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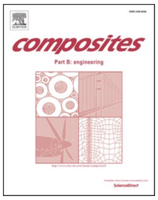

Characterization of rubberwood particleboard made using carboxymethyl starch mixed with polyvinyl alcohol as adhesive

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ABSTRACT

The aim of the study was to produce and characterize the modified starches and their suitability as wood adhesive for the particleboard manufacturing. The adhesive properties and particleboard manufactured from rubberwood using the modified starch and modified starch mixed with polyvinyl alcohol (PVA) were evaluated. Mixing of PVA with modified starch reduced the viscosity but increased the solid content and thermal property of the modified starch. Particleboard bonded with modified starch mixed with PVA also had improvement in physical and mechanical properties, showing great potential of modified starch and PVA as an adhesive for the green particleboard with good properties.

1. Introduction

Many adhesives of natural origin such as glues are derived from animal tissues casein. They have been used in a wide variety of applications. However, these glues typically lack of durability under extreme conditions. As a result, formaldehyde-based thermosetting adhesives such as commercially produced urea-formaldehyde (UF), phenol-formaldehyde (PF) resorcinol-formaldehyde (RF) or melamine-formaldehyde adhesives are introduced due to their better bonding properties and cost. Synthetic resins such as formaldehyde-based adhesives are considered priority pollutants due to their formaldehyde emission. Besides, formaldehyde has also been classified as a carcinogen that may cause nasopharyngeal cancer in humans, which has become recent research projects [1,2]. Formaldehyde risk posed by its emission in the environment could be a threat to the health of consumers and the workers at manufacturing facilities. Furthermore, the synthetic resins used in the manufacturing of wood-based composites such as particleboard and plywood are derived from non-renewable resources such as natural oil and gas. This may affect the future cost and availability of these wood adhesives. Thus, there is a need to find alternative for petroleum-based wood adhesives [1].

Natural resources have their unique advantages and properties. Starch is considered as one of the most abundant natural polymers which has a long history in the adhesive industry [3]. Starch is produced by plants as a way to store the chemical energy that they produce during photosynthesis. Starch can be found primarily in the seeds, fruits, tubers, and stem pith of plants, corn, wheat, rice, sago, and potatoes. Starch-based adhesives have excellent affinity for polar materials such as cellulose. However, panels made with non-modified starch such as corn starch or wheat flour met the standards for general purposes in dry conditions but the mechanical properties were not strong enough and the water resistant were poor. Research study showed that the properties of starch-based adhesives could be improved by modification to open up the starch granules so that it can develop adhesive bonding [4,5]. However, the use of conventional natural adhesives is limited due to issues of performance in poor physical and mechanical, thus need certain modification to improve the targeted properties so that it can be comparable with the synthetic adhesives. Various researchers

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demonstrated the improvement on the mechanical and physical properties of particleboard and met the selected standard when using starch-based adhesives using different types of starches including corn starch [6,7], rice starch [8], wheat starch [9] and oil palm starch [9,10] with different method of modification.

Carboxymethyl starch (CMS) is an example of etherified starch. The hydroxyl groups of starch molecules were etherified by carboxymethyl groups [11]. In carboxymethylation, starch is suspended in an aqueous alcohol solvent along with sodium hydroxide (NaOH) and sodium chloroacetate [12]. The reaction is carried out in the presence of strong bases in order to increase the nucleophilicity of the hydroxyl group and to aid the swelling of the starch particles [8,13]. The phosphoryl chloride is added as cross-linking agent for starch [5]. The rate of swelling to reach peak viscosity and cooked out viscosity of the modified starch is higher than natural starch. The CMS paste is more cohesive and tendency to gel. The retrogradation is greatly diminished [11]. The adhesive properties of starch can be improved by introducing carboxymethyl groups to starch molecules. This is because abundant polar carboxyl in carboxymethyl starch improve its cohesive forth to cellulosic materials [14].

Besides, it is suggested to use polyvinyl alcohol (PVA) within starch-derived adhesive in order to improve the water resistant properties [5]. Polyvinyl alcohol (PVA) is a water-soluble resin and produced by the hydrolysis of polyvinyl acetate. Resin properties vary according to the molecular weight of the parent polyvinyl acetate and the degree of hydrolysis. They are excellent adhesives and highly resistant to solvent, oil and grease. The PVA could form tough, clear films that have high tensile strength and abrasion resistance [15]. Besides, according to Shukla and Kamdem [16], PVA can be used to reduce the swelling of wood as well. Thus, the PVA can be used as water repellent chemicals in order to reduce the rate of water sorption in wood and wood products for short-term protection. Therefore, the development of wood adhesives from natural resources having good bonding properties and performance is one of our focus in this research. This study aims to produce and evaluate particleboard from rubberwood that using starch based as an adhesive for the particleboard manufacturing with the modification of the native starch and addition of PVA to improve both mechanical and physical properties of the particleboard so that it can be used for targeted green composites applications.

2. Experimental

2.1. Preparation of modified starch

The commercial wheat starch was used and modified into carboxymethyl starch. Preparation of the modified starch was carried out following the procedure described in a previous work by Kim and Lim [17]. About 100 g of wheat starch based on oven-dried weight was dispersed in a 300 ml of distilled water and the slurry was adjusted to pH 11.0 with 1 N sodium hydroxide solution. Then, 1 ml of phosphoryl chloride ($POCl_3$) as the cross-linking agent was added dropwise over 10 min, while maintaining the pH at 11.0 with the sodium hydroxide solution. The starch dispersion was stirred for 1 h at room temperature and then filtered. The filtered starch cake was dispersed in 300 ml of absolute ethanol and a 50% sodium hydroxide solution (20 g) was slowly added. Sodium chloroacetate (20% v/w, based on oven-dried weight of starch) was added in the starch–ethanol dispersion. Then, the mixture was stirred for 2 h at 45 °C in a sealed container. After the reaction, the starch slurry was filtered, washed three times with distilled water, and then dried at 40 °C overnight in an oven before the oven-dried starch was ground into powder. The modified starch mixed with polyvinyl alcohol were prepared. Polyvinyl alcohol with high molecular weight (average M_w 126 000–146 000, 99+ % hydrolyzed) bought form Sigma Aldrich was used. About 5% of PVA (oven-dried wt %) was dissolved in 120 ml of distilled water and heated with a temperature of 90 °C. Then, the solution was cooled to 50 °C before 10% of modified starch (oven-dried wt %) was added into the solution. Finally, the mixture was stirred until the solution became homogeneous.

2.2. Properties of starch

Properties of modified starch and modified starch mixed with PVA such as solid content and viscosity were measured. For solid content, about 1 g of adhesive was dried in an oven for 3 h with a temperature of 105 °C. Then, the adhesive was reweighed. The solid content of adhesive was calculated and expressed in percentage [18]. Viscosity of the adhesives were done using rotary rheometer. About 120 ml of the adhesive was taken and the adhesive viscosity was measured at 30 °C.

2.3. Preparation of particleboard

Commercially produced Rubberwood (*Hevea brasiliensis*) particles supplied by Heveaboard Company in Negeri Sembilan, Malaysia were used. The particles were dried in an oven until they reached a moisture content of 2% before the experimental particleboards were manufactured. Two types of particleboard panels (15% oven-dried wt) were made with target density of 0.80 g/cm^2. The first type was particleboard bonded with modified starch (denoted as MSB) using 15% based on oven-dried weight particles of modified starch in powder form that was mixed homogenously with 120 ml of distilled water. While the second type of particleboard was bonded with modified starch mixed with PVA (denoted as MSPVAB). A solution of 5% of PVA and 10% of modified starch based on oven-dried weight particles were prepared, stirred until the solution became homogeneous before applying as binder for particleboards. The starch adhesive was mixed manually with the rubberwood particles before placed into a mold with a dimension of 20.1 cm × 20.1 cm x 0.5 cm and followed by a pre-pressing in order to form a mat. After that, the mat was hot-pressed by using a hot press machine at 5 MPa at temperature of 165 °C for 15 min. All particleboards produced were cooled and conditioned before carrying out further tests. The panels were cooled and placed in an air conditioning room at a temperature of 25 °C ± 2 °C with a relative humidity of 65 °C ± 2 °C for a week before further tests.

2.4. Physical and mechanical properties of the samples

The physical properties of particleboard bonded with modified starch and that bonded with modified starch mixed with polyvinyl alcohol were evaluated. The physical properties including density, moisture content, water absorption (WA) and thickness swelling (TS) were carried out according to the Japanese Industrial Standard [19]. A size of 5 cm × 5 cm from each panel was cut for density, thickness swelling and water absorption test. The density was measured by taking the measurements of the length, width, thickness, and weight for each sample. Then, the volume was calculated. The moisture content value was taken from the average result of samples from each type of particleboard. The initial weight of samples was recorded and the samples were put in an oven with a temperature of 105 °C until a constant weight was achieved. The moisture was then calculated same the formula in Japanese Industrial Standard [19]. Water absorption and thickness swelling were carried out simultaneously. Initially, the thickness and weight of each sample were recorded before immersing in water. After immersing for 2 h and 24 h, the increase in thickness and weight of each sample were recorded.

The mechanical properties of particleboard bonded with modified starch and particleboard bonded with modified starch mixed with polyvinyl alcohol were tested as well. The mechanical properties included modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB) strength were carried out according to the Japanese Industrial Standard [19]. Samples with a size of 20 cm × 5 cm x 0.5 cm were cut from each panel for MOR and MOE tests. The Instron Tensile Machine Model 5582 was used with a crosshead speed of 10 mm/min.

Span of supporting beam was 120 mm and a load was applied at the center of the sample. Besides, samples with a size of 5 cm × 5 cm x 0.5 cm were cut from each panel for IB test. The Instron Tensile Machine Model 5582 was used with a crosshead speed of 2 mm/min for IB test. (JIS A 5908).

2.5. *Fourier transform infrared spectroscopy (FTIR)*

Fourier transform infrared spectroscopy (FTIR) is used to determine the functional groups in an organic or inorganic compound. Potassium bromide (KBr) pellet technique was used to obtain the infrared spectrum of a compound in solid form. The FTIR spectra of each samples were obtained in the range of 4000-500 cm^{-1} and recorded on a PerkinElmer 2000 FTIR spectrophotometer. The native starch, modified starch and modified starch mixed with polyvinyl alcohol were analyzed in powder form by FTIR.

2.6. *Thermogravimetric analysis (TGA)*

Thermogravimetric analysis (TGA) was used to measure the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. Measurements are used primarily to determine the composition of materials and to predict their thermal stability. The TGA was performed at heating rate of 20 °C/min and the measurement was carried out with a temperature range of 30–800 °C in a nitrogen atmosphere. Modified starch, modified starch mixed with polyvinyl alcohol, particleboard bonded with modified starch and particleboard bonded with modified starch mixed with polyvinyl alcohol were analyzed in powder form by TGA.

2.7. *Scanning electron microscope (SEM)*

Scanning electron microscope (SEM) was used to study the morphological differences between panels. The model used was LEO SUPRA 55VP Ultra High Resolution Analytical FESEM. Particleboard bonded with modified starch and particleboard bonded with modified starch mixed with polyvinyl alcohol were examined by SEM. Small cube samples was prepared by cutting from a cross-cut view of panels and glued onto a stub using tape. Next, the samples were coated with a thin layer of gold before examined.

3. Results and discussion

3.1. *Adhesive analysis*

Table 1 shows solid content and viscosity of modified starch and modified starch mixed with polyvinyl alcohol. It was found that the viscosity of modified starch adhesives was higher compared to the modified starch adhesive mixed with polyvinyl alcohol. Pure starch pastes can be described as a suspension of swollen particles dispersed in a continuous phase. Starch granules swell and break in starch cooking and eventually swollen particles are formed. They are mainly composed of entangled amylopectin. Carboxymethyl starch (CMS) is prepared by etherification, in which some of the hydroxyl groups in starch are replaced by carboxymethyl groups. The groups are polar and hydrophilic. The presence of the polar groups such as carboxymethyl groups causes further swelling of the starch particles. This will eventually lead to greater expansion of the coiled starch macromolecules [20]. Besides, higher density of negatively charged carboxymethyl groups causes greater electrostatic repulsion between high degree substations of polysaccharide chains, molecules tended to exist in a more expanded state [21]. Therefore, a high viscosity was obtained for modified starch adhesives. Mixing of modified starch with polyvinyl alcohol tended to reduce the viscosity of the modified starch. This was because addition of polyvinyl alcohol reduced the resistance to flow of modified starch suspension. As a result, the viscosity decreased.

Table 1
Solid content and viscosity of modified starch and modified starch mixed with polyvinyl alcohol.

Sample	Viscosity (Pa.s)	Solid Content (%) at 105° ± 2 °C (%)
Modified Starch	9.010 (0.17)	16.92 (0.15)
Modified Starch + Polyvinyl Alcohol	4.764 (0.26)	19.03 (0.21)

However, the viscosity of adhesive should be controlled at appropriate level because high viscosity adhesive has problem when it comes to the manufacturing process. High viscosity adhesive is hard to disperse well on wood particles. So, it is suggested to add urea, sodium nitrate and salicylic acid as plasticizer in order to reduce the viscosity during the starch adhesive preparation. Urea is the most commonly used plasticizer and it may be added at a level of 1–10% based on dry starch [5]. The solid content of modified starch was only about 16.92%. On the other hand, the modified starch mixed with polyvinyl alcohol was 19.03%. The solid content of modified starch with addition of polyvinyl alcohol was found to be higher than that of the modified starch as a result of addition of the high molecular weight of polyvinyl alcohol.

3.2. *Fourier transform infrared spectroscopy (FTIR)*

The changes in the modified starch and modified starch with polyvinyl alcohol were examined using break abscissa in the FTIR spectra as shown in Fig. 1. In the spectra of native starch as shown in Fig. 1, a broad and strong band resulting from vibration of the hydroxyl groups (OH) appeared at 3438 cm^{-1}. In the spectra of modified starch mixed with polyvinyl alcohol, the absorption peak at 3449 cm^{-1} was due to the OH group stretching vibrations of carboxymethyl starch and polyvinyl alcohol. The intensity of absorption peak at 3443 cm^{-1} in modified starch was changed and shifted to 3449 cm^{-1} after mixing with polyvinyl alcohol. The peak at 2920 cm^{-1} was due to the vibration characteristic of the CH_2 symmetrical stretching. The peak at 1155 and 1079 cm^{-1} were attributed to C–O bond stretching vibration in the ordered structures of starch while peak at 1020 cm^{-1} was associated to the amorphous structures of starch [22].

There was a change from the peak for both starches at 2000 to 500 cm^{-1} as compared to the native starch. Peaks intensity at 1639 cm^{-1}, 1422 cm^{-1} and 1389 cm^{-1} for both modified starch and modified starch with polyvinyl alcohol showed slightly higher than the native starch but the intensity of bands was not strong. The absorption band at 1639 cm^{-1} of carboxymethyl starch shifted to 1655 cm^{-1} in carboxymethyl starch mixed with polyvinyl alcohol. It seems that the COO^{-} and OH groups of carboxymethyl starch participate in intermolecular hydrogen bonds with the OH groups of PVA, respectively [23]. It is worth noting that the intensity of the peaks also could be affected by a degree of substitution of the carboxymethyl starch where higher degree of substitution tends to give strong absorption peak where carboxylate (–COO–) gives the strong intensity at about 1600, 1440 and 1325 cm^{-1} [22,24]. However, further study on the effect of degree of substitution need to be carried out to confirm the statement.

3.3. *Physical properties of the samples*

The physical properties of the particleboards made with modified starch and mixing of modified starch with polyvinyl alcohol at same density levels and with a same pressing time are given in Table 2. The average actual densities for the two types of panels met the target density (0.80 $\mathrm{g/cm}^3$). The actual average density for panels bonded with modified starch was 0.77 $\mathrm{g/cm}^3$. The actual average density for particleboards bonded with modified starch and polyvinyl alcohol was 0.76 $\mathrm{g/cm}^3$.The variation of density was due to particle loss happened during raw material preparation and trimming process.

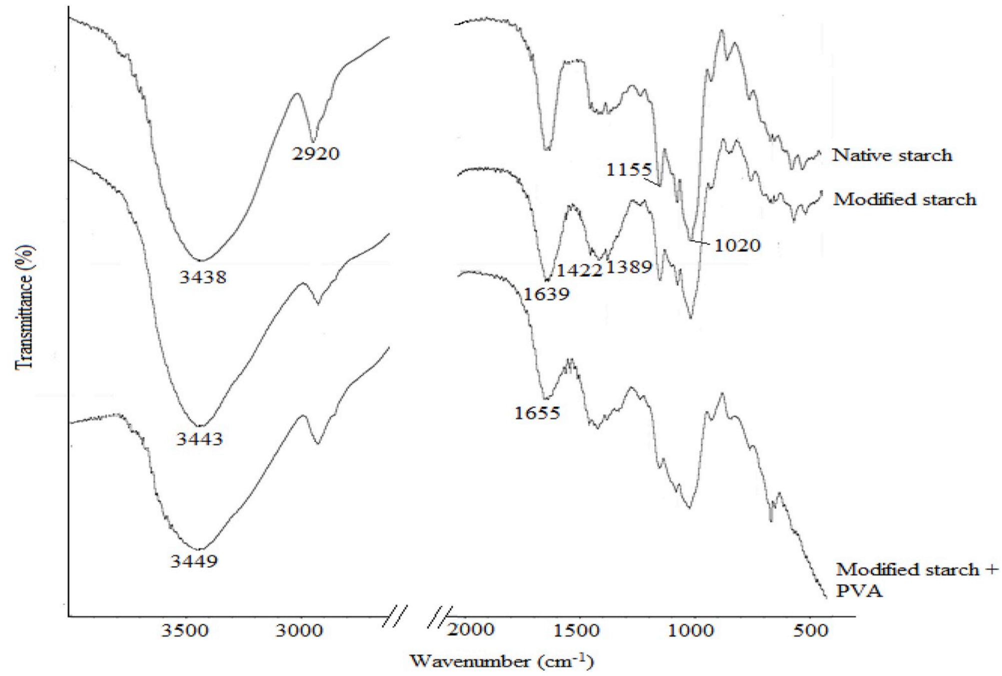

Fig. 1. FTIR spectra using a break abscissa in the 500-1800 cm^{-1} and 2800-4000 cm^{-1} of region of native starch, modified starch and modified starch mixed with polyvinyl alcohol.

Table 2
Physical testing of particleboards with two different types of starch adhesives.

Sample	Target Density (g/cm^3)	Physical Testing					
		Density (g/cm^3)	Moisture Content (%)	Water Absorption (%)		Thickness Swelling (%)	
				2 h	24 h	2 h	24 h
MSB	0.80	0.77 (0.02)	2.82 (0.11)	130.44 (11.71)	208.38 (15.85)	58.59 (7.77)	114.46 (11.31)
MSPVAB	0.80	0.76 (0.02)	2.66 (0.53)	63.55 (5.60)	95.16 (5.11)	29.22 (2.92)	47.36 (3.18)

*Values in parenthesis indicates the standard deviation of data.
**MSB: Particleboard bonded with modified starch adhesives; MSPVAB: Particleboard bonded with modified starch and polyvinyl alcohol.

Based on the results obtained for water absorption (WA), the particleboard bonded with modified starch mixed with polyvinyl alcohol (MSPVAB) had lower WA values than the particleboards bonded with modified starch (MSB) as shown in Table 3. Particleboard bonded with modified starch showed high affinity to water. This was due to the presence of carboxymethyl groups in the modified starch [25]. The addition of PVA with the modified starch into the particleboard tends to lower the WA value. This was because addition of high molecular weight of PVA manage to improve the water resistant [15]. Thus, the particleboard bonded with modified starch mixed with polyvinyl alcohol showed decreasing in WA value. In addition, water diffusion in a composite also depends on factors such as volume, voids, viscosity of matrix, humidity and temperature [26]. Apart from this, a high WA value could be attributed to the presence of porosity or void on the surface of the particleboard. With the presence of voids on the surface of panel, the weight of panel will be increased because water can be trapped inside the voids [26]. With the hydrophilic nature of starch that able to absorb water also could attribute to high WA value.

Table 3
Mechanical testing of particleboards with two different types of starch adhesives.

Sample	Mechanical Testing		
	Modulus of Rupture (MOR) (MPa)	Modulus of Elasticity (MOE) (GPa)	Internal Bond (IB) (MPa)
MSB	9.04 (2.35)	2.64 (0.34)	0.29 (0.06)
MSPVAB	16.9 (3.35)	3.16 (0.19)	0.54 (0.10)

*Values in parenthesis indicate the standard deviation of data.
*MSB: Particleboard bonded with modified starch adhesives; MSPVAHB: Particleboard bonded with modified starch and polyvinyl alcohol.

Thickness swelling (TS) of the particleboard increased after 2 h and 24 h as shown in Table 2. This is because the hydrophilic properties of wood materials and the capillary action will cause the intake of water when composites were immersed into water. This eventually increases the dimension of composites and also cause the swelling of fiber. As a result, dimensional stability of particleboard are increased [26]. The TS of the particleboard bonded with modified starch were the highest. Initially, the TS of these particleboard was 58.59% after immersing in water for 2 h and increased drastically to 114.46% after 24 h. This is due to the presence of carboxymethyl groups in the modified starch which contributed to high affinity to water [25]. The particleboard bonded with modified starch and polyvinyl alcohol showed the low TS values as compared to particleboard bonded with modified starch. Initially, the thickness swelling after 2 h of this panels was only about 29.22% and slightly increased to 47.36% after 24 h. The presence of PVA tends to reduce the water absorption of the panels since PVA is a good water resistant material [15]. In addition, PVA can be used to reduce the swelling of wood as well [16].

Even though the thickness swelling value was reduced, the panels did not meet the requirements stated in the Japanese Industrial Standard

[19], and the maximum acceptance level of thickness swelling is 12%. Therefore, it is recommended to overcome this problem by treating wood particles with water repellent such as melamine or adding paraffin wax before particleboard manufacturing [16]. Additionally, wax ranges from 0.3% to 1% based on the oven-dried weight of the particles could be added during the particleboard preparation process in order to improve short-term moisture resistance [27].

3.4. Mechanical properties of particleboard

The mechanical properties of the particleboard such as modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond strength (IB) were measured. The mean values of each mechanical properties are tabulated in Table 3. All the mechanical properties values obtained for the particleboards met the minimum requirement as stated in the Japanese Industrial Standard [19]. The minimum requirement for the MOR in the standard is 8 MPa, where the mean values of the MOR obtained in this study were in the range of 9.04 MPa and 16.9 MPa. The minimum requirement for the MOE in the standard is 2.00 GPa, where the mean values of the MOE obtained in this study were in the range of 2.64 GPa and 3.16 GPa. On the other hand, the minimum requirement for IB strength is 0.15 MPa, where the mean values the IB strength of the panels in this study were in the range of 0.29 MPa–0.54 MPa.

Particleboard bonded with modified starch mixed with polyvinyl alcohol (MSPVAB) demonstrated a better mechanical property compared to particleboard bonded with modified starch (MSB) as shown in Table 3. The MOR value of MSB particleboard was about 9.04 MPa while the MSPVAB particleboard was 16.0 MPa, respectively. This indicated that the flexural strength of the panels was improved after mixing with polyvinyl alcohol. This was because incorporation of PVA improved the chain flexibility and the bonding strength as well since the starch was compatible with aqueous polyvinyl alcohol [28,29]. Thus, the property of resistance to bending was enhanced.

The MOE for particleboard MSPVAB was higher than that of the panels MSB which are 3.16 GPa and 2.64 GPa, respectively as shown in Table 3. This indicated that addition of polyvinyl alcohol was able to increase tendency of particleboard to be deformed elastically when a force was applied. Besides, high molecular weight of polyvinyl alcohol tends to increase the adhesive strength as well [15].

The IB strength for the particleboard bonded with modified starch was increased greatly after mixing with polyvinyl alcohol. The IB strength for particleboard MSB was 0.29 MPa and the IB strength for panels MSPVAB was 0.54 MPa. This indicated that the adhesive performance was due to the addition of polyvinyl alcohol. This could be explained by incorporation of high molecular weight of polyvinyl alcohol which tends to improve the adhesive strength [15]. Thus, the bonding strength was also improved.

The results found in this study were comparable with other study that used epichlorohydrin to modify different starches and used it to produce the rubberwood particleboard [7,8]. The IB, MOR and MOE value of MSPVAB particleboard showed better mechanical properties compared to the mechanical properties of particleboard using modified wheat starch and oil palm starch [9] and rice starch [8]. The MSPVAB particleboard also showed an increase in value of MOR, MOE, and IB when compared to UF resin based particleboard (MOR-11.27 MPa, MOE-2.11 GPa, IB-0.41 MPa) [9].

3.5. Thermal analysis

According to Fig. 2, modified starch experienced weight loss in three major stage whilst the modified starch mixed with polyvinyl alcohol experience weight loss in three steps. The first stage involves the evaporation of water at a temperature range of 60–120 °C. The second and the third stage correspond to the decomposition of the starch material and the dehydration of polymer chains. Water is formed by inter- and intramolecular condensation of hydroxyl groups. It is the main product of decomposition below about 300 °C. When the temperature is heating up to 500 °C, this eventually results in carbonization and formation of

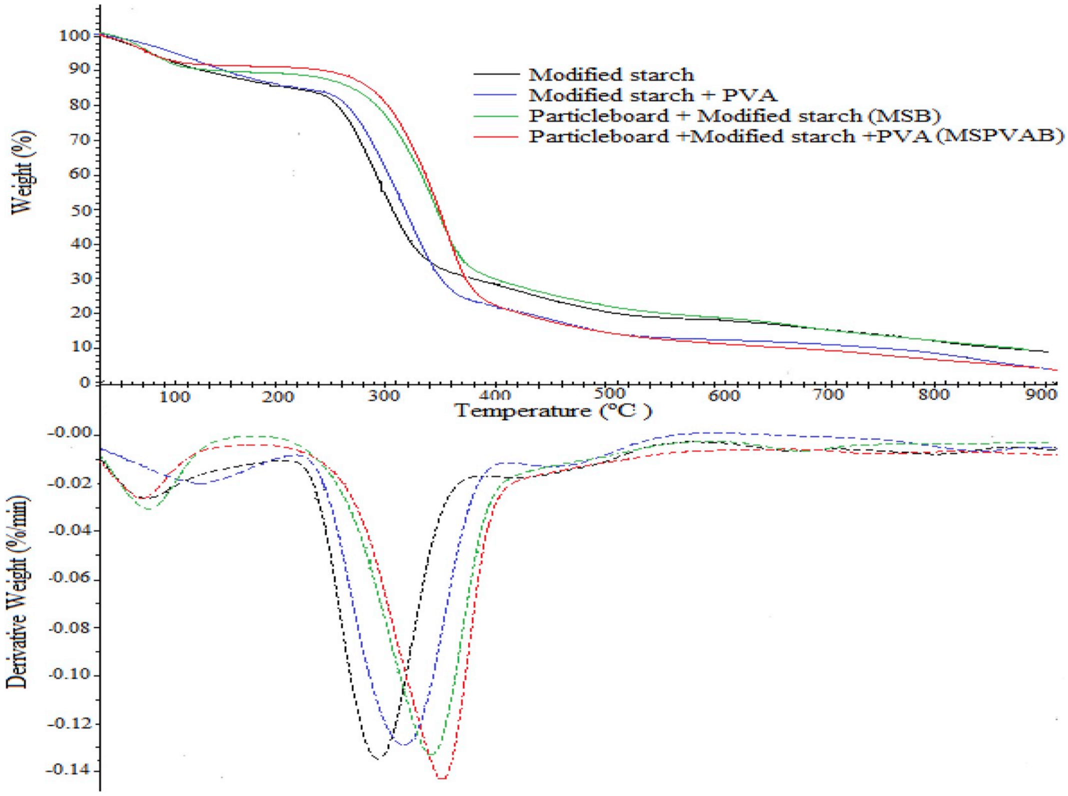

Fig. 2. TG and DTG of all samples.

ash and CO_2 is released [21]. The onset temperatures of the weight loss were 191 °C and 197 °C for modified starch and modified starch mixed with polyvinyl alcohol, respectively. The observation on the weight loss curved (TG) showed that modified starch mixed with polyvinyl alcohol had higher maximum temperature (T_{max}) of 300 °C as compared to the modified starch (280 °C). This indicated that the modified starch mixed with polyvinyl alcohol was more resistant to heat. At the end of the analysis, the residue left for modified starch and modified starch mixed polyvinyl alcohol were 8.48% and 3.74%, respectively. This reflected that the modified starch mixed with polyvinyl alcohol had experienced more weight loss as compared to modified starch.

Particleboard bonded with modified starch and panel bonded with modified starch mixed with polyvinyl alcohol also experience weight loss in three stage. First stage attributed to the evaporation of water and easily volatile materials. Stage 2 and 3 are attributed to pyrolysis and the evaporation of large amounts of the pyrolytic products. These stage are the main degradation process of products [30]. The onset temperatures of the weight loss at the first stage were 164 °C and 163 °C for particleboard bonded with modified starch and particleboard bonded modified starch mixed with polyvinyl alcohol, respectively. The maximum temperature (T_{max}) of the particleboard bonded with modified starch mixed with polyvinyl alcohol measured at 340 °C is higher compared to particleboard bonded with modified starch (335 °C) indicating higher resistant to heat. At the end of the analysis, the residue left for modified starch and modified starch mixed polyvinyl alcohol were 16.60% and 16.07%, respectively. This indicated that the particleboard bonded with modified starch mixed with polyvinyl alcohol had experienced more weight loss as compared to particleboard bonded with modified starch. Based on results obtained, it seems that particleboard bonded with modified starch mixed with polyvinyl alcohol degraded faster and showed higher rate of decomposition at a higher temperature as compared to modified starch.

3.6. Scanning electron microscope (SEM)

The SEM analysis was done in order to observe the compactness and effect of modified starch and modified starch mixed with polyvinyl alcohol as binder in particleboard as shown in Fig. 3. Based on the micrograph obtained, it could be observed that cell walls and fibers of rubberwood particles were compressed. This was believed that the compressed structures formed were due to the pressure applied during the hot pressing of particleboard panels. Starch adhesives were allowed to disperse evenly within the particles by compressing the particles. As a result, these would eventually to allow more interaction between the particles and the modified starch. Thus, more bonding could be formed during the interaction. Particleboard bonded with modified starch mixed with polyvinyl alcohol showed better interaction between the starch molecules and the particles as shown in Fig. 3(d) as compared to particleboard bonded with modified starch as shown in Fig. 3(a). This phenomenon was clearer when a high magnification was used. As shown in Fig. 3(f), the modified starch mixed with polyvinyl alcohol was able to disperse and adhere well on the parenchyma cells and cell walls. On the hand, the modified starch was able to disperse on the some of the cell walls as shown Fig. 3(c). When the dispersion of adhesive is good, this will improve the physical and mechanical properties of particleboard especially particleboard bonded with modified starch mixed with polyvinyl alcohol.

4. Conclusions

The modified starch and modified starch mixed with PVA has been produced to be used as a binder in the particleboard manufacturing. Mixing of polyvinyl alcohol with modified starch reduce the viscosity of modified starch and increased the solid content of modified starch. Particleboard bonded with modified starch mixed with polyvinyl alcohol (MSPVAB) showed better mechanical properties of modulus of rupture (16.9 MPa), modulus of elasticity (3.16 GPa) and internal bond strength (0.54 MPa) as compared to panels bonded with modified starch (MSB). It can be concluded that all particleboard panels satisfied the Japanese Industrial Standards (JIS) for mechanical properties. Even though dimensional stability showing an improvement but, resistance of the panels towards moisture still need to be explore. The thermal analysis showed that particleboard bonded with modified starch mixed with polyvinyl alcohol was more resistant to heat. The scanning electron micrograph showed that particleboard made added with modified starch mixed with polyvinyl alcohol was well dispersed between the compressed wood particles that contributed to good interaction as compared to modified starch.

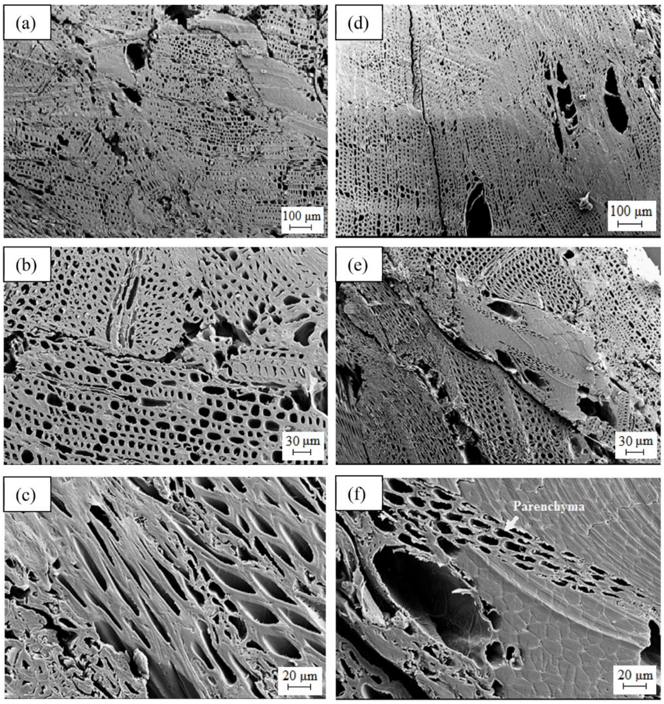

Fig. 3. SEM micrograph of cross sectional view of particleboards bonded with (a,b,c) modified starch, and (d,e,f) modified starch mixed with polyvinyl alcohol.

Declaration of competing interest

None.

CRediT authorship contribution statement

Junidah Lamaming: Conceptualization, Visualization, Writing - original draft, Writing - review & editing. **Ng Boon Heng:** Conceptualization, Methodology, Writing - original draft. **Amina Adedoja Owodunni:** Investigation, Methodology. **Sofie Zarina Lamaming:** Investigation, Methodology. **Nurul Khizrien Abd Khadir:** Investigation. **Rokiah Hashim:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing. **Othman Sulaiman:** Funding acquisition. **Mohamad Haafiz Mohamad Kassim:** Funding acquisition. **Mohd Hazwan Hussin:** Funding acquisition. **Yazmin Bustami:** Funding acquisition. **Mohd Hazim Mohamad Amini:** Funding acquisition. **Salim Hiziroglu:** Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compositesb.2019.107731.

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