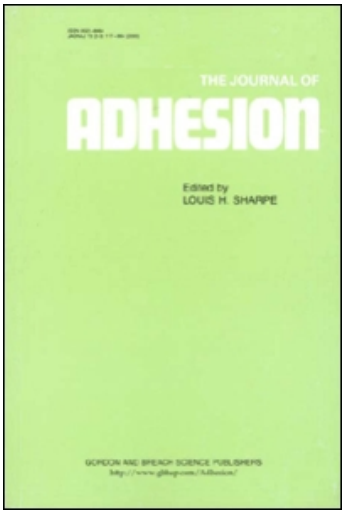

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A Formaldehyde-Free Soy-Based Adhesive for Making Oriented Strandboard

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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 usage 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 usage 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 store.

Keywords: Internal bond; Oriented strandboard; Soy flour; Wood adhesive

1. 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 strips 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

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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 formaldehyde that is released to the atmosphere during the hot-press of making OSB panels. Formaldehyde is considered to be carcinogenic [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.

Li and colleagues have been working on the development and commercialization of formaldehyde-free and environmentally friendly wood adhesives from renewable materials since 2000 [2–6]. One of the 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 (VOC) by up to 90% for the plywood plant that does not dry its veneer (veneer drying is one of biggest sources of volatile organic compounds in a plywood plant). Li and colleagues have recently developed another formaldehyde-free adhesive that consists of soy flour (SF), polyethylenimine (PEI), maleic anhydride (MA), and sodium hydroxide [2]. It was found that SF, PEI, MA, and sodium hydroxide were essential components of this adhesive [2] that be used for making decorative hardwood plywood. In this study, it was investigated whether this adhesive could also be used for making R-OSB and OSB panels.

2. EXPERIMENTAL

2.1. Materials

SF [100 mesh, 90 protein dispersibility index (PDI), 92.05% solids content] was donated by Cargill Incorporated (Minneapolis, MN, USA). PEI (50% solids content), MA (99%), and sodium hydroxide were purchased from Aldrich Chemical (Milwaukee, WI, USA) and used as received. Southern yellow pine (SYP) flakes (7–8% moisture content) were donated by Louisiana Pacific Corporation (Nashville, TN, USA). Two commercial OSB panels with the dimensions of

$7/16 \times 48 \times 96$ inches ($1.11 \times 122 \times 244$ cm) for each panel were purchased from a local Home Depot store.

2.2. Methodology

2.2.1. Preparation of 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.

2.2.2. 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) 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 a spinning disc atomizer onto a mixture of SF (933.65 g wet, 859.42 g dry) and SYP flakes (14.77 kg) in a 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 manner similar to 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) 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. The solution of PEI, water, MA, and NaOH could rapidly come out of an addition funnel by its own gravity and was easily 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%.

2.2.3. Preparation of the 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 × 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 by hand. 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. Two R-OSB panels were made for each condition.

2.2.4. 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 × 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. Two OSB panels were made for each condition.

2.2.5. 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 ASTM D 1037-99 [7]. Eight test specimens with nominal dimensions of $406.4 \times 76.2 \times 11.1$ 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 [8]. 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 [8]. 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.

2.2.6. 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 ASTM D 1037-99 [7]. Twelve test specimens with nominal dimensions of $50.8 \times 50.8 \times 11.1$ 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 [8].

2.2.7. 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. RESULTS

The effect of the hot-press temperature on the IB of the R-OSB panels is shown in Fig. 1. The IB at 150 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 to 170°C. Increasing the temperature from 170 to 180°C somehow significantly decreased the IB. When the temperature was further increased from 180 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 and 190°C.

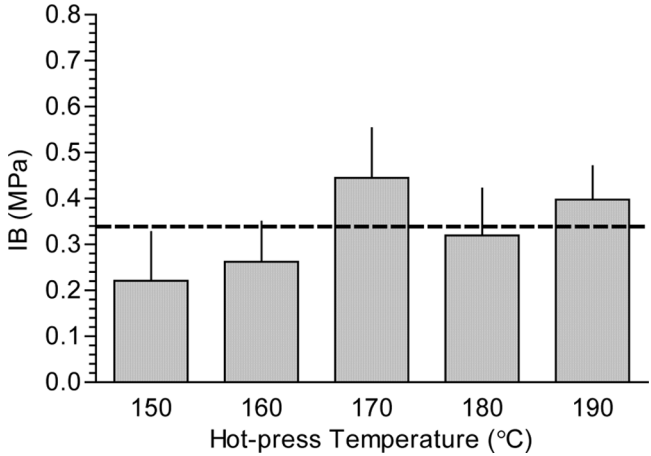

FIGURE 1 Effect of hot-press temperature on the IB of R-OSB panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press time, 5 min. Data are the means of 12 replications, and the error bar represents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

The effects of the hot-press temperature on the MOR and MOE are shown in Fig. 2. Increasing the temperature from 150 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 to 190°C met the minimum industry requirement as indicated by the horizontal dashed line. The MOE at 150°C was not significantly different from that at 160°C (Fig. 2). Increasing the hot-press temperature from 160 to 170°C led to significant increase in MOE (Fig. 2). MOE did not significantly change when the temperature was in the range of 170–190°C. The average MOE at 160°C was the only one that did not meet the minimum industry requirement as shown by the horizontal solid line (Fig. 2).

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 Fig. 3. The IB at the hot-press times of 3 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 to 4 min. Increasing the hot-press time from 4 to

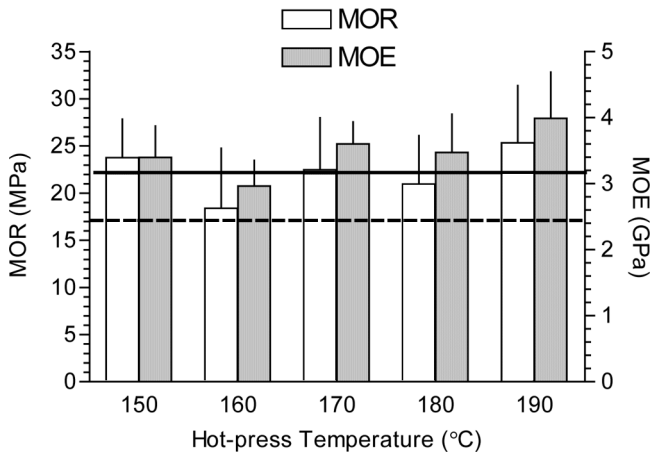

FIGURE 2 Effect of hot-press temperature on the MOR and MOE of R-OSB panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press time, 5 min. Data are the means of eight replications, and the error bar represents one standard deviation of the mean].

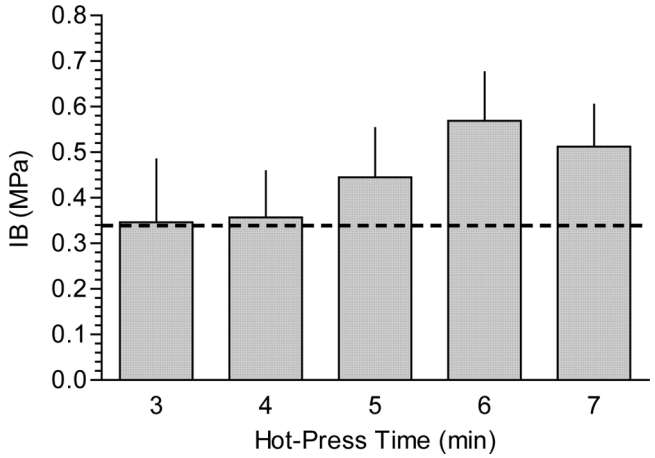

FIGURE 3 Effect of hot-press time on the IB of R-OSB panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press temperature, 170°C. Data are the means of 12 replications, and the error bar represents one standard deviation of the mean].

6 min significantly increased the IB. When the hot-press time was further increased from 6 to 7 min, the IB did not significantly change.

The effects of hot-press time on the MOR and MOE of the R-OSB panels is shown in Fig. 4. When the hot-press time was in the range of 3 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 to 5 min and from 5 to 7 min. However, the MOR at 4 min was significantly lower than those at 6 and 7 min. The MOE at the hot-press time of 3 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 to 7 min. All IB, MOR, and MOE in the range of 3 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 usage rate (called add-on rate) on the IB of the R-OSB panels is shown in Fig. 5. When the usage 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 usage rate was further increased from 5 to 7%, the IB significantly

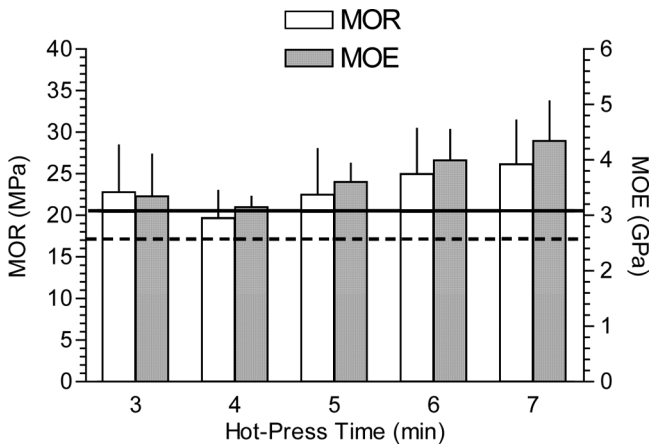

FIGURE 4 Effect of hot-press time on the MOR and MOE of R-OSB panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press temperature, 170°C. Data are the means of eight replications, and the error bar represents one standard deviation of the mean].

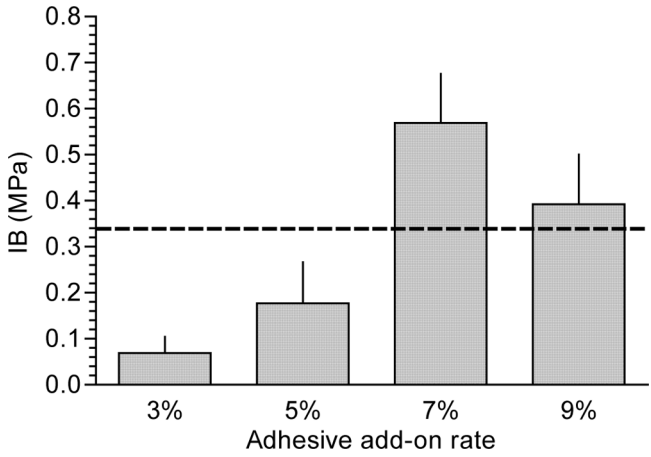

FIGURE 5 Effect of adhesive usage rate (dry basis on wood flakes) on the IB of R-OSB panels. (SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170°C and 6 min. Data are the means of 12 replications, and the error bar represents one standard deviation of the mean).

increased and exceeded the minimum industry requirement. When the usage rate was further increased from 7 to 9%, the IB significantly decreased, but exceeded the minimum industry requirement.

The effects of the adhesive usage rate on the MOR and MOE are shown in Fig. 6. The MOR significantly increased when the usage rate was increased from 3 to 7%. Further increasing the usage 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 usage rate was increased from 3 to 7%. Further increasing the usage rate from 7 to 9% did not significantly change the MOE. The MOE met the minimum industry requirement when the usage rate was in the 5–9% range. The 7% usage rate yielded the highest average MOE. The 7% usage rate was the lowest usage rate where the IB, MOR, and MOE all met the minimum industry requirements. The lower the usage rate the lower the cost of OSB panels. Therefore, the 7% usage rate was used for the further investigations.

The comparison of the IB values of commercial OSB panels and panels bonded with the SF-PEI-MA adhesive is shown in Fig. 7. The IB from the panels bonded with the SF-PEI-MA adhesive was significantly higher than that of the commercial OSB panels. However, the

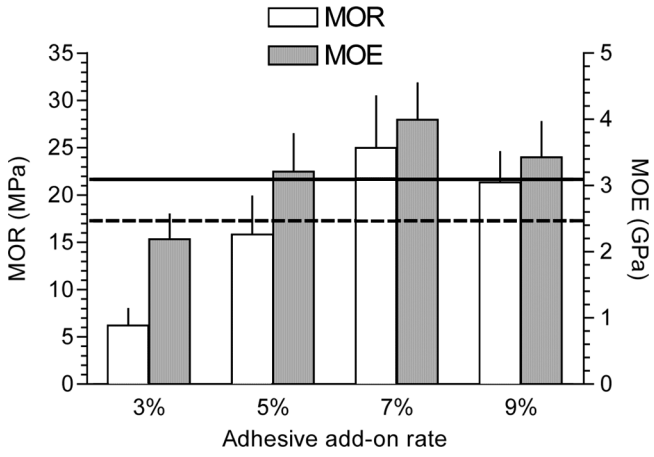

FIGURE 6 Effects of adhesive usage rate (dry basis on wood flakes) on the MOR and MOE of R-OSB panels. (SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170°C and 6 min. Data are the means of eight replications, and the error bar represents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

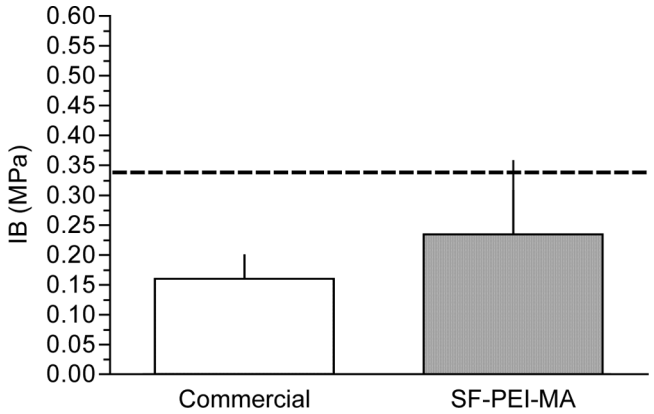

FIGURE 7 Comparison of IB in OSB panels bonded with the PEI adhesive and commercial panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the PEI adhesive, 30%; hot-press conditions, 170°C and 6 min. Data are the means of 24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

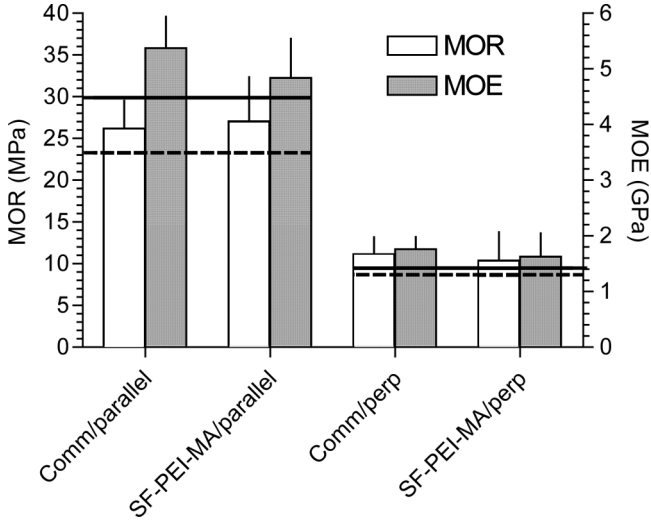

FIGURE 8 Comparison of MOR and MOE of OSB panels bonded with the SF-PEI-MA adhesive and commercial panels. [Adhesive usage rate (dry basis on wood flakes), 7%; SF/PEI/MA/NaOH dry weight ratio, 7/1/0.32/0.1; total solids content of the adhesive, 30%; hot-press conditions, 170°C and 6 min. Data are the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

two types of panels both had their IB values below the minimum industry requirement as indicated by the horizontal dashed line.

The parallel MOR of the OSB panels bonded with the SF-PEI-MA adhesive was comparable with that from the commercial OSB panels (Fig. 8). The parallel MOE of the OSB panels bonded with the SF-PEI-MA adhesive was slightly lower than that of the commercial OSB panels (Fig. 8). The perpendicular MOR and MOE of the panels bonded with the SF-PEI-MA adhesive were, respectively, comparable with those of the commercial OSB panels (Fig. 8).

4. 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 the 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 with that in the commercial production of the 11.1-mm thick OSB panels using PF and PMDI adhesives. The adhesive usage rate was found to have a significant impact on the strength properties of R-OSB panels. When the adhesive usage 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 usage rate was increased from 3 to 7%. However, too much adhesive on the wood surfaces would weaken the bonding. As shown in Figs. 5 and 6, the IB and MOE decreased and the MOR remained the same when the adhesive usage rate was increased from 7 to 9%.

It is still poorly understood why 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 with 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.

Both PEI and MA are derived from petrochemicals. But over 80 wt% of this SF-PEI-MA adhesive is inexpensive, renewable, and readily available SF. Because of the high cost of PEI, this SF-PEI-MA adhesive is currently more expensive than PF resins. Efforts of producing a polyamine from renewable materials, such as glycerol, to replace PEI are currently ongoing in our laboratory.

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