

AN ABSTRACT OF THE THESIS OF

Matthew John Schwarzkopf for the degree of Master of Science in Wood Science
presented on April 8, 2009.

Title: Development and Evaluation of Oriented Strandboard Bonded with Soy-Based
Formaldehyde-Free Adhesives

Abstract approved:

Kaichang Li

Synthetic adhesives like phenol formaldehyde (PF) and isocyanates dominate the wood based structural panel market. The raw materials that makeup these adhesives are based on petroleum and natural gas. The sustainability and the continued success of the wood based structural panel industry will benefit from the development of alternative adhesives from renewable materials. In this study, we developed two soy-based formaldehyde free adhesives.

The first adhesive is a formaldehyde-free soy flour (SF)-curing agent (CA) adhesive and was investigated for making randomly oriented strandboard (R-OSB) and oriented strandboard (OSB). Two methods (the wet method and the dry method) were investigated for applying the SF-CA adhesive onto wood flakes. The wet method

included the thorough mixing of SF and CA to form an adhesive mixture and then spraying the adhesive mixture onto wood flakes. The SF:CA weight ratio, the adhesive add-on rate, hot-press conditions were optimized in terms of enhancing internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity(MOE) of the resulting R-OSB panels. The highest IB, MOR and MOE were obtained at the 1:1 SF:CA weight ratio. The IB, MOR and MOE of the R-OSB panels that were made at the adhesive add-on rate of $\geq 7\%$, a hot-press temperature between 170 °C and 220 °C, and a hot-press time of ≥ 4 min exceeded the minimum industry requirements. The dry method included spraying aqueous CA solution onto a mixture of SF and wood flakes. The dry method was able to increase the SF:CA ratio up to 7:1 where the strengths of the resulting R-OSB panels still exceeded the minimum industry requirements. OSB panels made with the SF-CA adhesive had their strengths higher than or comparable to those commercial OSB panels purchased at a local Home Depot.

The second adhesive investigated was a formaldehyde-free adhesive using soy flour (SF) and was investigated for use in randomly oriented strandboard (R-OSB) and oriented strandboard (OSB). The main ingredients of this adhesive included SF, polyethylenimine (PEI), maleic anhydride (MA), and sodium hydroxide. The application included spraying an aqueous solution of PEI, MA, and sodium hydroxide onto a mixture of wood flakes and SF. The adhesive hot-press conditions and add-on rate were optimized in terms of enhancing internal bond strength (IB), modulus of

rupture (MOR), and modulus of elasticity (MOE) of the resulting R-OSB and OSB panels. The highest IB, MOR and MOE of the R-OSB and OSB panels was achieved at a hot-press temperature of 170 °C, a hot-press time of 4-5 min, and an adhesive addition rate of 7% which exceeded the minimum industry requirements. Wax was added to PEI bonded OSB panels. Comparisons of IB, MOR, and MOE with PEI and commercial OSB panels were made. An addition of 1% wax (dry basis wood flakes) showed comparable results to the PEI panels with no wax.

©Copyright by Matthew John Schwarzkopf
April 8, 2009
All Rights Reserved

Development and Evaluation of Oriented Strandboard Bonded with Soy-Based
Formaldehyde-Free Adhesives

by
Matthew John Schwarzkopf

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented April 8, 2009
Commencement June 2009

Master of Science thesis of Matthew John Schwarzkopf

presented on April 8, 2009.

APPROVED:

Major Professor, representing Wood Science

Head of the Department of Wood Science and 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.

Matthew John Schwarzkopf, Author

ACKNOWLEDGEMENTS

I would like to thank Dr. Kaichang Li for his support and guidance through my Master's study. I am grateful for his work on reviewing and revising my thesis documents. His enthusiastic and professional approach to research has taught me a valuable tool for my future.

I would like to thank Dr. Joseph Karchesy, Dr. Willie E. Skip Rochefort, and Dr. Marvin R. Pyles for being my committee members and their time on reviewing my thesis.

My sincere thanks to the members of our research group, especially for the assistance of Jian Huang in the study design, data collection, and interpretation of data.

I would like to acknowledge the financial support of the United Soybean Board.

CONTRIBUTION OF AUTHORS

Jian Huang assisted in sample preparation, interpretation of the data, and preliminary research with adhesives used in Chapters 2 and 3.

TABLE OF CONTENTS

	<u>Page</u>
1 GENERAL INTRODUCTION	1
1.1 Introduction of Wood-based Structural Panels.....	1
1.1.1 Plywood.....	2
1.1.1.1 Manufacture of Plywood	2
1.1.1.2 Adhesives Used in Plywood.....	4
1.1.2 Oriented Strandboard (OSB).....	4
1.1.2.1 Manufacture of Oriented Strandboard (OSB)	5
1.1.2.2 Adhesives Used in Oriented Strandboard (OSB).....	7
1.2 Introduction of Wood Adhesives	7
1.2.1 Adhesives from Natural Materials	8
1.2.1.1 Animal Glues.....	8
1.2.1.2 Casein.....	8
1.2.1.3 Blood	9
1.2.1.4 Soy-based Adhesives.....	9
1.2.1.4.1 Soy Protein	9
1.2.1.4.2 Soy Protein-based Wood Adhesives	10
1.2.2 Adhesives from Synthetic Materials	11
1.2.2.1 Phenol Formaldehyde (PF).....	11
1.2.2.1.1 Resole PF.....	12

TABLE OF CONTENTS (continued)

1.2.2.1.2 Novalak PF	12
1.2.2.2 Isocyanates	13
1.3 Issues Associated with Synthetic Adhesives	14
1.3.1 Environmental Concerns	14
1.3.2 Adhesive Materials from Non-Renewable Resources.....	15
1.4 References	16
2 SOY FLOUR (SF) – CA1000 (CA) ADHESIVE	19
2.1 Abstract	19
2.2 Keywords.....	20
2.3 Introduction	20
2.4 Materials and Methods	21
2.4.1 Materials	21
2.4.2 Methods	22
2.4.2.1 Preparation of Southern Yellow Pine (SYP) Flakes	22
2.4.2.2 Preparation of Adhesive Coated Core and Face Materials.....	22
2.4.2.3 Preparation of the Randomly Oriented Strandboard (R-OSB) Panels .	24
2.4.2.4 Preparation of the OSB Panels	25
2.4.2.5 Strength and Stiffness of the R-OSB and OSB Samples.....	26
2.4.2.6 Internal Bond Strength of R-OSB and OSB Samples	26

TABLE OF CONTENTS (continued)

2.4.2.7 Statistical Analysis of Strength Data.....	27
2.5 Results	27
2.6 Discussion	32
2.7 Acknowledgements	35
2.8 References	35
2.9 Figures	36
3 SF – POLYETHYLENIMINE (PEI) – MALEIC ANHYDRIDE (MA) ADHESIVE	49
3.1 Abstract	49
3.2 Keywords.....	49
3.3 Introduction	49
3.4 Materials and Methods	51
3.4.1 Materials	51
3.4.2 Methods	51
3.4.2.1 Preparation of Southern Yellow Pine (SYP) Flakes	51
3.4.2.2 Preparation of Adhesive-Coated Face and Core Materials	52
3.4.2.3 Preparation of the Randomly Oriented Strandboard (R-OSB) Panels .	53
3.4.2.4 Preparation of the OSB Panels	54

TABLE OF CONTENTS (continued)

3.4.2.5 Strength and Stiffness of R-OSB and OSB Samples	55
3.4.2.6 Internal Bond Strength of R-OSB and OSB Samples	55
3.4.2.7 Statistical Analysis of Strength Data.....	56
3.5 Results	56
3.6 Discussion	60
3.7 Acknowledgements	62
3.8 References	62
3.9 Figures	63
4 GENERAL CONCLUSIONS	71

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2.1 Effect of SF:CA dry weight ratio on the IB of R-OSB panels.	36
2.2 Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels.....	37
2.3 Effect of the adhesive add-on rate (dry basis on wood flakes) on the IB of R-OSB panels.....	38
2.4 Effect of the adhesive add-on rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels.....	39
2.5 Effect of hot-press temperature on the IB of R-OSB panels.....	40
2.6 Effect of hot-press temperature on the MOR and MOE of R-OSB panels.....	41
2.7 Effect of hot-press time on the IB of R-OSB panels.....	42
2.8 Effect of hot-press time on the MOR and MOE of R-OSB panels.....	43
2.9 Effect of SF:CA dry weight ratio on the IB of R-OSB panels.....	44
2.10 Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels.....	45
2.11 Comparison of OSB panels bonded with the SF-CA adhesive and commercial OSB panels on their IB.....	46
2.12 Comparison of OSB panels bonded with the SF-CA adhesive and commercial OSB panels on their MOR and MOE.....	47
3.1 Effect of hot-press temperature on the IB of R-OSB panels.....	63
3.2 Effect of hot-press temperature on the MOR and MOE of R-OSB panels.....	64
3.3 Effect of hot-press time on the IB of R-OSB panels.....	65

LIST OF FIGURES (continued)

3.4 Effect of hot-press time on the MOR and MOE of R-OSB panels.	66
3.5 Effect of adhesive add-on rate (dry basis on wood flakes) on the IB of R-OSB panels.	67
3.6 Effects of adhesive add-on rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels.	68
3.7 Comparison of IB in OSB panels bonded with the PEI adhesive and commercial panels.	69
3.8 Comparison of MOR and MOE of OSB panels bonded with the SF-PEI-MA adhesive and commercial panels.	70

DEVELOPMENT AND EVALUATION OF ORIENTED STRANDBOARD BONDED WITH SOY-BASED FORMALDEHYDE-FREE ADHESIVES

1 GENERAL INTRODUCTION

1.1 Introduction of Wood-based Structural Panels

Wood-based panels are comprised of woody materials such as veneer or particles (i.e. flakes, wafers) and non-woody materials like adhesives and/or waxes. The woody materials are processed into a variety of geometries and can be arranged into different products. The processing of these woody materials into smaller size components does two things. First, it allows lower value wood resources to be used. Small diameter logs, underutilized tree species, waste material, and recycled material can be used for producing a panel. Second, naturally occurring defects can be eliminated or more evenly distributed throughout the panel, thus increasing the uniformity of the panel properties. Because the panel has a much more uniform strength and stiffness than solid lumber, engineering performance of panel products are more predictable than solid lumber (1). Wood-based structural panels are widely used for flooring, roof sheathing, wall sheathing, and concrete forming. Panels are usually manufactured in 4 x 8' dimensions of varying thicknesses. This large coverage area increases construction speed compared to using dimension of panels covers more construction areas than dimensional lumber. There are two major types of wood-based structural panels: softwood plywood and oriented strandboard (OSB).

1.1.1 Plywood

Plywood as seen today has been used since 1905 when it was created in St. Johns, OR by the Portland Manufacturing Company. This new panel product displayed dimensional stability, durability, strength, and good area coverage. Plywood at that time was primarily made with softwood such as Douglas-Fir. To promote quality assurance and awareness of this new product, the Douglas-Fir Plywood Association was formed in 1933. This organization has since changed to the American Plywood Association in 1964, and the APA-The Engineered Wood Association as known today. Plywood use didn't boom until it gained full acceptance in the mid-30s when a water-resistant adhesive was used. In the 1940s plywood was used extensively during World War II and was mainly manufactured with a water-resistant synthetic adhesive (1). Plywood has been largely used as flooring, roof sheathing, wall sheathing, and for concrete forming in residential and commercial construction. The use and production of plywood continued to increase with housing demands and advances in production technology and peaked in the 1980s (2).

1.1.1.1 Manufacture of Plywood

Douglas-fir logs from the Pacific Northwest were first used for plywood but expanded to include use of southern yellow pine species in the southern United States. Logs coming into mills are debarked and cut into blocks with lengths ranging from 4 to 10'. Conditioning may occur in which the blocks are soaked in hot water. This makes them

easier to peel by softening the wood (1). In structural plywood panels, a rotary lathe is used almost exclusively to produce veneer sheets (3). A knife positioned with a particular angle and pressure peels a continuous ribbon of veneer as the block spins against it. The veneer ribbon is then cut into usable lengths with thickness ranging from 1/16 to 3/16". The veneer is then dried around 200°C and will achieve a moisture content <6% (1, 3). Before lay-up an adhesive is applied to the veneer with a variety of methods. Phenol-formaldehyde (PF) is the major adhesive used in plywood manufacturing and is used to create durable, water resistant bonding. The basic lay-up of plywood is based on altering the primary grain direction in each veneer-ply. Each ply is perpendicular to the next with the top and bottom face being parallel to each other. Traditionally a manual lay-up of plywood has been used and is still used along with automated systems to achieve flexibility in products produced (1, 3). The lay-up is then transferred to be pressed into panels. The lay-up is first cold-pressed to ensure complete transfer of adhesive to the veneers. After cold pressing, they are hot-pressed by a multi-layered, heated hydraulic press. Boards are heated to temperatures of 120 to 160°C and pressed at 100 to 200 psi. This temperature and pressure allows consolidation of veneers, good adhesive penetration, and proper adhesive curing. Press time depends greatly on the thickness of the plywood being produced. After pressing, the plywood is stacked while still hot to fully cure the adhesive (1, 3).

1.1.1.2 Adhesives Used in Plywood

Structural plywood almost exclusively uses phenol-formaldehyde (PF) adhesive. PF forms water resistant bonds that are suitable for exterior exposures. The good cross-linking that occurs in the PF adhesive makes a bond that is durable, dimensionally stable, strong, and has low flammability (4).

1.1.2 Oriented Strandboard (OSB)

OSB initially began as waferboard. Waferboard has a random, un-oriented flake distribution within the panel. Waferboard was first developed in 1954 as a product composed of the “un-valuable” tree species being left after traditional harvesting in the Pacific Northwest. Aspen was first used in waferboard to take advantage of its long fiber length. Waferboard was bonded with PF adhesives and displayed similar characteristics as plywood. Waferboard was converted into OSB in the early 1980s. Around the same time, the industry expanded to the southern US where southern yellow pine was used. Since its introduction OSB has been used as I-joist webbing, flooring, roof sheathing, and wall sheathing in residential and commercial construction (5). OSB exhibits similar or higher mechanical properties than plywood and has been gaining favor in the past three decades, largely in part to its low cost.

1.1.2.1 Manufacture of Oriented Strandboard (OSB)

Logs arriving at an OSB mill are first debarked. After debarking they may be soaked in hot water and travel to a disk strander, or may skip the soaking and go directly to stranding. Groups of debarked logs are sent to a disk strander where flakes are produced that have a uniform thickness and a high length-to-thickness ratio. This high ratio is important to achieve the high uniformity, high strength, and high dimensional stability of OSB panels. Common flake lengths are 4.5 to 6" with thicknesses from 0.0023 to 0.0027". These flakes are next dried to a moisture content of 2 to 6% in a rotary or screen-type dryer. The temperature used in drying is around 200 °C. Dried flakes are then blended with an adhesive, wax, and sometimes some water. Flakes used for the face and core layers are blended separately to achieve flexibility in the amount of a resin applied, moisture content, and resin type. Waxes and adhesives are applied to the flakes using a spinning disc atomizer or spray nozzles. The spinning disc atomizer spins at a high speed and creates very small droplets of resin and wax which form a cloud inside the blenders. This cloud creates uniform coverage of the adhesive on the flakes. Wax is usually applied prior to the adhesive and is typically 0.25 to 2% of the dry weight of the wood flakes. Wax comes in as an emulsified form for easy pumping and spraying. The adhesive type and the adhesive application method vary between the face and core materials, and the usage of the adhesive is about 2 to 5% of the dry weight of the wood flakes. Additional water is sometimes sprayed to the face flake material to facilitate heat transfer from the hot-press to the

center of the board. The blended materials are formed into a mat and then placed onto a forming belt typically 4' in width. Each layer of the mat is added in sequential order by a forming head. The bottom face material drops through a forming head that consists of spinning discs to orient the material and typically accounts for 25% of the board material. The face flakes are longer than the core materials and are oriented parallel to the length of the board and mat. The next two forming heads account for 50% of the board material. These forming heads orient the core material perpendicular to length of the board and mat. The cross section of the core material forming head has a star shaped profile. The remaining 25% of the face material is added in a similar fashion as the bottom face. After mat formation, the mat is cut into billets which are loaded into a hot press charger. Multiple layers of OSB mats are pressed at once to maximize production efficiency. Once loaded into the heated hydraulic hot-press, the OSB mats are pressed to a constant thickness typically ranging from 7/16 to 3/4". Depending on board thickness and adhesive type, the hot-press is carried out at a range of 175 to 205 °C for 3 to 6 minutes. The panels are then ejected from the hot-press and are cut to size, usually 4 x 8'. These panels are then hot-stacked upon each other for a 24 hour period to fully cure the adhesive. Hot stacking saves time in the press, which increases overall production efficiency. Some OSB panels receive a light sanding on their surface and may have a moisture resistance coating applied to them (3, 5).

1.1.2.2 Adhesives Used in Oriented Strandboard (OSB)

OSB is bonded with two major adhesives, phenol-formaldehyde (PF) and isocyanates such as PMDI (polymeric diphenylmethane diisocyanate). PF is commonly used on the face materials of OSB. The OSB panels bonded with the PF adhesive are durable, dimensionally stable, strong, and have low flammability, thereby being suitable for exterior application (4). PMDI is commonly used in the core material of OSB for several reasons. The first is that PMDI is very reactive and cures at a lower temperature than the PF, thus shortening pressing times. Secondly, PMDI creates durable, water-resistant, and heat-resistant OSB panels that can be used for exterior exposure. However, PMDI strongly bonds with the hot-press platens and cannot be used without applying a release agent onto the platens first. PMDI is more expensive than PF, but is more efficient than PF, i.e., requiring a smaller amount than PF for bonding the same amount of materials (6).

1.2 Introduction of Wood Adhesives

Wood adhesives have been used for many years and have been found in inlaid wood veneers on furniture that was created for Egyptian Pharaohs using animal glue (1, 7). Adhesive technology has since evolved and along with animal glues has produced synthetic polymers. Wood adhesives can be divided into natural and synthetic adhesives.

1.2.1 Adhesives from Natural Materials

1.2.1.1 Animal Glues

Animal glues are protein-based adhesives. Collagen is obtained from rendering animal products like hides, bones, tendons, cartilage, and connective tissues (8). The protein present in collagen is composed of amino acids. Interactions of functional groups in amino acids are linked to adhesive strength. Unlike other adhesives animal glues have the ability to gel. They can be warmed and liquefied for use and application and will thicken and cure when cooled (9). Animal glues are used in furniture assembly, stringed instruments, antique repair, and paper tapes (9, 10). These adhesives have not proven useful for wood panel products due to their quick gelation, low moisture resistance, biologic degradation, and limited availability (8, 10, 11).

1.2.1.2 Casein

Casein is a precipitated milk protein when milk is acidified. Casein contains more carboxylic acid groups than collagen used in animal glues. When divalent or polyvalent metal ions are added, they react with the carboxylic acid groups in casein and cross-link casein, thus improving the water resistance of the casein-based adhesive. Calcium hydroxide can be mixed with casein to form an adhesive called casein-lime glue. Casein-based adhesives have been used for interior applications. Beams, doors, joints, and laminated lumber can be made with casein-based adhesives.

Due to their moderate water resistance, wood panels bonded with casein-based adhesives will lose their strength with increasing moisture content (9).

1.2.1.3 Blood

Blood has a high amount of protein and can thus be processed to form an adhesive. Blood is obtained from cattle, sheep, and hog slaughterhouses (8). Due to blood protein being in a globular form, acceptable reactivity is achieved by dispersion in an alkaline solution. This alkaline treatment opens the protein and allows good adhesion to occur. Before synthetic resins became more available, blood glues were used in plywood as water-resistant adhesives. Addition of PF resins to blood glues increased the water resistance of blood glues and the plywood bonded with the PF-modified blood glues were close to meet the requirements of exterior applications (9). However, the blood glues cannot meet the stable supply and volume required by the current wood panel industry. In addition, blood glues used in wood panels have difficulties in meeting current standards (8).

1.2.1.4 Soy-based Adhesives

1.2.1.4.1 Soy Protein

Soy proteins, like blood proteins are globulins which solubilize readily in salts. A high pH promotes soy protein solubility. The primary proteins in soy are tightly packed and

certain intermolecular bonds must be broken to take advantage of the polypeptides for adhesive applications. There are three types of soybean products that may potentially be used for adhesives. These are defatted soy flour, soy protein concentrate (SPC), and soy protein isolate (SPI). Defatted soybean flour (soybean meal) is obtained by removing the oil from the soybean with a solvent-extraction method or a press method. The defatted soy flour contains 40-60% of protein. SPC is obtained from defatted soy meal by a partial removal of carbohydrates in defatted soy meal with an acid treatment. SPC contains about 60-70% of protein. SPI is also obtained by removing carbohydrates in defatted soy meal, but has a higher protein content (ca. 90%) than SPC (12).

1.2.1.4.2 Soy Protein-based Wood Adhesives

Defatted soybean flour was used as an adhesive in the 1930s. Increases in annual consumption of wood adhesives continued through World War II, and slowly through the 1960s. Since the 1960s, soy-based adhesives were replaced by synthetic resins such as urea-formaldehyde (UF) and PF resins because they had lower strength and lower water resistance than synthetic adhesives. Various methods have been investigated for improving the water resistance and strengths of soy-based adhesives. For example, mixtures of soy protein with other natural proteins such as blood and casein were found to have adhesive properties different from soy adhesive alone. The soy/blood adhesives displayed a higher strength and higher water resistance, but a

lower heat stability than soy adhesives alone. Soy/casein mixtures improved the strength, water resistance, and heat resistance over soy alone (13). Soy-based adhesives have recently regained the interest of the wood products industry because of high oil price. For improving the water resistance and strength of soy-based adhesives to the level of synthetic resins, a number of methods have been investigated in modification of soy protein. Modifications of soy protein with protease enzymes and chemicals such as alkali and urea have been shown to improve the strength and water-resistance of soy-based adhesives (14). However, these modification methods have not been used in commercial production of wood-based composite panels. The only commercial success of soy-based adhesives is from mimicking mussel adhesive protein (15-17).

1.2.2 Adhesives from Synthetic Materials

The phenol-formaldehyde (PF) and isocyanates are almost exclusively used for making wood-based structural panels.

1.2.2.1 Phenol Formaldehyde (PF)

PF resins are used in both structural plywood and OSB production. PF is prepared from phenol and formaldehyde. By changing the catalyst used in the reaction and varying the formaldehyde to phenol ratio, two types of resins are produced. If the

catalyst is a base, the PF resin produced is called a resole and if the catalyst is an acid, the PF resin produced is called a novalak.

1.2.2.1.1 Resole PF

A resole PF resin is created by two primary reactions: methylation and condensation. Methylation is carried out by a molar excess of formaldehyde being added to the phenol in alkaline conditions. Phenol is substituted by methylol groups. Due to the excess formaldehyde, several methylol substitutions may be made. In the condensation reaction, the methylolated phenol derivatives are polymerized to form methylene and/or methylene ether linkages. Reaction conditions control the degree of polymerization. Time, temperature, pH, and the formaldehyde to phenol ratio all contribute to the degree of polymerization. At this stage the PF can be applied to wood substrates easily and fully crosslinked with the addition of heat. Resole PF resins are the first choice in the wood adhesive industry because of their relatively low cost, short press time, high water resistance, high durability, and high thermal stability. A resole PF resin is a thermosetting resin (9, 18).

1.2.2.1.2 Novalak PF

The preparation of a novalak PF resin is carried out under acidic conditions. Methylation and condensation occur at the same time. Unlike the preparation of the

resole, an excess of phenol rather than formaldehyde is used. In novalak PF resins, no free methylol groups are available for further crosslinking. Additional formaldehyde has to be added for curing the resin. Due to this additional step of adding formaldehyde the novalak PF resins tend to have a slower curing time and lower level of crosslinking than resoles, which is undesirable in the wood panel industry (9, 18).

1.2.2.2 Isocyanates

The most commonly used isocyanate for making structural wood-based panels is polymeric diphenylmethane diisocyanate (PMDI). PMDI is widely used for making OSB. PMDI is much more efficient, i.e., requires a less amount for bonding the same amount of wood flakes than PF resins. PMDI is usually used only in the core of OSB panels because of the following two reasons: 1) PMDI has a shorter curing time than PF resins. The use of PMDI instead of the PF resins in the core can shorten the hot-press time of making OSB panels; 2) PMDI bonds wood and the hot-press platens very well. The use of PMDI only in the core can avoid the direct contact of PMDI-coated wood with the hot-press platens, thus preventing wood from sticking onto platens. A release agent is also often sprayed onto the hot-press platens in the commercial production of OSB panels. PMDI may form covalent linkages with hydroxyl groups in wood. PMDI also reacts quickly with water in wood to form an amine that further reacts with isocyanate groups in PMDI, thus creating adhesive networks (19).

1.3 Issues Associated with Synthetic Adhesives

1.3.1 Environmental Concerns

Formaldehyde emission from wood-based composite panels has been acknowledged since the 1940s. Exposure to formaldehyde was not recognized as a threat when the low quantities of wood-based panels were produced. With increased popularity of wood-based composite panels bonded with formaldehyde-based adhesives, the formaldehyde exposure has now become a source of concern. In 2004, the International Agency for Research on Cancer reclassified formaldehyde from a possible human carcinogen to a known human carcinogen and in 2007, the California Air and Resource Board (CARB) voted to limit the amount of formaldehyde emitted from wood-based composite panels such as decorative hardwood plywood, particleboard, and medium density fiberboard sold and used in California. Urea-formaldehyde (UF) resin is the primary concern for the formaldehyde emission because UF bonds are not stable under hot and humid conditions and can be readily hydrolyzed to release formaldehyde. The UF resin also contains free (un-reacted) formaldehyde (20). Phenol-formaldehyde (PF) resin also contains free formaldehyde that will emit during the hot-press of making wood-based composite panels. The exhaust gas from the hot-press has to be treated such as burned with natural gas before it can be released to the atmosphere. The treatment of the exhaust gas can be very expensive. The amount of formaldehyde emitted from cured PF resin is negligible. Therefore, the concern over formaldehyde emission for the PF resin is only limited in

the production of wood-based composite panels. Wood-based structural panels like OSB and softwood plywood typically do not use UF resin. The formaldehyde emission from structural wood-based composite panels is typically not an issue and is not affected by the CARB regulation. Isocyanates such as PMDI are acutely toxic. Special protective equipment has to be used for handling isocyanates. The exhaust gas from the hot-press operation of making isocyanate-bonded wood-based composite panels has also to be treated.

1.3.2 Adhesive Materials from Non-Renewable Resources

The synthetic adhesives used today in wood-based structural panels are all derived from non-renewable petrochemicals. PF and isocyanates are derived from petroleum and/or natural gas. Phenol is derived from benzene which is a petrochemical, formaldehyde is a product of methanol which comes from natural gas, and isocyanates are also derived from petrochemicals. Petroleum and natural gases are a finite reserve and will be in short supply in the future. The development of environmentally friendly adhesives from renewable abundant raw materials will ensure the continued success of the wood-based composite panel industry.

1.4 References

1. McKay, M. 1997. Plywood. In *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*. S. Smulski, editor PFS Research Foundation, Madison, WI.
2. FAOSTAT. 2009.
3. Bowyer, J.L., R. Shmulsky, and J.G. Haygreen. 1996. *Forest Products and Wood Science*. Iowa State Press, Ames, IA.
4. Baldwin, R.F. 1995. *Plywood and Veneer-Based Products: Manufacturing Practices*. Miller Freeman Books, San Francisco, CA.
5. Lowood, J. 1997. Oriented Strandboard and Waferboard. In *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*. S. Smulski, editor PFS Research Foundation, Madison, WI.
6. Gollob, L., and J.D. Wellons. 1990. Wood Adhesion. In *Handbook of Adhesives*. I. Skeist, editor Van Norstrand-Reinhold Publication, New York, NY.
7. Blomquist, R.F. 1981. Adhesives: An Overview. In *Adhesive Bonding of Wood and Other Structural Materials*. R.F. Blomquist, A.W. Christiansen, R.H. Gillespie, and G.E. Myers, editors. Pennsylvania State University,
8. Sellers, T.J. 1985. *Plywood and Adhesive Technology*. Marcel Dekker, Inc, New York, NY.
9. Subramanian, R.V. 1981. Adhesives: An Overview. In *Adhesive Bonding of Wood and Other Structural Materials*. R.F. Blomquist, A.W. Christiansen, R.H. Gillespie, and G.E. Myers, editors. Pennsylvania State University. 137-188,
10. Forest Products Laboratory. 1999. *Wood Handbook: Wood as an Engineering Material*. General Technical Report 113. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.
11. Eckelman, C.A. 1997. *A Brief Survey of Wood Adhesives*. FNR 154. Purdue University Cooperative Extension, West Lafayette, IN.

12. Kumar, R., V. Choudhary, S. Mishra, I.K. Varma, and B. Mattiason. 2002. Adhesives and Plastics Based on Soy Protein Products. *Industrial Crops and Products* 3:155-172.
13. Kumar, R., V. Choudhary, S. Mishra, I.K. Varma, and B. Mattiason. 2004. Enzymatically-Modified Soy Protein Part 2: Adhesion Behaviour. *J Am Oil Chem Soc* 18:261-273.
14. Hettiarachchy, N.S., U. Kalapathy, and D.J. Myers. 1995. Alkali-Modified Soy Protein with Improved Adhesive and Hydrophobic Properties. *J Am Oil Chem Soc* 1461-1464.
15. Li, K. Formaldehyde-free lignocellulosic adhesives and composites made from the adhesives. U.S. Patent No. 7,252,735. Issued date, August 7, 2007.
16. Li, K., and X. Geng. Adhesive compositions and methods of using and making the same. U.S. Patent No. 7,265,169. Issued date, September 4, 2007.
17. Li, K., and Y. Liu. Modified protein adhesives and lignocellulosic composites made from the adhesives. U.S. Patent No. 7,060,798. Issued date, June 13, 2006.
18. Zheng, J. 2002. Studies of PF Resole and Isocyanate Hybrid Adhesives. Virginia Polytechnic Institute and State University,
19. Wirpsza, Z. 1993. Polyurethanes, Chemistry, Technology, and Applications. Ellis Horwood Inc, New York, NY.
20. Meyer, B., and K. Hermanns. 1986. Formaldehyde Release from Wood Products: An Overview. In ACS Symposium Series 316 - Formaldehyde Release from Wood Products. B. Meyer, B.A. Kottes Andrews, and R.M. Reinhardt, editors. American Chemical Society, Washington D.C. 1-6.

CHAPTER 2: PREPARATION AND EVALUATION OF ORIENTED
STRANDBOARD BONDED WITH A SOY-BASED ADHESIVE

Matthew John Schwarzkopf, Jian Huang, Kaichang Li

Department of Wood Science and Engineering, Oregon State University

Corvallis, OR 97331

Submitted to Journal of American Oil Chemists' Society for publication

2 SOY FLOUR (SF) – CA1000 (CA) ADHESIVE

2.1 Abstract

A formaldehyde-free soy flour (SF)-curing agent (CA) adhesive was investigated for making randomly oriented strandboard (R-OSB) and OSB. Two methods (the wet method and the dry method) were investigated for applying the SF-CA adhesive onto wood flakes. The wet method included the thorough mixing of SF and CA to form an adhesive mixture and then spraying the adhesive mixture onto wood flakes. The SF:CA weight ratio, the adhesive add-on rate, hot-press conditions were optimized in terms of enhancing internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE) of the resulting R-OSB panels. The highest IB, MOR and MOE were obtained at the 1:1 SF:CA weight ratio. The IB, MOR and MOE of the R-OSB panels that were made at the adhesive add-on rate of $\geq 7\%$, a hot-press temperature between 170 °C and 220 °C, and a hot-press time of ≥ 4 min exceeded the minimum industry requirements. The dry method included spraying aqueous CA solution onto a mixture of SF and wood flakes. The dry method was able to increase the SF:CA ratio up to 7:1 where the strengths of the resulting R-OSB panels still exceeded the minimum industry requirements. OSB panels made with the SF-CA adhesive had their strengths higher than or comparable to those commercial OSB panels purchased at a local Home Depot.

2.2 Keywords

Wood adhesives, soy flour, oriented strandboard, internal bond

2.3 Introduction

Oriented strandboard (OSB) is made with wood flakes (long and thin strip and often of a rectangular shape) and adhesives. OSB typically includes two face layers and a core layer. The lengths of wood flakes for the face layers are typically longer than those for the core layer. The wood flakes in each layer can be aligned along the lengths. The direction of the wood flake length for the face layers is perpendicular to that for the core layer. The wood flakes can also be randomly oriented to make randomly oriented strandboard (R-OSB). Two types of adhesives are currently used in the industry for making OSB. Phenol-formaldehyde (PF) is used in the face layers and polyisocyanates (e.g., PMDI) in the core layer. Both PF and PMDI are petrochemical-based adhesives. The high prices of fossil oil and natural gas have detrimental impacts on the wood composite panels industry. Since the reserves for fossil oil and natural gas are limited, the sustainability and the continued success of the OSB panel industry will benefit from the development of alternative adhesives from renewable materials.

In June of 2004 the International Agency for Research on Cancer reclassified formaldehyde as a human carcinogen (1). The residual formaldehyde in the PF resins is released in the production of OSB panels. The exhaust gas from the hot-press of

making OSB panels is typically burned with natural gas to remove the formaldehyde and other toxic air pollutants, which is an expensive and energy-consuming process. This expensive process may be eliminated if an environmentally friendly adhesive that does not generate any toxic air pollutant can be developed. PMDI is acutely toxic. A special protection method has to be used when PMDI is used for making OSB panels. The exhaust gas also has to be treated before being released to atmosphere. An environmentally friendly alternative adhesive will make the special protection measure unnecessary and may allow the direct release of the exhaust gas to atmosphere.

Soy flour is abundant, inexpensive, renewable, and environmentally friendly. Our group has recently developed environmentally friendly soy-based adhesives (2-7). One of the soy-based adhesives has successfully been used to replace urea-formaldehyde resins for the commercial production of plywood since 2004 (6). The replacement of urea-formaldehyde with the soy-based adhesive can reduce the emission of volatile organic compounds by up to 90% in each plywood plant. In this study, we investigated if the soy-based adhesive could also be used for making OSB panels.

2.4 Materials and Methods

2.4.1 Materials

Soy flour (SF) (100 mesh, 90 PDI (protein dispersibility index), 92.5% solids content) was donated by Cargill Incorporated (Minneapolis, MN). CA 1000 (CA) (20% solids

content) was donated by Hercules Incorporated (Wilmington, DE). Southern yellow pine (SYP) flakes (7-8% moisture content) were donated by Louisiana Pacific (Nashville, TN).

2.4.2 Methods

2.4.2.1 Preparation of Southern Yellow Pine (SYP) Flakes

SYP flakes were placed in a rotary dryer and dried for 30 min. The drying reduced the moisture content of the flakes to less than 2%. After drying, the flakes were sorted using a two-tiered separator into face (longer flakes) and core (shorter flakes) materials.

2.4.2.2 Preparation of Adhesive Coated Core and Face Materials

Two different preparation methods were used and will be referred to as wet and dry methods.

The following is a representative wet method for the preparation of the adhesive-coated face materials. CA (4199.66 g wet, 839.93 g dry) and water (487.62 g) was slowly mixed in a large mixing bowl. SF (912.26 g wet, 843.84 g dry) was added to the CA-water solution and then mixed at a higher rate of speed at room temperature for 5 min. The total solids content of the resulting adhesive was 30%. The resulting SF-CA adhesive (5599.54 g wet, 1683.77 g dry) was pumped into a spinning disc atomizer with a piston-driven pump and was sprayed via the atomizer onto the SYP

face flakes (23.99 kg dry) in a rotating drum-type blender. The drum blender was rotated at a speed of 16 rpm and the atomizer was rotated at 6000 rpm.

For the adhesive-coated core materials, the following ingredients were sequentially mixed in the same way as in the preparation of the SF-CA adhesive for the face materials. CA (2099.83 g wet, 419.97 g dry), water (243.81 g), and SF (456.13 g wet, 421.92 g dry) were mixed to form an adhesive with 30% total solids content. The resulting SF-CA adhesive (2799.77 g wet, 841.89 g dry) was sprayed onto the core flakes (11.99 kg dry) in the same way as in the preparation of adhesive-coated face materials.

The following is a representative dry method for the preparation of adhesive-coated face materials. A solution of CA (1938.32 g wet, 387.66 g dry) and water (225.08 g) was sprayed through the spinning disc atomizer onto a mixture of SF (421.04 g wet, 389.46 g dry) and the wood flakes (11.08 kg) in the rotary blender with the blender rotating at 16 rpm and the spinning disc atomizer rotating at 6000 rpm. The total solids content of the adhesive (SF + water + CA 1000) was 30%.

Adhesive-coated core materials were prepared in the same way as in the preparation of the adhesive-coated face materials. More specifically, a solution of CA (969.16 g wet, 193.83 g dry) and water (112.54 g) was sprayed onto a mixture of SF (210.52 g wet,

194.73 g dry) and wood flakes (5538 g). The total solids content of the adhesive (CA1000 + water + SF) was 30%.

2.4.2.3 Preparation of the Randomly Oriented Strandboard (R-OSB) Panels

The R-OSB panels were comprised of three layers with each layer having the same weight of the adhesive-coated materials. The outer layers were adhesive-coated face materials and the inner layer was adhesive-coated core materials. The adhesive-coated face flakes (23.99 kg wet, 23.51 kg dry) were flatly and uniformly distributed in a 22x22" forming box on top of a metal screen and an aluminum sheet, followed by the adhesive-coated core materials (11.99 kg wet, 11.75 kg dry) and the adhesive-coated face materials (23.99 kg wet, 23.51 kg dry). Flakes were randomly oriented within the forming box. The flake mat was hand-pressed within the box to remove excess air. The forming box was then removed and the mat on top of a metal screen and aluminum sheet was placed in a hot-press. Pre-determined hot-press temperature and time were used in making R-OSB. The target density of the R-OSB panels was 800 kg/m³. The target thickness for the R-OSB panel was 11.1 mm. The mat was pressed at a constant thickness of 8 mm to account for springback. The resulting R-OSB panels were hot stacked and allowed to cool to room temperature overnight before testing.

2.4.2.4 Preparation of the OSB Panels

The OSB panels were comprised of three layers with each layer having the same weight of the adhesive-coated materials. The outer layers were adhesive-coated face materials made with the previously described dry method and the inner layer was adhesive-coated core materials made with the previously described dry method. The direction of the wood flake length for the outer layers was perpendicular to that for the core layer. The adhesive-coated face flakes (2584.39 g wet, 778.63 g dry) were flatly and uniformly distributed in a 22x22" forming box on top of a metal screen and an aluminum sheet with all flakes aligned into one direction. The adhesive-coated core materials (1292.2 g wet, 389.31 g dry) were flatly and uniformly distributed on top of the previously formed face flakes with the core flakes perpendicular to the face flakes. At the end, the adhesive-coated face materials (2584.39 g wet, 778.63 g dry) were flatly and uniformly distributed on top of the previously formed core layers with the face flakes perpendicular to the core flakes. The flake mat was hand-pressed within the box to remove excess air. The forming box was then removed and the mat on top of a metal screen and aluminum sheet was placed in a hot-press. Hot-press temperature (170 °C) and time (5 min) were used in making the OSB panels. The target density of the OSB panels was 800 kg/m³. The target thickness for the OSB panel was 11.1 mm. The mat was pressed at a constant thickness of 8 mm to account for springback. The resulting OSB panels were hot stacked and allowed to cool to room temperature overnight before testing.

2.4.2.5 Strength and Stiffness of the R-OSB and OSB Samples

The modulus of rupture (MOR) and modulus of elasticity (MOE) of the R-OSB and OSB samples were determined by a static, three point bending test in accordance with the American Society for Testing Materials; Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials (ASTM D 1037-99). Eight test specimens with nominal dimensions of 406.4 x 76.2 x 11.1 mm were cut from test panels for each condition. MOR and MOE values were calculated and recorded for each specimen. The minimum industry requirements of MOR and MOE for R-OSB panels are 17.24 MPa and 3.10 GPa, respectively. The minimum industry requirements of MOR and MOE for the OSB panels are 23.45 MPa for the “parallel” MOR, 9.66 MPa for the “perpendicular” MOR, 4.48 GPa for the “parallel” MOE and 1.31 GPa for the “perpendicular” MOE. “Parallel” means that the longer dimension of the test panels is parallel to the length direction of face flakes and “perpendicular” means that the longer dimension of the test panels is perpendicular to the length direction of face flakes.

2.4.2.6 Internal Bond Strength of R-OSB and OSB Samples

The internal bond strength (IB) of the OSB samples was determined by testing tensile strength perpendicular to the OSB surface in accordance with the American Society for Testing Materials; Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials (ASTM D 1037-99). Twelve test specimens with nominal dimensions of 50.8 x 50.8 x 11.1 mm were cut from test panels for each

condition. The IB was calculated and recorded after each specimen was tested to failure. These values were compared with a minimum industry requirement of IB (0.34 MPa) for both R-OSB and OSB panels.

2.4.2.7 Statistical Analysis of Strength Data

Strength data were analyzed with a two-sample t-test using S-PLUS statistical software (Version 8.0, Insightful Corp., Seattle, WA, USA). All comparisons were based on a 95% confidence interval.

2.5 Results

For the wet method, the effect of SF:CA ratio on the IB of R-OSB panels is shown in Figure 2.1. The minimum industry requirement of the IB for the R-OSB panels is shown as a horizontal dashed line in the Figure 2.1. At the SF:CA ratios of either 1:2 or 1:1, the IB met the minimum requirement. The effects of the SF:CA ratio on the MOR and MOE are shown in Figure 2.2. The minimum industry requirement for the MOR is 17.24 MPa as indicated by a horizontal dashed line and the minimum requirement for the MOE is indicated by a horizontal solid line. The MOR met the minimum requirement when the SF:CA ratio was lower than 2:1. The MOR was the highest at the 1:1 SF:CA ratio. The MOE still met the minimum requirement when the SF:CA ratio was as high as 5:1. The highest MOE also occurred at the 1:1 SF:CA ratio. With the IB, MOR, and MOE all being considered, the panels met the minimum

industry requirements when the SF:CA ratios were either 1:2 or 1:1. The 1:1 SF:CA ratio appeared to be the optimum ratio, and was used for further investigation.

The effect of an adhesive add-on rate on the IB of the R-OSB panels made with the wet method is shown in Figure 2.3. When the add-on rate was increased from 3% to 5%, the IB increased, but was still lower than the minimum industry requirement as indicated by the horizontal dashed line. When the add-on rate was further increased to 7%, the IB significantly increased and exceeded the minimum industry requirement. Further increasing the add-on rate from 7% to 9% did not significantly affect the IB. The effects of the add-on rate on the MOR and MOE are shown in Figure 2.4. At the 3% add-on rate, the MOR was slightly below the minimum industry requirement as indicated by the horizontal dashed line. The MOR increased when the add-on rate was increased from 3% to 9%, and met the minimum industry requirement when the add-on rate was $\geq 5\%$. The MOE met the minimum industry requirement when the add-on rate was at the 3-9% range. The 7% add-on rate was the lowest add-on rate where the IB, MOR and MOE all met the minimum industry requirements. The lower the add-on rate the lower the cost of OSB panels. Therefore, the 7% add-on rate was used for the further investigations.

The effect of the hot-press temperature on the IB of the R-OSB panels is shown in Figure 2.5. The IB at 160 °C was somehow the lowest and was the only one that

could not meet the minimum industry requirement as indicated by the horizontal dashed line. As a matter of fact, all IB values were not significantly different at the 140-200 °C range. The IB increased when the hot-press temperature was increased to 210 °C and 220 °C. The average IB was the highest at 220 °C. The effects of the hot-press temperature on the MOR and MOE are shown in Figure 2.6. The MOR at 140 °C was higher than that at 150 °C. The MOR values at 150 °C and 160 °C were statistically the same. The MOR significantly increased when the hot-press temperature was increased from 160 °C to 170 °C. The MOR values at the 170-220 °C range were not significantly different from each other. The MOR values at the 140-220 °C range all met the minimum industry requirement as indicated by the horizontal dashed line. The MOE values at the 140-160 °C range were all statistically the same and did not meet the minimum industry requirement as indicated by the horizontal solid line. The MOE significantly increased when the hot-press temperature was increased from 160 °C to 170 °C. The MOE values at the 170-220 °C range were statistically the same and all met the minimum industry requirement. When the temperature was at the 170-220 °C range, the IB, MOR and MOE all met the minimum industry requirements.

The effect of hot-press time on the IB of the R-OSB panels made with the wet method is shown in Figure 2.7. The IB at 3 min was statistically the same as that at 4 min. The IB significantly increased when the hot-press time was increased from 4 min to 5

min. However, the IB significantly decreased when the hot-press time was increased from 5 min to 6 min. The IB at 6 min was statistically the same as that at 7 min. The IB was the highest at 5 min. The IB at the 3-7 min range all met the minimum industry requirement as indicated by the horizontal dashed line. The effects of the press time on the MOR and MOE are shown in Figure 2.8. The MOR increased when the hot-press time was increased from 3 min to 4 min. The MOR values were statistically the same at the hot-press times of 4, 5, and 6 min. The MOR significantly decreased when the hot-press time was increased from 6 min to 7 min. All MOR values at the 3-7 min range met the minimum industry requirement as indicated by the horizontal dashed line. The MOE gradually increased when the hot-press time was increased from 3 min to 5 min. The MOE significantly decreased when the hot-press time was further increased from 5 min to 6 min. The MOE did not significantly change when the hot-press time was increased from 6 min to 7 min. Except at 3 min, the MOE values at other hot-press times of 4-7 min all exceeded the minimum industry requirement as indicated by the horizontal solid line.

The effect of SF:CA ratio on the IB of R-OSB panels made with the dry method is shown in Figure 2.9. The IB decreased when the SF:CA ratio was increased from 1:1 to 2:1. The IB at the 2:1 SF:CA ratio was not significantly different from that at the 3:1 SF:CA ratio. The IB decreased when the SF:CA ratio was further increased from 3:1 to 5:1. The IB values at the SF:CA ratios of 5:1 and 7:1 were statistically the

same. When the SF:CA ratio was further increased from 7:1 to 9:1, the IB significantly decreased. When the SF:CA ratio was at the 1:1 to 7:1 range, all IB values exceeded the minimum industry requirement as indicated by a horizontal dashed line. The effects of the SF:CA ratio on the MOR and MOE of the R-OSB panels made with the dry method are shown in Figure 2.10. The MOR values were not significantly different at the SF:CA ratio range of 1:1 to 9:1 and all exceeded the minimum industry requirement as indicated by the horizontal dashed line. The MOE values were also statistically the same for the SF:CA ratio range tested and all exceeded the minimum industry requirement as indicated by the horizontal solid line. The strengths of the resulting R-OSB panels (the IB, MOR and MOE) met the minimum industry requirements at the SF:CA ratio range of 1:1 to 7:1 (Figures 2.9 and 2.10).

The IB of OSB panels made with the SF-CA adhesive and the dry method exceeded the minimum industry requirement (0.34 MPa) and was much higher than that of commercial OSB panels that were purchased from a local Home Depot (Figure 2.11). For the parallel direction, the MOR of the OSB panels made with SF-CA adhesive and the dry method was higher than that of the commercial OSB panels (Figure 2.12). The OSB panels made with the SF-CA adhesive and the commercial OSB panels met the minimum industry requirement as indicated by the horizontal dashed line in the left portion of Figure 2.12 for the MOR. The OSB panels made with the SF-CA adhesive

and the commercial OSB panels had statistically the same MOE and both met the minimum industry requirement as indicated by the horizontal solid line in the left portion of Figure 2.12 for the MOE. For the perpendicular direction, the MOR and MOE of the OSB panels made with SF-CA adhesive and the dry method were correspondingly higher than those of the commercial OSB panels. The MOR and MOE of the OSB panels made with SF-CA adhesive and the commercial OSB panels all met the minimum industry requirements, the horizontal dashed line being for the MOR and the horizontal solid line for the MOE (the right portion of Figure 2.12).

2.6 Discussion

Our results showed that the SF:CA ratio had very significant impacts on the strengths of R-OSB panels. It is still poorly understood that the 1:1 SF:CA ratio was much better than all other ratios in terms of increasing the strengths of R-OSB panels. When the adhesive add-on rate increases, the adhesive-covered surface area of the wood flakes increases and the bonding among the wood flakes inside the OSB panels also increases, which manifests on the enhancement of the strengths of the resulting OSB panels. This explanation is consistent with our results that the IB and MOR increased along with increasing the add-on rate from 3% to 7% (Figures 2.3 and 2.4). When most of the flake surfaces are covered by the adhesive, further increase in the adhesive add-on rate would not significantly further increase the bonding among flakes, i.e., strengths of the resulting OSB panels. This is consistent with our results that increasing the add-on rate from 7% to 9% did not significantly increase the IB and

MOR. Our results indicate that any temperature at the 170-220 °C range can be used to cure the SF-CA adhesive for making OSB panels (Figures 2.5 and 2.6). This implies that the hot-press temperature has a wide operational window if this adhesive is used for commercial production of OSB panels. Although the 5 min hot-press time is used for commercial production of OSB panels. Although the 5 min hot-press time resulted in the highest IB, MOR and MOE, the 4 min hot-press time also generated the R-OSB panels whose strengths were much higher than the minimum industry requirements. The 4 min hot-press time for making 11.1 mm-thick OSB panels is competitive to the industry processes of making OSB panels with PF and isocyanate adhesives.

The results from Figures 2.1 – 2.8 demonstrated that the SF-CA adhesive could be used for making superior OSB panels. However, the SF-CA adhesive at the 1:1 SF:CA ratio may not have any cost-saving advantage over PF and isocyanates for making OSB. CA is much more expensive than SF. To make the SF-CA adhesive more cost-competitive, we investigated on how to increase the SF:CA ratio. We discovered that the dry method, i.e., spraying CA solution onto a mixture of wood flakes and SF, was able to significantly increase the SF:CA ratio up to 7:1 at which the IB, MOR and MOE of resulting R-OSB panels were still higher than the minimum industry requirements (Figures 2.9 and 2.10). At the 7:1 SF:CA ratio, the SF-CA adhesive is certainly cost-competitive to PF and isocyanates for making OSB panels.

An adhesive that can be used to make superior R-OSB panels can typically be used to make superior OSB panels whose face layer is perpendicular to the core layer. We used the dry method to verify that the SF-CA adhesive was indeed able to make superior OSB panels (Figures 2.11 and 2.12). The strength properties of the OSB panels made with the SF-CA adhesive were better than or comparable to those commercial products purchased from a local Home Depot.

This study demonstrates that the formaldehyde-free, environmentally friendly SF-CA adhesive can potentially be used to replace PF and isocyanates for production of OSB panels with superior strength properties. We are investigating the thickness swelling, linear expansion, and other water-resistant properties of OSB panels to see if this SF-CA adhesive can qualify as an exterior grade wood adhesive.

2.7 Acknowledgements

This project was funded by the United Soybean Board. We thank Cargill Incorporated (Minneapolis, MN) for the defatted soy flour, Hercules Incorporated (Wilmington, DE) for the CA-1000, and Louisiana Pacific (Nashville, TN) for the SYP flakes.

2.8 References

1. International Agency for Research on Cancer. 2004. IARC Classifies Formaldehyde as Carcinogenic to Humans. Press Release 153.
2. Huang, J., L. Kaichang. 2008. A New Soy-Flour Based Adhesive for Making Interior Type II Plywood. *J Am Oil Chem Soc.* (85): 155-172.
3. Li, K., S. Peshkova, X. Geng. 2004. Investigation of Soy Protein-Kymene Adhesive Systems for Wood Composites. *J Am Oil Chem Soc.* (81): 487-491.
4. Liu, Y., K. Li. 2002. Chemical Modification of Soy Protein for Wood Adhesives. *Macromol Rapid Commun.* (23): 739-742.
5. Liu, Y., K. Li. 2004. Modification of Soy Protein for Wood Adhesives Using Mussel Protein as a Model: the Influence of the Mercapto Group. *Macromol Rapid Commun.* (25): 1835-1838.
6. Liu, Y., K. Li. 2004. Wood Adhesives from Demethylated Kraft Lignin. In *The 7th Pacific Rim Biobased Composites Symposium*. Nanjing, P R China.
7. Liu, Y., K. Li. 2007. Development and Characterization of Adhesives from Soy Protein for Bonding Wood. *Int J of Adhesion and Adhesives.* (27): 59-67.

2.9 Figures

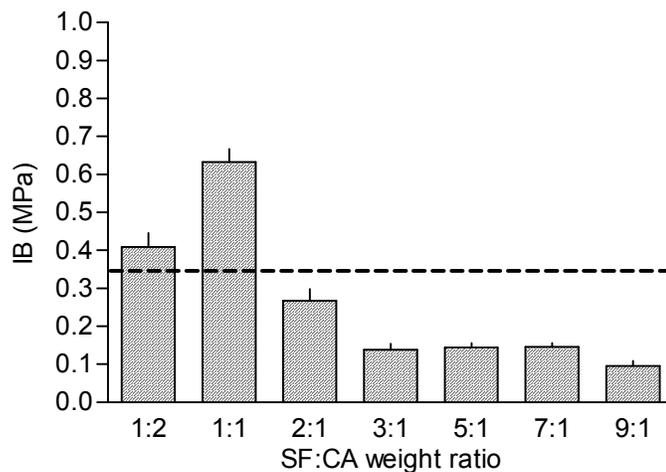


Figure 2.1 Effect of SF:CA dry weight ratio on the IB of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 220 °C and 5 min. the adhesive application method: the wet method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

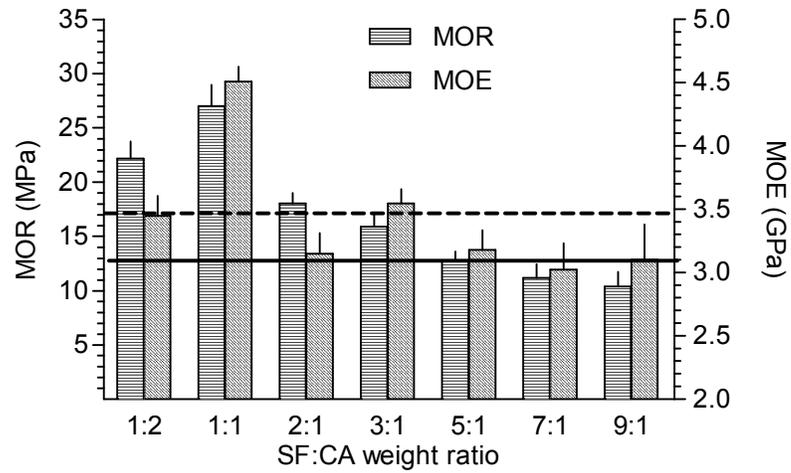


Figure 2.2 Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 220 °C and 5 min. the adhesive application method: the wet method. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

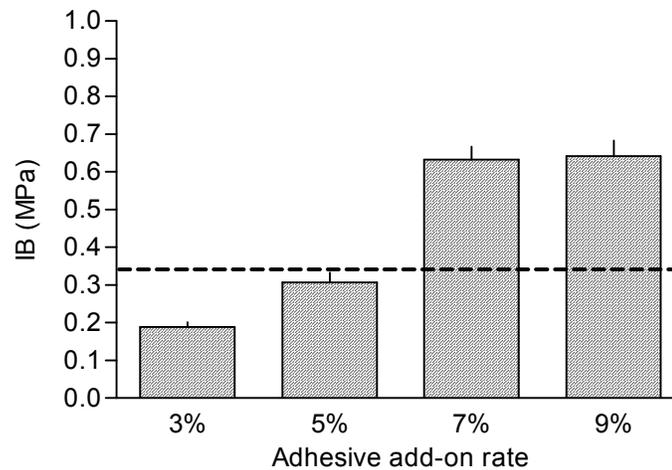


Figure 2.3 Effect of the adhesive add-on rate (dry basis on wood flakes) on the IB of R-OSB panels. (SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 220 °C and 5 min. the adhesive application method: the wet method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

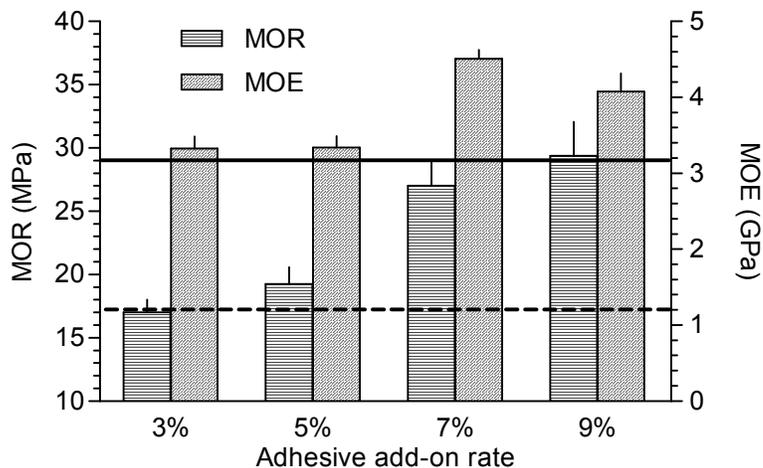


Figure 2.4 Effect of the adhesive add-on rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels. (SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 220 °C and 5 min. the adhesive application method: the wet method. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

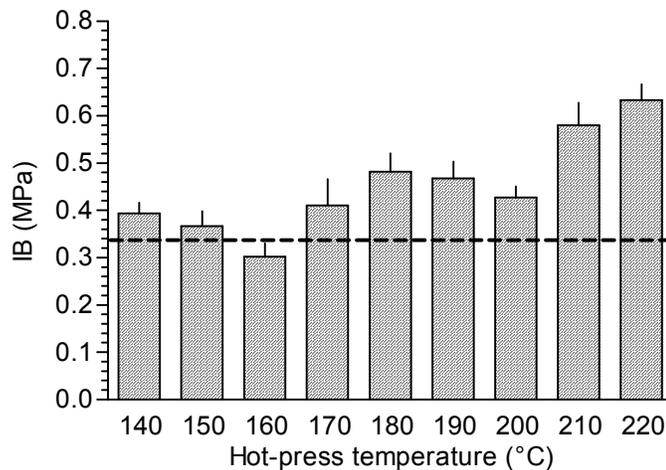


Figure 2.5 Effect of hot-press temperature on the IB of R-OSB panels. (Adhesive addition rate (dry basis on wood flakes), 7%; SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press time, 5 min. the adhesive application method: the wet method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

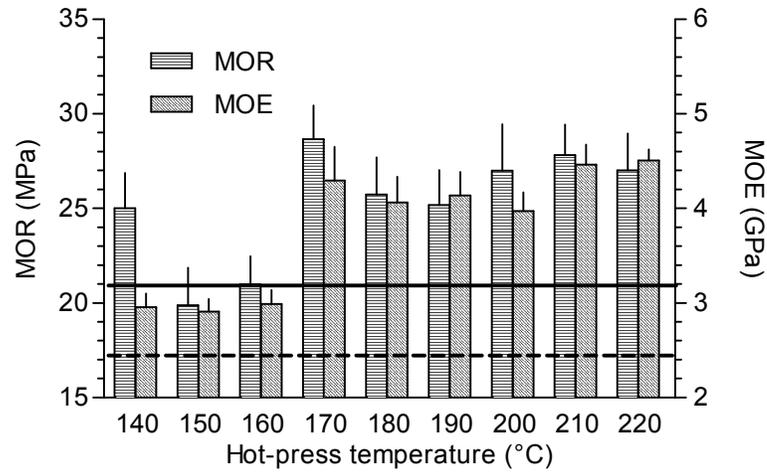


Figure 2.6 Effect of hot-press temperature on the MOR and MOE of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press time, 5 min. the adhesive application method: the wet method. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

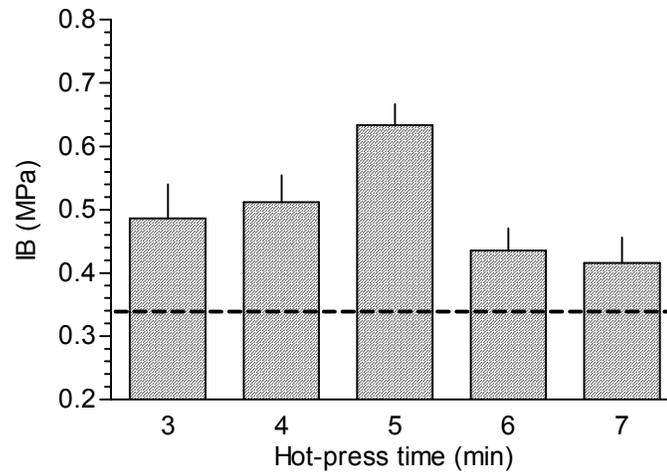


Figure 2.7 Effect of hot-press time on the IB of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press temperature, 220 °C. the adhesive application method: the wet method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

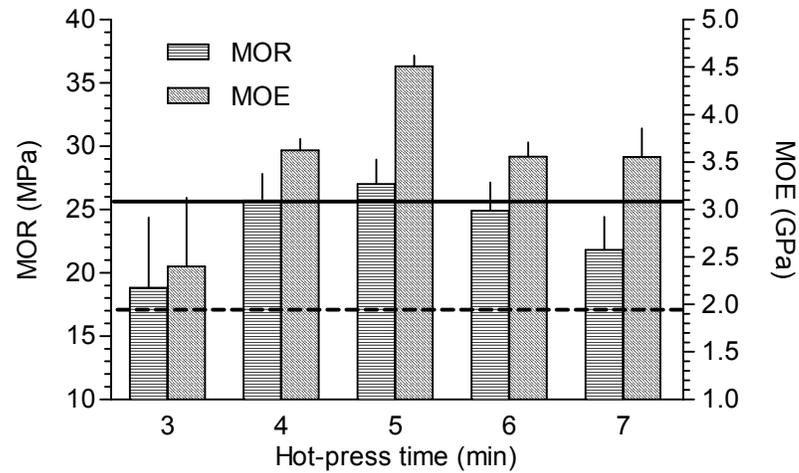


Figure 2.8 Effect of hot-press time on the MOR and MOE of R-OSB panels.

(Adhesive add-on rate (dry basis on wood flakes), 7%; SF:CA dry weight ratio, 1:1; total solids content of the SF-CA adhesive, 30%; hot-press temperature, 220 °C. the adhesive application method: the wet method. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

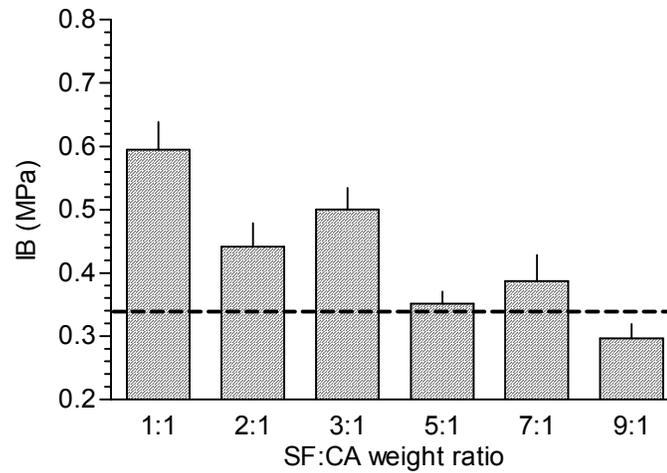


Figure 2.9 Effect of SF:CA dry weight ratio on the IB of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 170 °C and 5 min. the adhesive application method: the dry method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

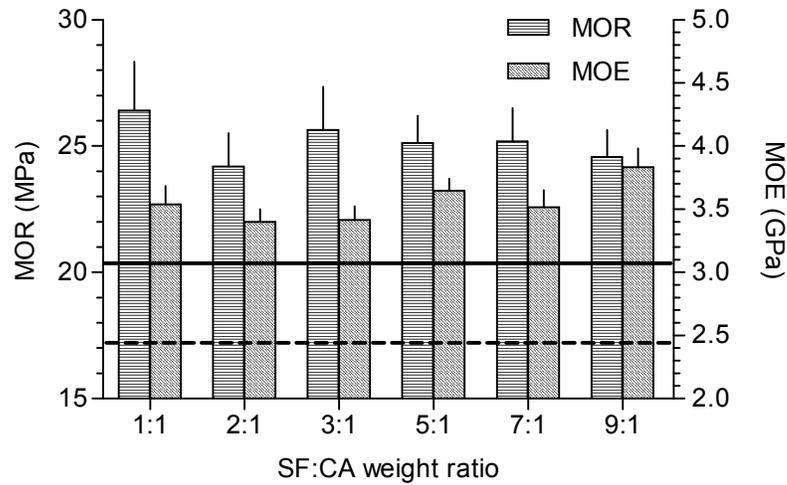


Figure 2.10 Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 170 °C and 5 min. the adhesive application method: the dry method. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

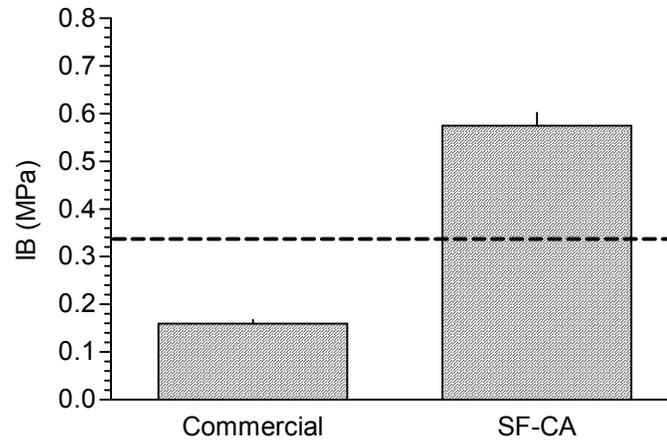


Figure 2.11 Comparison of OSB panels bonded with the SF-CA adhesive and commercial OSB panels on their IB. (Preparation of the OSB panels bonded with the SF-CA adhesive: adhesive add-on rate (dry basis on wood flakes), 7%; the SF:CA dry weight ratio, 7:1; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 170 °C and 5 min. the adhesive application method: the dry method. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

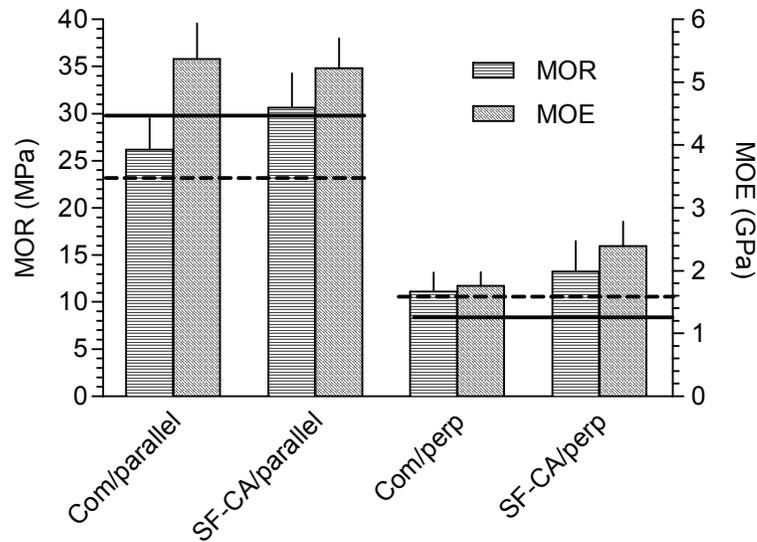


Figure 2.12 Comparison of OSB panels bonded with the SF-CA adhesive and commercial OSB panels on their MOR and MOE. (Preparation of the OSB panels bonded with the SF-CA adhesive: adhesive add-on rate (dry basis on wood flakes), 7%; the SF:CA dry weight ratio, 7:1; total solids content of the SF-CA adhesive, 30%; hot-press conditions: 170 °C and 5 min. the adhesive application method: the dry method; “Com” stands for commercial OSB panels; “Perp” means perpendicular. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

CHAPTER 3: A FORMALDEHYDE-FREE SOY-BASED ADHESIVE FOR
MAKING ORIENTED STRANDBOARD

Matthew John Schwarzkopf, Jian Huang, Kaichang Li

Department of Wood Science and Engineering, Oregon State University

Corvallis, OR 97331

Submitted to Journal of Adhesion for publication

3 SF – POLYETHYLENIMINE (PEI) – MALEIC ANHYDRIDE (MA) ADHESIVE

3.1 Abstract

A formaldehyde-free adhesive consisting of soy flour, polyethylenimine, maleic anhydride, and sodium hydroxide was investigated for making randomly oriented strandboard (R-OSB) and oriented strandboard (OSB). The hot-press conditions and the adhesive add-on rate were optimized in terms of enhancing internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE) of the resulting R-OSB and OSB. The IB, MOR and MOE were the highest at a hot-press temperature of 170 °C, a hot-press time of 4-5 min, and an adhesive add-on rate of 7%. The strengths of the OSB panels made with this formaldehyde-free adhesive were compared with those of commercial OSB panels purchased at a local Home Depot.

3.2 Keywords

Wood adhesives, soy flour, oriented strandboard, internal bond

3.3 Introduction

The commonly used wood composite panels include plywood, particleboard, medium density fiberboard, hardboard, and oriented strandboard (OSB). OSB is made with wood flakes (long and thin strip and often of a rectangular shape) and adhesives. OSB typically includes two face layers and a core layer. The lengths of wood flakes for the face layers are typically longer than those for the core layer. The wood flakes in each layer can be aligned along the lengths. The direction of the wood flake length for the

face layers is perpendicular to that for the core layer. The wood flakes can also be randomly oriented to make randomly oriented strandboard (R-OSB). Phenol-formaldehyde (PF) is commonly used in the face layers and polyisocyanates (e.g., PMDI) in the core layer. There are several disadvantages of using PF and PMDI. Both PF and PMDI are petrochemical-based adhesives and are not sustainable. The PF resin typically contains free carcinogenic formaldehyde that is released to atmosphere during the hot-press of making OSB panels (1). PMDI is toxic and has to be handled with protective equipment. The exhaust gases from the use of both PF and PMDI have to be treated such as burned with natural gas to remove formaldehyde and other hazardous air pollutants, which can be expensive and energy-consuming. An environmentally friendly alternative adhesive from renewable materials will reduce our dependency on petrochemicals and may allow the direct release of the exhaust gas to the atmosphere.

Our group has been working the development and commercialization of formaldehyde-free and environmentally friendly wood adhesives from renewable materials since 2000 (2-6). One of our soy-based adhesives has successfully been used to replace urea-formaldehyde resins for the commercial production of plywood since 2004 (3). The replacement of urea-formaldehyde with the soy-based adhesive can reduce the emission of volatile organic compounds by up to 90% in each plywood plant. We have recently developed another formaldehyde-free adhesive that consists

of soy flour (SF), polyethylenimine (PEI), maleic anhydride (MA), and sodium hydroxide (2). We have found that SF, PEI, MA, and sodium hydroxide are essential components of this adhesive. This adhesive can be used for making decorative hardwood plywood. In this study, we investigated if this adhesive could also be used for making R-OSB and OSB panels.

3.4 Materials and Methods

3.4.1 Materials

SF (100 mesh, 90 PDI (protein dispersibility index), 92.05% solids content) was donated by Cargill Incorporated (Minneapolis, MN). PEI (50% solids content), MA and sodium hydroxide were purchased from Aldrich Chemical (Milwaukee, WI) and used as received. Southern yellow pine (SYP) flakes (7-8% moisture content) were donated by Louisiana Pacific Corporation (Nashville, TN). Commercial OSB panels with the dimension of 7/16 x 48 x 96" for each panel were purchased from a local Home Depot.

3.4.2 Methods

3.4.2.1 Preparation of Southern Yellow Pine (SYP) Flakes

SYP flakes were placed in a rotary dryer and dried for 30 min. The drying reduced the moisture content of the flakes to less than 2%. After drying, the flakes were sorted using a two-tiered separator into face (longer flakes) and core (shorter flakes)

materials.

3.4.2.2 Preparation of Adhesive-Coated Face and Core Materials

The following is a representative method for the preparation of the adhesive-coated face materials. PEI (245.55 g wet, 122.78 g dry) and water (2214.72 g) were slowly mixed in a large mixing bowl. MA (39.68 g wet, 39.28 g dry) and NaOH (12.27 g) were added to the PEI-water solution and then mixed at a higher speed at room temperature for 5 min. A solution of the PEI, water, MA, and NaOH was sprayed through the spinning disc atomizer onto a mixture of SF (933.65 g wet, 859.42 g dry) and SYP flakes (14.77 kg) in the rotary blender. The total solids content of the resulting adhesive (SF + PEI + water + MA + NaOH) was 30%. The drum blender was rotated at a speed of 16 rpm and the spinning disc atomizer was rotated at 6000 rpm.

The following is a representative method for the preparation of adhesive-coated core materials. The adhesive-coated core materials were prepared in a similar manner as the adhesive-coated face materials. More specifically, a solution of PEI (122.77 g wet, 61.39 g dry) and water (1107.36 g) was slowly mixed in a large mixing bowl. MA (19.84 g wet, 19.64 g dry) and NaOH (6.13 g) were added to the PEI-water solution and then mixed at a higher speed at room temperature for 5 min. A solution of the PEI, water, MA, and NaOH was sprayed through the spinning disc atomizer onto a

mixture of SF (466.83 g wet, 429.72 g dry) and SYP flakes (7.38 kg) in the rotary blender. The total solids content of the resulting adhesive (SF + PEI + water + MA + NaOH) was 30%.

3.4.2.3 Preparation of the Randomly Oriented Strandboard (R-OSB) Panels

The R-OSB panels were comprised of three layers with each layer having the same weight of the adhesive-coated materials. The outer layers were adhesive-coated face materials and the inner layer was adhesive-coated core materials. The adhesive-coated face flakes (923.06 g) were flatly and uniformly distributed in a 558.8 x 558.8 mm forming box on top of a metal screen and an aluminum sheet, followed by the adhesive-coated core materials (923.06 g) and the adhesive-coated face materials (923.06 g). Flakes were randomly oriented within the forming box. The flake mat was hand-pressed within the box to remove excess air. The forming box was then removed and the mat on top of a metal screen and aluminum sheet was placed in a hot-press. Pre-determined hot-press temperature and time were used in making R-OSB. The target density of the R-OSB panels was 800 kg/m^3 . The target thickness for the R-OSB panel was 11.1 mm. The mat was pressed at a constant thickness of 8 mm to account for springback. The resulting R-OSB panels were hot stacked and allowed to cool to room temperature overnight before testing.

3.4.2.4 Preparation of the OSB Panels

The OSB panels were comprised of three layers with each layer having the same weight of the adhesive-coated materials. The outer layers were adhesive-coated face materials and the inner layer was adhesive-coated core materials. The direction of the wood flake length for the outer layers was perpendicular to that for the core layer. The adhesive-coated face flakes (923.06 g) were flatly and uniformly distributed in a 558.8 x 558.8 mm forming box on top of a metal screen and an aluminum sheet with all flakes aligned into one direction. The adhesive-coated core materials (923.06 g) were flatly and uniformly distributed on top of the previously formed face flakes with the core flakes perpendicular to the face flakes. At the end, the adhesive-coated face materials (923.06 g) were flatly and uniformly distributed on top of the previously formed core layers with the face flakes perpendicular to the core flakes. The flake mat was hand-pressed within the box to remove excess air. The forming box was then removed and the mat on top of a metal screen and aluminum sheet was placed in a hot-press. Pre-determined hot-press temperature and time were used in making OSB. The target density of the OSB panels was 800 kg/m^3 . The target thickness for the OSB panel was 11.1 mm. The mat was pressed at a constant thickness of 8 mm to account for springback. The resulting OSB panels were hot stacked and allowed to cool to room temperature overnight before testing.

3.4.2.5 Strength and Stiffness of R-OSB and OSB Samples

The modulus of rupture (MOR) and modulus of elasticity (MOE) of the R-OSB and OSB samples were determined by a static, three-point bending test in accordance with the American Society for Testing Materials; Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials (ASTM D 1037-99). Eight test specimens with nominal dimensions of 406.4 x 76.2 x 11.1 mm were cut from test panels for each condition. MOR and MOE values were calculated and recorded for each specimen. The minimum industry requirements of MOR and MOE for R-OSB panels are 17.24 MPa and 3.10 GPa, respectively. The minimum industry requirements of MOR and MOE for the OSB panels are 23.45 MPa for the “parallel” MOR, 9.66 MPa for the “perpendicular” MOR, 4.48 GPa for the “parallel” MOE and 1.31 GPa for the “perpendicular” MOE. “Parallel” means that the longer dimension of the test panels is parallel to the length direction of face flakes and “perpendicular” means that the longer dimension of the test panels is perpendicular to the length direction of face flakes.

3.4.2.6 Internal Bond Strength of R-OSB and OSB Samples

The internal bond strength (IB) of the R-OSB and OSB samples was determined by testing tensile strength perpendicular to the panel surface in accordance with the American Society for Testing Materials; Standard Test Methods for Evaluating

Properties of Wood-Base Fiber and Particle Panel Materials (ASTM D 1037-99).

Twelve test specimens with nominal dimensions of 50.8 x 50.8 x 11.1 mm were cut from test panels for each condition. The IB was calculated and recorded after each specimen was tested to failure. These values were compared with a minimum industry requirement of IB (0.34 MPa) for both R-OSB and OSB panels.

3.4.2.7 Statistical Analysis of Strength Data

Strength data were analyzed with a two-sample t-test using S-PLUS statistical software (Version 8.0, Insightful Corp., Seattle, WA, USA). All comparisons were based on a 95% confidence interval.

3.5 Results

The effect of the hot-press temperature on the IB of the R-OSB panels is shown in Figure 3.1. The IB at 150 °C and 160 °C did not meet the minimum industry requirement as indicated by the horizontal dashed line. The IB significantly increased and met the minimum industry requirement when the temperature was increased from 160 °C to 170 °C. Increasing the temperature from 170 °C to 180 °C somehow significantly decreased the IB. When the temperature was further increased from 180 °C to 190 °C, the IB significantly increased. The IB at 170 °C was not significantly different from that at 190 °C. It is still poorly understood why the IB at 180 °C was significantly lower than those at 170 °C and 190 °C.

The effects of the hot-press temperature on the MOR and MOE are shown in Figure 3.2. Increasing the temperature from 150 °C to 190 °C did not significantly change the MOR except that the MOR at 160 °C was significantly lower than that at 190 °C. The MOR in the range of 150 °C to 190 °C met the minimum industry requirement as indicated by a horizontal dashed line. The MOE at 160 °C was the lowest among all temperatures tested and was the only one that did not meet the minimum industry requirement as shown by a horizontal solid line. The lower the hot-press temperature the lower the cost is to make OSB panels. The lowest temperature that allowed the IB, MOR, and MOE to meet their industry requirements was 170 °C. This hot-press temperature was used in all subsequent panel preparations.

The effect of hot-press time on the IB of the R-OSB panels is shown in Figure 3.3. The IB at the hot-press times of 3 min to 7 min all met the minimum industry requirement as indicated by the horizontal dashed line. The IB did not significantly change when the hot-press time was increased from 3 min to 4 min. Increasing the hot-press time from 4 min to 6 min significantly increased the IB. When the hot-press time was further increased from 6 min to 7 min, the IB did not significantly change.

The effect of hot-press time on the MOR and MOE of the R-OSB panels is shown in Figure 3.4. When the hot-press time was in the range of 3 min to 7 min, the MOR met

the minimum industry requirement as indicated by the horizontal dashed line. The MOR did not significantly change when the hot-press time was increased from 3 min to 5 min and from 5 min to 7 min. However, the MOR at 4 min was significantly lower than those at 6 min and 7 min. The MOE at the hot-press time of 3 min to 7 min all met the minimum industry requirement as indicated by the solid horizontal line. The MOE at 3 min was not significantly different from that at 4 min. MOE values showed an upward trend when the hot-press time was increased from 4 min to 7 min. All IB, MOR, and MOE in the range of 3 min to 7 min of the hot-press time met the minimum industry requirements. The 6 min hot-press time was used in subsequent preparations of R-OSB and OSB panels because the average IB was the highest at that hot-press time.

The effect of an adhesive add-on rate on the IB of the R-OSB panels is shown in Figure 3.5. When the add-on rate was increased from 3% to 5%, the IB increased, but was still lower than the minimum industry requirement as indicated by the horizontal dashed line. When the add-on rate was further increased from 5% to 7%, the IB significantly increased and exceeded the minimum industry requirement. When the add-on rate was further increased from 7% to 9%, the IB significantly decreased, but exceeded the minimum industry requirement.

The effects of the adhesive add-on rate on the MOR and MOE are shown in Figure

3.6. The MOR significantly increased when the add-on rate was increased from 3% to 7%. Further increasing the add-on rate from 7% to 9% did not significantly change the MOR. The MOR at 3% and 5% did not meet the minimum industry requirement as indicated by the horizontal dashed line, whereas the MOR at 7% and 9% exceeded the requirement. The MOE significantly increased when the add-on rate was increased from 3% to 7%. Further increasing the add-on rate from 7% to 9% reduced the MOE. The MOE met the minimum industry requirement when the add-on rate was at the 5-9% range. The 7% add-on rate yielded the highest MOE. The 7% add-on rate was the lowest add-on rate where the IB, MOR and MOE all met the minimum industry requirements. The lower the add-on rate the lower the cost of OSB panels. Therefore, the 7% add-on rate was used for the further investigations.

The comparison of the IB values from commercial OSB panels and panels bonded with the SF-PEI-MA adhesive is shown in Figure 3.7. The IB from the panels bonded with the SF-PEI-MA adhesive was significantly higher than that from the commercial OSB panels. However, two types of panels both had their IB values below the minimum industry requirement as indicated by the horizontal dashed line.

The “parallel” MOR from the OSB panels bonded with the SF-PEI-MA adhesive was comparable to that from the commercial OSB panels (Figure 3.8). The “parallel” MOE from the OSB panels bonded with the SF-PEI-MA adhesive was also not

significantly different from that from the commercial OSB panels. The “perpendicular” MOR and MOE from the panels bonded with the SF-PEI-MA adhesive were respectively comparable to those from the commercial OSB panels.

3.6 Discussion

Our previous study on this SF-PEI-MA adhesive revealed that the optimum SF/PEI/MA/NaOH weight ratio was 7/1/0.32/0.1 in terms of increasing the strengths and water-resistance of plywood panels (2). We directly used this weight ratio in this study, as we assume that this weight ratio is also optimum for making OSB panels. In our previous study of making plywood panels, all components of this adhesive were mixed together before being applied onto veneer (2). The adhesive prepared by this method had a high viscosity and could not be readily sprayed onto wood flakes. To resolve this high viscosity issue, we sprayed a solution of PEI, MA, NaOH, and water onto a mixture of SF and wood flakes in the rotary drum blender. This application method turned out to be an excellent improvement over the method of spraying the premixed adhesive onto wood flakes. With this new application method, this SF-PEI-MA adhesive can be easily plugged in any commercial production of OSB panels.

Our results showed that 170 °C appeared to be the optimum hot-press temperature to cure the SF-PEI-MA adhesive for making OSB panels. This temperature is commonly used in commercial production of OSB panels. Our results showed that a 4 min hot-press time was sufficient to allow the IB, MOR and MOE of the R-OSB panels to

exceed the minimum industry requirements. This hot-press time is comparable to that in the commercial production of the 11.1 mm thick OSB panels using PF and PMDI adhesives. The adhesive add-on rate was found to have a significant impact on the strength properties of R-OSB panels. When the adhesive add-on rate increased, the surface areas of wood flakes that were coated by the adhesive would increase, which would result in the increase in the strengths. This is consistent with the results that the IB, MOR and MOE all increased when the adhesive add-on rate was increased from 3% to 7%. However, too much adhesive on the wood surfaces would weaken the bonding. As shown in Figures 3.5 and 3.6, the IB and MOE decreased and the MOR remained the same when the adhesive add-on rate was increased from 7% to 9%.

It is still poorly understood that the IB of R-OSB panels met the minimum industry requirement, and the IB of OSB panels did not. Overall, the strengths of OSB panels bonded with the SF-PEI-MA adhesive were comparable to those of commercial OSB panels. This implies that this SF-PEI-MA adhesive can potentially be used for commercial production of OSB panels. The PEI in this SF-PEI-MA adhesive is still a petrochemical-based product. We are developing a polyamine from renewable materials such as glycerol for replacing PEI in this adhesive. We will continue to investigate the water-resistance and long-term durability of OSB panels bonded with the SF-PEI-MA adhesive to see if this adhesive can be used for exterior application. The durability study will take a long time. We would like to first publish these

encouraging results to promote research activities in development of environmentally friendly adhesives from renewable materials.

3.7 Acknowledgements

This project was funded by the United Soybean Board. We thank Cargill Incorporated (Minneapolis, MN) for the defatted soy flour and Louisiana Pacific Corporation (Nashville, TN) for the SYP flakes.

3.8 References

1. International Agency for Research on Cancer. 2004. IARC Classifies Formaldehyde as Carcinogenic to Humans. Press Release 153.
2. Huang, J., L. Kaichang. 2008. A New Soy-Flour Based Adhesive for Making Interior Type II Plywood. *J Am Oil Chem Soc.* (85): 155-172.
3. Li, K., S. Peshkova, X. Geng. 2004. Investigation of Soy Protein-Kymene Adhesive Systems for Wood Composites. *J Am Oil Chem Soc.* (81): 487-491.
4. Liu, Y., K. Li. 2002. Chemical Modification of Soy Protein for Wood Adhesives. *Macromol Rapid Commun.* (23): 739-742.
5. Liu, Y., K. Li. 2004. Modification of Soy Protein for Wood Adhesives Using Mussel Protein as a Model: the Influence of the Mercapto Group. *Macromol Rapid Commun.* (25): 1835-1838.
6. Liu, Y., K. Li. 2004. Wood Adhesives from Demethylated Kraft Lignin. In *The 7th Pacific Rim Biobased Composites Symposium*. Nanjing, P R China.

3.9 Figures

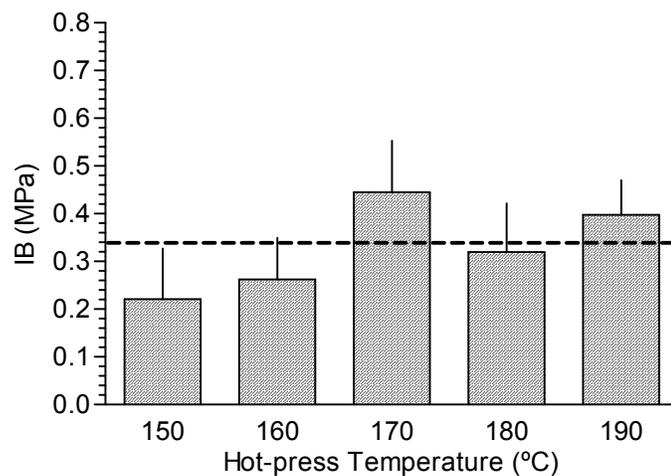


Figure 3.1 Effect of hot-press temperature on the IB of R-OSB panels (Adhesive addition rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press time, 5 min. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

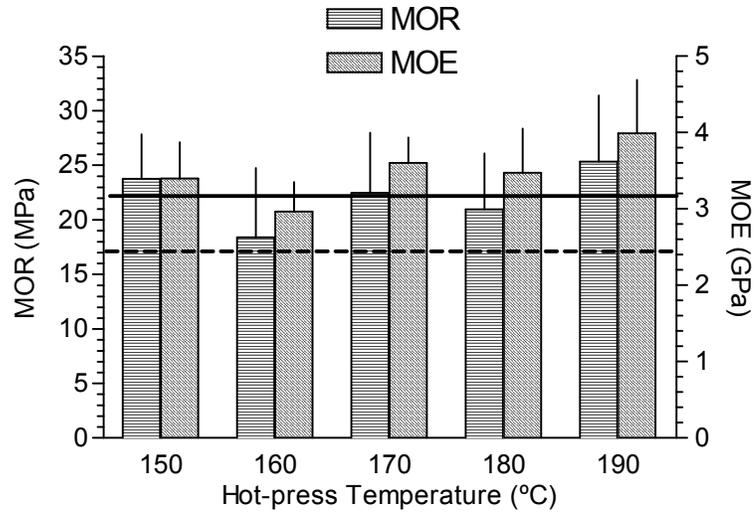


Figure 3.2 Effect of hot-press temperature on the MOR and MOE of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press time, 5 min. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

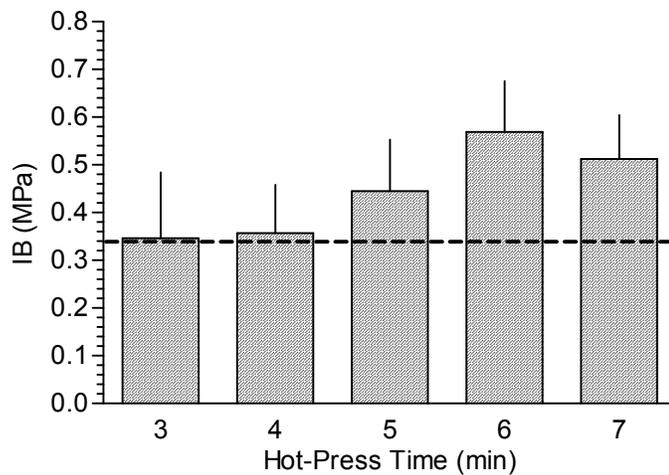


Figure 3.3 Effect of hot-press time on the IB of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/.32/.1; total solids content of the PEI adhesive, 30%; hot-press temperature, 170 °C. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

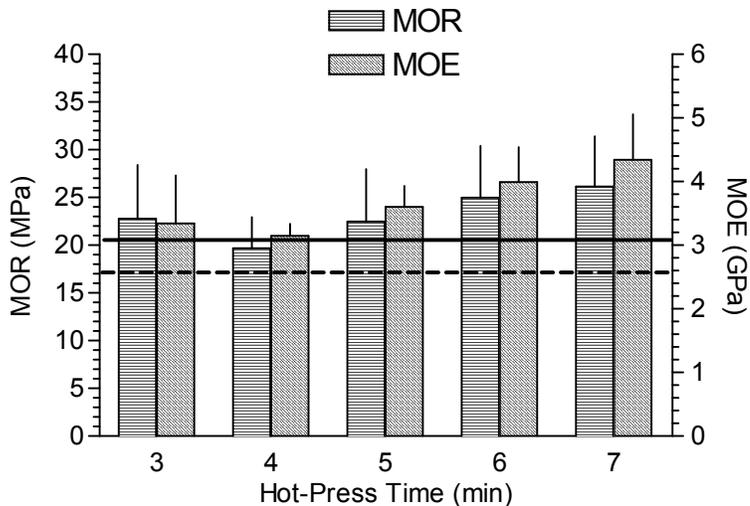


Figure 3.4 Effect of hot-press time on the MOR and MOE of R-OSB panels.

(Adhesive add-on rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/.32/.1; total solids content of the PEI adhesive, 30%; hot-press temperature, 170 °C. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

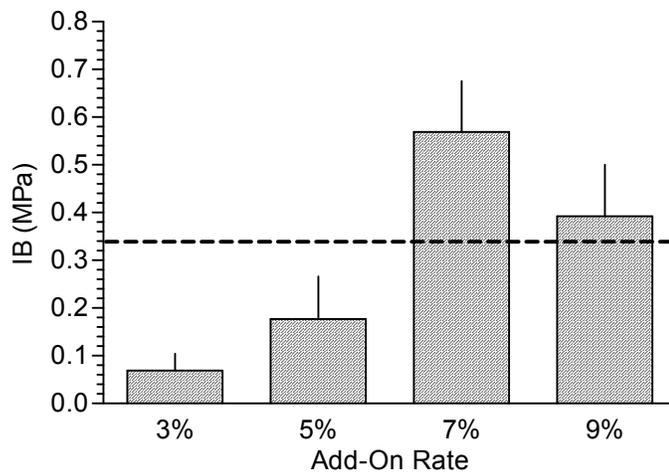


Figure 3.5 Effect of adhesive add-on rate (dry basis on wood flakes) on the IB of R-OSB panels. (SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170 °C and 6 min. Data are the means of 12 replications, and the error bar represents one standard error of the mean)

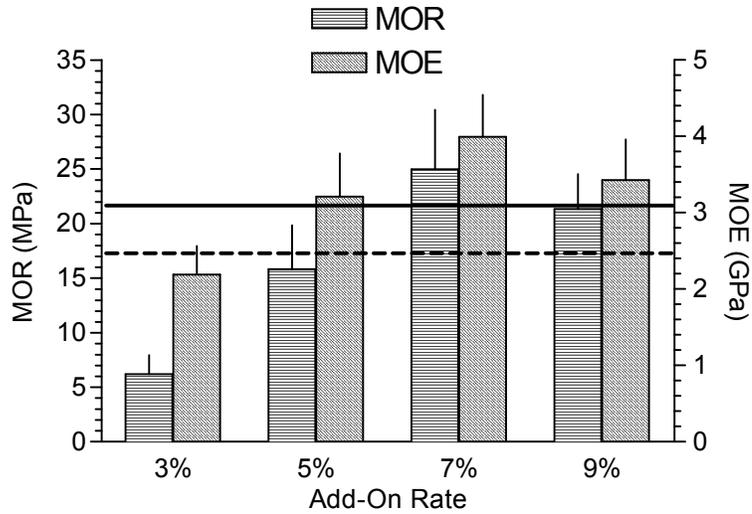


Figure 3.6 Effects of adhesive add-on rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels. (SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170 °C and 6 min. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

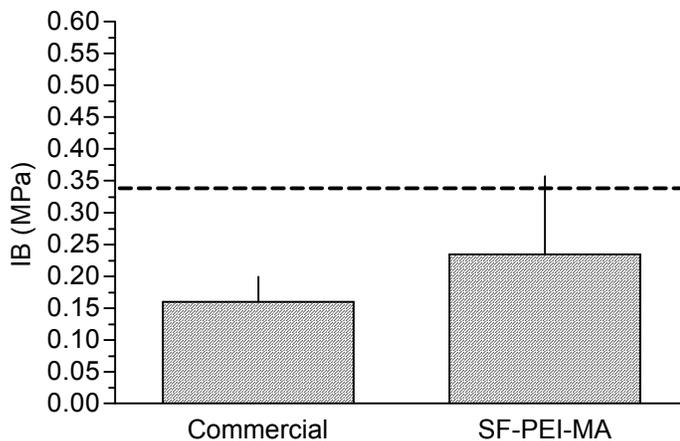


Figure 3.7 Comparison of IB in OSB panels bonded with the PEI adhesive and commercial panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170 °C and 6 min. Data are the means of 24 replications, and the error bar represents one standard error of the mean)

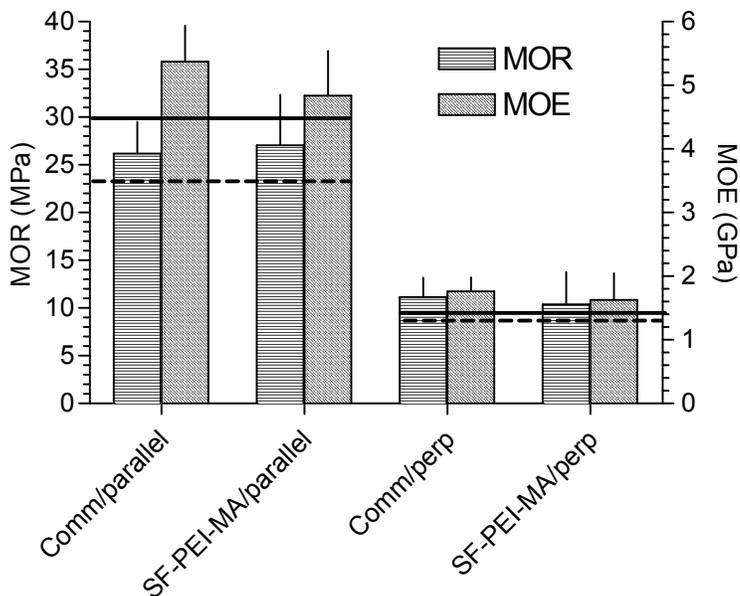


Figure 3.8 Comparison of MOR and MOE of OSB panels bonded with the SF-PEI-MA adhesive and commercial panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the adhesive, 30%; hot-press conditions, 170 °C and 6 min. Data are the means of 8 replications, and the error bar represents one standard error of the mean)

4 GENERAL CONCLUSIONS

Two soy-based adhesives were investigated for making randomly oriented strandboard (R-OSB) and oriented strandboard (OSB). The first adhesive system included soy flour (SF) and a curing agent (CA1000). The second was comprised of SF, polyethylenimine (PEI), maleic anhydride (MA), and sodium hydroxide.

For the SF – CA1000 adhesive, the SF/CA1000 weight ratio, the adhesive add-on rate, hot-press time, and hot-press temperature were optimized in terms of increasing the modulus of rupture (MOR), modulus of elasticity (MOE), and the internal bond (IB). Using the optimal conditions, the MOR, MOE, and IB of the resulting R-OSB and OSB panels bonded with this SF-CA1000 adhesive were comparable to or better than commercial OSB panels purchased from a local Home Depot.

For the SF-PEI-MA adhesive, the adhesive add-on rate, hot-press time, and hot-press temperature were optimized in terms of increasing the MOR, MOE, and the IB. Under the optimal conditions, the MOR, MOE, and IB of the resulting R-OSB and the MOR and MOE of the resulting OSB panels all exceeded the industrial requirements. The IB of the resulting OSB panels was somehow below the industrial requirement, but was higher than that of commercial OSB panels purchased from a local Home Depot.

BIBLIOGRAPHY

Baldwin, R.F. 1995. Plywood and Veneer-Based Products: Manufacturing Practices. Miller Freeman Books: San Francisco, CA.

Blomquist, R.F. 1981. Adhesives: An Overview. In Adhesive Bonding of Wood and Other Structural Materials. R.F. Blomquist, A.W. Christiansen, R.H. Gillespie, G.E. Myers, editors. Pennsylvania State University.

Bowyer, J.L., R. Shmulsky, J.G. Haygreen. 1996. Forest Products and Wood Science. Iowa State Press: Ames, IA.

Eckelman, C.A. 1997. A Brief Survey of Wood Adhesives. FNR 154. Purdue University Cooperative Extension: West Lafayette, IN.

FAOSTAT. 2009. <http://faostat.fao.org>.

Forest Products Laboratory. 1999. Wood Handbook: Wood as an Engineering Material. General Technical Report 113. United States Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI.

Gollob, L., J.D. Wellons. 1990. Wood Adhesion. In Handbook of Adhesives. I. Skeist, editor. Van Nostrand-Reinhold Publication: New York, NY.

Hettiarachchy, N.S., U. Kalapathy, D.J. Myers. 1995. Alkali-Modified Soy Protein with Improved Adhesive and Hydrophobic Properties. J Am Oil Chem Soc. (72): 1461-1464.

Huang, J., K. Li. 2008. A New Soy-Flour Based Adhesive for Making Interior Type II Plywood. J Am Oil Chem Soc. 85(1): 155-172.

International Agency for Research on Cancer. 2004. IARC Classifies Formaldehyde as Carcinogenic to Humans. Press Release 153.

Kumar, R., V. Choudhary, S. Mishra, I.K. Varma, B. Mattiason. 2002. Adhesives and Plastics Based on Soy Protein Products. Industrial Crops and Products. 3(16): 155-172.

Kumar, R., V. Choudhary, S. Mishra, I.K. Varma, B. Mattiason. 2004. Enzymatically-Modified Soy Protein Part 2: Adhesion Behaviour. J Am Oil Chem Soc. 18(2): 261-273.

Lambuth, A.L. 1977. Soybean Glues. In Handbook of Adhesives. I. Skeist, editor. Van Norstrand-Reinhold Publication: New York, NY.

Li, K., and X. Geng. Adhesive compositions and methods of using and making the same. U.S. Patent No. 7,265,169. Issued date, September 4, 2007.

Li, K. Formaldehyde-free lignocellulosic adhesives and composites made from the adhesives. U.S. Patent No. 7,252,735. Issued date, August 7, 2007.

Li, K., S. Peshkova, X. Geng. 2004. Investigation of Soy Protein-Kymene Adhesive Systems for Wood Composites. *J Am Oil Chem Soc.* 81(5): 487-491.

Li, K., and Y. Liu. Modified protein adhesives and lignocellulosic composites made from the adhesives. U.S. Patent No. 7,060,798. Issued date, June 13, 2006.

Liu, Y., K. Li. 2002. Chemical Modification of Soy Protein for Wood Adhesives. *Macromol Rapid Commun.* 23(13): 739-742.

Liu, Y., K. Li. 2004. Modification of Soy Protein for Wood Adhesives Using Mussel Protein as a Model: the Influence of the Mercapto Group. *Macromol Rapid Commun.* 25(21): 1835-1838.

Liu, Y., K. Li. 2004. Wood Adhesives from Demethylated Kraft Lignin. In *The 7th Pacific Rim Biobased Composites Symposium*. Nanjing, P R China.

Liu, Y., K. Li. 2007. Development and Characterization of Adhesives from Soy Protein for Bonding Wood. *Int J of Adhesion and Adhesives.* 27(1): 59-67.

Lowood, J. 1997. Oriented Strandboard and Waferboard. In *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*. S. Smulski, editor. PFS Research Foundation: Madison, WI.

McKay, M. 1997. Plywood. In *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*. S. Smulski, editor. PFS Research Foundation: Madison, WI.

Meyer, B., K. Hermanns. 1986. Formaldehyde Release from Wood Products: An Overview. In *ACS Symposium Series 316 - Formaldehyde Release from Wood Products*. B. Meyer, B.A. Kottes Andrews, R.M. Reinhardt, editors. American Chemical Society: Washington D.C. 1-6.

Sellers, T.J. 1985. *Plywood and Adhesive Technology*. Marcel Dekker, Inc: New York, NY.

Subramanian, R.V. 1981. Adhesives: An Overview. In *Adhesive Bonding of Wood*

and Other Structural Materials. R.F. Blomquist, A.W. Christiansen, R.H. Gillespie,

G.E. Myers, editors. Pennsylvania State University. 137-188.

Wirpsza, Z. 1993. Polyurethanes, Chemistry, Technology, and Applications. Ellis Horwood Inc: New York, NY.

Yang, I., M. Kuo, D.J. Myers, A. Pu. 2006. Comparison of Protein-Based Adhesive Resins for Wood Composites. *Journal of Wood Science*. (52): 503-508.

Zheng, J. 2002. Studies of PF Resole and Isocyanate Hybrid Adhesives. Virginia Polytechnic Institute and State University

