failure according to ASTM D-2339 using a universal test machine (Instron, 100kN, Norwood, MA), with maximum load in tension recorded. Estimated mass of resin was used to determine a specific failure stress in Newtons per milligram (N/mg). Data for aspen and southern pine can be seen in Figure 4-2 and Figure 4-3, respectively.

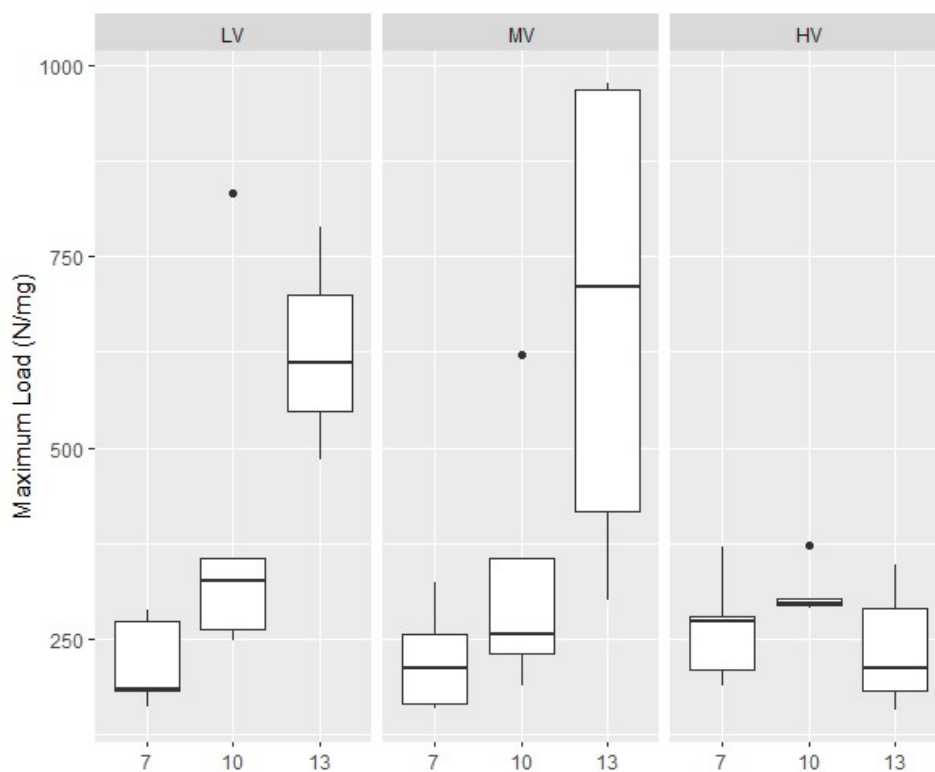


Figure 4-2, Box plot of aspen lap-shear specific failure stress for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.

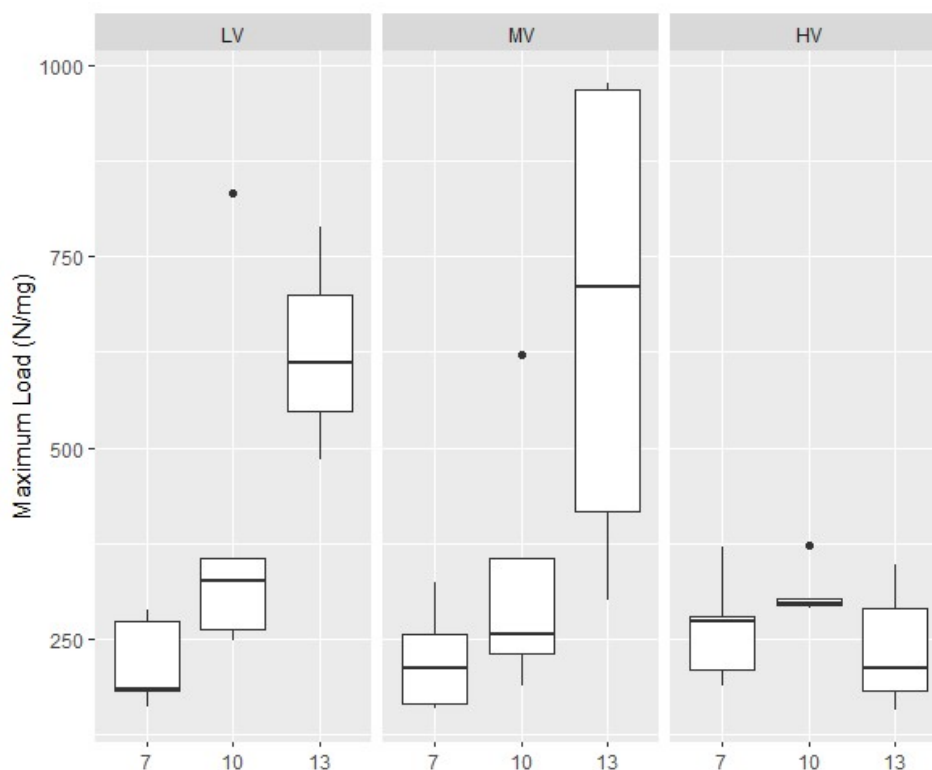


Figure 4-3, Box plot of southern pine lap-shear specific failure stress for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.

A two-way ANOVA was used to determine if resin molecular weight, atomizer RPM, or interaction of these parameters had an effect on the bondline performance based on a significance level of 0.05. As stated in the materials and methods, the lap-shear data appeared to need a log transformation based on the residuals vs. fitted and normality plot, so the natural log function was applied to the continuous variable “maximum load”. ANOVA table outputs can be seen for aspen and southern pine specimens in Table 4-3 and Table 4-4 respectively.

Table 4-3, Aspen lap-shear two-way ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	2.1356	1.06782	6.4474	0.004132
RPM	2	2.0211	1.01053	6.1015	0.005330
Resin:RPM	4	0.5304	0.13261	0.8007	0.533006
Residuals	35	5.7967	0.16562		

Table 4-4, Southern pine lap-shear two-way ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	0.4941	0.24704	1.8517	0.1734001
RPM	2	2.4363	1.21814	9.1306	0.0007289
Resin:RPM	4	2.3726	0.59316	4.4460	0.0057021
Residuals	32	4.2692	0.13341		

From the aspen ANOVA table, low p-values were seen for resin type (0.0041) and atomizer RPM (0.0053), so the null hypothesis can be rejected that these variables have no effect on the bondline performance. The interaction of resin and RPM had a p-value of 0.533, so there is evidence that an interaction between the resin and the atomizer RPM had an effect on the aspen lap-shear bond line performance.

From the southern pine ANOVA table, there was a high p-value for resin type (0.173) and low p-value was seen for the atomizer RPM (0.0007). This means that resin type did not have an impact on the lap-shear bondline performance, but atomizer RPM did. The interaction between resin type and atomizer RPM had a moderate p-value of 0.0057, which means the interaction of the two factors could have had an impact on the performance of the bondline.

4.3 Panel Testing

4.3.1 Internal Bond

Internal bond specimens were tested to failure according to ASTM D-1037 using a universal test machine (Instron, 100kN, Norwood, MA), which recorded maximum load in tension. Data for aspen and southern pine can be seen in Figure 4-4 and Figure 4-5, respectively.

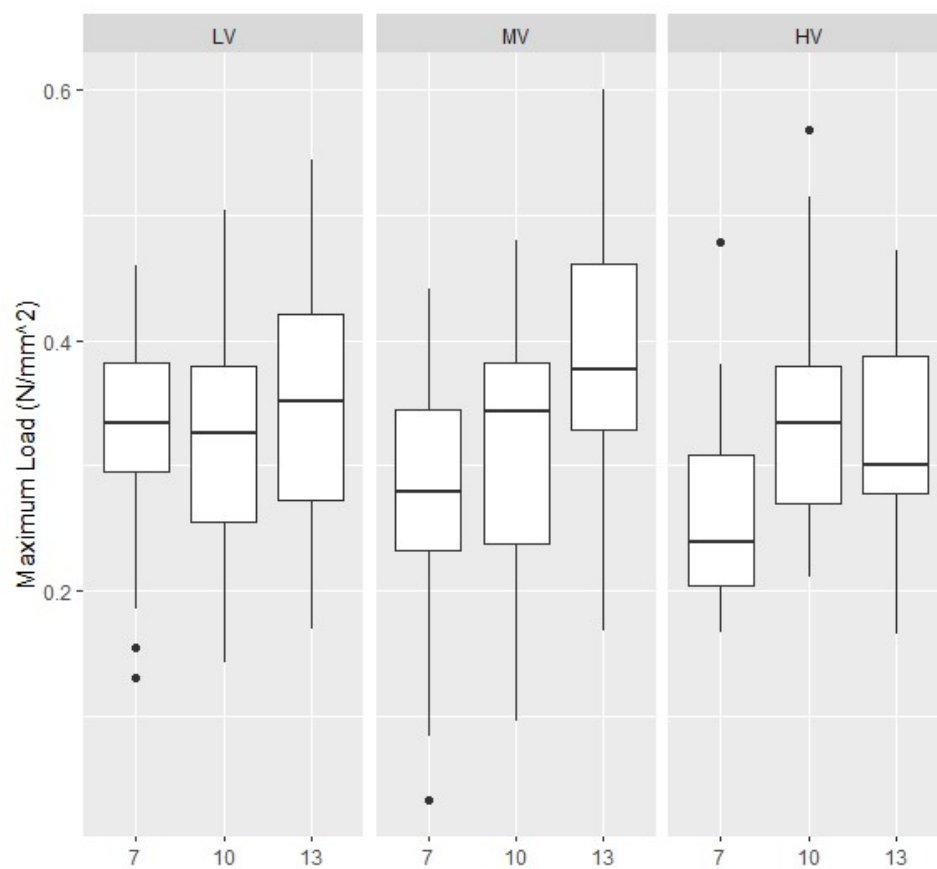


Figure 4-4, Box Plot of aspen internal bond strength for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.

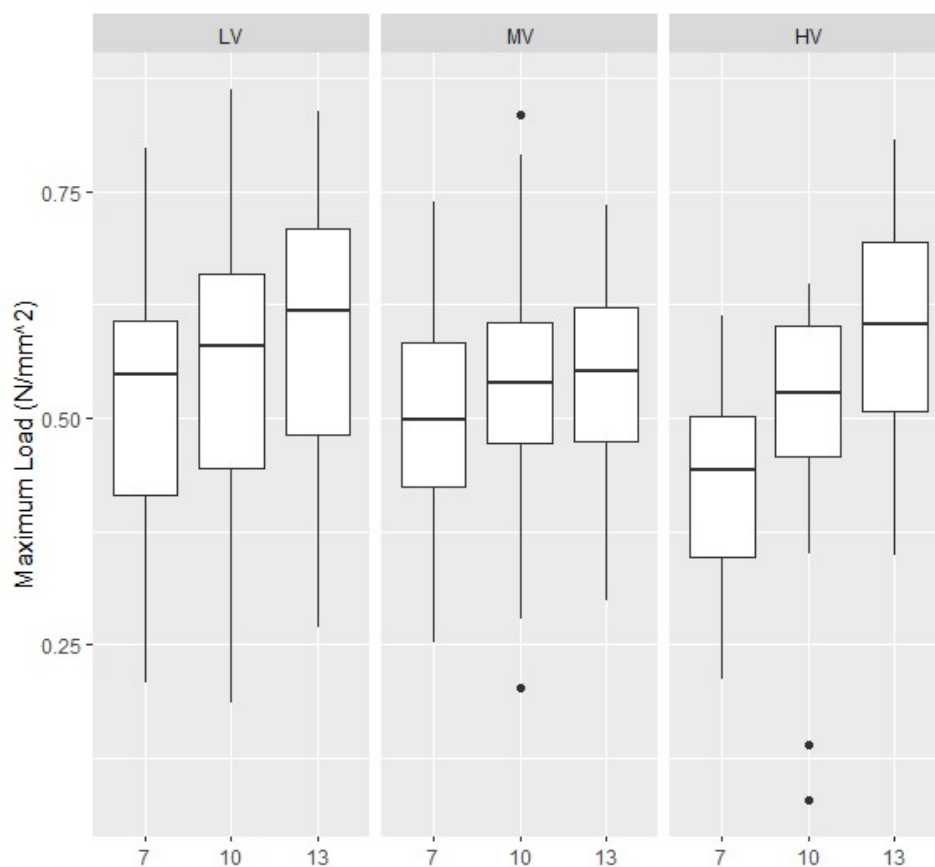


Figure 4-5, Box Plot of southern pine internal bond strength for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM..

A two-way ANOVA was used to determine if resin molecular weight, atomizer RPM, or interaction of the two had an effect on the bondline performance. ANOVA table outputs can be seen for aspen and southern pine specimens in Table 4-5 and Table 4-6.

Table 4-5. Aspen internal bond ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	107820	53910	0.9292	0.396275
RPM	2	1080378	540189	9.3106	0.000127
Resin:RPM	4	608310	152078	2.6212	0.035564
Residuals	243	14098547	58019		

Table 4-6, Southern pine internal bond ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	436701	218350	1.8493	0.1595
RPM	2	2361769	1180885	10.0014	0.00006659
Resin:RPM	4	926273	231568	1.9612	0.101
Residuals	247	29163822	118072		

From the aspen ANOVA table, a high p-value was seen for the resin type (0.396) and a low p-value for the atomizer RPM (0.00013). This means that resin type did not have an effect on the bondline performance, but atomizer RPM did. The interaction between resin type and atomizer RPM had a moderate p-value (0.0356). So, there is a possibility that there is an interaction of resin type and atomizer RPM having an effect on the bondline performance.

From the southern pine ANOVA table, a high p-value was seen for the resin type (0.16) and a low p-value for the atomizer RPM (0.00007). This means that resin type did not have an effect on the bondline performance, but atomizer RPM did. The interaction between resin type and atomizer RPM had a high p-value (0.101). Consequently, there is evidence that an interaction of resin type and atomizer RPM did not have an effect on the bondline performance.

It is likely that density of individual IB specimens influenced results and contributed to variability of the IB data. However, density was not measured for the low viscosity and high viscosity resin specimens. Density was measured for the medium viscosity resin specimens.

4.3.2 Medium Viscosity Resin Internal Bond

Density of each internal bond specimen was only recorded for the medium viscosity resin. Density can be a factor that effects composite performance, so an analysis of covariance (ANCOVA) was conducted to determine if specimen density and atomizer RPM had an effect on bondline performance. Data for aspen and southern pine MV internal bond test can be seen in Figure 4-6 and Figure 4-7, respectively. IB did show a correlation with density. Therefore, ANCOVA is appropriate.

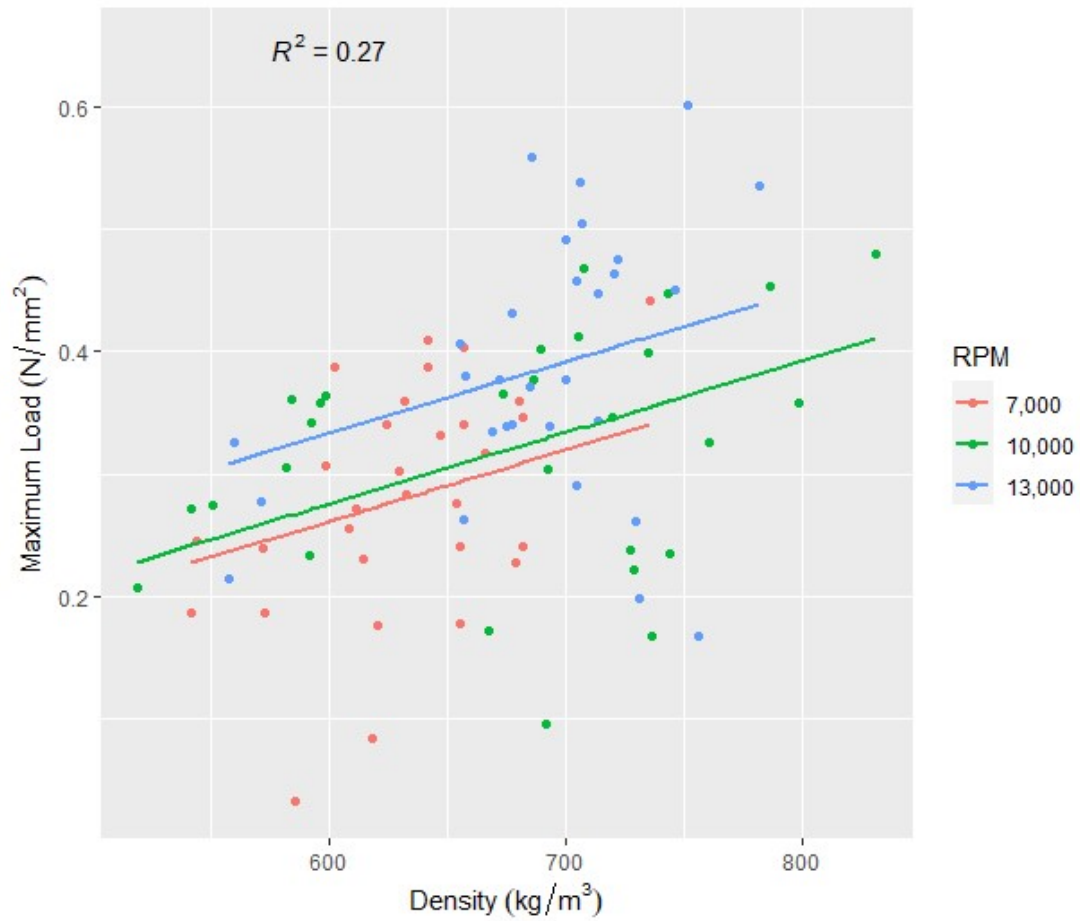


Figure 4-6, Plot of medium viscosity resin aspen internal bond strength as a function of density, with atomizer speeds: 7,000 RPM (Red), 10,000 RPM (Green), and 13,000 RPM (Blue).

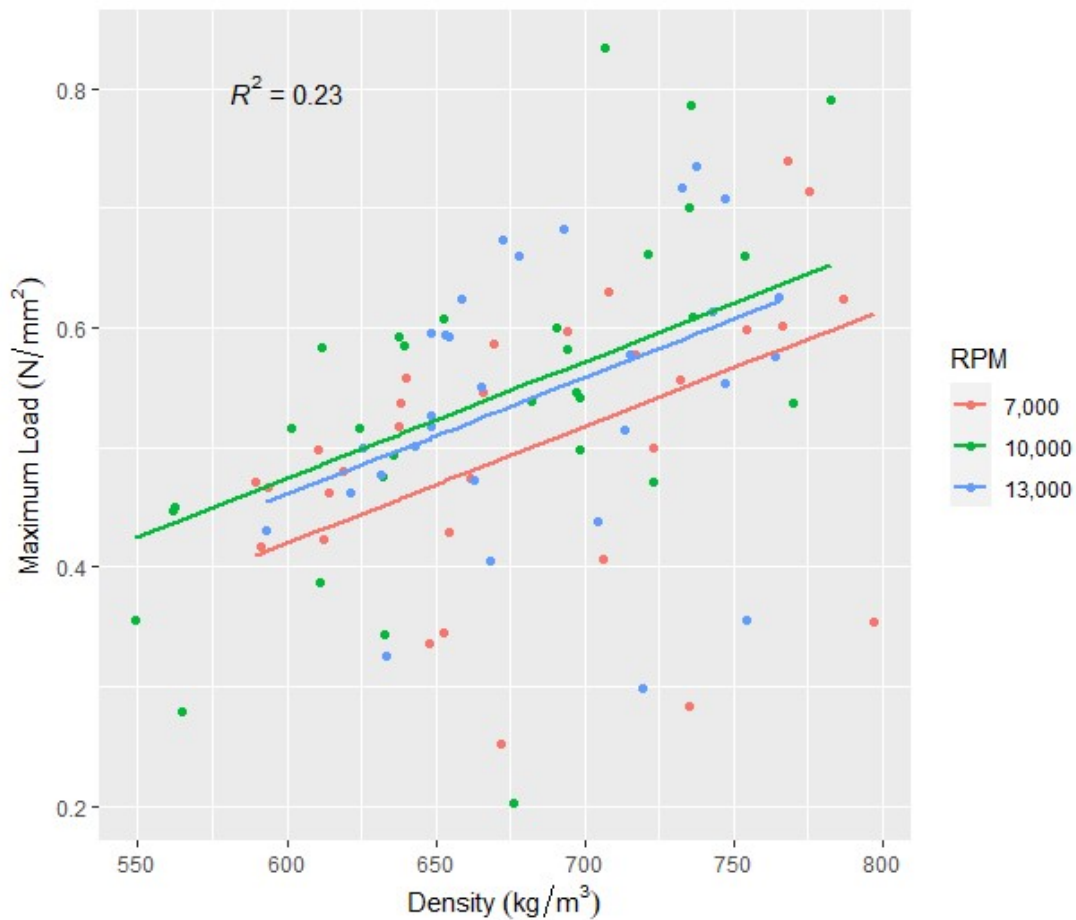


Figure 4-7, Plot of medium viscosity resin southern pine internal bond strength as a function of density, with atomizer speeds: 7,000 RPM (Red), 10,000 RPM (Green), and 13,000 RPM (Blue).

ANOVA table outputs can be seen for aspen and southern pine specimens in Table 4-7 and Table 4-8 respectively. From the aspen ANOVA table, a low p-value was seen for atomizer RPM (0.0002) and specimen density (0.0009). This means that both atomizer RPM and density had a significant impact on the bondline performance.

From the southern pine ANOVA table, a high p-value was seen for atomizer RPM (0.246) and a low p-value was seen for specimen density (0.000007). This means that there is no evidence that atomizer RPM had an impact on the bondline performance, but density had a significant impact.

Table 4-7, Aspen medium viscosity resin internal bond ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
RPM	2	1137773	568887	9.3391	0.0002176
Density	1	726188	726188	11.9215	0.0008715
Residuals	84	4955144	60429		

Table 4-8, Southern pine medium viscosity resin internal bond ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
RPM	2	239242	119621	1.4249	0.2461
Density	1	1931064	1931064	23.0029	0.00000673
Residuals	86	7003242	83372		

4.3.3 Three Point Bending

Three-point bending specimens were tested to failure according to ASTM D1037 using a universal test machine (Instron, 100kN, Norwood, MA), with modulus of rupture (MOR) recorded. From the maximum load, MOR was found according to the equation:

$$\text{MOR} = \frac{3FL}{2bd^2} \quad \text{Eq. 8}$$

Where:

Modulus of Rupture (MOR)

Maximum Load (F)

Length of Specimen (L)

Width of Specimen (b)

Depth of Specimen (d)

Data for aspen and southern pine can be seen in in Figure 4-8 and Figure 4-9, respectively.

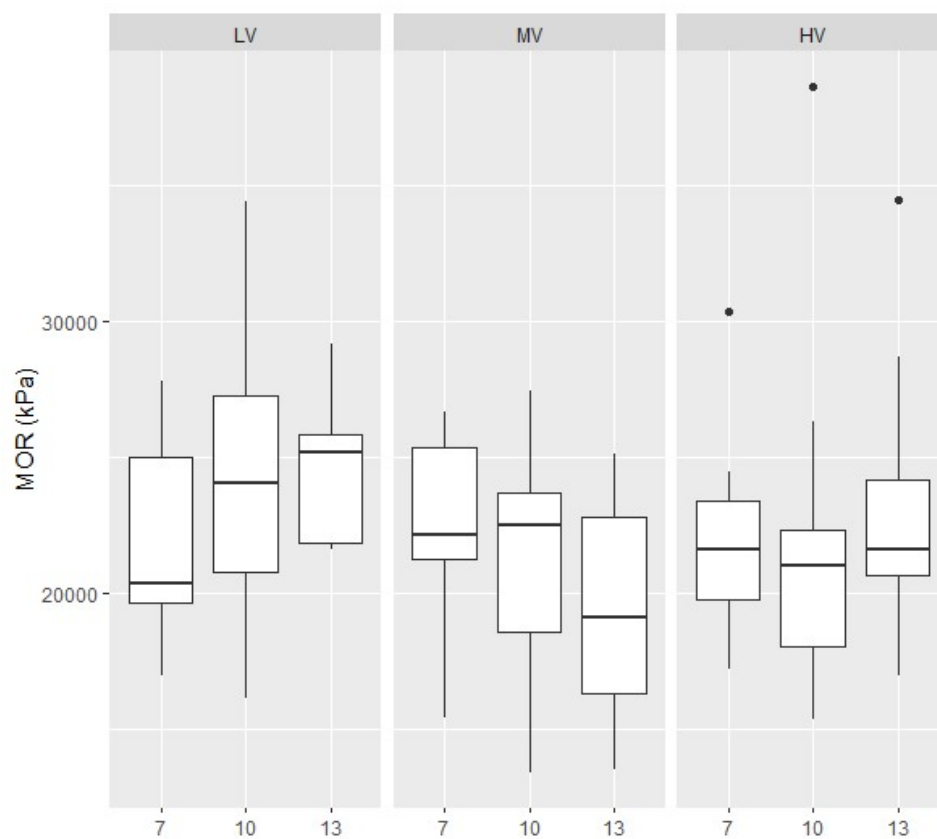


Figure 4-8, Box plot of aspen strand board MOR for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.

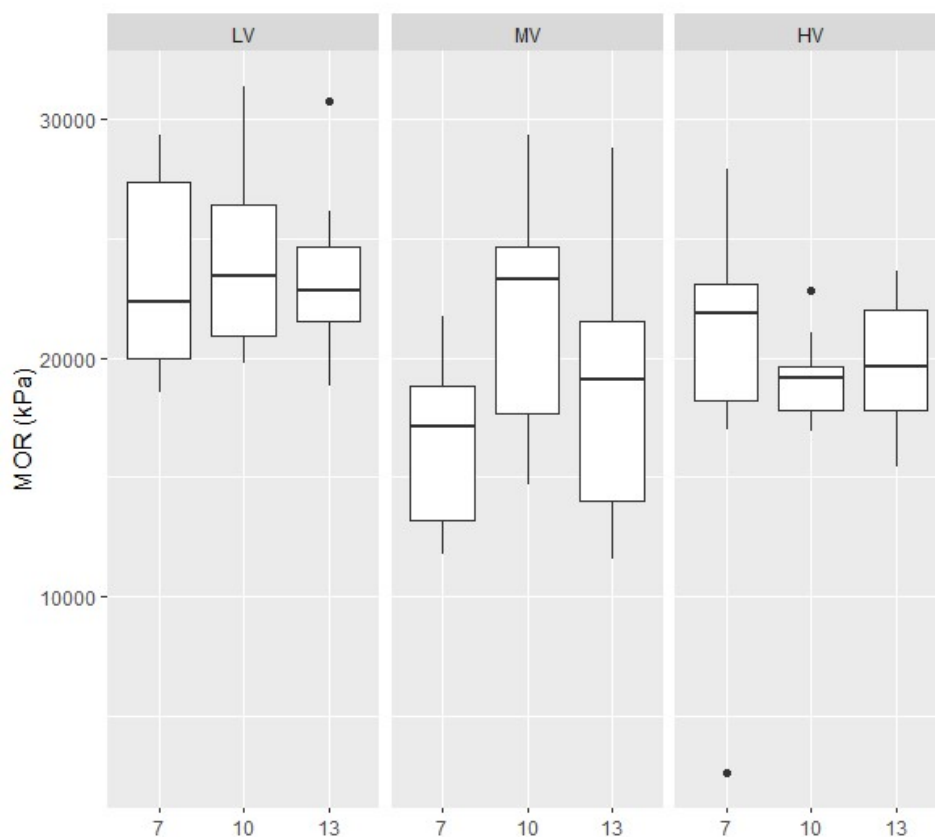


Figure 4-9, Box plot for southern pine MOR for resins LV, MV, and HV across three atomizer speeds 7,000, 10,000, and 13,000 RPM.

A two-way ANOVA was used to determine if resin type, atomizer RPM, or an interaction of the two had an effect on bending strength. ANOVA table outputs can be seen for aspen and southern pine specimens in Table 4-9 and Table 4-10.

Table 4-9, Aspen strand board MOR ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	96761037	48380519	2.2774	0.1099
RPM	2	4626429	2313214	0.1089	0.897
Resin:RPM	4	80098542	20024635	0.9426	0.4444
Residuals	72	1529529555	21243466		

Table 4-10, Southern pine strand board MOR ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
--	--------------------	----------------	--------------	---------	---------

Resin	2	341705325	170852662	8.2144	0.0006118
RPM	2	45976025	22988013	1.1052	0.3366834
Resin:RPM	4	100137690	25034422	1.2036	0.3167718
Residuals	72	1497537933	20799138		

From the aspen ANOVA table, a high p-value was seen for resin type (0.110), atomizer RPM (0.897), and the interaction between the two (0.444). Therefore, no factors had a significant influence on the performance of the maximum bending strength.

From the southern pine ANOVA table, a low p-value was seen for resin type (0.0.0006118) and a high p-value was seen for atomizer RPM (0.337). A high p-value was observed for the interaction between resin type and atomizer RPM (0.317). This means the only significant impact made on the maximum load was from the resin type.

4.4 Resin Distribution

Data of resin spot size on strands was combined for each population of strands based on the type of resin used and atomizer speed. Resin spots were ordered based on area from smallest to largest. Then a cumulative resin spot area was calculated across the ordered spot size data. The cumulative fraction of resin coverage, in order of spot area, was determined based on the total area of resin detected. This data was plotted and provides information on the distribution of resin spot size for each group of resin types and atomizer RPMs.

Four plots were made for the cumulative fraction of area coverage, 0-25%, 0-50%, 0-75%, and 0-100%. The expanded scales were used to better illustrate differences between the distributions at the lower range of resin spot size because the lines can overlap when view across the entire range of area coverage.

The analyzed blender and lap-shear strands all appear to have a consistent trend of the resin spot size decreasing with increasing resin viscosity and increasing disk speed for aspen and southern pine strands. This observation is consistent with Eq. 4. Increasing atomizer disk speed causes droplets to have more momentum, thus allowing them to break up into smaller particles. The influence of viscosity on atomization is less clear. Pelofsky (1966) reported an empirical relationship for surface tension versus

viscosity for 33 liquid systems, where surface tension was found to be inversely proportional to viscosity. Increasing viscosity would relate to decreasing surface tension. Decreasing surface tension would promote the breakup of ligaments from a spinning disk into smaller droplets. The observation in the current study is consistent with the results of Pelofsky.

4.4.1 Blender Strand Image Analysis

Strands pulled from blender furnish are subject to a wide distribution of droplet sizes and patterns due to their varying proximity to the head of the atomizer and attrition blending.

Cumulative fraction of area coverage plots for aspen blender strands can be seen in Figure 4-10, Figure 4-11, Figure 4-12, and Figure 4-13. Droplet size data for each quarter of the cumulative fraction of area coverage can be seen in Table 4-11.

Table 4-11, Resin spot size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of aspen blender strands in mm².

Strand Group	Cumulative Fraction of Area Coverage			
	0.25	0.5	0.75	1.0
<i>LV 7</i>	0.0138	0.0519	0.1530	13.185
<i>LV 10</i>	0.0123	0.0435	0.1197	4.588
<i>LV 13</i>	0.0086	0.0304	0.1008	5.055
<i>MV 7</i>	0.0109	0.0369	0.0958	2.085
<i>MV 10</i>	0.0088	0.0279	0.0832	9.500
<i>MV 13</i>	0.0064	0.0192	0.0655	8.254
<i>HV 7</i>	0.0098	0.0371	0.1070	2.456
<i>HV 10</i>	0.0063	0.0209	0.0610	5.042
<i>HV 13</i>	0.0042	0.0136	0.0413	3.187

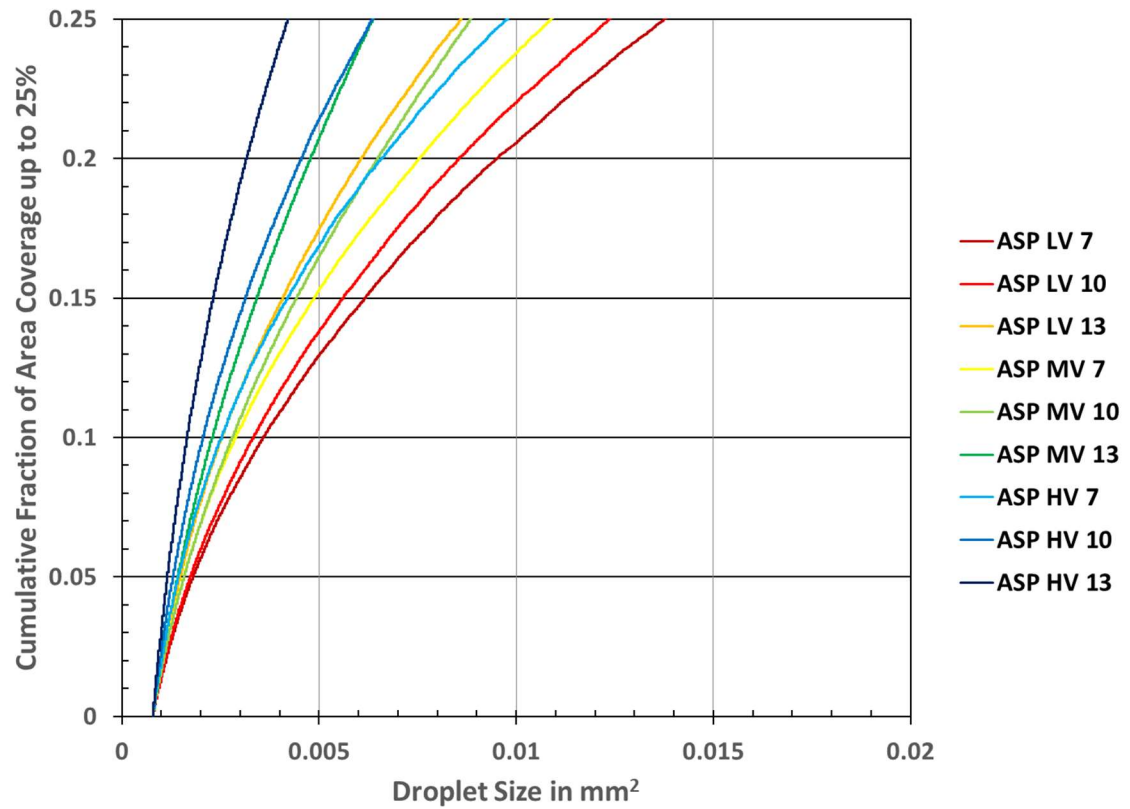


Figure 4-10, Cumulative fraction of area coverage up to 25% for aspen blender strands.

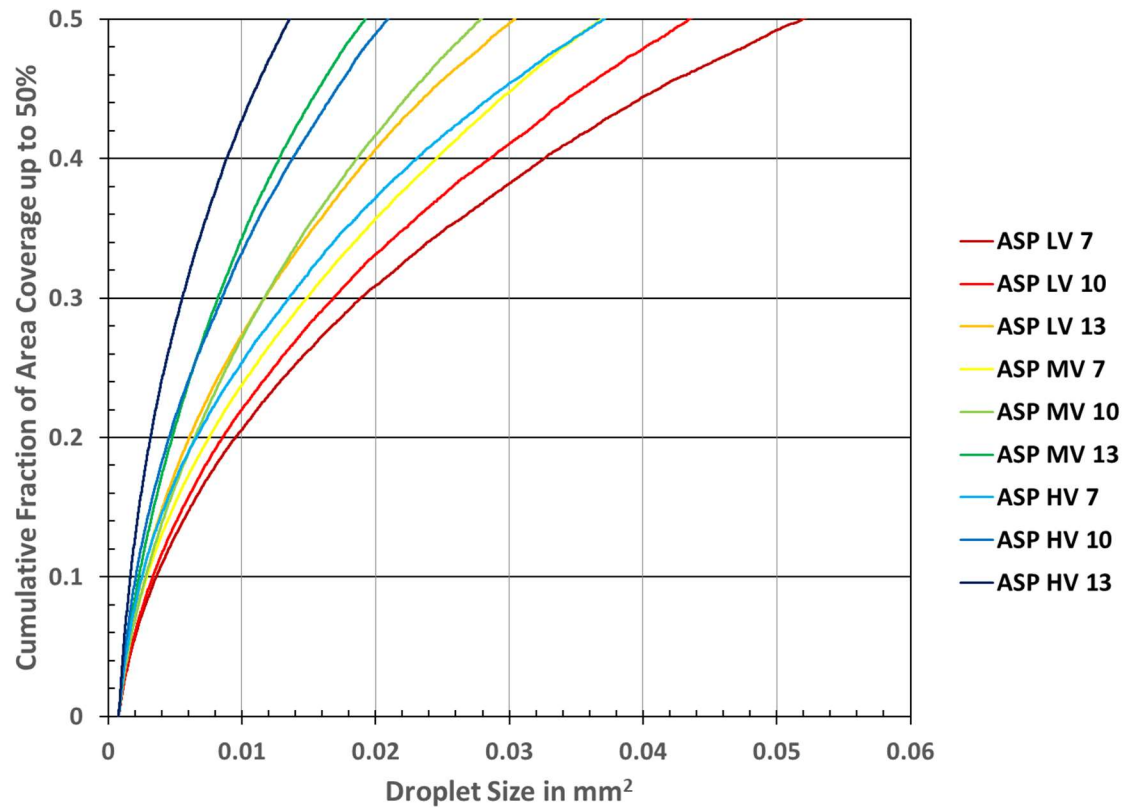


Figure 4-11, Cumulative fraction of area coverage up to 50% for aspen blender strands.

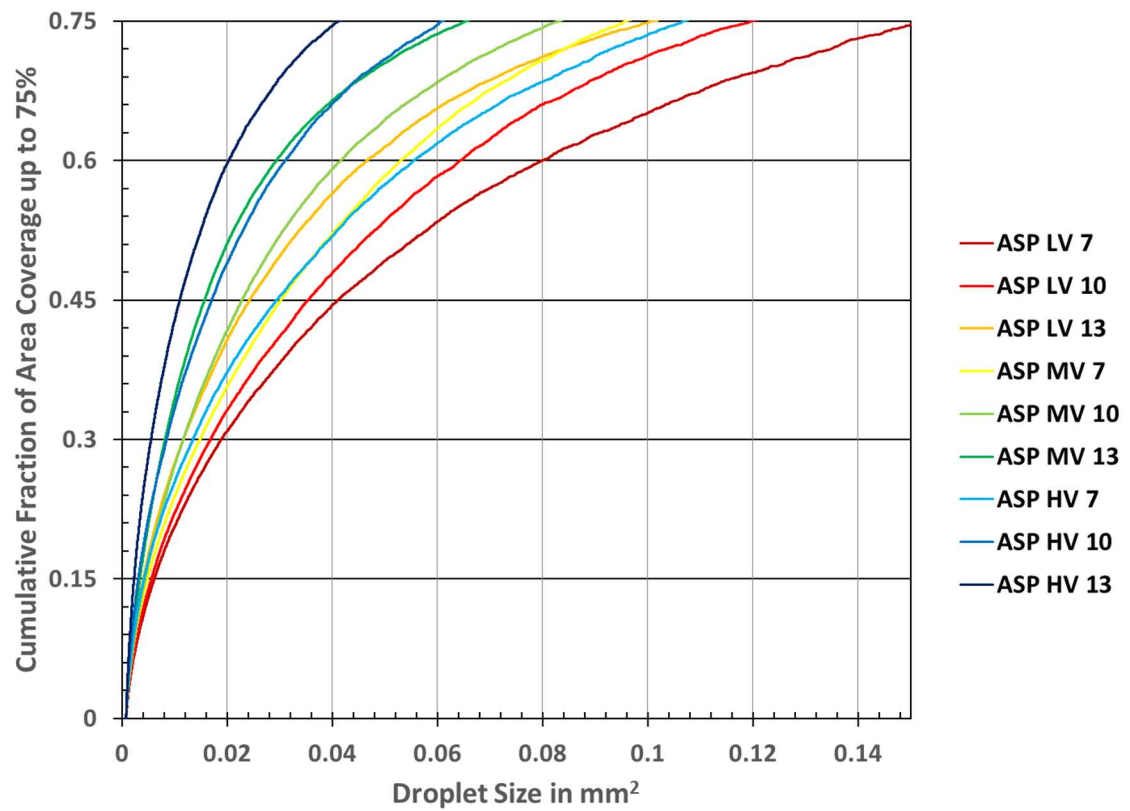


Figure 4-12, Cumulative fraction of area coverage up to 75% for aspen blender strands.

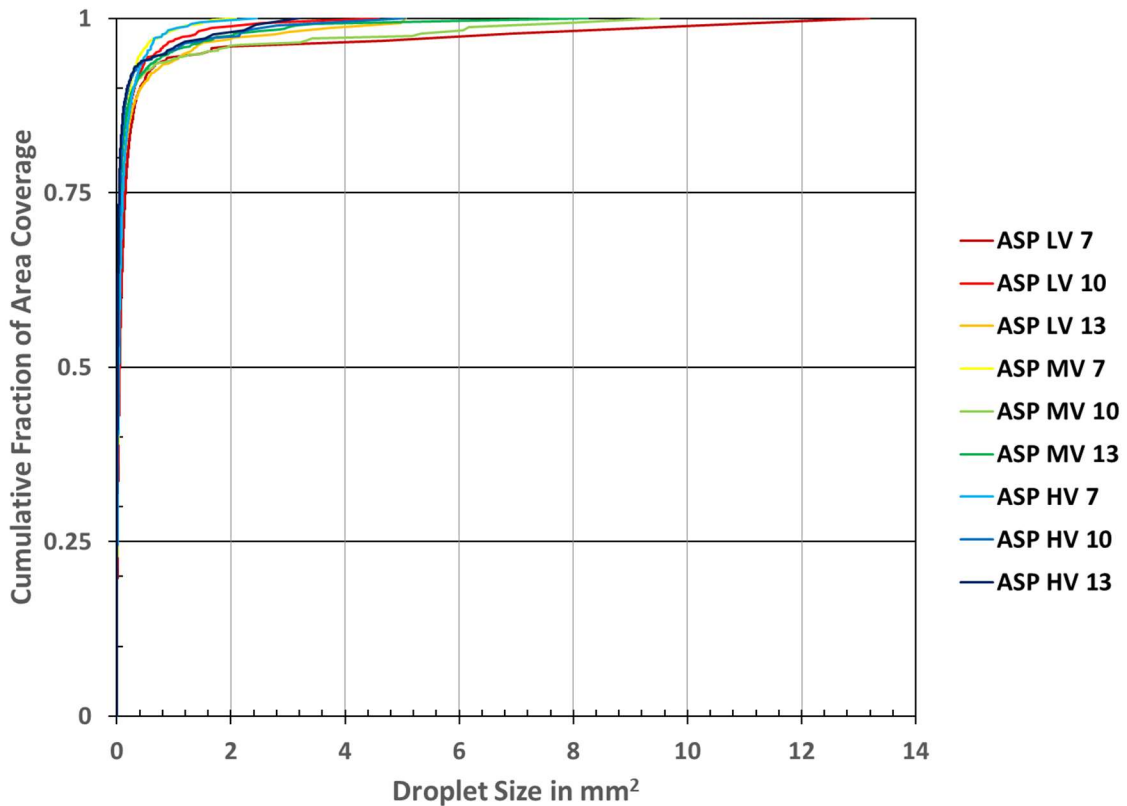


Figure 4-13, Cumulative fraction of area coverage for aspen blender strands.

Cumulative fraction of area coverage plots for southern pine blender strands can be seen in Figure 4-14, Figure 4-15, Figure 4-16, and Figure 4-17. Resin spot size data for each quartile of the cumulative fraction of area coverage can be seen in Table 4-12Table 4-11.

Table 4-12, Resin spot size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of southern pine blender strands in mm².

Strand Group	Cumulative Fraction of Area Coverage			
	0.25	0.5	0.75	1.0
LV 7	0.0297	0.110	0.333	6.03
LV 10	0.0180	0.065	0.233	9.71
LV 13	0.0101	0.038	0.166	6.58
MV 7	0.0231	0.074	0.194	4.22
MV 10	0.0120	0.039	0.139	14.26
MV 13	0.0083	0.027	0.120	12.89

<i>HV 7</i>	0.0151	0.054	0.153	2.21
<i>HV 10</i>	0.0098	0.031	0.100	1.89
<i>HV 13</i>	0.0101	0.031	0.091	1.95

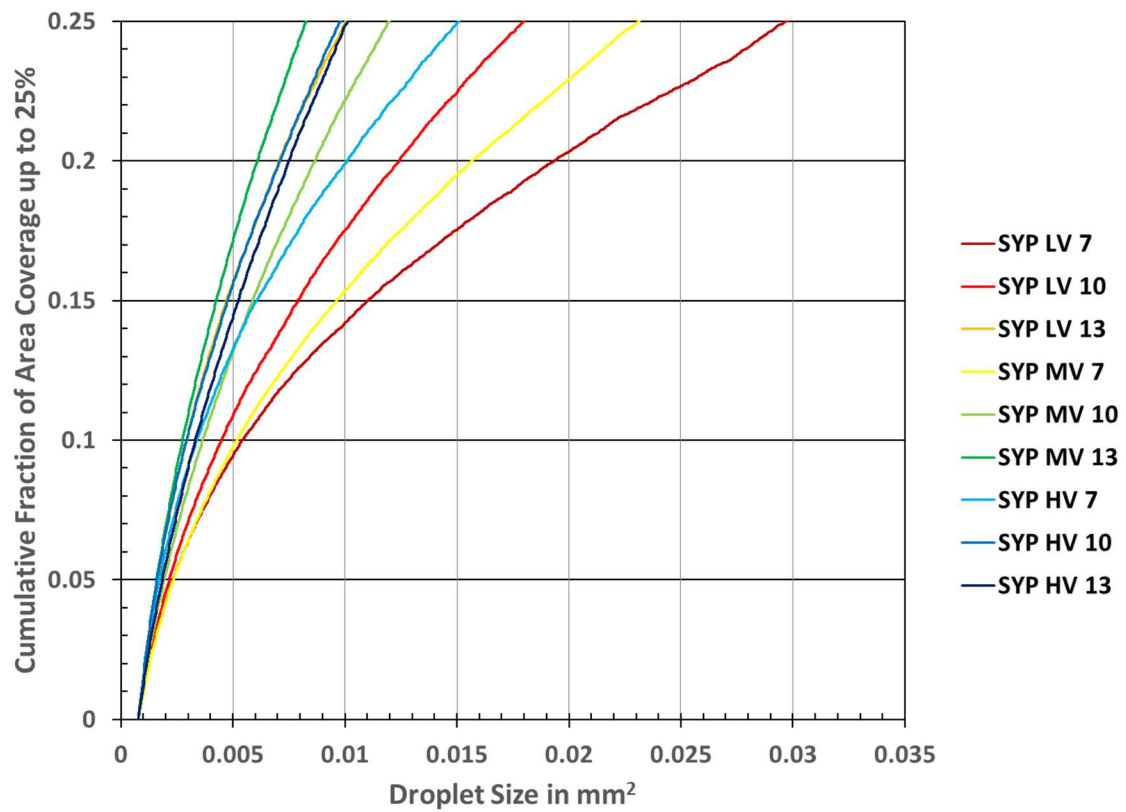


Figure 4-14, Cumulative fraction of area coverage up to 25% for southern pine blender strands.

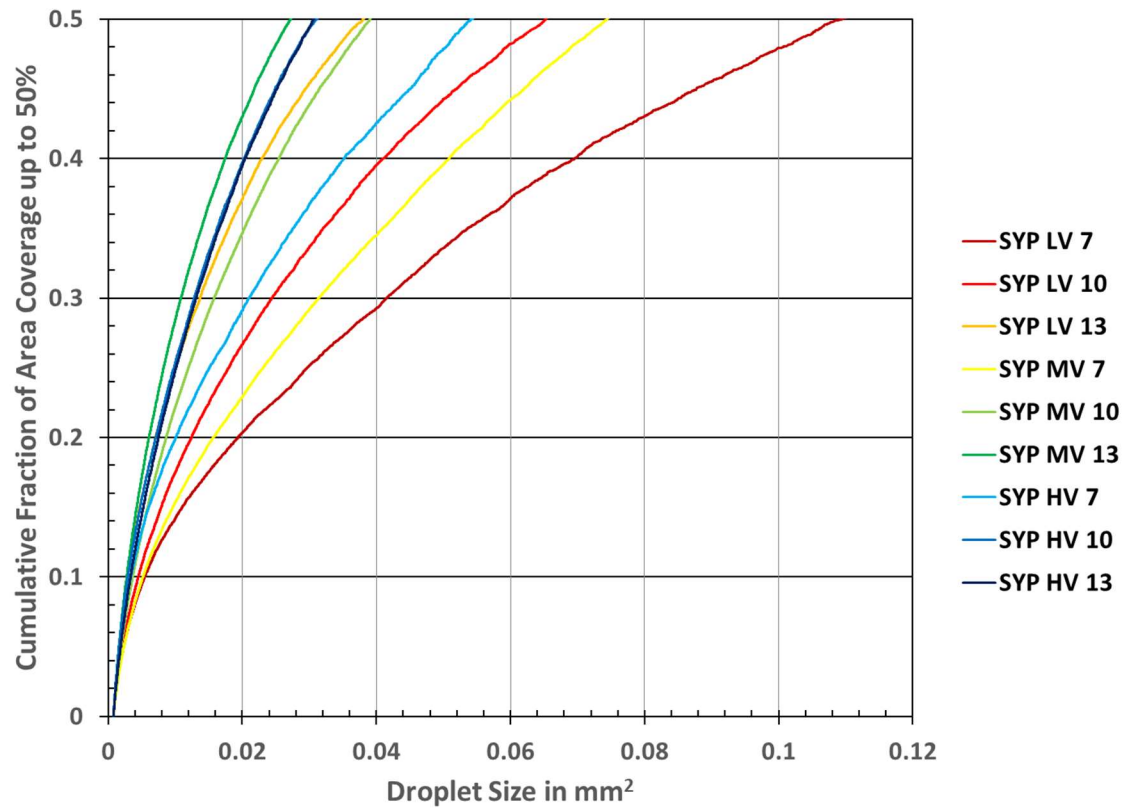


Figure 4-15, Cumulative fraction of area coverage up to 50% for southern pine blender strands.

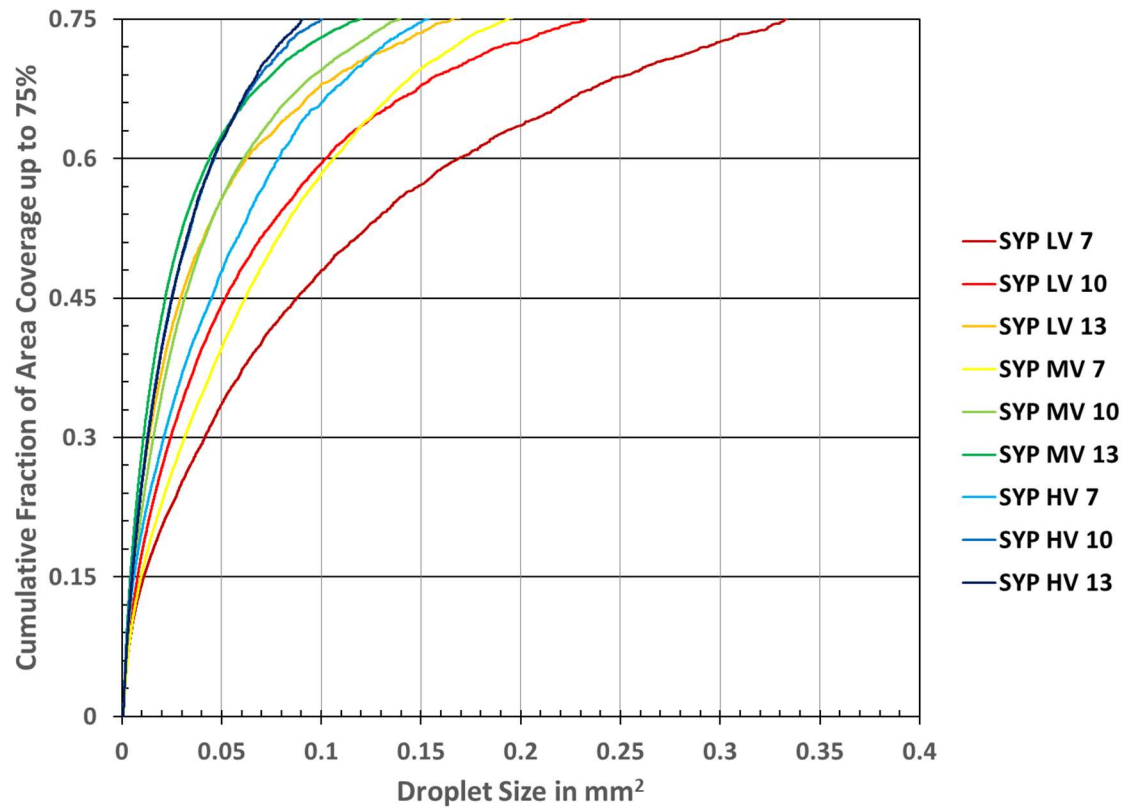


Figure 4-16, Cumulative fraction of area coverage up to 75% for southern pine blender strands.

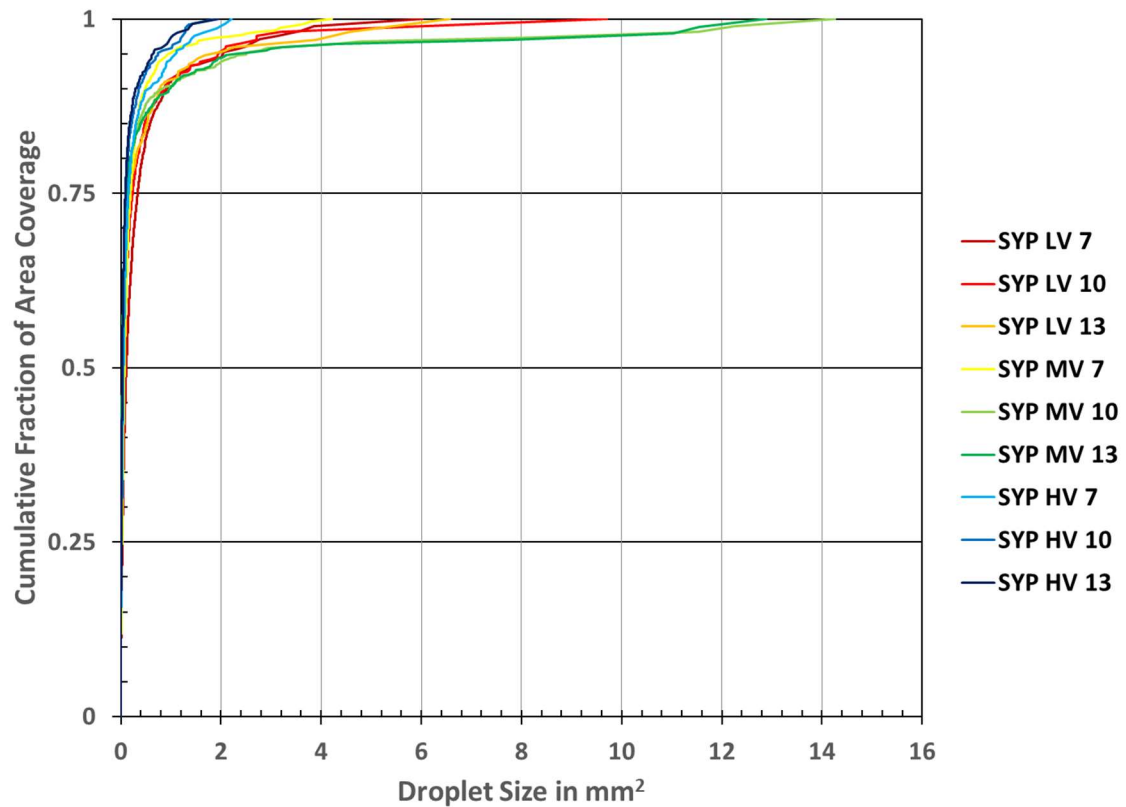


Figure 4-17, Cumulative fraction of area coverage for southern pine blender strands.

4.4.2 Lap-Shear Strand Image Analysis

Cumulative fraction of area coverage plots for aspen lap-shear strands can be seen in Figure 4-18, Figure 4-19, Figure 4-20, and Figure 4-21. Droplet size data for each quarter of the cumulative fraction of area coverage can be seen in **Error! Reference source not found.**Table 4-11.

Strand Group	Cumulative Fraction of Area Coverage			
	0.25	0.5	0.75	1
ASP LV 7	0.012118	0.025711	0.052672	0.586602
ASP LV 10	0.012374	0.027666	0.069246	1.626347
ASP LV 13	0.012567	0.034302	0.099829	1.801866
ASP MV 7	0.03286	0.045427	0.066008	0.606253
ASP MV 10	0.016606	0.036963	0.061808	0.396272
ASP MV 13	0.003013	0.018946	0.036578	0.139165
ASP HV 7	0.040746	0.054627	0.076876	0.244284

ASP HV 10	0.019075	0.031609	0.044433	0.230146
ASP HV 13	0.004937	0.01074	0.029429	0.117045

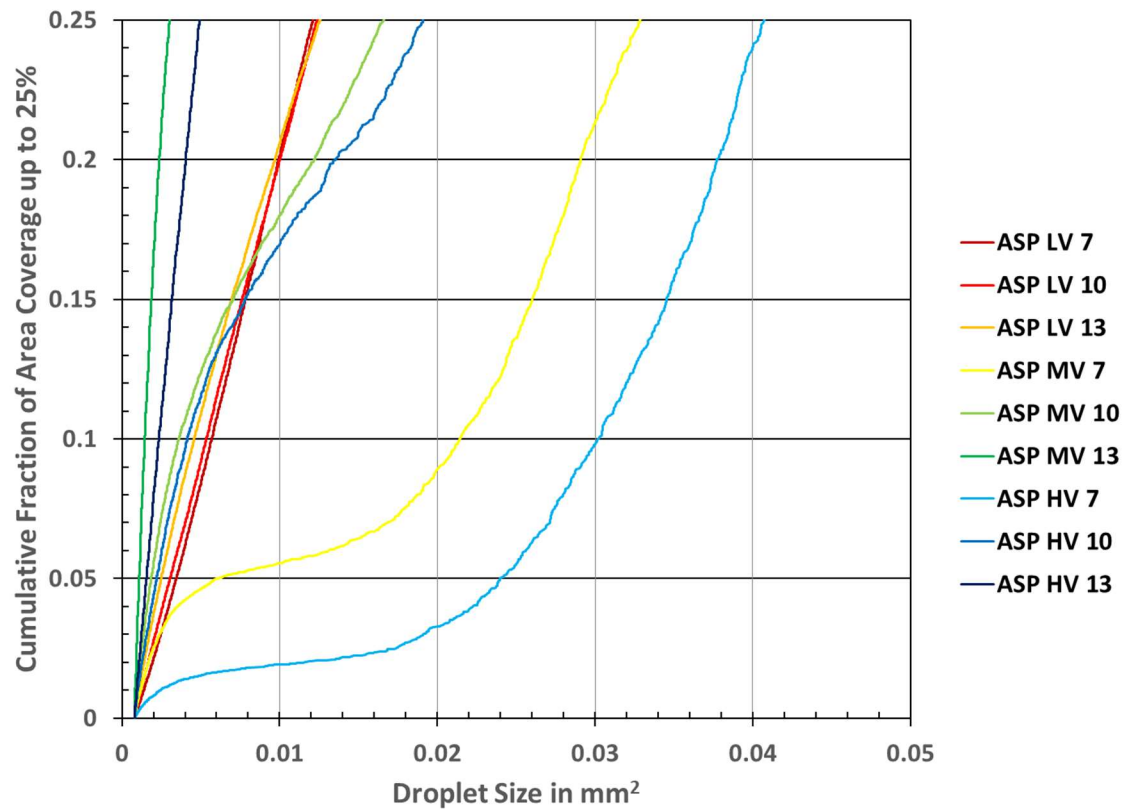


Figure 4-18, Cumulative fraction of area coverage up to 25% for aspen lap-shear strands.

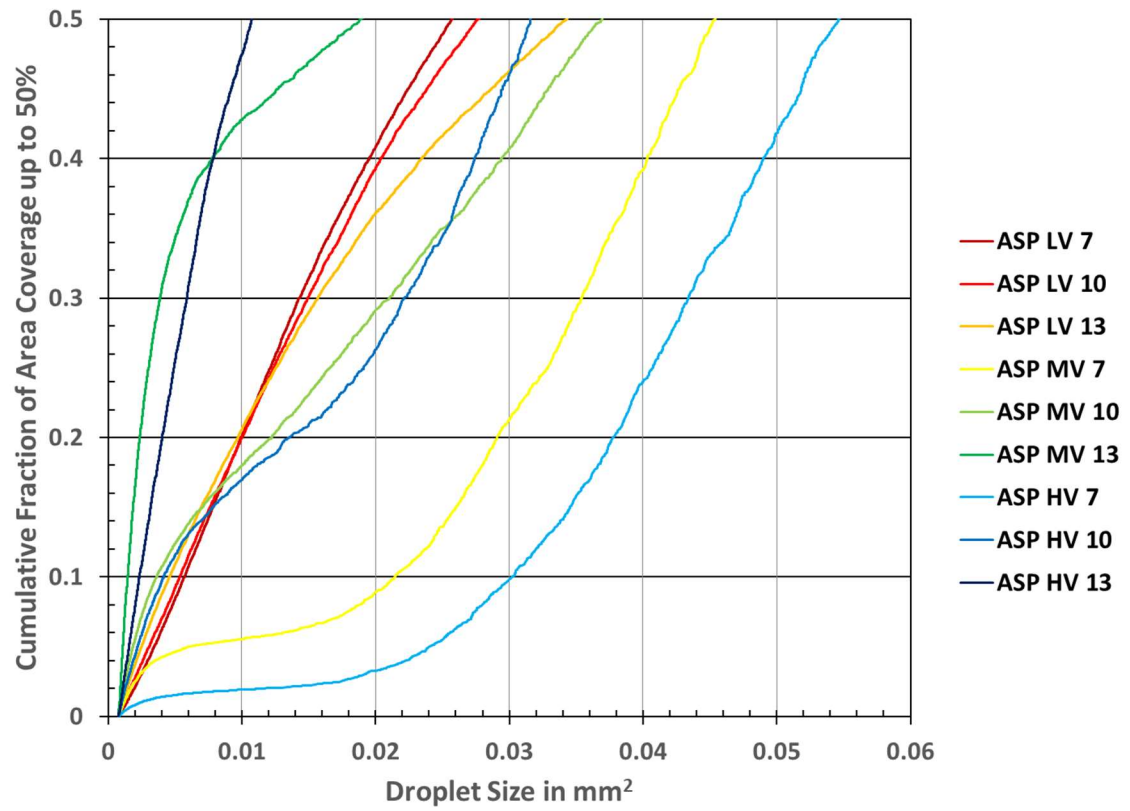


Figure 4-19, Cumulative fraction of area coverage up to 50% for aspen lap-shear strands.

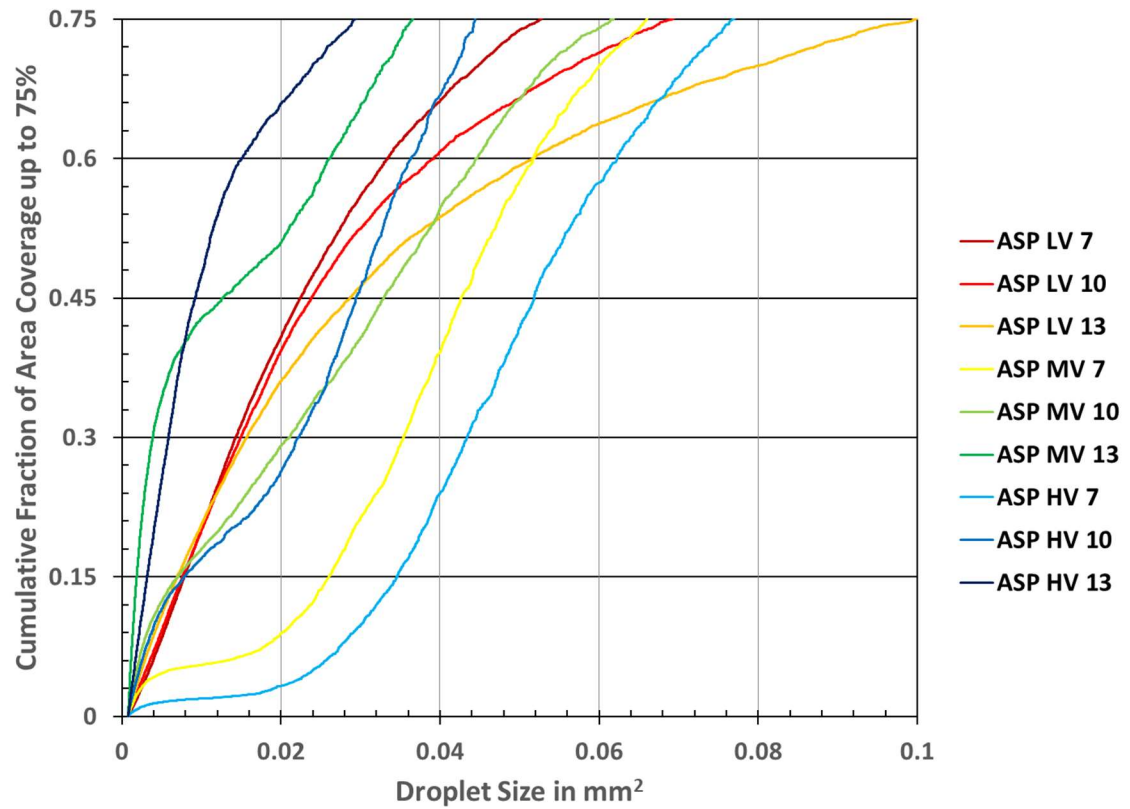


Figure 4-20, Cumulative fraction of area coverage up to 75% for aspen lap-shear strands.

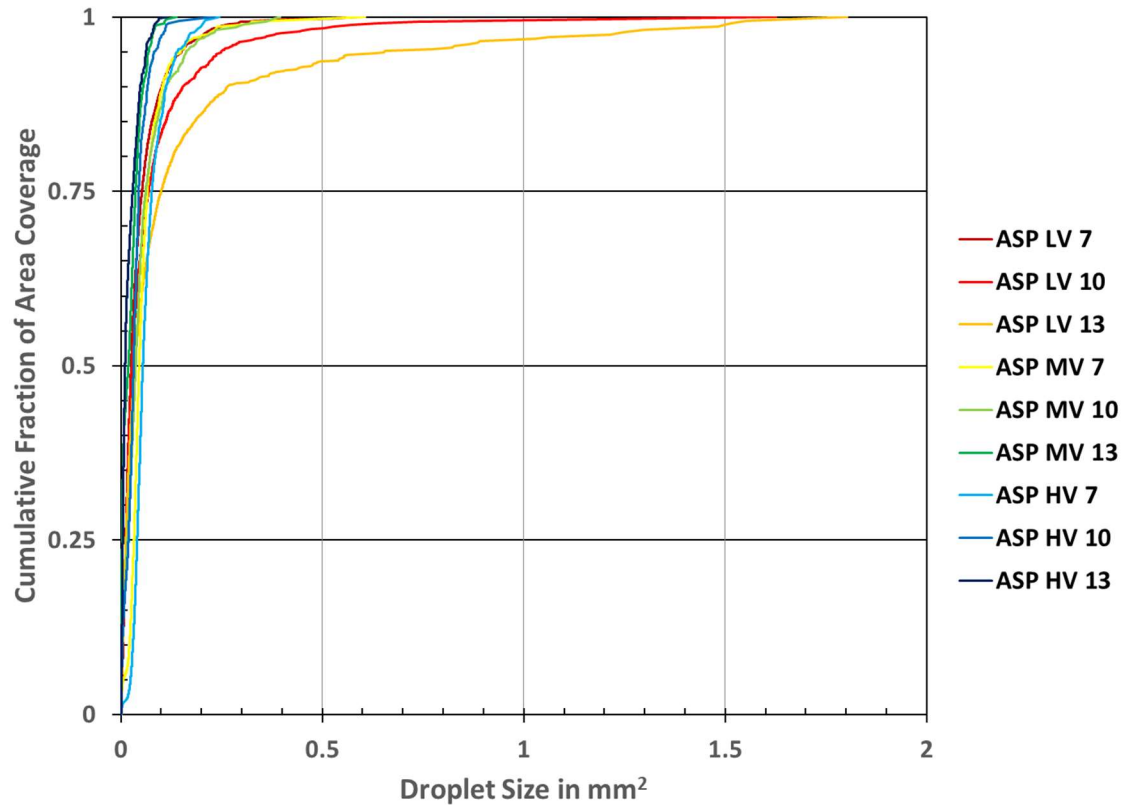


Figure 4-21, Cumulative fraction of area coverage for aspen lap-shear strands.

Cumulative fraction of area coverage plots for southern pine lap-shear strands can be seen in Figure 4-22, Figure 4-23, Figure 4-24, and Figure 4-25. Droplet size data for each quarter of the cumulative fraction of area coverage can be seen in Table 4-13Table 4-11.

Table 4-13, Droplet size at 25%, 50%, 75%, and 100% of the cumulative fraction of area coverage PF resin for each population of southern pine lap-shear strands in mm^2 .

Strand Group	Cumulative Fraction of Area Coverage			
	0.25	0.5	0.75	1.0
LV 7	0.049	0.133	0.390	2.877
LV 10	0.027	0.070	0.136	0.964
LV 13	0.004	0.039	0.067	0.251
MV 7	0.042	0.055	0.083	0.557
MV 10	0.031	0.046	0.065	0.189
MV 13	0.004	0.027	0.042	0.113

HV 7	0.072	0.106	0.183	0.700
HV 10	0.035	0.057	0.097	0.813
HV 13	0.016	0.038	0.078	0.758

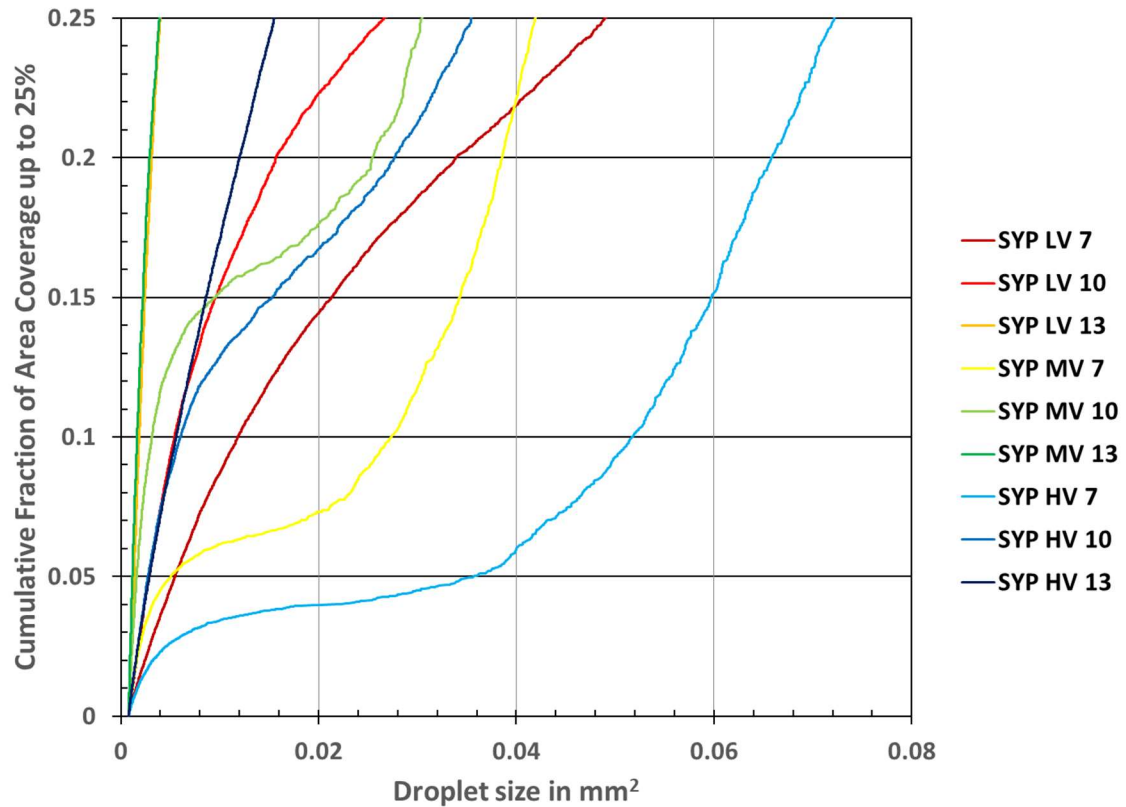


Figure 4-22, Cumulative fraction of area coverage up to 25% for southern pine lap-shear strands.

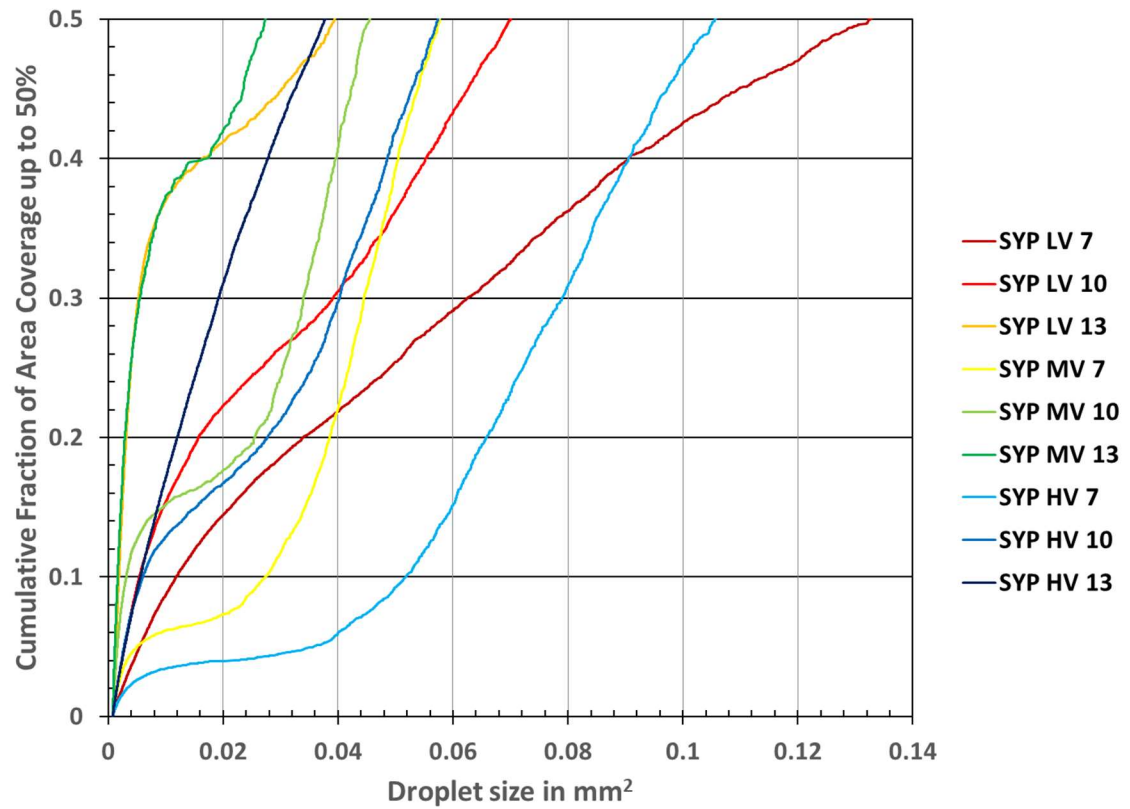


Figure 4-23, Cumulative fraction of area coverage up to 50% for southern pine lap-shear strands.

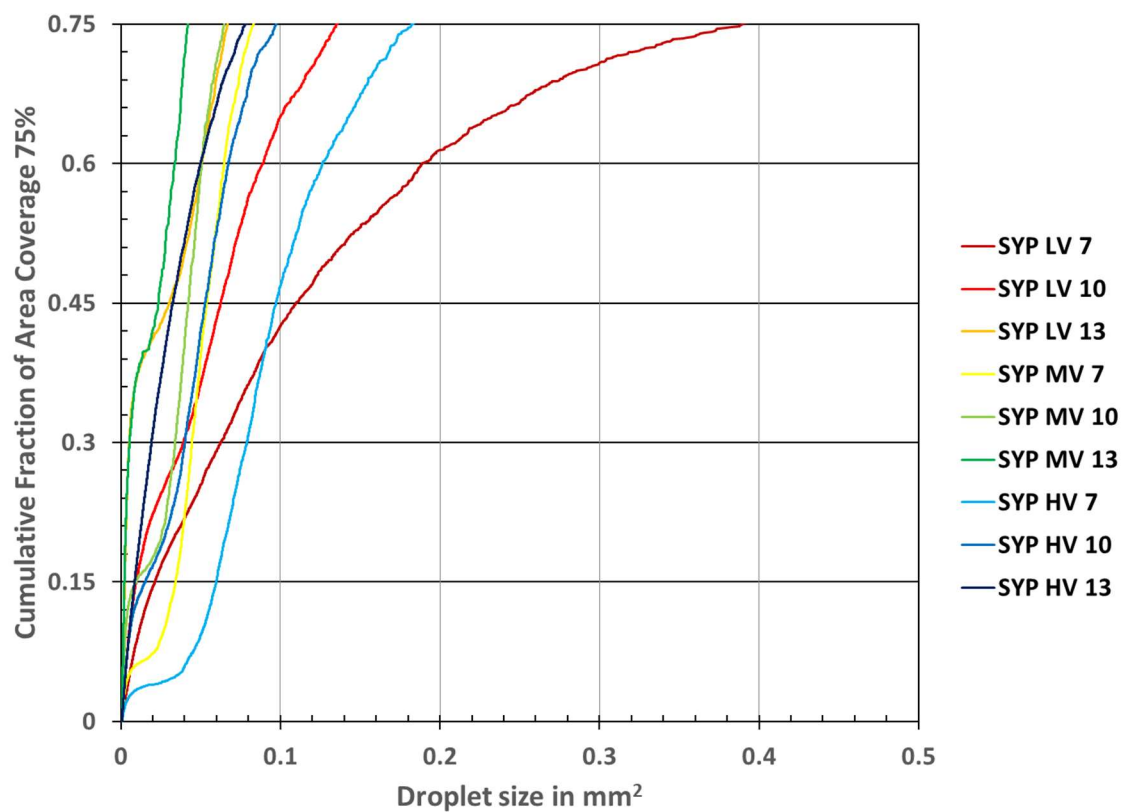


Figure 4-24, Cumulative fraction of area coverage up to 75% for southern pine lap-shear strands.

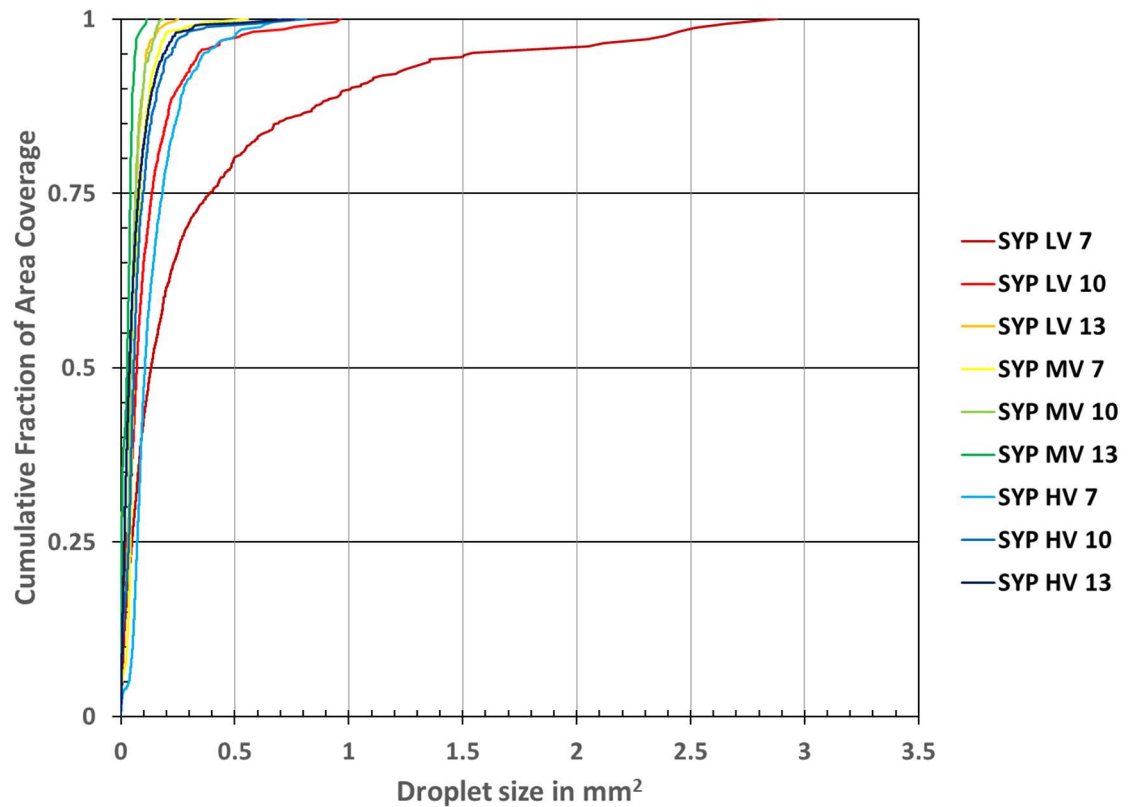


Figure 4-25, Cumulative fraction of area coverage for southern pine lap-shear strands.

4.4.3 Blender Strand Resin Area Coverage

Results of the resin area coverage for blender strands for aspen and southern pine determined through image analysis can be seen in Figure 4-26, Figure 4-27, and Table 4-14. Resin area coverage is the total 2D projected area of resin spots detected divided by the field of view measured on the blender strands.

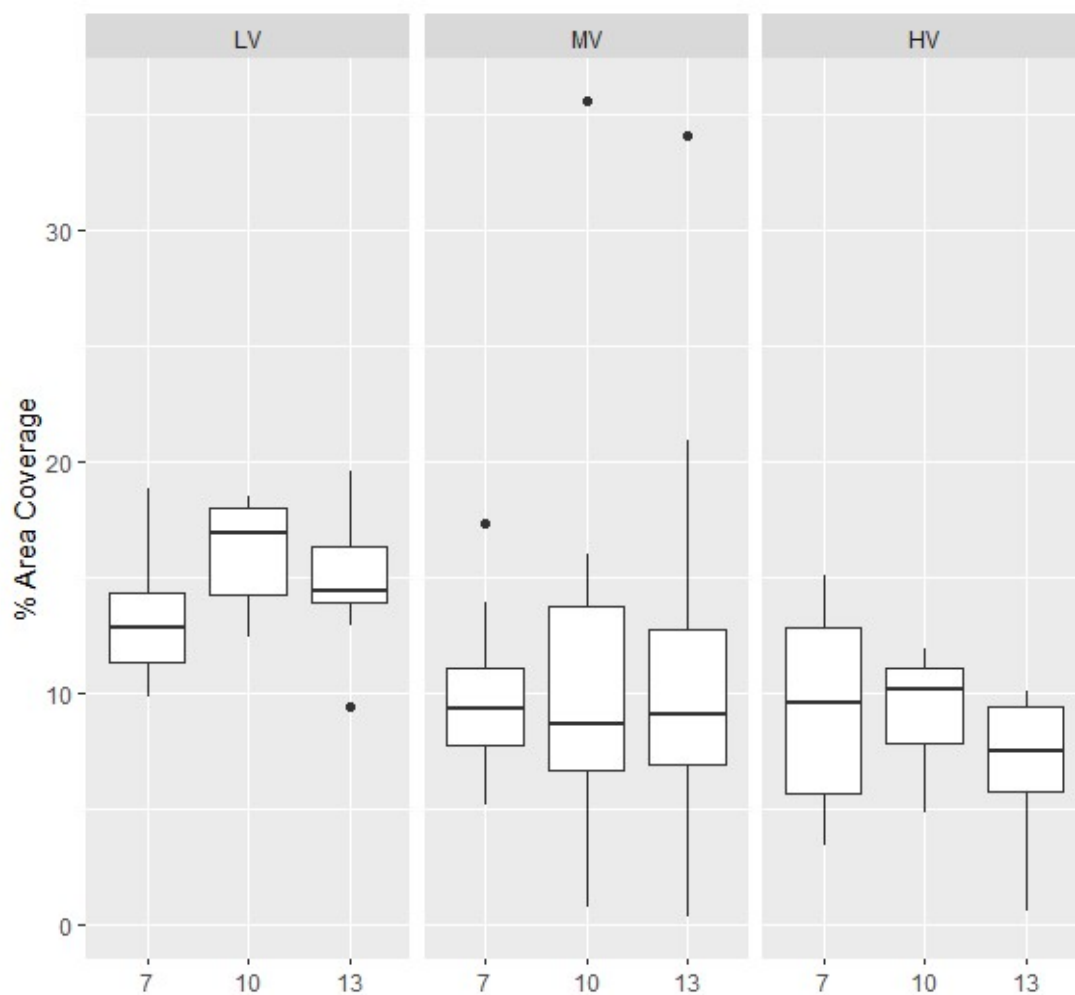


Figure 4-26, Percent strand area coverage of resin on aspen blender strands.

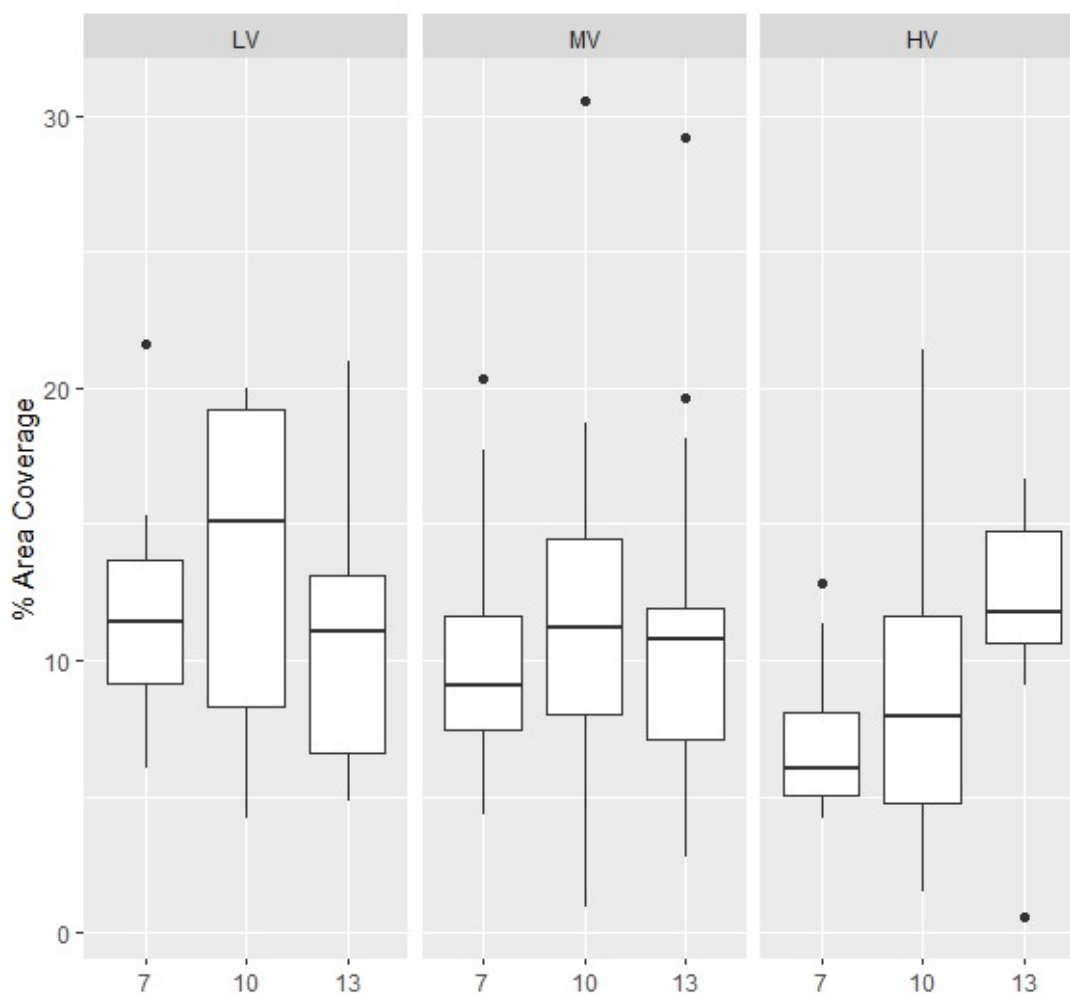


Figure 4-27, Percent strand area coverage of resin on southern pine blender strands

Table 4-14, Percent of strand area coverage of resin on blender strands.

Wood Species	Resin Viscosity	7,000 RPM		10,000 RPM		13,000 RPM	
		Avg	SD	Avg	SD	Avg	SD
Aspen	Low	13.0	2.6	16.2	2.1	14.9	2.8
	Medium	9.6	2.7	10.2	6.4	10.3	6.2
	High	9.4	4.0	9.4	2.2	6.8	3.1
Southern pine	Low	11.7	4.4	13.7	5.7	10.9	4.7
	Medium	10.3	3.6	11.7	5.2	10.8	5.4
	High	7.0	2.8	8.6	5.6	11.6	4.3

A two-way ANOVA was used to determine if resin type, atomizer RPM, or interaction of the two had an effect on the percent of resin area coverage. ANOVA table

outputs can be seen for aspen and southern pine specimens in Table 4-15 and Table 4-16.

Table 4-15, Percent of strand area coverage of resin on aspen strands ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	660.83	330.42	15.0751	0.000001166
RPM	2	22.83	11.92	0.5437	0.5818
Resin:RPM	4	79.22	19.81	0.9036	0.4637
Residuals	141	3090.44	21.92		

Table 4-16, Percent of strand area coverage on southern pine strands ANOVA

	Degrees of Freedom	Sum of Squares	Mean Squares	F Ratio	P Value
Resin	2	140.7	70.374	2.9248	0.05696
RPM	2	64.6	32.318	1.3432	0.26436
Resin:RPM	4	114.3	28.583	1.1879	0.31881
Residuals	140	3368.6	24.061		

As seen from Table 4-15, there was strong evidence (P value 0.000001) that resin type had an effect on the percent of area coverage and no evidence (P value 0.58) of an effect by atomizer RPM. There was also no evidence (P value 0.46) that an interaction between resin type and atomizer RPM had an effect on the percent of area coverage.

As seen from Table 4-16, there was moderate evidence (P value 0.057) that resin type had an effect on the area coverage and no evidence (P value 0.25) of an effect by atomizer RPM. There was also no evidence (P value 0.32) that an interaction between resin type and atomizer RPM had an effect on the percent of area coverage.

The LV resin had a greater surface coverage on the aspen strands, approximately 15%, compared to the MV and HV resins, which had approximately 9%. Analysis of variance indicated a slightly greater surface coverage of resins LV and MV on southern pine strands at approximately 12% coverage compared to approximately 9% coverage for the HV resin. Difference in coverage is may be due to greater wetting by the low viscosity resin compared to the high viscosity resin, which contributes to

larger resin spots. The resin distribution analysis showed that the lowest viscosity resin had a greater proportion of large spots than the highest viscosity resin (Table 4-11 and Table 4-12).

4.4.4 Observations and Comparisons from Image Analysis

As seen in Figure 4-10 through Figure 4-17, blender strand resin spot sizes follow a continuous logarithmic distribution where spot size remains relatively small until the 75th percentile of the cumulative fraction of resin area coverage. In Figure 4-18 through Figure 4-25 it would appear that the lap-shear cumulative fraction of resin area coverage would follow a similar trend, but on further inspection it appears that some treatments produced a bimodal distribution of spot size.

As seen in Figure 4-18 and Figure 4-22, the resin distribution curves of the MV and HV resin at the lowest atomizer speed (7,000 RPM) appear to have an “S” shape instead of following the typical logarithmic trend. This “S” shape is an indicator of a bimodal distribution, which means that there are two distinct ranges of resin spot sizes. This can be seen in Figure 4-28 and Figure 4-29 where there are a large number of resin spots less than 0.005 mm², then few spots between 0.005 and 0.02 mm², before spots between 0.02 mm² and 0.07 mm² increase in frequency. Resin spots larger than 0.07 mm², though small in number, dominate the volume of resin detected. Looking back in comparison to the aspen blender strands in Figure 4-10, there is no “S” shape in the distribution curves, and no indication of a bimodal distribution.

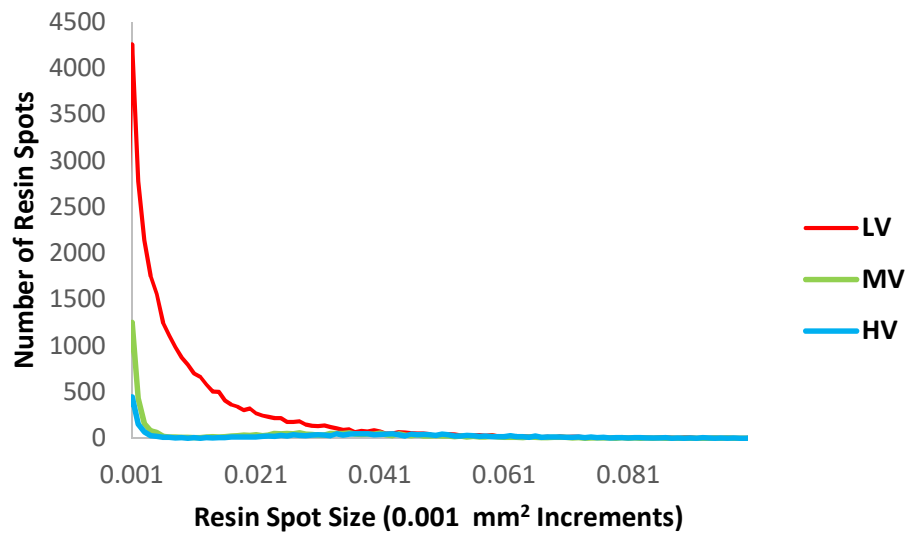


Figure 4-28, Resin spot size count for aspen lap-shear strands sprayed at 7,000 RPM in increments of 0.001 mm^2

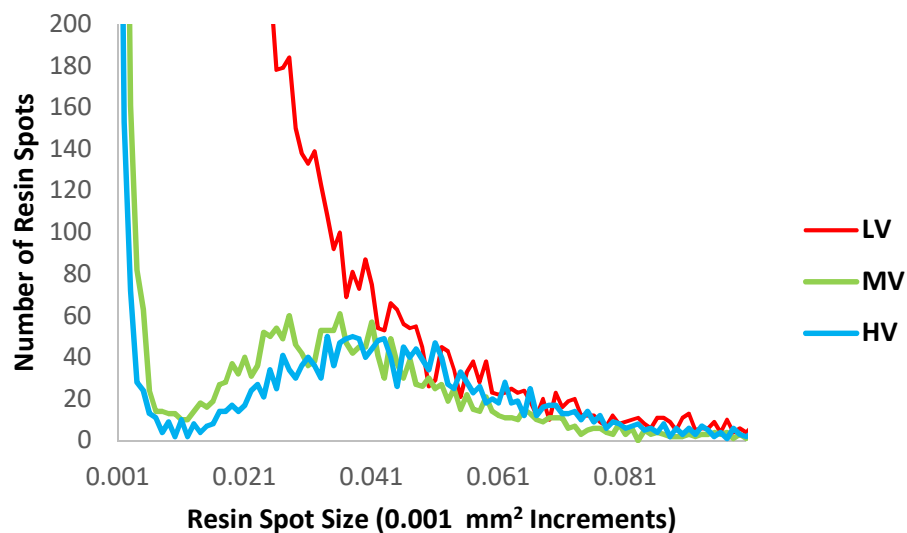


Figure 4-29, Resin spot size count for aspen lap-shear strands sprayed at 7,000 RPM in increments of 0.001 mm^2 with the vertical axis expanded

Because the lap-shear strands were kept in a fixed location inside the blender, they did not have the opportunity to be blended with other strands and rub together. This process is known as attrition blending and could be responsible for breaking down the size of larger resin spots. Furthermore, disk speed or resin viscosity, may affect the

pattern of atomization between the atomizer and the pneumatic insertion device. Blender strands randomly tumble throughout the entire volume of the rotating blender, and therefore, are exposed to the entire 360-degree spray pattern. Consequently, the blender strands and lap-shear strands did not have the same resin distribution.

Looking back at Figure 4-18 and Figure 4-22, the bimodal distribution of resin spot sizes, which caused the “S” shape, was either less prominent or nonexistent at higher RPM. Atomizer RPM had a significant impact on the lap-shear strength in testing and higher RPM led to increased bondline performance. The result suggests that a continuous distribution of resin spot size and smaller resin spots is favorable for bondline strength.

5. Conclusion

Phenol-formaldehyde resin distribution on aspen and southern pine wood strands, which is sprayed using a spinning disk atomizer, was impacted by the resin viscosity and atomizer speed in this study.

The PF resin used in this study was found to have viscosity that increased with increasing molecular weight and increased with decreasing temperature. Surface tension of the resin was not significantly impacted by change in temperature.

Increasing atomizer RPM improved the bondline performance for internal bond and lap-shear specimens. From image analysis, it was found that increasing atomizer RPM resulted in smaller resin spot size. This supports the hypothesis, that smaller resin spot size, with equal resin loading, improves bondline performance.

For internal bond specimens, resin viscosity did not appear to have any effect on the bondline performance. High viscosity resin improved the performance of aspen lap-shear strands but had an adverse effect on the southern pine.

Three-point bending specimens were not significantly impacted by changing atomizer RPM. Resin type appeared to have an effect on the southern pine three-point bending specimens with the low viscosity resin performing the best, but resin type had no significant impact on the aspen samples.

From image analysis, it was found that the slowest atomizer RPM's had the largest droplet size for the 25th, 50th, and 75th percentile of the cumulative fraction of area coverage for both aspen and southern pine. There was variability within the largest spot size from each population, but this can be explained by overlapping resin spots taking up a larger area.

From image analysis, it was found that resin type had a significant impact on average resin area coverage for blender strands, especially aspen. Atomizer RPM did not appear to have an impact on average resin area coverage.

During the lap-shear strand image analysis, there appeared to be a bimodal distribution of resin spot size associated with lower atomizer RPM's. This was consistent for aspen and southern pine strands. This bimodal distribution was not found in similar treatment types of blender strands. When comparing the lap-shear resin spot

size distribution, it was found that specimens sprayed at high RPM's had a more continuous resin spot size distribution and a better bondline performance.

DEDICATION

To my mother, Pam Willard.

6. Bibliography

- Anonymous. (2020). Wood composite panel industry averages for phenol-formaldehyde specifications as reported by two major adhesive manufacturers.
- ASTM. (2020). *D1037-12 Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials*.
- ASTM. (2021). *D2339-20 Standard Method for Strength Properties of Adhesives in Two-Ply Wood Construction in Shear by Tension Loading*.
- Broline, B. M., & Adams, R. A. (2006). A Practical Overview of Resin Systems for Oriented Strand. *40th International Wood Composites*. Seattle .
- Coil Manufacturing, L. (2020). *Coil Manufacturing Atomizers*. (Coil Manufacturing Ltd.) Retrieved April 25, 2020, from www.coilmanufacturing.com/atomizers/
- Conner, A. H. (2001). Wood: Adhesives. In *Encyclopedia of Materials: Science and Technology* (pp. 2-7). Elsevier.
- Conrad, M. P., Smith, G. D., & Fernlund, G. (2003). Fracture of Discontinuous Wood-Adhesive Bonds. *International Journal of Adhesion & Adhesives* , 23, 39-47.
- Coventry-Saylor, K. H. (2002, May 31). *USA Patent No. US 6,730,770 B2* .
- Dai, C., He, G., & Jin, J. (2010, April 20). Press-induced Lateral Resin Flow and its Effects on Resin. *Wood Sci Technol*, 45, 269-280. doi:10.1007/s00226-010-0332-8
- Dai, C., Yu, C., Groves, K., & Lohrasebi, H. (2007). Theoretical Modeling of Bonding Characteristics and Performance of Wood Composites. Part II. Resin Distribution. *Wood and Fiber Science* , 39(1), 56-70.
- Gollob, L. (1982). The Interaction of Formulation Parameters With Chemical Structure and Adhesive Performance of Phenol-Formaldehyde Resins. *Thesis*. Corvallis, Oregon : Oregon State University .
- Graco. (1995). Atomization Concept and Theory. Minneapolis, MN: Garco Inc.
- Gurke, T. (2002). Huntsmans Polyurethanes: New Advances in Polymeric MDI Variants. *EUROCOAT*.
- Hu, X.-M., Zhao, Y.-Y., & Cheng, W.-M. (2015). Effect of Formaldehyde/Phenol Ratio (F/P) on the Properties of Phenolic Resins and Foams Synthesized at

- Room Temperature. *Society of Plastics Engineers*, 1531-1540. doi:10.1002/pc.23060
- Kadant Inc. . (n.d.). *Stranders - SmartRING*. Retrieved April 25, 200, from www.kadant.com/en-us/products/smartring-stranders
- Kaestner, D. (2015, June). Life Cycle Assessment of the Oriented Strand. *Thesis*. Knoxville : University of Tennessee.
- Kamke, F. A., Kultikova, E., & Lenth, C. A. (1996). OSB Properties as Affected by Resin Distribution. *The Fourth International Oanel and Engineered-Wood Technology Conference & Exposition*. Atlanta.
- Keyence. (2019). 3D Laser Scanning Confocal Microscope VK-X1000 Series Iser Manual. Osaka, Japan: Keyence Corporation .
- Le, E. A. (2010). Numerical Modeling and Experiments on Wood-Strand Composites. *Thesis*. Corvallis, Oregon: Oregon State University.
- Lefebvre, A. H. (2011, February 2). *ATOMIZATION*. (Thermopedia) Retrieved April 25, 2020, from <http://www.thermopedia.com/content/573/>
- Liu, H. (2000). *Science and Engineering of Droplets: Fundamentals and Applications*. Norwich, New York: William Andrew Pub. Park Ridge.
- Longwood, J. (1997). Oriented Strand Board and Waferboard. In: Engineered Wood Products: A Guide to Specifiers, designers, and Users. *FPS Res. Foundation* , 147-172.
- Maietta, A., Dexter, J., & House, T. (2008, February 29). *USA Patent No. US 7,938,155 B2*.
- Mudge, R. D. (2002, June 12). *USA Patent No. US 2003/0230639 A1*.
- NDI, Inc. (2020). *Atomizers*. (Northern Industrial Design & Mfg.) Retrieved April 25, 2020, from <https://www.nidincorporated.com/atomizers.html>
- Painter, P. C., & Coleman, M. M. (2009). Polymer Melt Rheology. In *Essentials of Polymer Science and Engineering* (pp. 435-445). Lancaster, PA, USA: DEStech Publications.
- Pereira, C. M., Carvalho, L. H., & Costa, C. A. (2004). Modeling the Continuous Hot-Pressing of MDF. *Wood Science and Technology*, 308-326. doi:10.1007/s00226-006-0067-8

- Pizzi, A., Dinwoodie, J. M., Frisch, K. C., Goulding, T. M., Nimz, H. H., & Rumao, L. P. (1983). *Wood Adhesives: Chemistry and Technology*. New York: Marcel Dekker.
- Rueden, C. S. (2017). ImageJ2: ImageJ for the next generation of scientific image data. doi:10.1186/s12859-017-1934-z
- Siempelkamp. (2020). *Machines and Plants for Wood-Based Materials*. (Siempelkamp) Retrieved April 25, 2020, from <https://www.siempelkamp.com/produkte/maschinen-und-anlagenbau/holzwerkstoffanlagen/>
- Siempelkamp LP. (2004, June). Pressing Issues. Retrieved from <https://fliphtml5.com/hhwj/vzgr/basic>
- Smith, G. (2005). Direct observation of the tumbling of OSB strands in an industrial scale Coil blender. *Wood and Fiber Science*, 37(1), 147-159.
- Stark, N. M., Cai, Z., & Carll, C. (2010). Wood-Based Composite Materials: Panel Products, Glued-Laminated Timber, Structural Composite Lumber, and Wood–Nonwood Composite Materials. In *Wood Handbook* (pp. 7-15). Madison, WI: Forest Products Laboratory.
- The Engineered Wood Association. (2011, December). Performance Rated Panels Product Guide. Tacoma, WA, USA.
- The Engineered Wood Association. (2017, October). Oriented Strand Board Product Guide. *Guide*. Tacoma, WA, USA.
- Youngquist, J. A. (1999). Wood-based Composites. In *Wood Handbook* (pp. 1-31). Madison , WI, USA: Forest Products Labratory.
- Zerbe, J. I., Cai, Z., & Harpole, G. B. (2015). *An Evolutionary History of Oriented Strand Board*. USDA. Madison: Forest Products Laboratory .
- Zhang, X., Muszynski, L., & Gardner, D. J. (2008, November). Spinning Disk Atomization of Wood Resin-Adhesive: I. Sprak Characteristics, Atomization Mechanism, and Resin Efficiency. *Forest Products Journal*, 58(11), 62-68.
- Zhang, Y., Day, P., & Manz, A. (2012). *Physics of Multiphase Microflows and Microdroplets*. New York: Springer.

7. Appendix

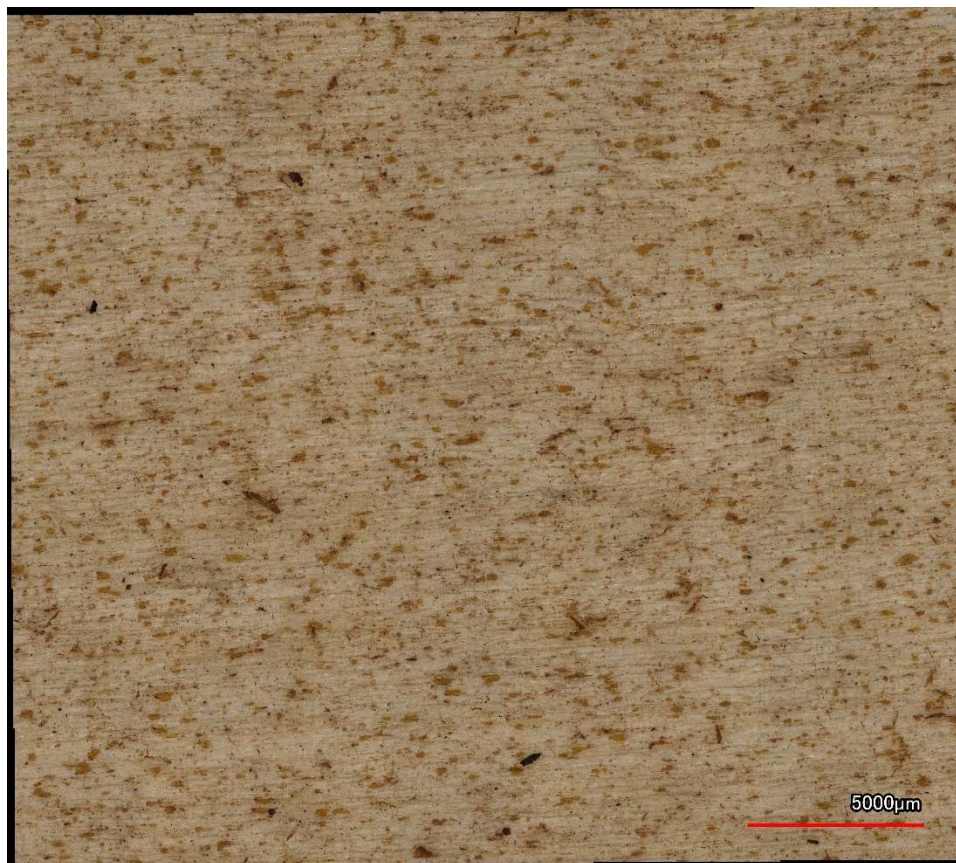


Figure 7-1, Aspen blender strand LV resin 7,000 RPM

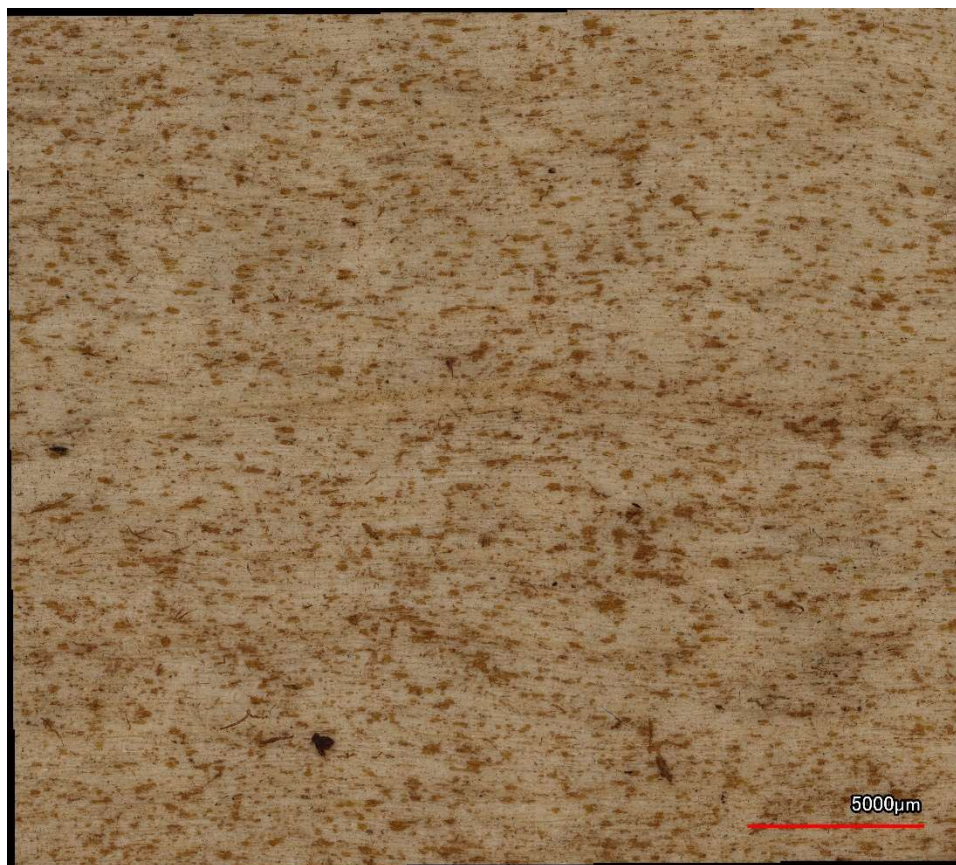


Figure 7-2, Aspen blender strand LV resin 10,000 RPM



Figure 7-3, Aspen blender strand LV resin 13,000 RPM



Figure 7-4, Aspen blender strand MV resin 7,000 RPM



Figure 7-5, Aspen blender strand MV resin 10,000 RPM



Figure 7-6, Aspen blender strand MV resin 13,000 RPM



Figure 7-7, Aspen blender strand HV resin 7,000 RPM



Figure 7-8, Aspen blender strand HV resin 10,000 RPM

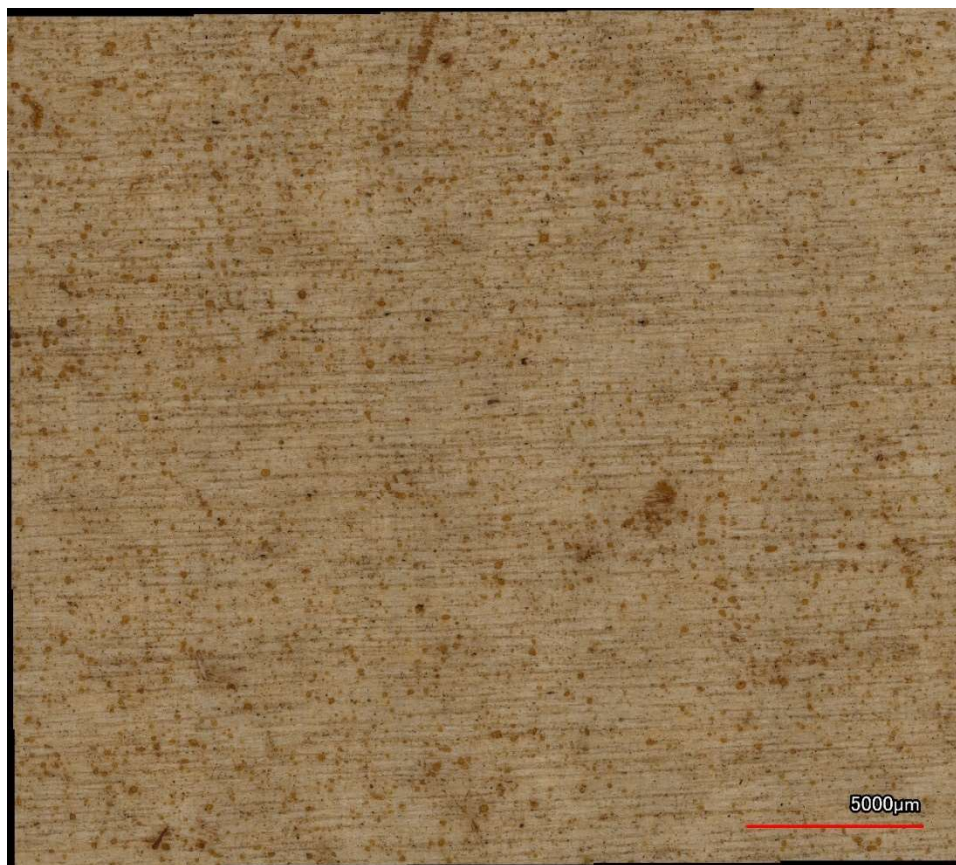


Figure 7-9, Aspen blender strand HV resin 13,000 RPM

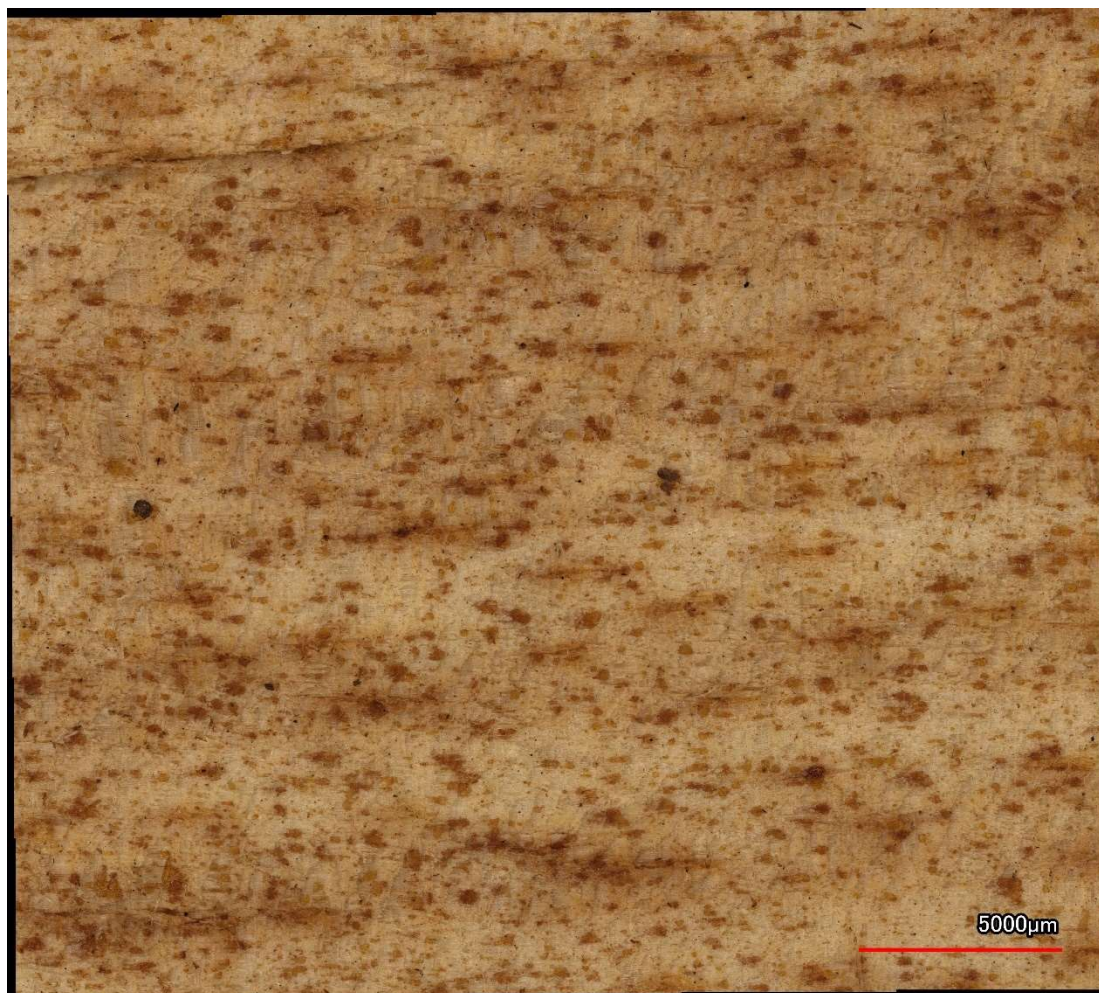


Figure 7-10, Southern pine blender strand LV resin 7,000 RPM

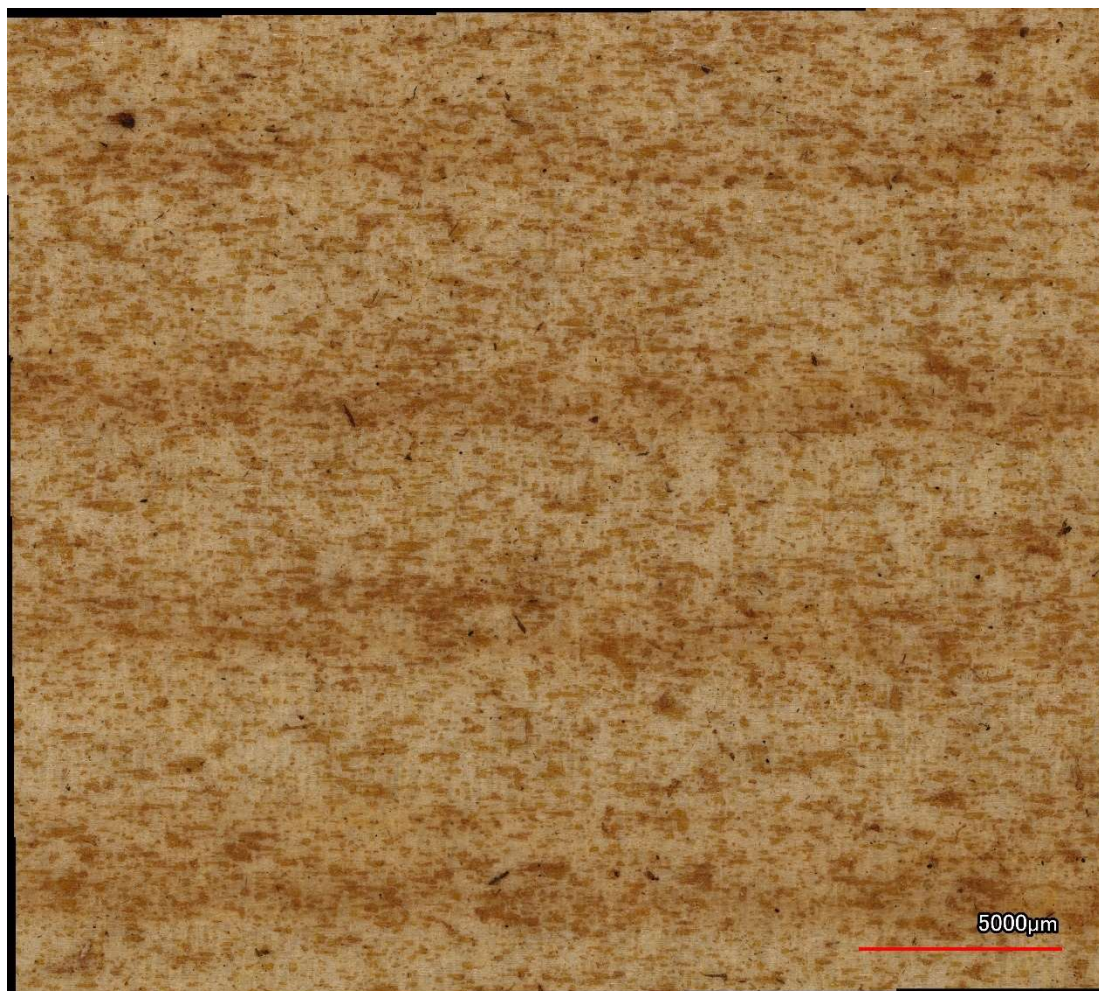


Figure 7-11, Southern pine blender strand LV resin 10,000 RPM

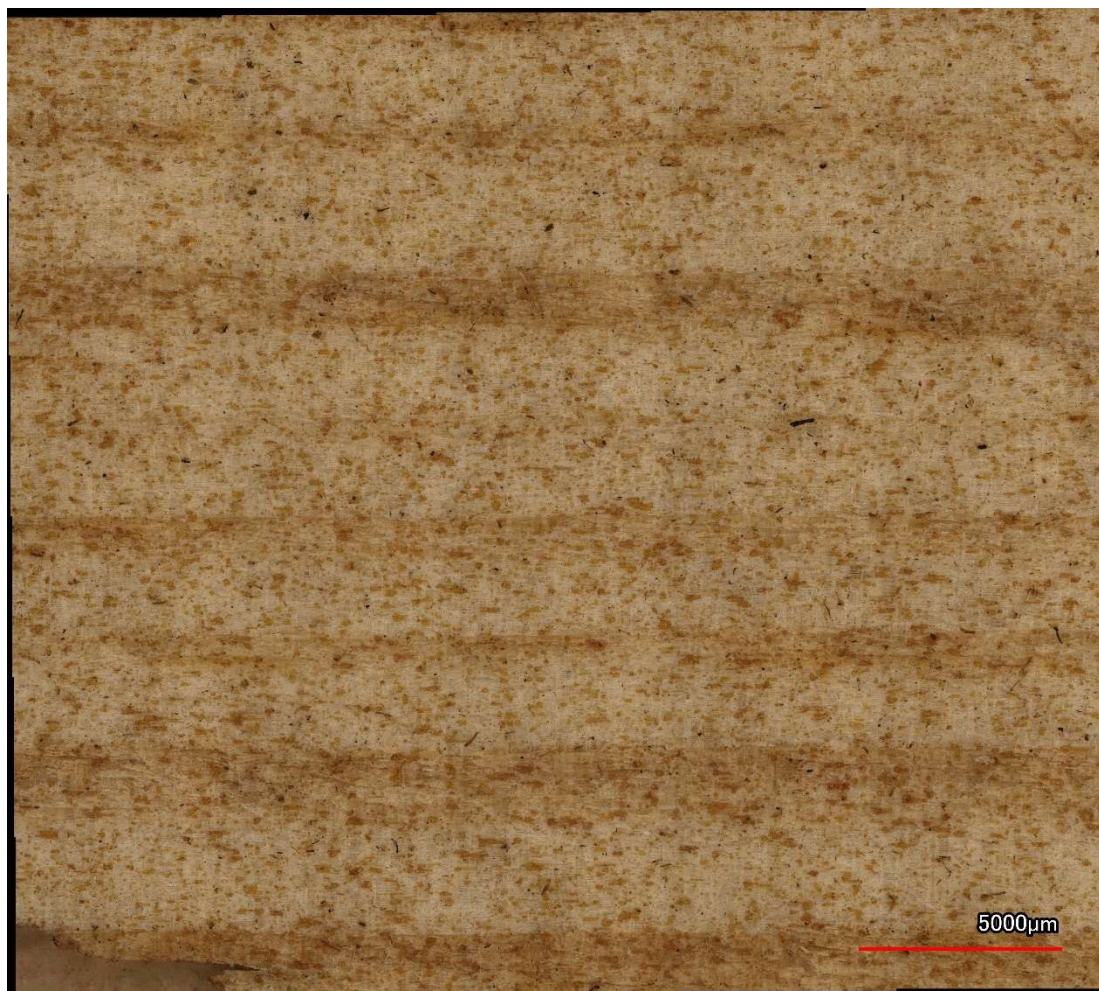


Figure 7-12, Southern pine blender strand LV resin 13,000 RPM

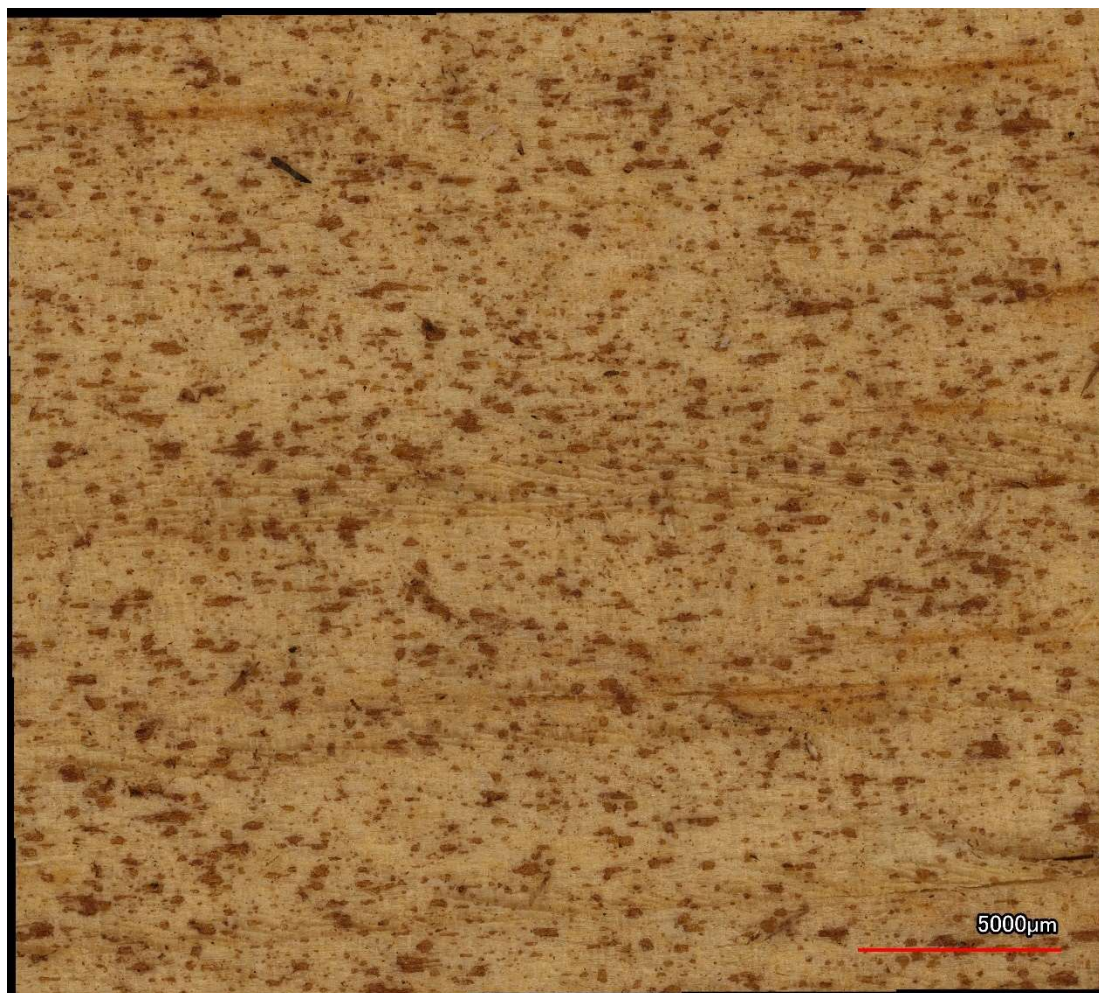


Figure 7-13, Southern pine blender strand MV resin 7,000 RPM

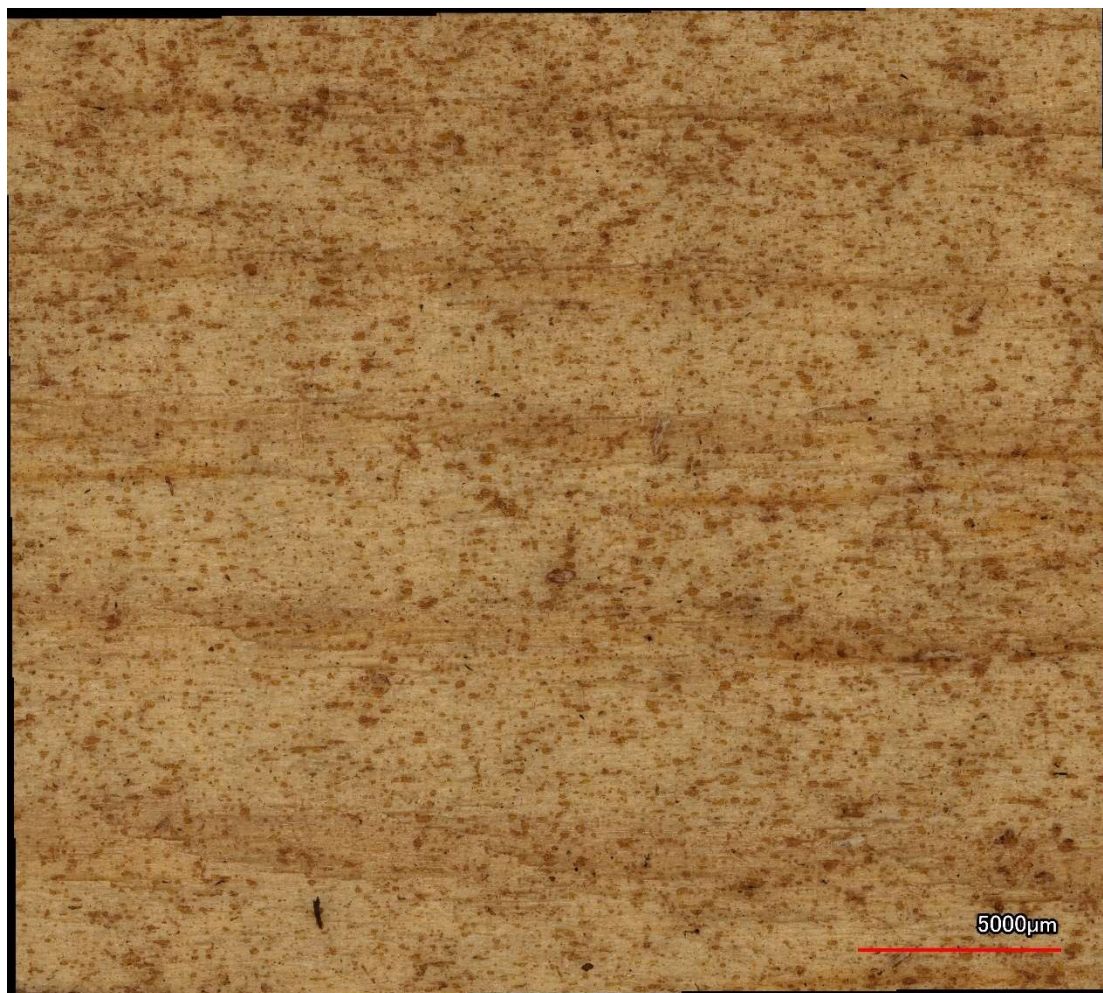


Figure 7-14, Southern pine blender strand MV resin 10,000 RPM



Figure 7-15, Southern pine blender strand MV resin 13,000 RPM

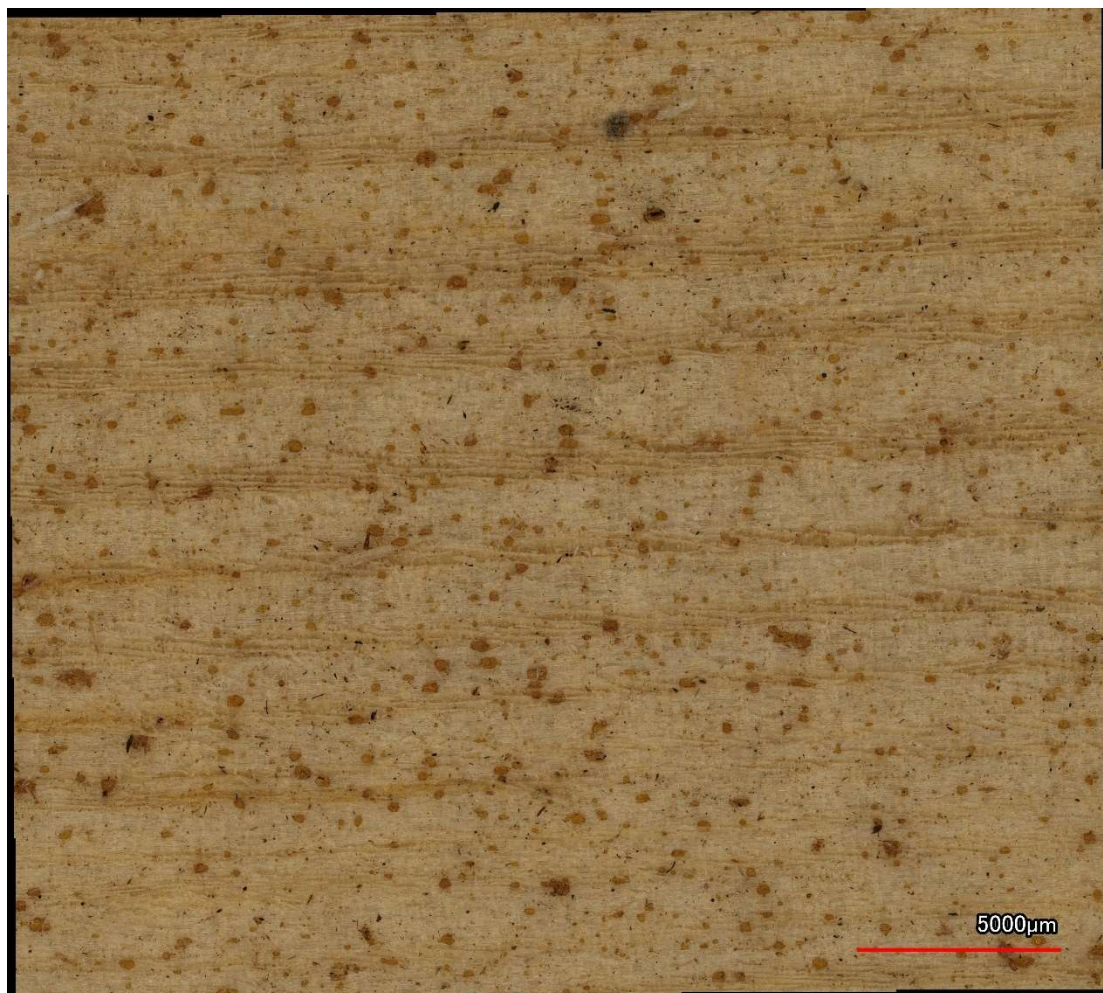


Figure 7-16, Southern pine blender strand HV resin 7,000 RPM



Figure 7-17, Southern pine blender strand HV resin 10,000 RPM

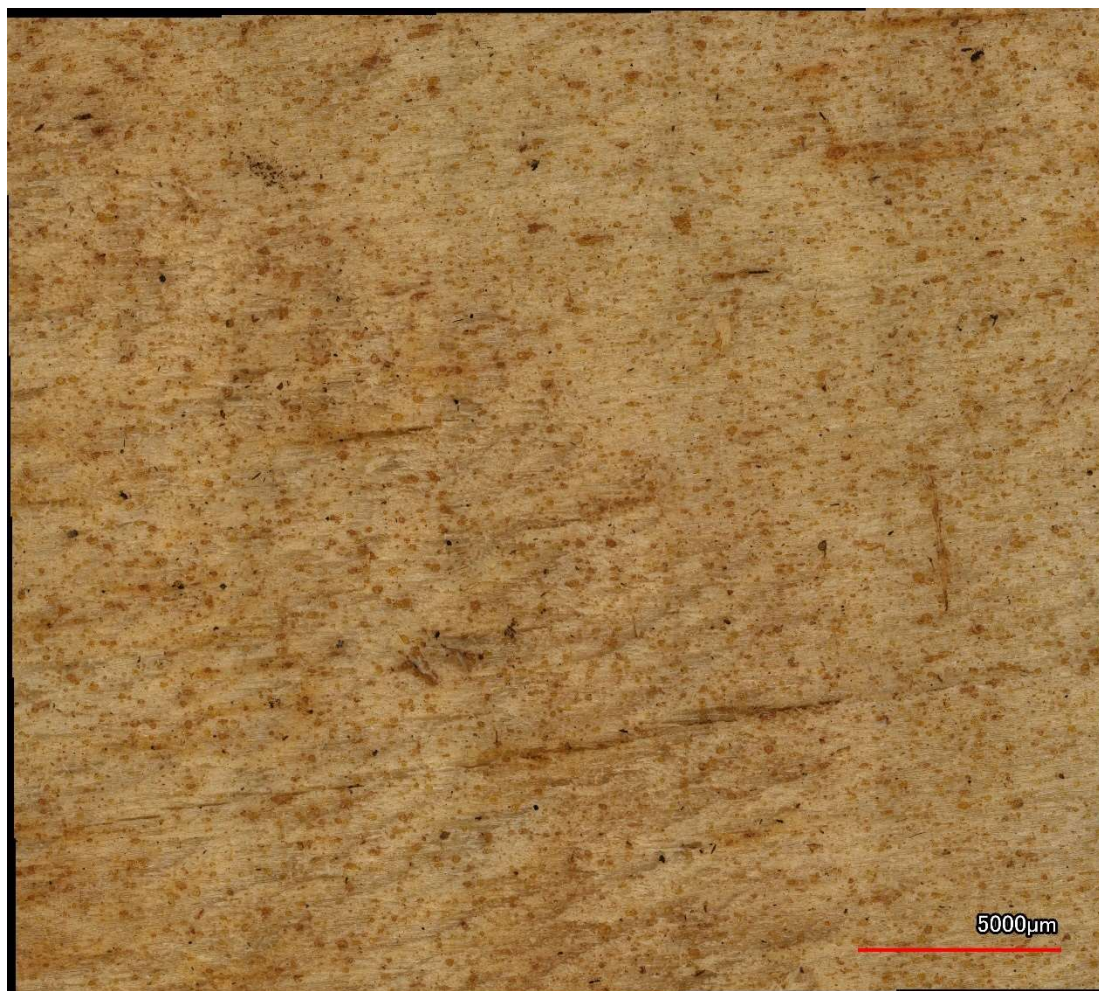


Figure 7-18, Southern pine blender strand HV resin 13,000 RPM



Figure 7-19, Aspen lap-shear strand LV resin 7,000 RPM



Figure 7-20, Aspen lap-shear strand LV resin 10,000 RPM

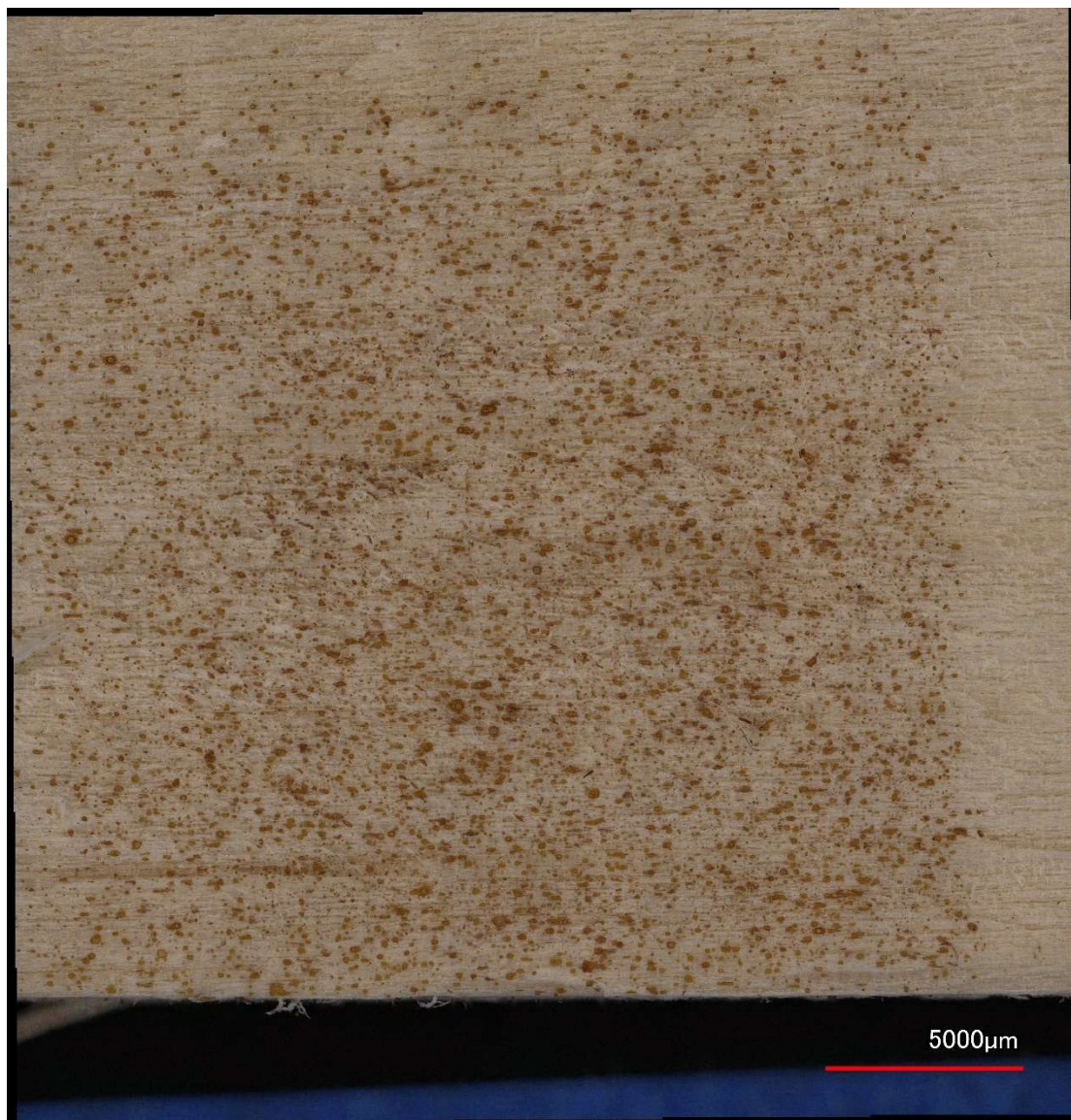


Figure 7-21, Aspen lap-shear strand LV resin 13,000 RPM



Figure 7-22, Aspen lap-shear strand MV resin 7,000 RPM

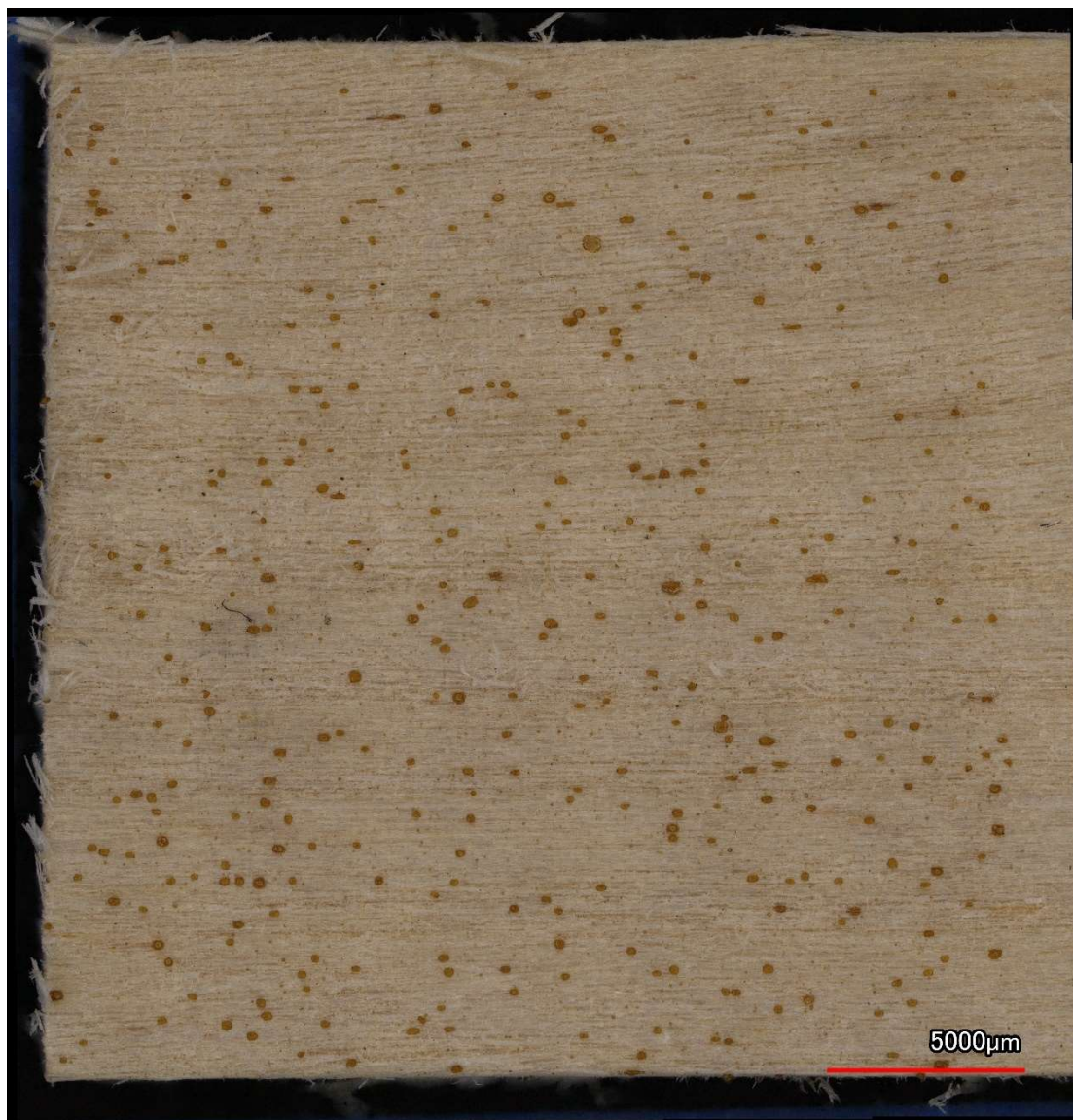


Figure 7-23, Aspen lap-shear strand MV resin 10,000 RPM



Figure 7-24, Aspen lap-shear strand MV resin 13,000 RPM



Figure 7-25, Aspen lap-shear strand HV resin 7,000 RPM



Figure 7-26, Aspen lap-shear strand HV resin 10,000 RPM

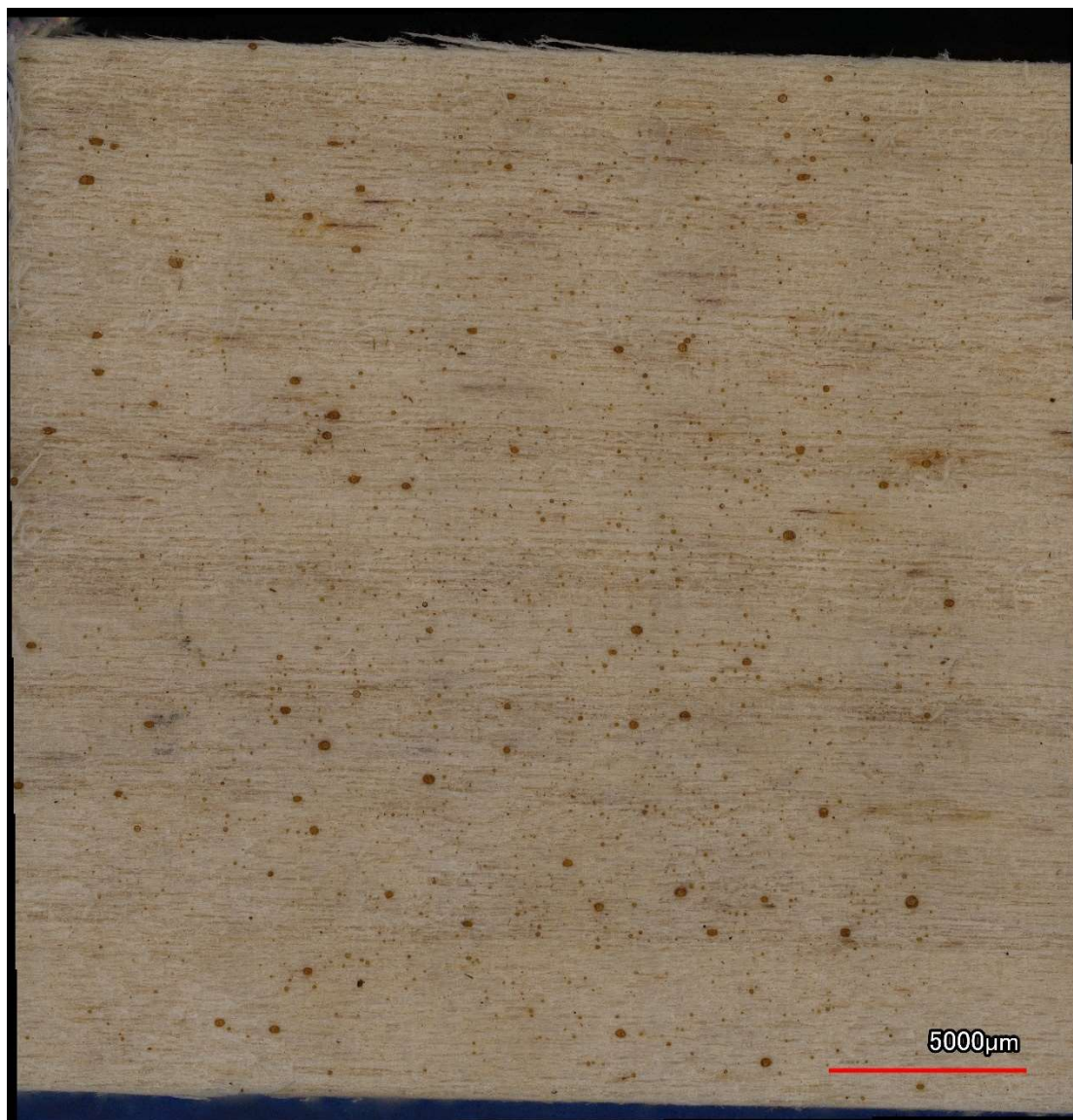


Figure 7-27, Aspen lap-shear strand HV resin 13,000 RPM

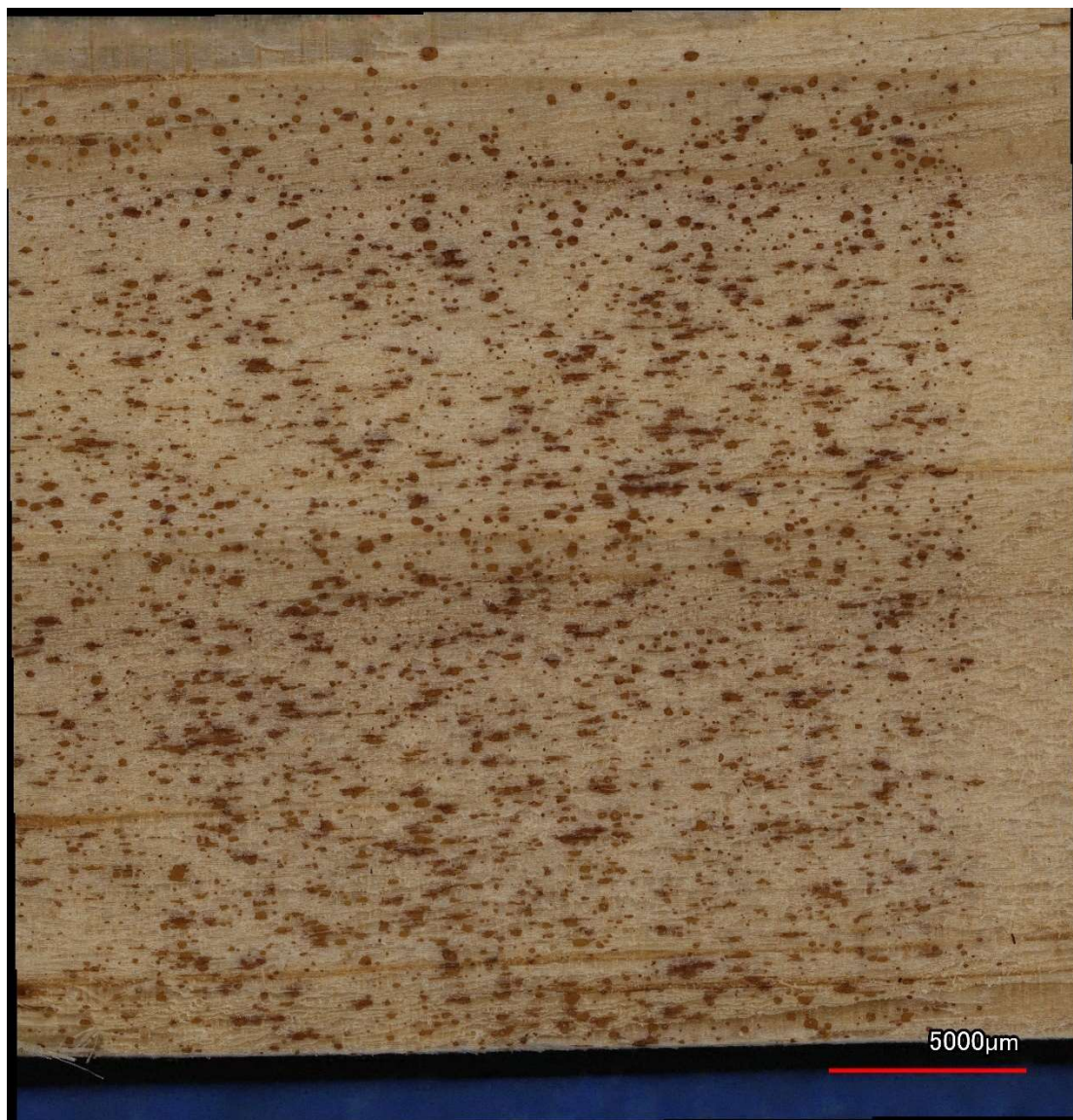


Figure 7-28, Southern pine lap-shear strand LV resin 7,000 RPM

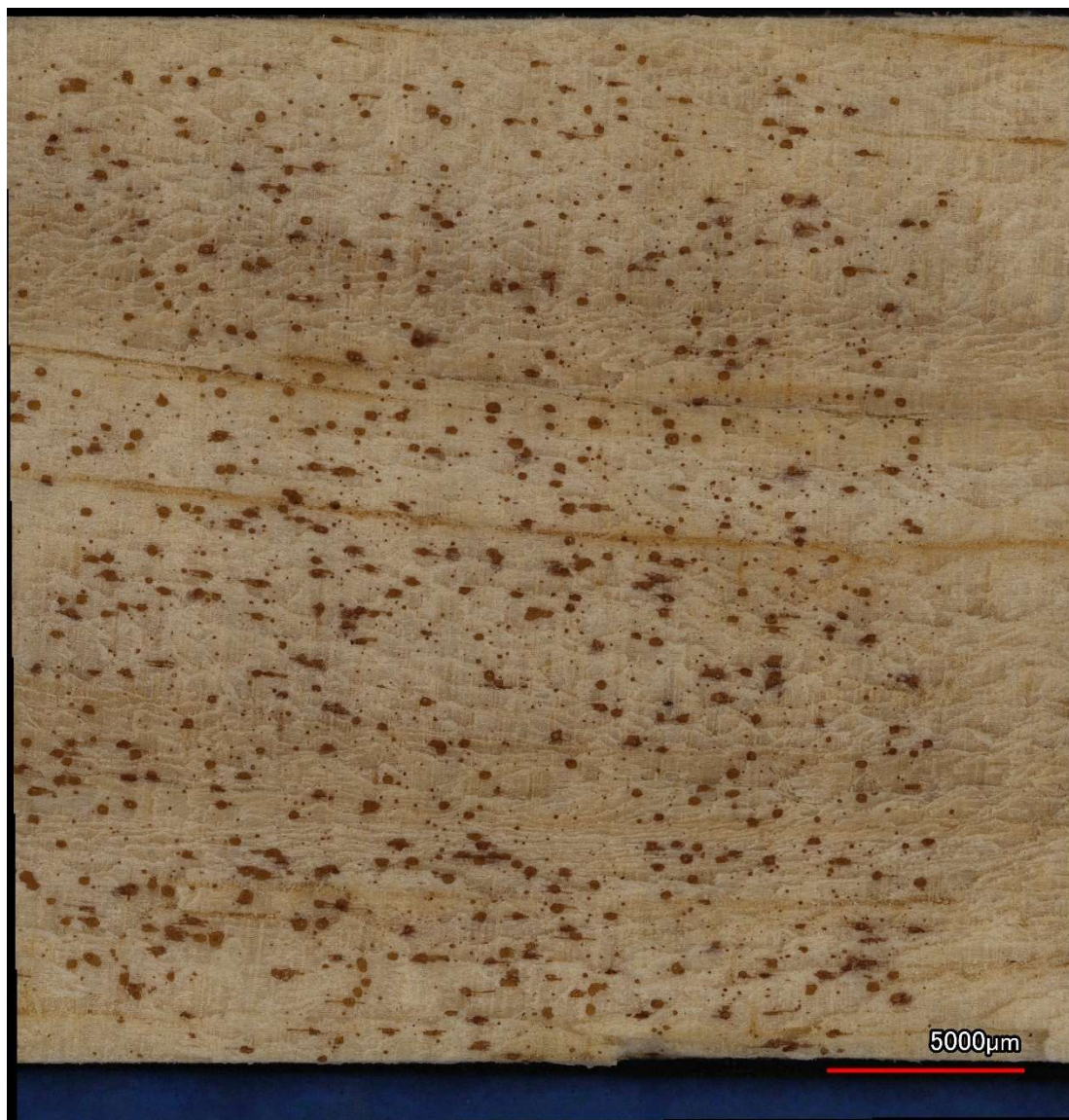


Figure 7-29, Southern pine lap-shear strand LV resin 10,000 RPM



Figure 7-30, Southern pine lap-shear strand LV resin 13,000 RPM

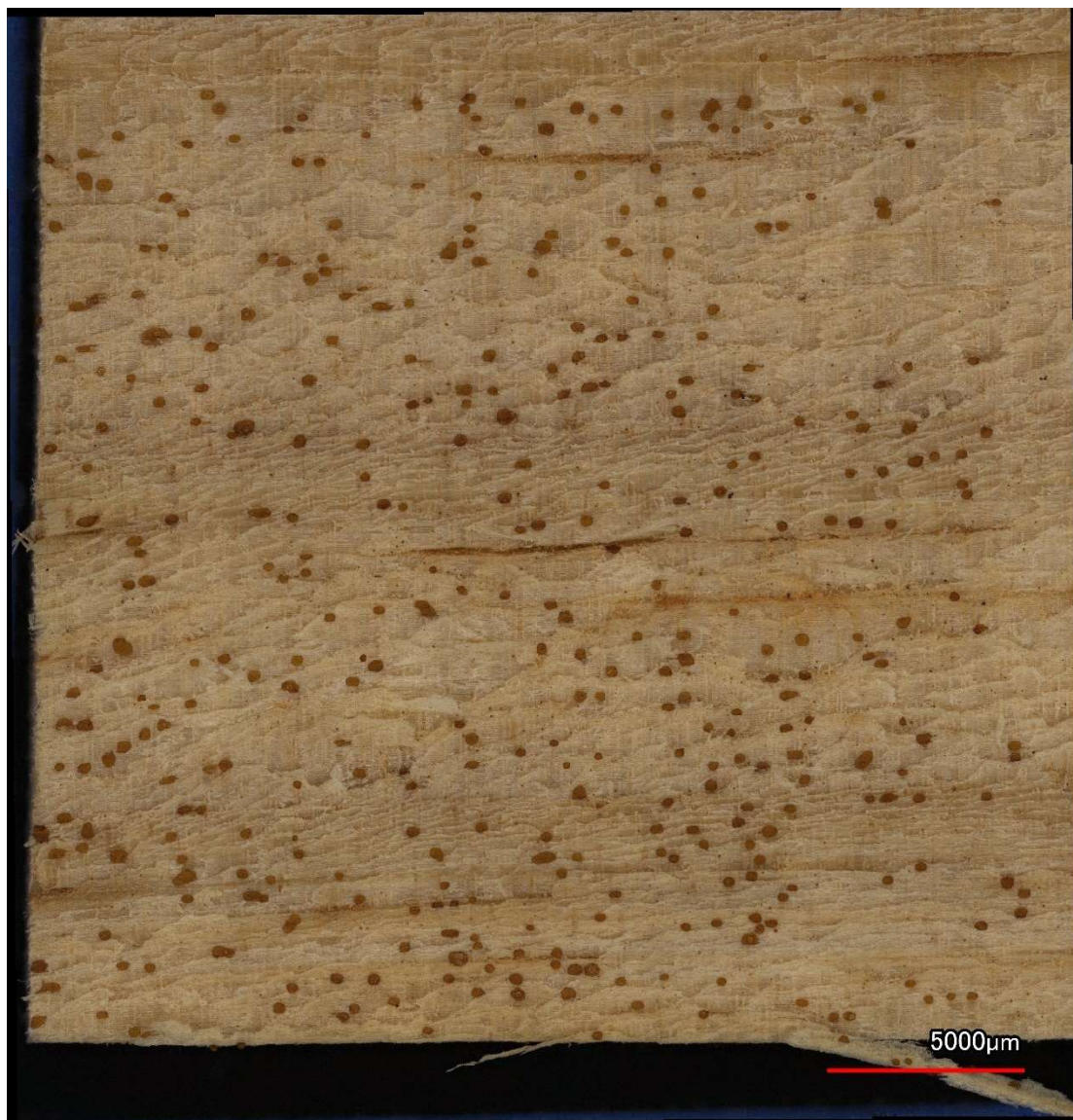


Figure 7-31, Southern pine lap-shear strand MV resin 7,000 RPM



Figure 7-32, Southern pine lap-shear strand MV resin 10,000 RPM



Figure 7-33, Southern pine lap-shear strand MV resin 13,000 RPM



Figure 7-34, Southern pine lap-shear strand HV resin 7,000 RPM



Figure 7-35, Southern pine lap-shear strand HV resin 10,000 RPM



Figure 7-36, Southern pine lap-shear strand HV resin 13,000 RPM

Tables Table 7-1 and Table 7-2 are the estimated mass of resin on the aspen and SYP lap shear strands measured in grams.

Table 7-1, Estimated mass of resin on Aspen lap-shear strands in grams

Aspen			
Resin	RPM	Specimen	Resin Mass (g)
LV	7,000	1	0.0028
LV	7,000	2	0.0027
LV	7,000	3	0.003

LV	7,000	4	0.0027
LV	7,000	5	0.0031
LV	10,000	1	0.0027
LV	10,000	2	0.0033
LV	10,000	3	0.0029
LV	10,000	4	0.003
LV	10,000	5	0.0029
LV	13,000	1	0.0027
LV	13,000	2	0.0017
LV	13,000	3	0.0007
LV	13,000	4	0.0024
LV	13,000	5	0.0026
MV	7,000	1	0.0021
MV	7,000	2	0.0012
MV	7,000	3	0.0019
MV	7,000	4	0.0013
MV	7,000	5	0.0011
MV	10,000	1	0.0022
MV	10,000	2	0.0008
MV	10,000	3	0.0006
MV	10,000	4	0.0012
MV	10,000	5	0.001
MV	13,000	1	0.0009
MV	13,000	2	0.0006
MV	13,000	3	0.0005
MV	13,000	4	0.0002
MV	13,000	5	0.0002
HV	7,000	1	0.0017
HV	7,000	2	0.0017
HV	7,000	3	0.002
HV	7,000	4	0.0029
HV	7,000	5	0.0018
HV	10,000	1	0.0011
HV	10,000	2	0.0012
HV	10,000	3	0.0012
HV	10,000	4	0.0014
HV	10,000	5	0.0019
HV	13,000	1	0.0013
HV	13,000	2	0.0008
HV	13,000	3	0.0012
HV	13,000	4	0.001

<i>HV</i>	<i>13,000</i>	<i>5</i>	<i>0.0005</i>
-----------	---------------	----------	---------------

Table 7-2, Estimated mass of resin on SYP lap-shear strands in grams

SYP			
Resin	RPM	Specimen	Resin Mass (g)
<i>LV</i>	<i>7,000</i>	<i>1</i>	<i>0.0029</i>
<i>LV</i>	<i>7,000</i>	<i>2</i>	<i>0.0021</i>
<i>LV</i>	<i>7,000</i>	<i>3</i>	<i>0.0026</i>
<i>LV</i>	<i>7,000</i>	<i>4</i>	<i>0.0027</i>
<i>LV</i>	<i>7,000</i>	<i>5</i>	<i>0.0021</i>
<i>LV</i>	<i>10,000</i>	<i>1</i>	<i>0.0016</i>
<i>LV</i>	<i>10,000</i>	<i>2</i>	<i>0.0015</i>
<i>LV</i>	<i>10,000</i>	<i>3</i>	<i>0.0012</i>
<i>LV</i>	<i>10,000</i>	<i>4</i>	<i>0.0006</i>
<i>LV</i>	<i>10,000</i>	<i>5</i>	<i>0.0014</i>
<i>LV</i>	<i>13,000</i>	<i>1</i>	<i>0.0005</i>
<i>LV</i>	<i>13,000</i>	<i>2</i>	<i>0.0003</i>
<i>LV</i>	<i>13,000</i>	<i>3</i>	<i>0.0005</i>
<i>LV</i>	<i>13,000</i>	<i>4</i>	<i>0.0007</i>
<i>LV</i>	<i>13,000</i>	<i>5</i>	<i>0.0006</i>
<i>MV</i>	<i>7,000</i>	<i>1</i>	<i>0.0022</i>
<i>MV</i>	<i>7,000</i>	<i>2</i>	<i>0.0018</i>
<i>MV</i>	<i>7,000</i>	<i>3</i>	<i>0.003</i>
<i>MV</i>	<i>7,000</i>	<i>4</i>	<i>0.0019</i>
<i>MV</i>	<i>7,000</i>	<i>5</i>	<i>0.0017</i>
<i>MV</i>	<i>10,000</i>	<i>1</i>	<i>0.0014</i>
<i>MV</i>	<i>10,000</i>	<i>2</i>	<i>0.0016</i>
<i>MV</i>	<i>10,000</i>	<i>3</i>	<i>0.0014</i>
<i>MV</i>	<i>10,000</i>	<i>4</i>	<i>0.0011</i>
<i>MV</i>	<i>10,000</i>	<i>5</i>	<i>0.0006</i>
<i>MV</i>	<i>13,000</i>	<i>1</i>	<i>0.0009</i>
<i>MV</i>	<i>13,000</i>	<i>2</i>	<i>0.0004</i>
<i>MV</i>	<i>13,000</i>	<i>3</i>	<i>0.0003</i>
<i>MV</i>	<i>13,000</i>	<i>4</i>	<i>0.0004</i>
<i>MV</i>	<i>13,000</i>	<i>5</i>	<i>0.0003</i>
<i>HV</i>	<i>7,000</i>	<i>1</i>	<i>0.0027</i>
<i>HV</i>	<i>7,000</i>	<i>2</i>	<i>0.0023</i>
<i>HV</i>	<i>7,000</i>	<i>3</i>	<i>0.0017</i>
<i>HV</i>	<i>7,000</i>	<i>4</i>	<i>0.0017</i>
<i>HV</i>	<i>7,000</i>	<i>5</i>	<i>0.0017</i>

<i>HV</i>	<i>10,000</i>	1	0.0016
<i>HV</i>	<i>10,000</i>	2	0.0014
<i>HV</i>	<i>10,000</i>	3	0.0017
<i>HV</i>	<i>10,000</i>	4	0.0014
<i>HV</i>	<i>10,000</i>	5	0.0018
<i>HV</i>	<i>13,000</i>	1	0.0022
<i>HV</i>	<i>13,000</i>	2	0.0022
<i>HV</i>	<i>13,000</i>	3	0.0019
<i>HV</i>	<i>13,000</i>	4	0.003
<i>HV</i>	<i>13,000</i>	5	0.0024