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Development of soy protein-based adhesive with high water resistance and bonding strength by waterborne epoxy crosslinking strategy

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ABSTRACT

The introduction of epoxy crosslinking agents is an efficient path to improve the water resistance and adhesion properties of a soy protein-based adhesive. However, it is still a challenge to directly incorporate cheap epoxy resin into a protein system other than by an expensive epoxy diluent. In this work, a waterborne epoxy emulsion (WEU) was prepared by grafting hydrophilic groups onto bisphenol-A (E44) followed by a phase-transformation process for the oil-in-water emulsion, with the aim to modify a soy protein-based adhesive. The effects of different neutralizers on the performance of the resulting adhesive were also analyzed. The prepared WEU presented excellent stability and admirable dispersibility in the adhesive system, as confirmed by digital photos, and served as an active crosslinker, contributing to multiple stable crosslinking networks with soy protein molecules, as characterized by Fourier transform infrared spectroscopy, scanning electron microscopy, and thermal gravimetric analysis. The results showed that a soy protein-based adhesive crosslinked by WEU neutralized by triethylamine could endow plywood with 20% higher wet shear strength than that of being crosslinked by WEU neutralized by N, N-dimethyl ethanolamine, which reached 1.14 MPa and 192.5% increment compared to a neat soy protein-based adhesive. Moreover, the residual rate of modified soy protein adhesives increased 4.2% while the moisture uptake of modified soy protein adhesives decreased 8.5% compared to pure SP adhesive. The authors hypothesize that the epoxy crosslinking modification of soy protein with WEU may be an effective method to fabricate high-performance soy protein-based adhesives for practical applications.

1. Introduction

Natural resources are attracting a significant amount of attention because of their unique nature – particularly for their sustainability, renewability, and environmental friendliness – and their products have been developed for a wide variety of applications, such as structure materials, absorbents, and functional panels [1–5]. Soy protein, with good reproducibility, processability, biodegradability, and biocompatibility, exhibits great promise in sustainable adhesive applications as a substitute for conventional petroleum-based adhesives [6–9]. However, the disadvantages of poor toughness and water resistance in soy protein-based adhesives have limited its applications [10–12]. To solve these issues, researchers have made various attempts to improve soy protein-based composite properties, such as by physical blending [12–14], chemical cross-linking [6,11,15], enzymatic degradation [16–18], and biomimetic design [19,20], with chemical cross-linking deemed as an effective and simple approach.

Epoxy crosslinking agents comprise a commonly used path to construct intra-penetrating or inter-penetrating networks with soy protein molecules for a stable crosslinking system [21,22]. Crosslinked soy protein-based adhesives present a uniform and tough network that can efficiently transform stress and prevent permeation of water molecules, thus improving wet adhesion properties [23]. For example, epoxied poly-amidoamine-epichlorohydrin, glycerol poly-glycidyl ether, and neopentyl glycol di-glycidyl ether were employed as crosslinkers to modify soy protein-based adhesive [21], demonstrating a substantial

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increment in adhesion and water-resistant properties. However, most epoxy crosslinkers are expensive, which impede its practical applications for soy protein-based adhesive systems. Thus, inexpensive epoxy resin has attracted extensive attention. Li. et al. discovered that the direct introduction of epoxy resin could cause severe phase separation in the protein system resulting in poor water-resistance and mechanical strength [21].

The introduction of aqueous polymer dispersions was another efficient way to endow the protein matrix with improved performance [14, 24,25,27]. The performance of polymer dispersions could be facilely regulated through the design of polymer molecular chains and an interior structure, showing many desirable properties for a wide variety of applications. For example, waterborne polyurethane, as an alternating copolymer with hard and soft segments, has been variously designed by regulating the interior microphase-separated structure to effectively strengthen the soy protein matrix [15,26,28,29]. However, interfacial interactions between the waterborne polymer emulsion and soy protein matrix were dominated by weak hydrogen bonding, which was easily destroyed under wet conditions. Thus, the development of an active polymer emulsion likely employing epoxy resin as the oil phase for the oil-in-water dispersion could meet expectations for direct use of epoxy resin and improved soy protein adhesive performances [30,31].

Recently, waterborne epoxy emulsion (WEU) has garnered significant interest due to its excellent application in coating fields [32,33]. One approach of WEU preparation is to disperse epoxy resin directly into water via an external emulsifier [34]. Another path is to graft hydrophilic groups onto epoxy resin molecules via an esterification reaction or free radical polymerization for the oil-in-water emulsion, which has been shown to be more stable and homogeneous than the former [31]. On the other hand, neutralizers (e.g. triethanolamine, di-ethanol amine, and triethylamine) play important roles in the properties of the resultant WEU emulsions.

In this work, a high-performance soy protein-based adhesive is explored by introducing a WEU crosslinker. First, hydrophilic groups were grafted onto bisphenol-A (E44), followed by a phase-transformation process for the resin-in-water epoxy emulsion. Then, the active WEU served as a multiple crosslinker to construct physical/chemical interactions with soy protein molecules to form a stable crosslinking network. Next, the effects of triethylamine (TEA) and N, N-dimethyl ethanolamine (DMEA) neutralizers on the performance of soy protein-based adhesives were evaluated. The resulting soy protein-based adhesives exhibited excellent water-resistance property and thermal stability due to the formation of a stable crosslinking system. The chemical structures, thermal properties, mechanical strength, and morphologies of the soy protein-based adhesives were further investigated to elucidate improvements in their adhesion strength and water resistance. This approach provided a simple and green strategy to employ epoxy resin in the construction of high-performance protein-based adhesives.

2. Materials and methods

2.1. Materials

Soy protein with 90% protein content was purchased from Yuwang Ecological Food Industry Company in Shandong province of China. Commercial grade liquid epoxy resin diglycidyl ether of bisphenol-A (E44) was obtained from Shandong Yousuo Chemical Technology Co. Ltd. Methacrylic acid, methyl methacrylate, styrene, benzoyl peroxide, n-butanol, 2-butoxyethanol, cyclohexane, triethylamine (TEA), and N, N-dimethylethanolamine (DMEA) were purchased from Lanyi Chemical Co. Ltd. (Beijing, China) without purification before use. Wen'an County provided poplar veneer with a moisture content of 8.0%. Other chemical reactants were analytical grade and obtained from Beijing Chemical Reagents Co. Ltd.

Table 1
Experimental formulations of soy protein-based adhesives.

No.	Sample entry	Weight Proportion (wt%)
1	SP	M (soy protein):M(water):M(WEU) = 15:85:0
2	SWD-1	M (soy protein):M(water):M(WEU-DMEA) = 15:85:5
3	SWD-2	M (soy protein):M(water):M(WEU-DMEA) = 15:85:10
4	SWD-3	M (soy protein):M(water):M(WEU-DMEA) = 15:85:15
5	SWT-1	M (soy protein):M(water):M(WEU-TEA) = 15:85:5
6	SWT-2	M (soy protein):M(water):M(WEU-TEA) = 15:85:10
7	SWT-3	M (soy protein):M(water):M(WEU-TEA) = 15:85:15

2.2. Preparation of WEU

First, 10.0 g E44 was dissolved in the mixture of 6.0 g 2-butoxyethanol and 5.0 g n-butanol (solvent) with stirring and heated to 110 °C. Second, 0.3 g benzoyl peroxide, 1.2 g methacrylic acid, 1.0 g methyl methacrylate, and 1.0 g styrene were dropped into a four-necked round-bottom flask using constant pressure funnel within 2 h at 120 °C. Following this, the mixture was heated at 120 °C for 3 h. Lastly, 2.1 g TEA or 2.7 g DMEA was used to neutralize the mixture at 85 °C for 0.5 h, and a certain amount of deionized water was added to form an oil-in-water emulsion with 10% solid content under vigorous stirring at 1000 r/min. After an hour-long thermal reaction at 50 °C, two kinds of waterborne epoxy emulsions, neutralized by TEA (T-WEU) and by DMEA (D-WEU), were obtained. The emulsions were extracted by the mixed solution of cyclohexane and absolute ethanol to obtain grafted E−44. The grafted E−44 was then extracted by acetone twice. Pure grafted E44 was obtained and dried in a vacuum under 35–40 °C for 7–8 h for further investigation.

2.3. Preparation of soy protein-based adhesives

The soy protein-based adhesives were prepared. Soy protein (7.5 g) was suspended in deionized water (42.5 g) under vigorous stirring for 15 min at 20 °C. WEU was then introduced into the mixture and stirred for 30 min at 20 °C for adhesive composites. The control adhesive groups were fabricated using the same method; the adhesive formulations are listed in Table 1.

2.4. Preparation of three-ply plywood samples

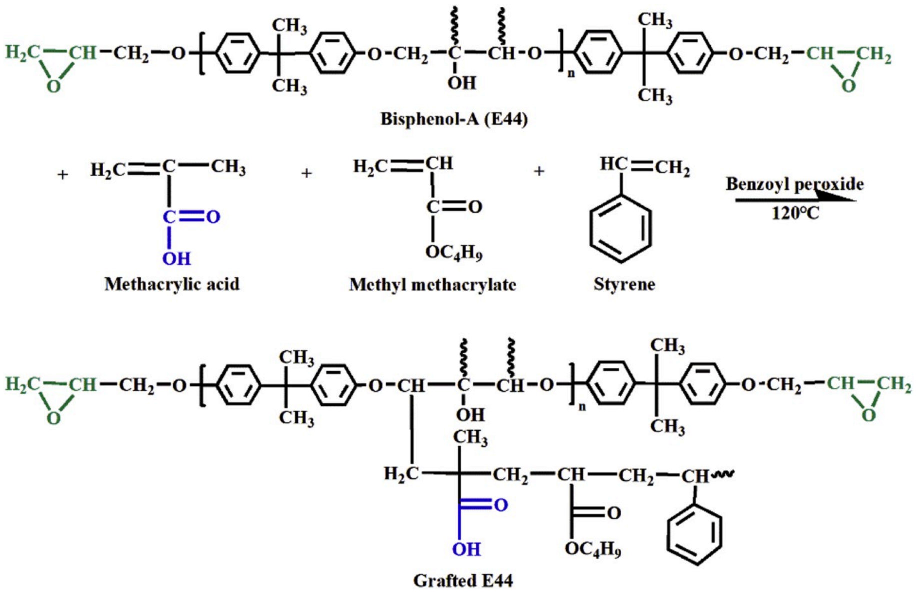
The adhesives were used to prepare three-plywood specimens with a spreading rate of 180 g/m^2 for each layer according to a previous study [13]. The three-ply plywood was next hot-pressed at 120 °C under pressure of 1.0 MPa for 315 s. After the hot-pressing process, the dried plywood was stored in ambient conditions for at least 12 h before further tests.

2.5. Characterization

The prepared adhesive samples were oven-dried at 120 °C for 24 h and ground into powder with 200 mesh. Fourier Transform Infrared Spectroscopy (FTIR) from 650 to 4000 cm^{-1} at a resolution of 4 cm^{-1} and 32 scans was applied to characterize WEU synthesis. X-ray diffraction data were collected in the range from 5° to 60° at a rate of 2°/min via X-ray diffractometry (Bruker AXS, Karlsruhe, Germany). The thermal properties of adhesive samples were characterized by thermogravimetric (TG) analysis, and samples were heated from 50 to 600 °C under nitrogen gas at a constant heating rate of 10 °C/min. A Hitachi S–3400 N (Hitachi Science System, Ibaraki, Japan) scanning electron microscope (SEM) was used to observe the fractured surfaces of the cured adhesives.

2.6. Shear strength measurement

The wet and boiling water shear strength of plywood specimens was determined according to China National Standard GB/T 17657–2013.



Scheme 1. Synthesis route of hydrophilic epoxy monomer.

Plywood samples were cut into 25 × 100 mm^2 rectangles with a bonding area of 25 × 25 mm^2 and submerged in 63 °C and boiling water for 3 h before being dried at room temperature for 10 min prior to shear strength testing. Wet and boiling water shear strength was tested using an Instron tensile strength testing system with 10 mm/min cross head speed. The wet and boiling water shear strength values were determined by taking the average value of six samples in each group. The force (N) required to break the glued wood specimen was recorded. The wet and boiling water shear strength (MPa) was calculated using the following equation:

$$\text{Shear strength (MPa)} = \text{Force (N)} / \text{Gluing area (cm}^2\text{)}$$

2.7. *Residual rate test*

Adhesive samples were placed in an oven at 120 °C until a constant weight (M) was reached, immersed in water for 6 h in an oven at 60 °C, and dried at 105 °C for 3 h until a constant weight (m) was reached. The residual rate was calculated as m/M × 100%.

2.8. *Moisture uptake measurement*

The moisture uptake of cured adhesives was determined by gravimetric analysis. Specifically, the weight of a given adhesive sample was recorded every 2 h at 50 °C and 80% relative humidity until a constant weight was reached. The moisture uptake was then calculated as follows:

$$\text{Moisture uptake (\%)} = (m_1 - m_0) / m_0 \times 100\%$$

where m_0 and m_1 are the weights of the adhesive before and after moisture uptake, respectively.

3. Results and discussions

3.1. *Synthesis and characterization of WEU*

The synthesis route of methacrylic acid grafted epoxy is displayed in Scheme 1. Fig. 1 presents the FTIR spectra of neat E44 epoxy and grafted E44 epoxy. The peak at 915 cm^{-1} is attributable to the characteristic absorption of epoxy group vibration peaks in epoxy resin [24]; peaks at 1607, 1581, and 1509 cm^{-1} are ascribed to the characteristic absorption of C═C bond stretching vibrations in the benzene ring [34]; peaks at 2966-2871 cm^{-1} were assigned to symmetric and asymmetric contraction vibrations of methylene absorption; peaks at 3700-3250 cm^{-1} are assigned to the characteristic absorption of hydroxyl (-OH) stretching vibrations [27]. Compared to the neat E44, a new absorption peak appeared at 1720 cm^{-1} (stretching vibration of carbonyl) in grafted E44 spectra, suggesting that the methacrylic acid was successfully grafted onto the E44 molecules [31]. Moreover, the absorption band (3700-3250 cm^{-1}) became broader, indicating that more –OH appeared in the WEU system mainly caused by ring-opening reactions of epoxy groups. After measuring the acid value of grafted E44, the experimental acid value (80 mg KOH/g) was close to the theoretical acid value of WEU, indicating that acrylic monomers were successfully grafted onto the E44 molecules.

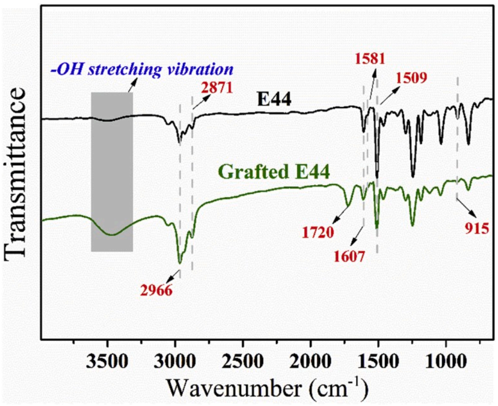


Fig. 1. FTIR spectra of neat and modified E44 epoxy resin.

3.2. *The dispersibility and stability of WEU emulsions*

The dispersibility of crosslinking agents in soy protein-based adhesive systems is vital for the mechanical properties of soy protein-based adhesives. Hence, the practical dispersibility of neat E44 and WEU emulsions is depicted in Fig. 2. The water mixed with neat E44 was dyed by methyl-red for visual observation. From Fig. 2, it was discovered that E44 could not disperse in water and presented stratification after 3–5

Fig. 2. The practical dispersibility in water of different samples: (**a**) neat E44 dispersed in water dyed by methyl-red; (**b**) WEU dispersed in water; and WEU stored for (**c**) 7 d and (**d**) 15 d.

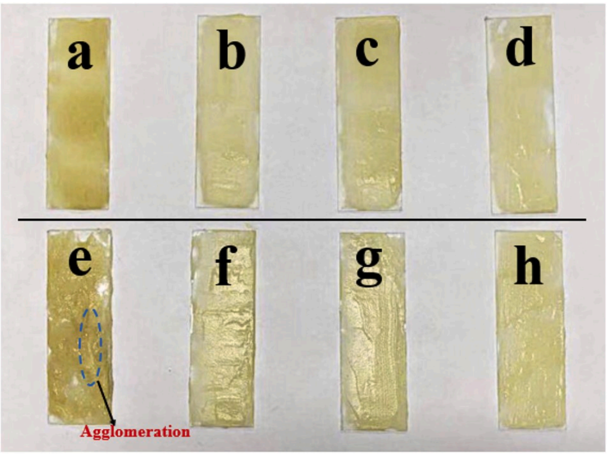


Fig. 3. Brush coating appearance of different adhesives: (a) SP adhesive, (b) SWD-1 adhesive, (c) SWD-2 adhesive, (d) SWD-3 adhesive, (e) soy protein/E44 adhesive, (f) SWT-1 adhesive, (g) SWT-2 adhesive, and (h) SWT-3 adhesive.

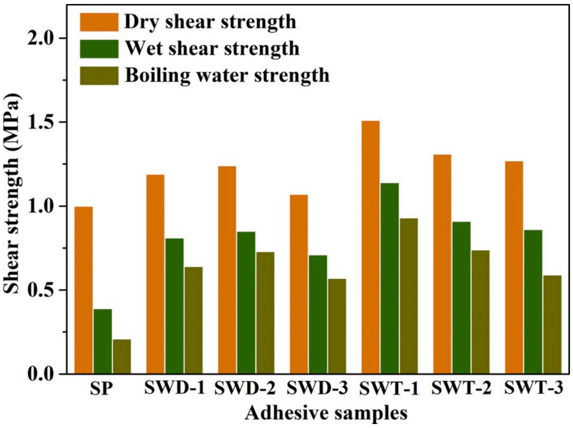


Fig. 4. Shear strength of various soy protein-based adhesives.

min, seriously impeding the application of E44 in the hydrophilic soy protein matrix [35]. Compared with the neat E44, the WEU emulsions dispersed easily in water dyed by methyl-red, and formed homogeneous and stable emulsions even after 15 d. The brush coating appearance of different adhesives are shown in Fig. 3. The SWD and SWT adhesives demonstrated favorable compatibility and presented a smooth adhesive layer after brush coating, indicating that WEU dispersed evenly onto the soy protein adhesive. On the contrary, E44 showed poor compatibility with the soy protein-based adhesive resulting in uneven agglomeration.

Table 2
Bonding strength of various soy protein-based adhesives.

Entry	Dry-shear strength (MPa)	Wet shear strength (MPa)	Boiling water strength (MPa)
SP	1.05	0.39	0.21
SWD-1	1.19	0.81	0.64
SWD-2	1.24	0.85	0.73
SWD-3	1.07	0.71	0.57
SWT-1	1.51	1.14	0.93
SWT-2	1.31	0.91	0.74
SWT-3	1.27	0.86	0.59

These results indicated that the WEU emulsions showed excellent compatibility with the hydrophilic system and can be used for soy protein-based composites [36].

3.3. Shear strength of soy protein-based adhesives

The dry shear strength, wet shear strength and boiling water strength of soy protein-based adhesives were tested to investigate the mechanical performance and water resistance of adhesives. As shown in Fig. 4 and Table 2, the dry shear strength of all soy protein-based adhesives met interior-use plywood requirements ($\geq$0.7 MPa). Wet shear strength is significant for soy protein-based adhesives. Based on the previous study, during the hot-pressing process, the hydrophilic groups of soy protein were exposed from the inside and accelerated the entanglement of soy protein molecules assisted by hydrogen bonding to generate bonding strength. However, the bonding system (mainly composed of weak hydrogen bonds) was easily destroyed by moisture intrusion, thus presenting poor water-resistance [37]. As shown in Fig. 4, the neat SP adhesive presented a wet shear strength of 0.39 MPa in accordance with the previous studies conducted by the authors [38], which did not meet the requirement of interior-use plywood [38]. After introducing D-WEU into the soy protein matrix, the wet shear strength increased from 0.39 MPa to 0.85 MPa as the D-WEU addition increased from 0% to 10%, which was a 117.9% increment compared to neat SP adhesive. Therefore, WEU could apparently form multiple interactions with soy protein for a stable and dense crosslinking network to endow composites with greater water-resistance. However, subsequent additions of D-WEU lowered the bonded wet shear strength, possibly due to the fact that the carboxyl groups of WEU resumed many epoxy groups and thus decreased interactions between WEU and soy protein molecules. The introduction of T-WEU could further improve the wet shear strength of the soy protein-based composite compared to D-WEU, which could reach 1.14 MPa with 5% T-WEU at an increment of 192.5% compared with the neat SP adhesive. Acrylic triethylamine salt could ‘release’ TEA under high temperature condition, thus serving as a small-molecule crosslinker to evoke further interactions between WEU and the soy protein matrix for a more stable crosslinking network [39,40]. The pH values of WEU before and after held in drying oven at 120 °C were measured. The pH value of T-WEU decreased after T-WEU was held in the drying oven for 1 h, indicating the volatilization of triethylamine. To further investigate the water resistance and mechanical properties of soy protein-based adhesives, boiling water strength was also tested. The boiling water strength presented similar trends with wet shear strength. With the introduction of WEU, the boiling water strength increased. In particular, T-WEU endowed adhesives with higher strength compared to D-WEU. As expected, the boiling water strength of SWT-1 reached a maximum of 0.93 MPa, which was far beyond that of pure SP adhesive.

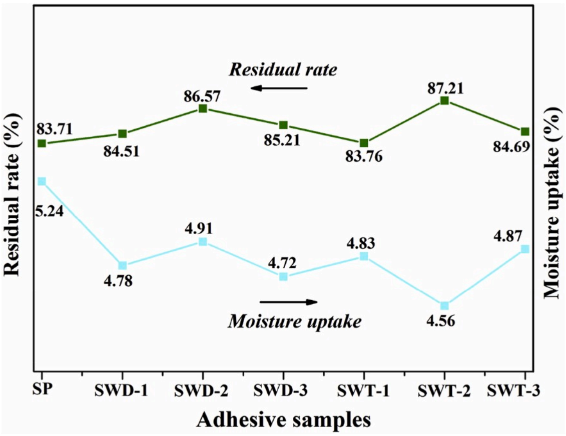


Fig. 5. The residual rates and moisture uptake of soy protein-based adhesives.

3.4. Residual rates and moisture uptake of soy-based adhesives

The water resistance of adhesives was measured by the residual rates test. As shown in Fig. 5, the residual rate of pure SP adhesive was only 83.71%, while the residual rates of SWD/SWT adhesives increased after introducing D-WEU/T-WEU. This increase was ascribed to the occurrence of a reaction between soy protein and WEU to form a crosslinking network and preventing water intrusion. The residual rates of SWD/SWT adhesives increased with the addition amount of D-WEU/T-WEU growing. However, a further increase of D-WEU/T-WEU content to 3 wt % in SWD-3/SWT-3 decreased the residual rates to 85.21% and 84.69%, respectively. This was attributed to unreacted hydrophilic WEU dispersing into the water.

Moisture uptake results of soy protein-based adhesives show an almost opposite trend compared to the residual rate results of adhesives. The moisture uptake of pure SP adhesive was 5.24% due to the abundant hydrophilic groups of soy protein. The introduction of WEU decreased the moisture uptake of adhesives, which was attributed to the crosslinking reaction between soy protein and WEU. This reaction consumed hydrophilic groups of soy protein and impeded water intrusion. Nevertheless, the moisture uptake of soy protein-based adhesives increased again when the addition amount of WEU was beyond 3 wt% in adhesives, which was consistent with the results of residual rates test.

3.5. Interaction between soy protein and WEU emulsions

Possible interactions between WEU and soy protein were presented in Scheme 2 and measured by FTIR spectroscopy, as shown in Fig. 6. For neat SP adhesive, the typical amide bands at 1644, 1538, and 1240 cm^{-1} were ascribed to amide I (C═O stretching), amide II (N–H bending), and amide III (C–N and N–H stretching), respectively [41]. A broad absorption band in the range of 3450–3250 cm^{-1} was associated with free and bound –OH and –NH group bending vibrations. The absorption peak at 2930 cm^{-1} was assigned to symmetric and asymmetric stretching vibrations of the $–CH_2$ groups in the soy protein-based adhesive [2]. After the introduction of WEU, several new peaks appeared at 1182, 1024, and 829 cm^{-1} in soy protein/WEU spectra, which is attributable to either the stretching or bending vibrations of C–O, C–O–C, and –CH of disubstituted benzene [3]. This finding indicated that the WEU was effectively inserted into the soy protein matrix and had excellent compatibility with the soy protein system. The addition of WEU shifted the amide II peak at 1538 to 1511 cm^{-1} due to the formation of multiple physical interactions between WEU and the soy protein matrix [42]. During the curing process, WEU with many epoxy groups served as a multiple crosslinker and formed crosslinking interactions with soy protein hydroxyl groups while generating hydroxyl groups due to epoxy ring-opening of epoxy, eliciting nearly no change for the absorption

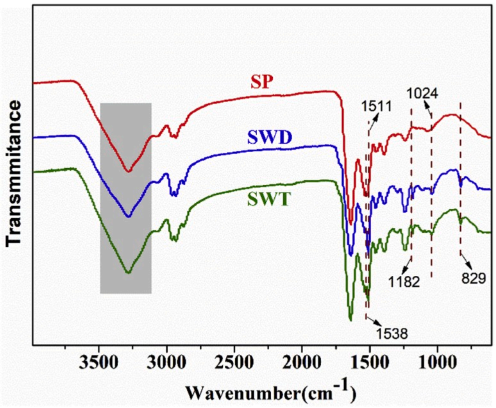
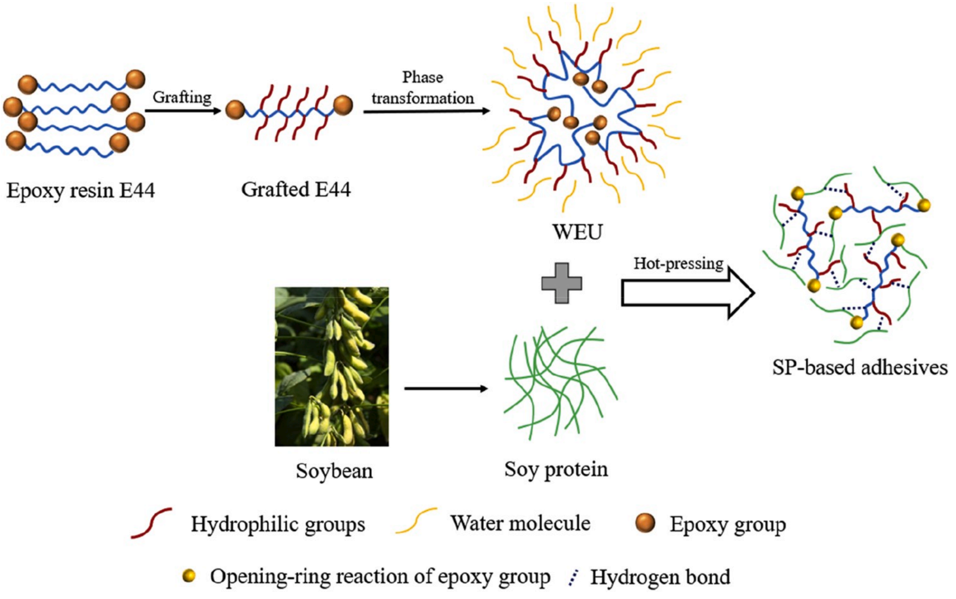


Fig. 6. FTIR spectra of different adhesives: SP, SWD, and SWT adhesives.



Scheme 2. Schematic illustration of soy protein/WEU adhesives cross-linking mechanism.

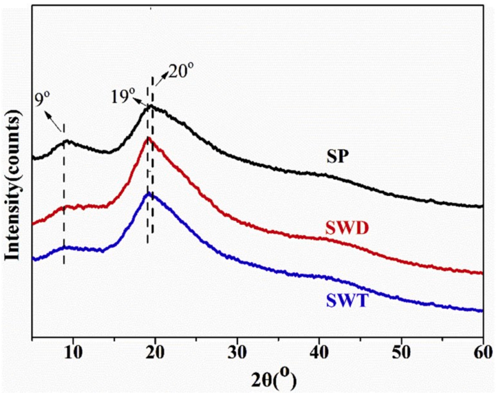


Fig. 7. XRD patterns of SP, SWD, and SWT adhesives.

Table 3
Crystallinity of soy protein/WEU adhesives.

Samples	SP	SWD-1	SWD-2	SWD-3	SWT-1	SWT-2	SWT-3
Crystallinity (%)	27.11	22.58	16.01	17.84	26.33	20.21	13.04

band at 3600-3200 cm^{-1} [21].

The effects of the WEU on structural conformations of soy protein-based adhesives were also characterized by XRD. As shown in Fig. 7, the broad characteristic peaks at 9° and 20° in the pure SP adhesive correspond to the α-helix and β-sheet structures of soy protein secondary conformation, respectively. Compared with the SP sample, the characteristic peak (β-helix) shifted from 20° to 19° and raised the intensity after incorporating with the WEU, which might be related to the partial denature in the soy protein crystalline structures due to cross-linking interactions between epoxy groups in WEU and the peptide chains of soy side chains. Besides, there were no crystallization peaks of WEU found in the adhesive, which implied favorable chemical compatibility and the physical distribution between WEU and soy protein molecular. This finding is consistent with organosilicon-acrylate microemulsions effect on soy protein observed by Zhao et al. It was also observed that the crystallinity of the adhesive decreased with the increase of WEU addition, as presented in Table 3. The reason for the above results may be that the cross-linking reaction between the WEU and soy protein lead to the rearrangement of soy protein chains, as confirmed by FTIR analysis.

SEM measurement was employed to further investigate interactions between WEU and the soy protein matrix. As illustrated in Fig. 8a, the neat SP adhesive presented a disordered and rough fracture surface with some holes and cracks, which were caused by water evaporation during the hot-pressing process [43]. These defects provided moisture in the channel, leading to easy intrusion of water molecules and compromised water-resistance of the adhesive. After the incorporation of WEU, the fracture surface of the soy protein/WEU adhesive became smoother and more compact, indicating that WEU served as a multiple crosslinker to construct strong physical and chemical interactions with the soy protein matrix to form a compact crosslinking network. However, the fracture surface of the SWD-2 became rougher than that of SWD-1, indicating that an excess of WEU would impede the form of a compact crosslinking network. Moreover, compared to WEU neutralized by DMEA, the fracture surface of SWT was denser due to the decomposition of acrylic triethylamine salt 'releasing' TEA, and thus providing more functional groups for crosslinking interactions in soy protein/WEU system [44], as supported by FTIR and XRD measurements.

3.6. *Thermal stability of soy protein/WEU adhesives*

The thermal stability of the SP and soy protein/WEU adhesives was investigated to further examine interactions between soy protein and WEU, as depicted in Fig. 9. For neat SP, the thermal degradation process was only one stage: 260–350 °C (I), which were ascribed to small molecule degradation and the breaking of unstable physical or/and chemical bonding. After introducing WEU into the soy protein matrix, a new peak appeared at the second stage around 350–430 °C due to the degradation of the formed crosslinking network and WEU benzene ring. Furthermore, incorporated WEU increased the residual weight of soy protein and shifted the peaks of the DTG curve in the second stage from 300 °C to 303 °C, following from the formation of a stable crosslinking network in soy protein/WEU that enhanced the thermal stability of composites [42]. These results indicated that the addition of WEU increased thermal stability of the cured soy protein-based adhesives by

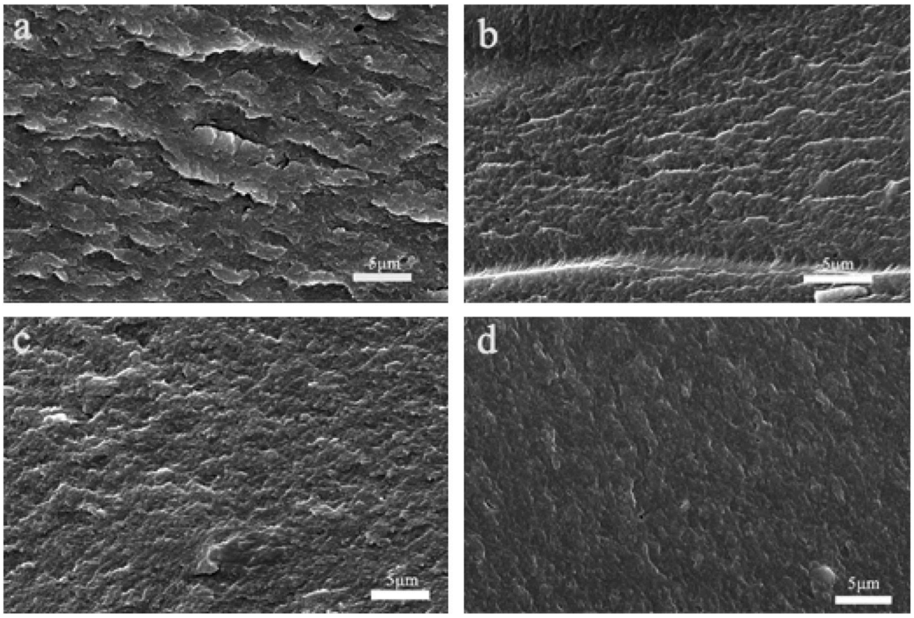


Fig. 8. Fracture surface micrographs of various cured soy protein-based adhesives: (a) SP adhesive, (b) SWD-1 adhesive, (c) SWD-2 adhesive, and (d) SWT-1 adhesive.

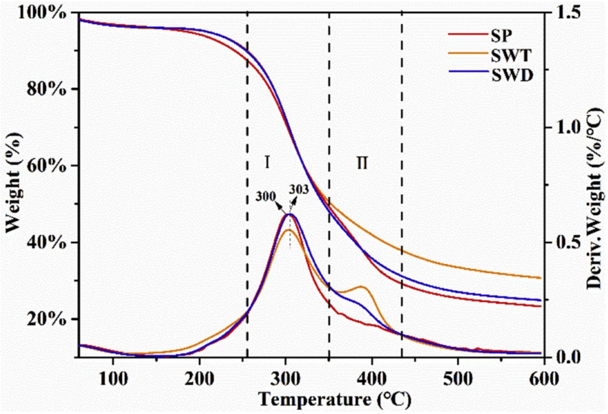


Fig. 9. Thermogravimetry (TG) curves and derivative thermogravimetry (DTG) curves of various soy protein-based adhesives: SP, SWT, and SWD adhesives.

constructing a crosslinking network, which is the same as the results of the SEM test [45].

4. Conclusions

In the present study, WEU was successfully prepared by graft polymerization grafting hydrophilic groups methacrylic acid onto bisphenol-A (E44) to form an oil-in-water emulsion. The fabricated WEU possessed favorable stability and dispersibility, and was regarded as an effective crosslinker to provide multiple stable crosslinking networks with soy protein molecules, as characterized by FTIR, XRD, SEM, and TG measurements. The modified soy protein-based adhesives exhibited more compact fractured morphology, along with improved thermal stability and water-resistance compared to the neat SP adhesive. The triethylamine neutralizer could endow the soy protein-based adhesive with 20% increment of wet shear strength in comparison to N, N-dimethyl ethanolamine, and the fabricated adhesive reached 1.14 MPa with 192.5% increment compared to neat soy protein-based adhesive. These properties meet the requirements of interior-use plywood (≥0.7 MPa). The soy protein/WEU adhesive fabricated in this work can provide a new avenue to develop high-performance engineered wood products.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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