

Enhanced Properties of Single-Layer Particleboard Made from Oil Palm Empty Fruit Bunch Fibre with Additional Water-Soluble Additives

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The efficacy of additional water-soluble additives was studied relative to the physical and mechanical properties of particleboards produced from oil palm empty fruit bunch (OPEFB). Polyethylene glycol, acrylamide, and acrylic resin were selected as water-soluble additives for use in the OPEFB particleboard production process. The effects of the three additives at two different concentrations (2% and 4% of dry OPEFB mass) on the particleboard properties were evaluated. Addition of water-soluble additives increased the performance of the OPEFB particleboard. The additive concentration has a significant effect on the properties of the particleboard. With the increase of additive concentration, the internal bonding and modulus of rupture value increased while the thickness swelling and water absorption decreased. Particleboards with an additional 4% of acrylamide or polyethylene glycol achieved the highest modulus of rupture (22 MPa), highest internal bonding strength (1 N/mm²), and lowest thickness swelling (9%). All the particleboards produced with 4% of water-soluble additive achieved the standard requirements of JIS A 5908:2003 for physical and mechanical properties.

Keywords: Particleboard; Empty fruit bunch; Water-soluble additive; Acrylic resin; Acrylamide; Polyethylene glycol

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INTRODUCTION

Wood is one of the most abundant biomaterials and has piqued the interest of researchers in both academia and industry. Due to its high strength-to-weight ratio, renewable nature, and environmentally friendly nature, high quality solid wood has been used extensively in construction and furniture for thousands of years. As a significant part of the global manufacturing sector, China's furniture market reached almost USD 600 billion in 2018 (Xiong *et al.* 2020). In addition, wood has gradually attracted greater attention from the latest global trends for the improvement of living standards and increasing concerns about environmental protection (Popescu and Pfriem 2020). Regrettably, high-quality solid wood is currently experiencing reduced supply due to low growth rates and stricter global environmental regulations (Qiu *et al.* 2018). These issues have led the scientific research to look for new alternatives to replace traditional polymer composites, looking for ways that have lower environmental impact and thus are often referred to as “ecocomposites” or “biocomposites” (La Mantia and Morreale 2011). Hence, biocomposites are an important development trend in the modern manufacturing industry

as a new manufacturing approach.

In the furniture industry, particleboard is one of the most commonly used composite panels due to its versatility and low cost (Owodunni *et al.* 2020). Malaysia is one of the world's important players for export of particleboard. According to the Malaysian Timber Industry Board (MTIB), the total exports for particleboard were 68,489 m³ and valued at RM85.3 million in 2017 (Harun 2018). Wood-based industry players are continually in a race to explore new potential resources for continuous stable production to meet the future demand. In Malaysia, the main raw material used in the production of particleboard is rubberwood. Syeed *et al.* (2019) reported that at least 4 out of 7 particleboard mills in Malaysia used solely rubberwood for particleboard production with a total installed capacity of approximately 1530 m³/day. Rubberwood is a mass-produced wood that is now being used and marketed for higher-value applications, including the wood panels, pulp and paper, as well as latex production. The Covid-19 pandemic has cast the spotlight on Malaysia's rubber industry, particularly on downstream latex players such as glove makers. At present, the manufacturing of gloves is mainly focused on natural latex gloves, which account 40% for the total production of glove in Malaysia (Surendran and Ng 2020). Due to the high consumption rate of rubberwood in various other industries, the particleboard industry continues to seek other diverse sources of raw materials and to meet the high demand for particleboard.

One of the ideal raw materials for particleboard production in Malaysia is oil palm empty fruit bunch (OPEFB). Malaysia is one of the world's largest palm oil producers and exporters (Chin *et al.* 2019). The total export of products based on palm oil in the country amounted to 25.2 million tonnes, generating export earnings of RM67.5 billion (Yusof 2019). The palm oil mill generated a large volume of solid waste residues, including 5.5-8% palm kernel shell, 20-23% OPEFB and 15% palm fibre from fresh fruit bundles (Rahayu *et al.* 2019). In comparison with rubberwood, OPEFB is an under-utilized resource. It has various potential applications as long as suitable pretreatments or processing methods have been determined and carried out (Killmann and Hong 2000). Substantially, various research and development activities aim to explore the used of the enormous waste from the palm oil industry as an alternative source and innovative reliable raw material for high demand products (Peter *et al.* 2020).

The abundant availability of OPEFB has gained continuous interest among researchers and is potentially considered as the main candidate to substitute woody materials due to the shortage of resources. However, until today OPEFB is hardly accepted by particleboard manufacturers due to the hygroscopic characteristics of the OPEFB fibre itself (Ismail *et al.* 2012). Without any treatment, particleboard made from OPEFB is unable to achieve the JIS A 5908 standard on the physical and mechanical properties of particleboard, including tensile strength, internal bonding, water absorption, thickness swelling, and density (Zaidon *et al.* 2007). It is impossible to develop a market for OPEFB particleboard without overcoming these restrictive parameters.

Biocomposites can be used in a variety of industrial applications. However, there are some issues, such as reduction of the ductility and poor processability. Many of these limitations can be overcome with the use of adhesion promoters, additives, or chemical modifications to the filler. According to Brahmia *et al.* (2020) and Wei and Tomita (2001), the mechanical properties and dimensional stability of cement-wood composite were significantly improved with increasing amounts of the additives. Unlike for the cement-wood composites, the concept of the usage of additives has not yet been investigated for

particleboard. To date, the most fundamental question on how addition of additive effects on the physical and mechanical strength on the particleboard remain unanswered.

Among these, water-soluble and biodegradable polymer matrixes would be a better choice to be utilized for biocomposite production. According to Fredi *et al.* (2019), water-soluble additives can penetrate deeply into the heartwood, thus offering prospects of greater protection of the wood. Acrylamide is a water-soluble monomer that is biodegradable and widely used in a variety of chemical and environmental included production of plastics, dyes, and paper, in the treatment of drinking water, wastewater, and sewage (Kusnin *et al.* 2015; Tepe and Çebi 2019). Water-soluble polyethylene glycol (PEG) is a well-known compound with a wide range of medical and industrial applications (Chen *et al.* 2005, 2007; Vafaezadeh and Hashemi 2015). It is inexpensive and significantly less hazardous than other potential additives that require organic solvents. In addition, PEG products are stable under ambient conditions because they have negligible vapour pressure and do not release volatile organic compounds (Vafaezadeh and Hashemi 2015). As stated by Behzad and Sain 2004, a new environmentally friendly curable acrylic resin was characterized to develop a high-performance biocomposite for future work. A significant problem concerning the scientific application of curable acrylic resins is their biodegradation (Vivek 2017). Moreover, water-soluble acrylic resin is a potential zero formaldehyde emission binder for particleboard production (Amazio *et al.* 2011).

This paper presents the methods and the efficiency results from an experimental investigation of water-soluble additives mixed with urea formaldehyde resin for the production of single-ply OPEFB particleboard. Additional water-soluble additives were tested, with the aim to reduce water absorption and to improve dimensional stability and mechanical properties of the OPEFB particleboard. The purpose of the investigation was to determine the effect of different types of water-soluble additives (PEG, acrylic resin and acrylamide) and concentrations (2% and 4% of dry OPEFB mass) of water-soluble additives on the physical and mechanical properties of the OPEFB particleboard. The results obtained were used to analyse the changes in the physical and mechanical properties of single-ply OPEFB particleboard with water-soluble additives and urea formaldehyde resin mixture. The differences may become visible by comparing the physical and mechanical test result and can be explained by the varying influence of the concentration of additives on the OPEFB particleboard.

EXPERIMENTAL

Material

OPEFB fibres were collected from the Hulu Langat Oil Palm Mill, Selangor. Urea formaldehyde (UF) Type E1 resin was provided by Dynea Malaysia Sdn Bhd. Three types of additives (PEG, curable Acrylic Resin, Acrylamide) used in this study were provided by CYTEC Chemical.

Methods

Single-layer particleboard production

In order to obtain particles with the size of 1.5 to 3.0 mm, OPEFB was flaked and sieved. The OPEFB particles were further dried prior to the production of particleboard to achieve a final moisture content below 6%. The targeted density of the particleboard was

700 kg/m³ and the size was 350 mm x 350 mm x 12 mm. Seven types of particleboards were produced with 5 replicates each (Table 1). A mixture of 11% E1 resin, 0.5% wax, and additives was sprayed on the OPEFB particles and mixed for 5 minutes. In the resin mixture, three types of water-soluble additives (PEG, acrylic resin, acrylamide) with two different concentrations (2% and 4% of dry OPEFB mass) were used, respectively. Particleboard without additional water-soluble additives were used as control samples.

The blended OPEFB particles were uniformly dispersed in a 350 mm x 350 mm wood box and cold-pressed for 5 minutes. The mat formation was hot-pressed at 100 MPa, 180 °C for 5 min. The particleboards were placed in the conditioning room with the relative humidity of conditioning room 65 ± 5% and temperature of 23± 3 °C until constant weight was reached. The particleboard's physical and mechanical properties were tested in compliance with the Japanese Industrial Standard (JIS) A5908:2003. Each of the conditioned particleboards was later trimmed and cut into testing specimens according to the JIS standard.

Table 1. Seven Types of Particleboards

Treatment ID	Type of additives	Additives concentration (%)
PG2	Polyethylene glycol	2
PG4	Polyethylene glycol	4
AM2	Acrylamide	2
AM4	Acrylamide	4
AC2	Acrylic resin	2
AC4	Acrylic resin	4
WAA	Without additional additives	

Note: UF resin was present in every condition, including the WAA.

Moisture content and density

According to JIS A 5908:2003, the air-dry density of test specimens with dimension of 50 mm by 50 mm was determined by weighing the specimens and measuring the volume of specimens. The density was calculated using the following formula:

$$\text{Density} \left(\frac{\text{kg}}{\text{m}^3} \right) = \frac{\text{Mass}}{\text{Volume}} \quad (1)$$

Specific gravity of test specimens was determined by dividing the oven-dry density of the specimens with density of water. Moisture content of the specimens was determined using conventional drying method according to JIS A 5908:2003. The specimens were oven-dried at temperature of 103±2 °C to constant weight in order to determine the oven-dry weight. The moisture content of the specimens was calculated as follows:

$$\text{Moisture Content}(\%) = \frac{\text{Initial Weight (g)} - \text{Oven-dry Weight (g)}}{\text{Oven-dry Weight (g)}} \times 100\% \quad (2)$$

Water absorption and thickness swelling

Test specimens with dimensions of 50 mm by 50 mm were weighed, and the dimensions were measured prior to submergence in 25 mm of distilled water at a temperature of 20 ± 1 °C. After 2 h of submersion, the water was removed and the specimens were drained for 10±2 min in order to remove excess surface water. The specimens were weighed, and the thickness of the specimens was measured immediately. The specimens were then submerged for a further 22 h. After submersion, the percentage

of water absorption and thickness swelling (based on the JIS A 5908:2003) were determined using the formula as follows:

$$\text{Water Absorption (\%)} = \frac{\text{Final Weight (g)} - \text{Initial Weight (g)}}{\text{Initial Weight (g)}} \times 100\% \quad (3)$$

$$\text{Thickness Swelling (\%)} = \frac{\text{Final Thickness (mm)} - \text{Initial Thickness (mm)}}{\text{Initial Thickness (mm)}} \times 100\% \quad (4)$$

Static Bending

Flatwise and edgewise three-point static bending tests were carried out on specimens with dimension 50 mm width by 180 mm length using INSTRON Universal Testing Machine in accordance to JIS A 5908:2003. The crosshead loading speed was kept at 10 mm/min continuously throughout the test. With the formula, the bending strength was calculated as in Eq. 5,

$$\text{MOR (N/mm}^2\text{)} = \frac{3FL}{2bh^2} \quad (5)$$

where F is the load at the fracture point (N), L is the length of the support span (mm), b is the width of specimen (mm), and h is the thickness of specimen (mm).

Internal bonding (IB)

Test specimens were cut to 50 mm x 50 mm were used for testing. Hot-melt resin was used to adhere both surfaces of each specimen on to two steel blocks. A tension load was applied vertically to the board surfaces, and the maximum load was measured at the time of failing force (breaking load of perpendicular tensile strength to the board). IB was calculated using Eq. 6,

$$\text{IB (N/mm}^2\text{)} = \frac{P}{2bL} \quad (6)$$

where P is the maximum load at the time of failing force (N), b is the width of the sample (mm), and L is the length of the sample (mm)

Data analysis

Statistical analyses were carried out using the statistical package SPSS for Windows, version 16.0 (SPSS, Chicago, IL, USA) to evaluate the data of physical and mechanical properties of particleboard for analysis of variance (ANOVA) at 95% confident level ($P \leq 0.05$). Regression analysis was conducted to evaluate the significance of the relationship between relevant variables. In order to further determine the levels of significance of average values for each treatment, Duncan's multiple range test was applied to analyse the differences of the treatment effects when significant difference was observed. The effects were considered not statistically significant when the p-value was higher than 0.05 at the 95% confidence level.

RESULTS AND DISCUSSION

The physical and mechanical properties of the OPEFB particleboard manufactured with different treatment parameters (types and concentrations of the water-soluble additive) were evaluated in this study. The analysis of the effect of the types and the concentration of additional water-soluble additives on the properties of the OPEFB particleboard is presented in Table 2. For all the models, the p-value was less than 0.01 for all parameters;

type of additives, concentration, and the interaction of the two factors, indicating that all parameters significantly affect the properties of the particleboards.

Table 2. ANOVA for the Effect of Additive to the Performance of OPEFB Particleboard

Source	Dependent Variable	F	Sig.
Type of Additive x Concentration of Additive	Board Density	10.104	.000**
	Thickness Swelling (TS)	30.216	.000**
	Water Absorption (WA)	17.024	.000**
	Internal Bonding (IB)	4.752	.002**
	Modulus of Rupture (MOR)	4.120	.014*

Notes:

* Significant, $p < 0.05$; ** Highly Significant, $p < 0.01$; ^{ns} Not significant, $p > 0.05$

Effect of the Additional Additive to the Physical Properties of Particleboard

The analysis of physical properties (density, thickness swelling, and water absorption) for OPEFB particleboard is shown in Figs. 1, 2, and 3, respectively.

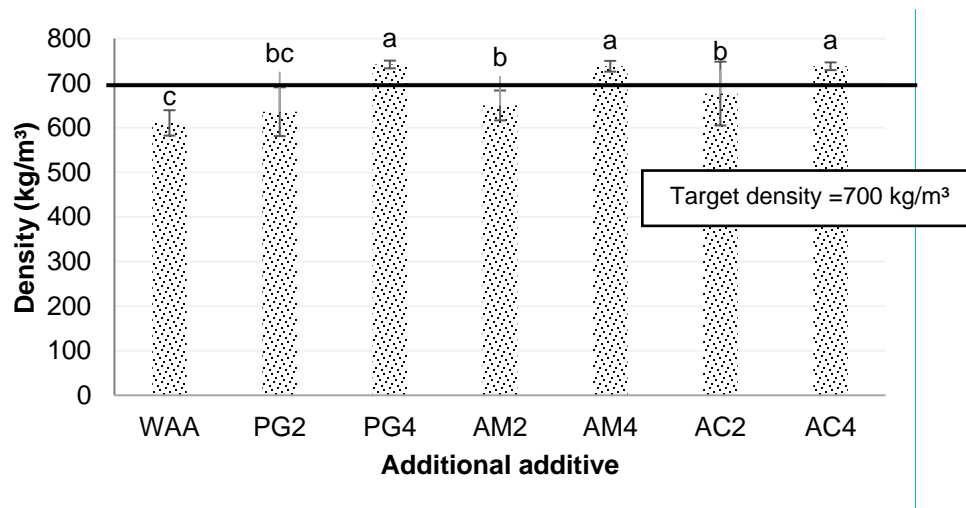


Fig. 1. Mean value of density of the particleboard

Notes: Means followed by the same letters are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test. The p-values reveal the strength of differences between factors (types of concentration x concentration of additive) on the density of the OPEFB particleboard. UF resin was present in every condition, including the WAA.

In this study, the target density for the OPEFB particleboard was 700 kg/m^3 . Figure 1 shows that particleboards with a higher additive concentration were significantly higher in density compared to particleboards with a lower additive concentration. This outcome reveals that the particleboard with a higher additive concentration improved the bonding without increasing resin content. Regardless of the types of additives, particleboard with 4% concentration of additive achieved the target density of 700 kg/m^3 . The target density of 700 kg/m^3 was not achieved by particleboards with 2% additive concentration and without any use of additive. In other words, the density of the particleboard substantially

depends on the additive concentration. According to Sumardi and Suzuki (2014), thickness swelling and water absorption of the particleboard are affected by the board density.

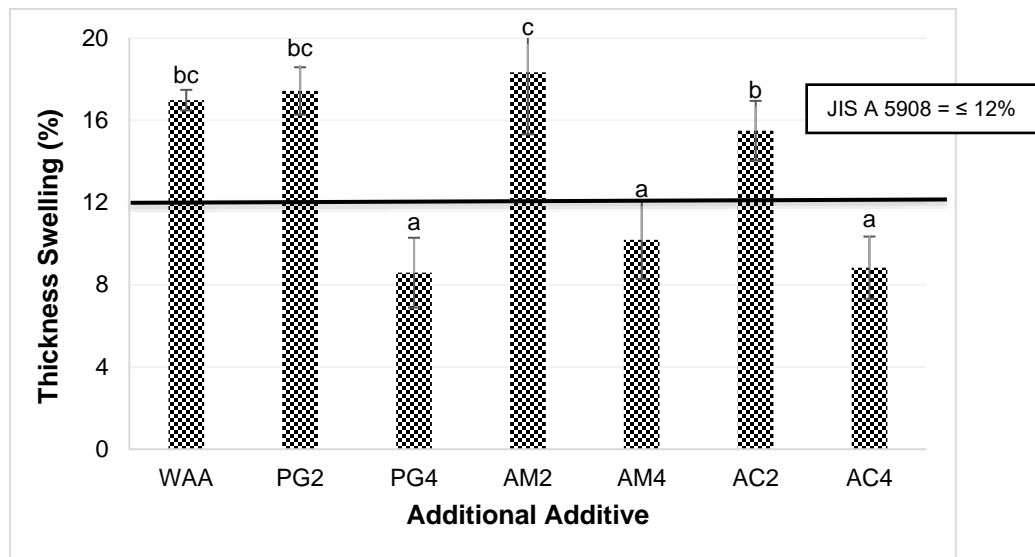


Fig. 2. Mean value of thickness swelling of the particleboard

Notes: Means followed by the same letters are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test. The p-values reveal the strength of differences between factors (types of concentration x concentration of additive) on the thickness swelling of the OPEFB particleboard. UF resin was present in every condition, including the WAA.

Heebink and Hefty (1968) claimed that it is very difficult to produce particleboards with minimal thickness swelling. According to the requirements of JIS A 5908:2003, the thickness swelling of particleboard shall not exceed 12%. Additives were employed with the aim to reduce the thickness swelling and to open new possibilities for particleboard produced from OPEFB. The results showed that a higher additives concentration of 4%, regardless of the types used in this study, produced particleboards with lower thickness swelling and reached the requirement of JIS A 5908:2003 (Fig. 2). With 2% concentration of additives, the thickness swelling was similar to non-treated particleboard, which indicated the insufficiency on the amount of additive to effectively reduce the thickness swelling. PG4 has the lowest thickness swelling (8.59%), followed by AC4 (8.83%) and AM4 (10.19%).

The fact that particleboard with PEG additive achieved the lowest thickness swelling which may due to the bulking effect of PEG filling up the cavities and eventually reducing the extent of swelling (Radzi *et al.* 2019). This result was also reported by Meints *et al.* (2018) that PEG is able to reduce the water-holding capacity simultaneously by crosslinking the cellulose chains of the component fibres. In addition, the additives acted as plasticizers and allowed the UF resin to be more effective in forming a strong connection between the solid surfaces have contributed to the improvement of water and moisture resistance. As stated by Mekonnen *et al.* (2013), PEG by acting as a plasticizer can reduce the chain-to-chain interaction and induce flexibility, moisture resistance and ease of processability. Thermoplastic toughening, by incorporating thermoplastics to prepare high-performance structural composites, has been widely used in materials science (Huang *et al.* 1993; Gopala *et al.* 1998; Luo *et al.* 2019). Das *et al.* (2008) revealed that by mixing

curable acrylic resin (thermoplastic additive) with UF resin (thermosetting amino resin) had improved impact strength via in situ polymerization. This has also contributed to the prevalent use of curable acrylic resin as a coating to protect wood surfaces from stains, scratches, water rings, and other types of damage (Ammar *et al.* 2019).

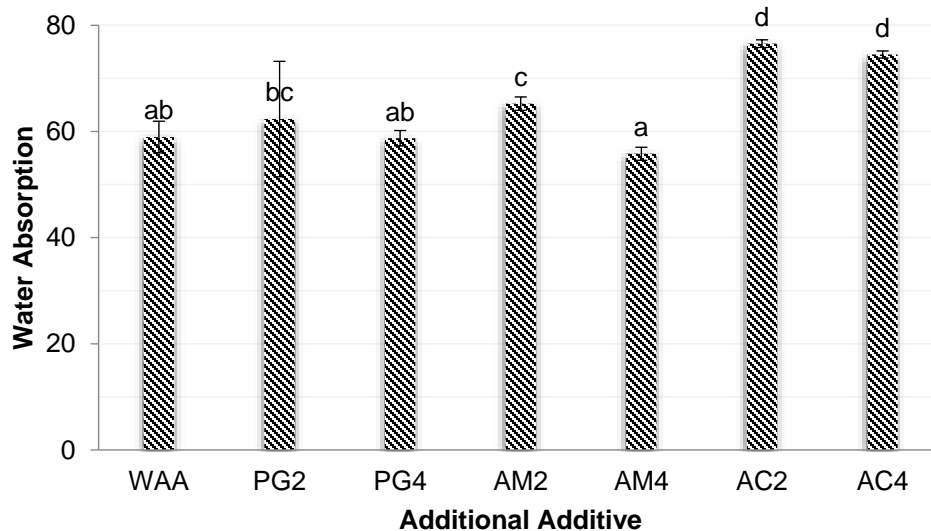


Fig. 3. Mean value of water absorption of the particleboard

Notes: Means followed by the same letters are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test. The p-values reveal the strength of differences between factors (types of concentration x concentration of additive) on the water absorption properties of the OPEFB particleboard. UF resin was present in every condition, including the WAA.

Natural fibres such as OPEFB have high hydroxyl content, which is consistent with the nature of cellulose. This which makes products formed from OPEFB susceptible to water absorption. Water absorption leads to swelling of the fibre and influences the mechanical properties of the particleboard (Meenalochani and Vijayasimha 2017). As shown in Fig. 3, the absorption of water decreased with the addition of water-soluble additive. The water-soluble polymer could effectively permeate into the wood cell walls and connected with the hydroxyl groups of the lignin and polysaccharides via covalent bonds (Qiu *et al.* 2018). AM4 achieved the highest water resistance (55.8%) compared to the other particleboards produced in this study. The relatively lower thickness swelling values showed that the board was dimensionally stable, while the low water absorption capacity was an indication that the board could be employed in outdoor situations (Júnior *et al.* 2017). The functional group (amide) of acrylamide provides a cross-linking to the cell wall component (Marimuthu *et al.* 2010). New bonds from crosslinking will reduce the water sorption and swelling of the composites. Furthermore, crosslinking also improved the properties of the water barrier (López De Dicastillo *et al.* 2016). Apart from that, the results showed that the density of the board had a negative correlation with the water absorption. This may cause water vapour to be more accessible to the board due to reduced density (Iswanto *et al.* 2013). Hence, higher density resulting from the additional additive of 4% contribute to the reduction of water absorption in the particleboard.

Effect of the Additional Additive to the Mechanical Properties of Particleboard

Figures 4 and 5 show the mechanical properties (IB and MOR) of the particleboard manufactured with different additives and concentrations. JIS A 5908:2003 required minimum IB and MOR values of 0.2 N/mm² and 13.00 N/mm², respectively. The evaluation of the mechanical properties of the OPEFB particleboard (IB and MOR) are depicted in Figs. 4 and 5.

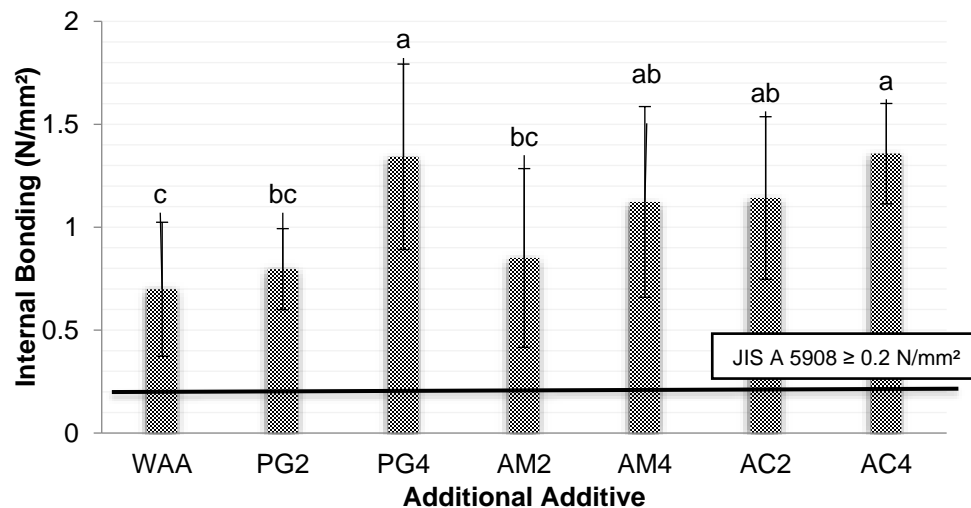


Fig. 4. Mean value of internal bonding of the particleboard

Notes: Means followed by the same letters are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test. The p-values reveal the strength of differences between factors (types of concentration x concentration of additive) on the internal bonding of the OPEFB particleboard. UF resin was present in every condition, including the WAA.

As stated by Stoeckel *et al.* (2013), UF resin is significantly problematic due to its inherent brittleness. Because of this characteristic, cured UF resins are very prone to cracking, and therefore exhibit poor impact resistance when applied to the wood panels. As shown in Fig. 4, the additional additive on particleboard OPEFB resulted higher IB values compared to the particleboard without additional water-soluble additives. AC4 and PG4 achieved the highest IB value with 1.36 and 1.34 N/mm² on maximum load. It is well known that IB strength is closely related to thickness swelling values as it is closely related to the inter-fibre bonding. A good bonding would result in the board with low thickness swelling and *vice versa* (Izani *et al.* 2012). While the low IB values indicates that the particles were not bonded strongly together, therefore, high volume of water were easily penetrated into spaces between particles of the porous structure (Zaidon *et al.* 2007). Both AC4 and PG4 obtained the highest IB strength and lowest thickness swelling value in this study (refer to Figs. 2 and 4). Acrylic resins are the preferred bonding materials as it contains functionalities (especially hydroxyl groups, *e.g.* from hydroxyl ethyl acrylate) that induce the chemical reactions and leads to cross-linking (Bulian and Graystone 2009; Patcas and Eliades 2017). As stated by Hashim *et al.* (2011) and Mo *et al.* (2003), a good core bonding may be enhanced by the hydrogen bonding. The high IB strength of PG4 could be achieved with the presence of polyurethane in PEG. PEG is normally used to stabilise green wood to prevent it from cracking, splitting and shrinking (Rao *et al.* 2019). Due to the high polarity and the hydrogen bonding between polyurethane and the

substrates, polyurethane was also used to bind various substrates such as metal, plastic, rubber, and wood. In acrylamide, the amide functionality provides cross linking sites that increases the inter-fibre bonding capacity (Marimuthu *et al.* 2010; Heydari *et al.* 2013).

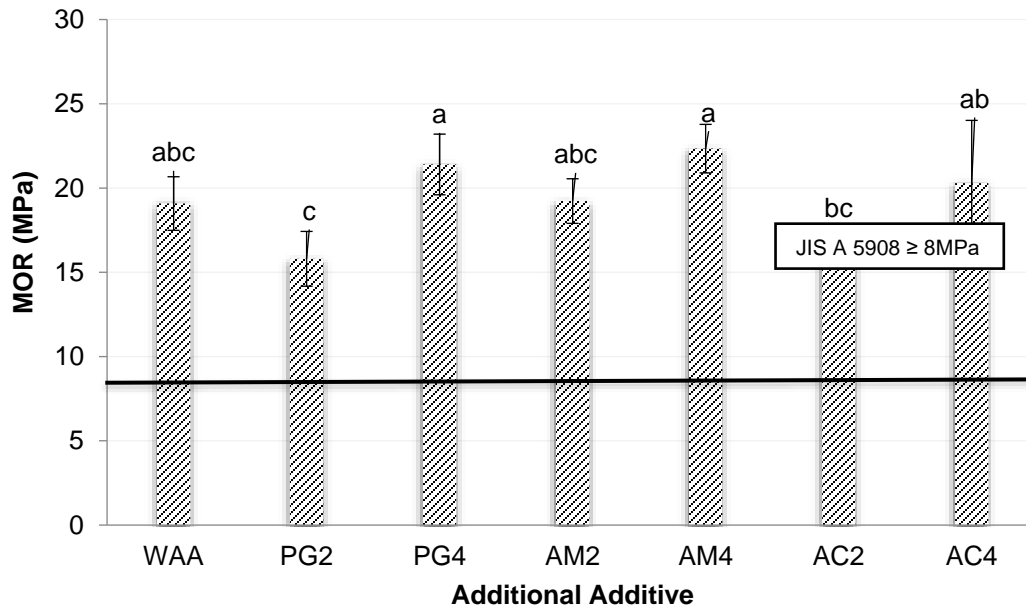


Fig. 5. Mean value of MOR of the particleboard

Notes: Means followed by the same letters are not significantly different at $p \leq 0.05$ according to Duncan's multiple range test. The p-values reveal the strength of differences between factors (types of concentration x concentration of additive) on the MOR value of the OPEFB particleboard. UF resin was present in every condition, including the WAA.

In Figs. 4 and 5, the results show that the high concentration of the additives greatly improved the mechanical properties (IB and MOR value) of the OPEFB particleboard. According to the Li *et al.* (2011); Qiu *et al.* (2018); Trey *et al.* (2012), the reduction of the hydrophilic -OH groups of the cell wall components or the filling of the pore in the wood improved the mechanical properties and dimensional stability of the wood. The highest MOR values were achieved by AM4 and PG4 (Fig. 5). Conventionally, dry strength additives acrylamide worked by complementing the number of inter-fibre hydrogen bonds. As stated by Tee *et al.* (2019), hydrogen bonding may alter and improve the mechanical properties of wood composite panel. Hydrogen bonding causes cellulose fibres to exhibit wide ranges of strength, stiffness, and toughness in mechanical tests (Renuart and Viney 2000). Particleboards treated with PEG have higher MOR value than the particleboards without additional additive. The properties of the particleboard were completely altered by the plasticization effect of PEG, which led to the high MOR value. PEG contributes in high elongation at break, and better impact resistance to the particleboard (Biron 2018). Besides, the MOR value for AC4 was higher in comparison of particleboard without additional additive. This was due to acrylic resin has high hardness and superior chemical resistance (Xu *et al.* 2009).

CONCLUSIONS

1. The use of water-soluble additives can open new opportunities for particleboard manufacturing using palm oil industry waste. All particleboards with additional water-soluble additives achieved better performance on the physical and mechanical properties in comparison with particleboard without a water-soluble additive.
2. Statistical analyses indicates that the concentration of additional water-soluble additive influenced the physical properties of particleboard. The decrease in thickness swelling and water absorption was found to be statistically significant when compared with the particleboard without water-soluble additives.
3. Regardless of the types of water-soluble additive, 4% concentration of additive achieved higher mechanical properties including internal bonding and modulus of rupture (MOR) of oil palm empty fruit bunch (OPEFB) particleboard compared to 2% concentration of additive. Particleboards with additional 4% of acrylamide or polyethylene glycol (PEG) achieved the highest modulus of rupture (mean value 22 MPa), internal bonding strength (mean value 1 N/mm³), and the lowest thickness swelling (mean value 9%).
4. An addition of additive up to of 4% concentration did not further deteriorate the physical and mechanical properties of OPEFB particleboard. All the particleboards produced with 4% of water-soluble additive achieve the requirements of JIS A 5908:2003 for the physical and mechanical properties.

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