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Effects of Adhesive Application Methods on Performance of a Soy-based Adhesive in Oriented Strandboard

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Abstract A wet method and dry method of applying a soy flour (SF)–curing agent (CA) adhesive onto wood flakes were evaluated for making randomly oriented strandboard (R-OSB) and OSB. The wet method involved the thorough mixing of SF and CA prior to spraying the SF–CA mixture onto wood flakes. SF:CA weight ratio, adhesive add-on rate, hot-press conditions were optimized for enhancing internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity(MOE) of the resulting R-OSB. The highest IB, MOR and MOE were obtained at the 1:1 SF:CA weight ratio. IB, MOR and MOE of R-OSB exceeded the minimum industrial requirements at a ≥7% adhesive add-on rate, a hot-press temperature in the 170–220 °C range, and a ≥4 min hot-press time. The dry method involved spraying aqueous CA solution onto a mixture of SF and wood flakes. The dry method allowed the strengths of the resulting R-OSB to exceed the minimum industrial requirements at a higher SF:CA ratio (up to 7:1). The dry method was superior to the wet method because a higher SF:CA ratio meant a lower adhesive cost. OSBs made with the SF–CA adhesive had strengths higher than or comparable to commercial OSBs.

Keywords Wood adhesives · Soy flour · Oriented strandboard · Internal bond

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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 been used successfully 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 (personal communications with a plywood manufacturer). In this study, we investigated if the soy-based adhesive could also be used for making OSB panels.

Materials and Methods

Materials

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

Preparation of SYP Flakes

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

Preparations 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 (839.93 g dry) and water (487.62 g) was slowly mixed in a large mixing bowl with a Hobart blender (Hobart Manufacturing Co., Troy, Ohio) at the speed 1. SF (843.84 g dry) was added to the CA-water solution and then mixed at a higher rate of speed (the speed 2) at room temperature for 5 min. The total solids content of the resulting adhesive was 30%. The resulting SF–CA adhesive (1,683.77 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 6,000 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 (419.97 g dry), water (243.81 g), and SF (421.92 g dry) were mixed to form an adhesive with 30% total solids content. The resulting SF–CA adhesive (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 (387.66 g dry) and water (225.08 g) was sprayed through the spinning disc atomizer onto a mixture of SF (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 6,000 rpm. The total solids content of the adhesive (soy flour + 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 (193.83 g dry) and water (112.54 g) was sprayed onto a mixture of SF (194.73 g dry) and wood flakes (5,538 g). The total solids content of the adhesive (CA1000 + water + SF) was 30%.

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 (23.51 kg dry) were flatly and uniformly distributed in a 56 × 56 cm forming box on top of a metal screen and an aluminum sheet, followed by the adhesive-coated core materials (11.75 kg dry) and the adhesive-coated face materials (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/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.

Preparation of the OSB Panels

The OSB panels comprised 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 of the core layer. The adhesive-coated face flakes (778.63 g dry) were flatly and uniformly distributed in the forming box described previously on top of a metal screen and an aluminum sheet with all flakes aligned into one direction. The adhesive-coated core materials (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 (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/m^3. The target thickness for the OSB panel was 11.1 mm. The mat was pressed to 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.

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 ASTM D 1037-99 [8]. Eight specimens with nominal dimensions of 406.4 × 76.2 × 11.1 mm were cut from test panels for each parameter analyzed. MOR and MOE values were calculated and recorded for each specimen.

Internal Bond Strength of OSB Samples

The internal bond strength (IB) of the OSB samples was determined by testing the tensile strength perpendicular to the OSB surface in accordance with ASTM D 1037-99 [8]. Twelve test specimens with nominal dimensions of 50.8 × 50.8 × 11.1 mm were cut from test panels for each parameter analyzed. The IB was calculated and recorded after each specimen was tested to failure. These values were compared with a minimum industrial requirement of IB (0.34 MPa) for both R-OSB and OSB panels.

Statistical Analysis

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.

Results and Discussion

For the wet method, the effect of SF:CA ratio on the IB of R-OSB panels is shown in Fig. 1a with the minimum industrial requirement (0.34 MPa) shown as a horizontal dashed line. 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 Fig. 1b. The MOR met the minimum industrial requirement of 17.24 MPa (horizontal dashed line) when the SF:CA ratio was lower than 2:1. The MOR was the highest at the 1:1 SF:CA ratio (Fig. 1b). The MOE still met the minimum industrial requirement of 3.10 GPa (horizontal solid line) 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 industrial 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 subsequent evaluations.

The effect of the adhesive add-on rate on the IB of the R-OSB panels made with the wet method is shown in Fig. 2a. When the add-on rate was increased from 3 to 5%, the IB increased, but was still lower than the minimum industrial requirement (horizontal dashed line). When the add-on rate was further increased to 7%, the IB significantly increased and exceeded the minimum industrial requirement (Fig. 2a). Increasing the add-on rate from 7 to 9% did not improve the IB (Fig. 2a). The effects of the add-on rate on the MOR and MOE are shown in Fig. 2b. At the 3% add-on rate, the MOR was slightly below the minimum industrial requirement (the horizontal dashed line). The MOR increased with increasing the add-on rate up to 9%, meeting the minimum industrial requirement at levels ≥5% (Fig. 2b). The MOE met the minimum industrial requirement when the add-on rate was at the 3–9% range (Fig. 2b). The 7% add-on rate was the lowest level where the IB, MOR and MOE all met the minimum industrial requirements. Lowering the add-on rates reduced the cost of OSB panels. Therefore, the 7% add-on rate was used for the subsequent investigations.

The effect of the hot-press temperature on the IB of the R-OSB panels is shown in Fig. 3a. The IB at 160 °C was the lowest and the only one that did not meet the minimum industrial requirement (the horizontal dashed line). However, all IB values were not significantly different within

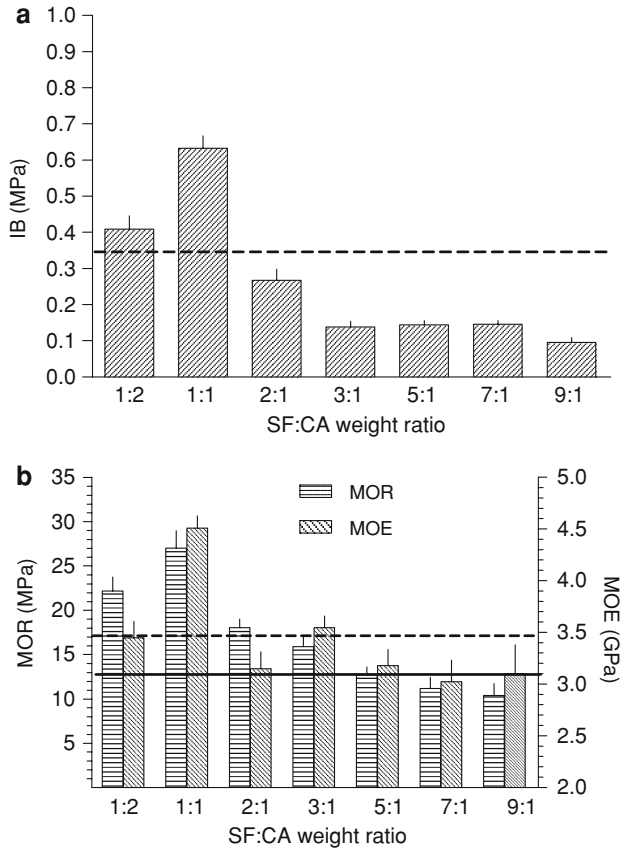

Fig. 1 **a** Effect of SF:CA dry weight ratio on the IB of R-OSB panels. [Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF–CA adhesive, 30%; hot-press conditions: 220 °C and 5 min. the adhesive application method: the wet method. Data are the means of 12 replications, and the *error bar* represents one standard error of the mean]. **b** Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels. (Processing parameters and statistical details are the same as those in **a**)

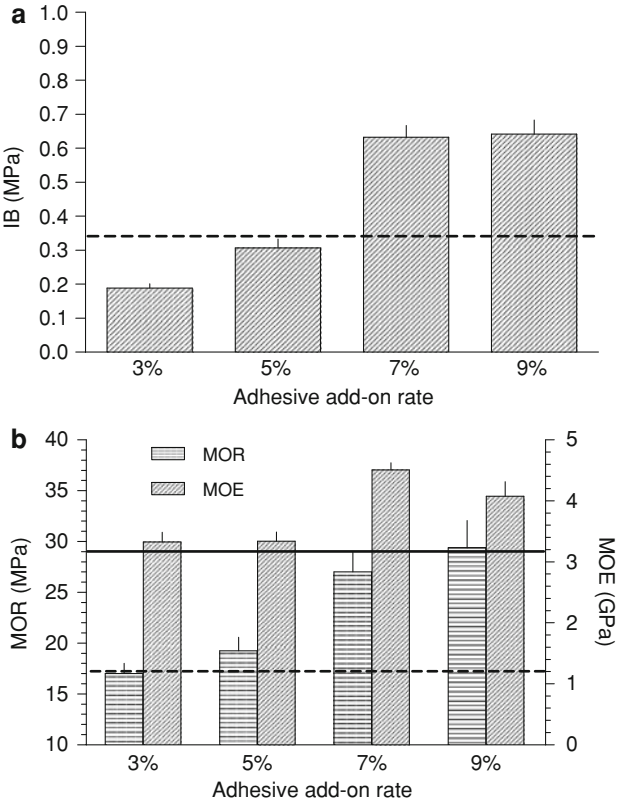

Fig. 2 **a** Effect of the adhesive add-on rate (dry basis on wood flakes) on the IB of R-OSB panels. **b** Effect of the adhesive add-on rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels. (SF:CA dry weight ratio, 1:1; refer to Fig. 1a caption for other processing parameter and statistical details)

the 140–200 °C range (Fig. 3a). The IB increased notably when the hot-press temperature was raised to 210 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 Fig. 3b. The MOR at 140 °C was higher than that at 150 °C, while values at 150 and 160 °C were statistically the same. The MOR significantly increased when the hot-press temperature was increased from 160 to 170 °C. The MOR values in 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 industrial requirement of 17.24 MPa (horizontal dashed line, Fig. 3b). The MOE values within the 140–160 °C range were all statistically the same and did not meet the minimum industrial requirement as indicated by the horizontal solid line (Fig. 3b). The MOE significantly increased when the hot-press temperature was raised from 160 to 170 °C. The MOE values in the 170–220 °C range were statistically the same and all met the minimum industrial requirement (Fig. 3b). When the temperature was at the 170–220 °C range, the IB, MOR and MOE of panels all met the minimum industrial requirements.

The effect of hot-press time on the IB of the R-OSB panels made with the wet method is shown in Fig. 4a. Pressing 3 or 4 min gave similar IB values (Fig. 4a). The IB significantly increased when the hot-press time was 5 min; however, the IB decreased markedly when the hot-press time was longer than 5 min (Fig. 4a). Despite this reduction, the IB values for press times tested all met the minimum industrial requirement (horizontal dashed line). The effects of the press time on the MOR and MOE are shown in Fig. 4b. The MOR increased when the hot-press time was increased from 3 to 4 min, and values obtained from 5 and 6 min were the same as that for 4 min. The MOR significantly decreased when the hot-press time was increased from 6 to 7 min. All MOR values in the 3–7 min range met the minimum industrial requirement (horizontal dashed line). The MOE gradually increased when the hot-press time was increased from 3 to 5 min, but significantly decreased when the hot-press time was longer than 5 min. The MOE values for hot-press times of 4–7 min all

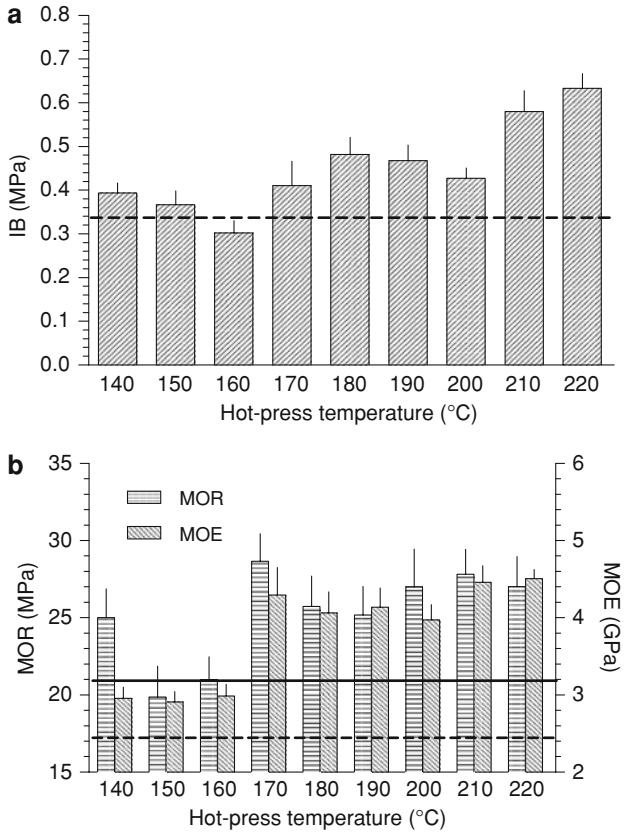

Fig. 3 **a** Effect of hot-press temperature on the IB of R-OSB panels. **b** Effect of hot-press temperature on the MOR and MOE of R-OSB panels. (SF:CA dry weight ratio, 1:1; refer to Fig. 1a caption for other processing parameters; data are the means of eight replications, and the *error bar* represents one standard error of the mean)

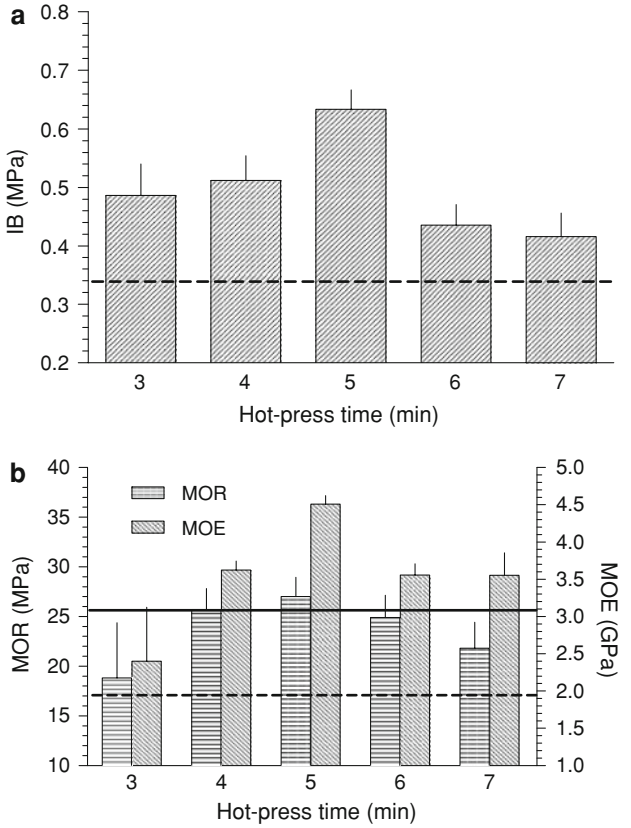

Fig. 4 **a** Effect of hot-press time on the IB of R-OSB panels. **b** Effect of hot-press time on the MOR and MOE of R-OSB panels. (SF:CA dry weight ratio, 1:1; refer to Fig. 1a caption for other processing parameter and statistical details)

exceeded the minimum industrial requirement (horizontal solid line, Fig. 4b).

The effect of the SF:CA ratio on the IB of R-OSB panels made with the dry method is shown in Fig. 5a. The IB decreased when the SF:CA ratio was increased from 1:1 to 2:1 (Fig. 5a). 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 (Fig. 5a). However, in the 1:1 to 7:1 range, all IB values still exceeded the minimum industrial requirement (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 Fig. 5b. The MOR values were not significantly different at the SF:CA ratio range of 1:1 to 9:1 and all exceeded the minimum industrial requirement (horizontal dashed line). The MOE values were also statistically the same for the SF:CA ratio range tested and all exceeded the minimum industrial requirement (the horizontal solid line). The strengths of the resulting R-OSB panels (the IB, MOR and MOE) met the minimum industrial requirements at the SF:CA ratio range of 1:1 to 7:1 (Fig. 5a, b).

The minimum industrial 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.

The IB of OSB panels made with the SF–CA adhesive applied by the dry method exceeded the minimum industrial requirement (0.34 MPa) and was much higher than that of commercial OSB panels that were purchased locally (Fig. 6). For the parallel direction, the MOR of our experimental SF–CA OSB panels was higher than that of the commercial OSB panels, but both met the minimum industrial requirement indicated by the horizontal dashed line in the left portion of Fig. 7. The SF–CA OSB panels and the commercial OSB

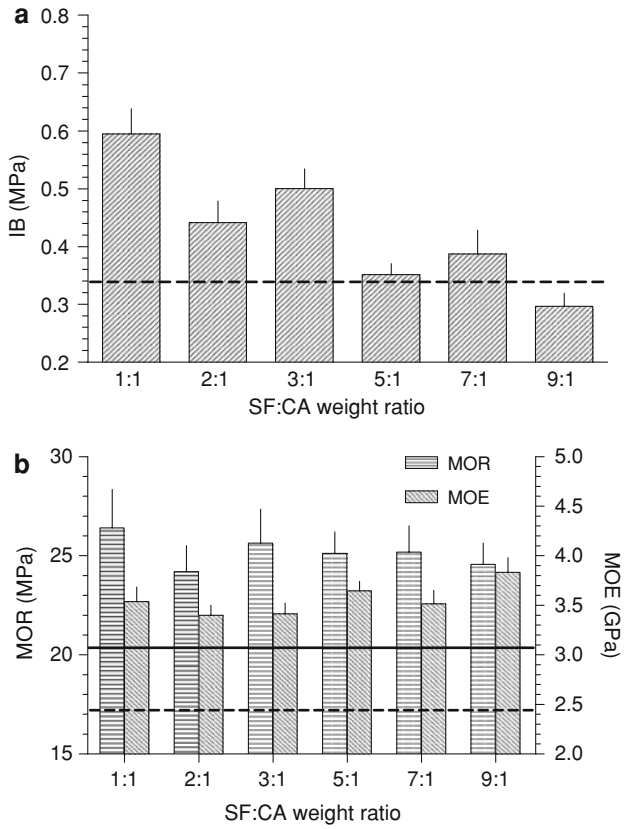

Fig. 5 **a**. Effect of SF:CA dry weight ratio on the IB of R-OSB panels. (Adhesive add-on rate (dry basis on wood flakes), 7%; total solids content of the SF–CA adhesive, 30%; hot-press conditions: 170 °C and 5 min. The adhesive application method:the dry method. Data are the means of 12 replications, and the *error bar* represents one standard error of the mean). **b**. Effects of SF:CA dry weight ratio on the MOR and MOE of R-OSB panels. (Processing parameters and statistical details are the same as those in Fig. 5a caption)

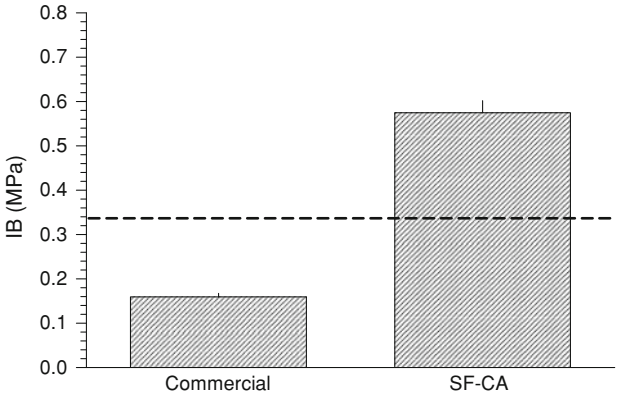

Fig. 6 Comparison of the SF–CA OSB panels and commercial OSB panels on their IB. (SF:CA dry weight ratio, 7:1; refer to Fig. 5a caption for other processing parameter and statistical details)

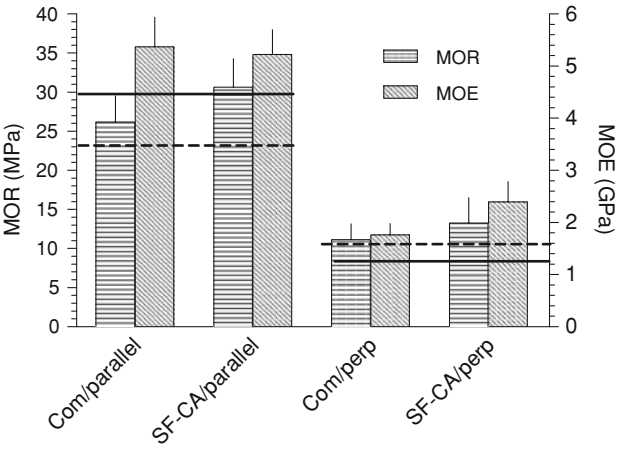

Fig. 7 Comparison of the SF–CA OSB panels and commercial OSB panels on their MOR and MOE. (SF:CA dry weight ratio, 7:1; refer to Fig. 5a caption for other processing parameter and statistical details; *Com* stands for commercial OSB panels; *Perp* means perpendicular)

panels had statistically similar MOE values and both met the minimum industrial requirement (horizontal solid line, left side, Fig. 7). For the perpendicular direction, the MOR and MOE of the SF–CA OSB panels were higher than those of the corresponding values for commercial OSB panels (Fig. 7, right side). The MOR and MOE of the SF–CA OSB panels and the commercial OSB panels all met the minimum industrial requirements (MOR, horizontal dashed line; MOE, horizontal solid line, Fig. 7).

CA1000 is a polyamidoamine–epichlorohydrin adduct that can react with amino groups and carboxylic acid groups in soy flour, thus crosslinking soy flour during hot pressing. The detailed curing mechanism was proposed in our previous publication [6]. 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 was manifested by 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% (Fig. 2a, b). When most of the flake surfaces are covered by the adhesive, further increase in the adhesive add-on rate is not expected to further increase the bonding among flakes, i.e., strengths of the resulting OSB panels. This is reflected by our results when increasing the add-on rate from 7 to 9% did not significantly increase the IB and MOR (Fig. 2a, b). Our results indicated that any temperature in the 170–220 °C range can be used to cure the SF–CA adhesive for making OSB panels (Fig. 3a, b). 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 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 industrial requirements. The 4-min hot-press time for making 11.1 mm-thick OSB panels is competitive with regard to the industrial processes of making OSB panels with PF and isocyanate adhesives.

The results shown in Figs. 1–4 demonstrate 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 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 soy flour, 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 industrial requirements (Fig. 5a, b). At the 7:1 SF:CA ratio, the SF–CA adhesive is certainly cost-competitive to PF and isocyanates for making OSB panels (personal communications with adhesive suppliers).

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 (Figs. 6, 7). The strength properties of the OSB panels made with the SF–CA adhesive were actually better than or comparable to those commercial products purchased from locally (Figs. 6, 7).

Conclusions

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. The dry method allows the strengths of R-OSB panels to meet the minimum industrial requirements at a higher SF:CA weight ratio than the wet method. The dry method is superior to the wet method in terms of reducing the adhesive cost.

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References

1. International Agency for Research on Cancer (2004) International Agency for Research on Cancer classifies formaldehyde as carcinogenic to humans. Press release # 153
2. Liu Y, Li K (2002) Chemical modification of soy protein for wood adhesives. Macromol Rapid Commun 23:739–742
3. Liu Y, Li K (2004) Modification of soy protein for wood adhesives using mussel protein as a model: the influence of a mercapto group. Macromol Rapid Commun 25:1835–1838
4. Liu Y, Li K (2006) Preparation and characterization of demethylated lignin-polyethylenimine adhesives. J Adhes 82:593–605
5. Liu Y, Li K (2007) Development and characterization of adhesives from soy protein for bonding wood. Int J Adhes Adhes 27:59–67
6. Li K, Peshkova S, Geng X (2004) Investigation of soy protein-Kymene® adhesive systems for wood composites. J Am Oil Chem Soc 81:487–491
7. Huang J, Li K (2008) A new soy flour-based adhesive for making interior type II plywood. J Am Oil Chem Soc 85:63–70
8. The American Society for Testing Materials ASTM D 1037-99 Standard test methods for evaluating properties of wood-base fiber and particle panel materials. The American Society for Testing Materials, West Conshohocken, PA, USA