

DRYING OF OIL PALM LUMBER BY COMBINING FORCED-AIR DRYING AND MODIFIED SUPER-FAST DRYING METHODS

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ABSTRACT

In this study, super-fast drying (SFD) method was modified by adding forced-air drying (AFD) method in the beginning stage. The modified drying method is called modified super-fast drying (MSFD). This method eliminates the holing process in SFD and makes it more favourable by wood-based manufacturers. Inner and outer portion of oil palm lumber (OPL) were segregated and dried using both SFD and MSFD methods. The drying rate and drying defects of the OPL dried with AFD method were compared with conventional air drying (AD) method. The OPL dried with MSFD were compared with SFD in terms of drying defects, rate, physical and mechanical properties. The results revealed that AFD method exhibited significantly effective drying rate compared to AD by shorten the time needed to achieve desired moisture content (MC). On the other hand, MSFD were found to be able to reduce the outer OPL to 10% within 3 hr. The SFD method reported the same rate of drying performance. However, MSFD did not involve the unfavourable holing process as in SFD method. In addition, OPL dried using MSFD exhibited better mechanical and physical properties than SFD. The findings suggested the MSFD method is an enhanced method compared to SFD method.

Keywords: drying procedure, drying rate, forced-air drying, modification, oil palm lumber.

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INTRODUCTION

Declining in the supply of traditional high density hardwood has made the attention of manufacturer shifted to other resources, for example, oil palm wood (*Elaeis guineensis*) owing to its enlarging area of plantation in Malaysia. Existing abundantly in the country and readily availability has made oil palm trunk (OPT) a very promising materials for the sustainability of wood-based industry. The total oil

palm planted area in Malaysia has seen a steadily increasing trend from the year of 2013-2019. In 2019, the total planted area of oil palm is recorded as 5.90 million hectares, an increase of 13.8% compared to the 5.23 million hectares recorded in the year of 2013 (MPOB, 2020; Mohammad Padzil *et al.*, 2020). The main agri-based wastes that existing in the country are oil palm biomass (in the form of fronds, trunks and fibres), paddy straw, rice husk, banana residues, sugarcane bagasse, coconut husk and pineapple waste (Goh *et al.*, 2010). Oil palm biomass is the main contributor among these agri-based wastes which accounted for 46 000 kilotonne in the form of fronds and 11 000 kilotonne in the form of trunks. Oil palm biomass has been utilised in producing a wide range of value-added products. Products manufactured using oil palm biomass include medium density fibreboard (Laemsak and Okuma, 2000), particleboard (Lee *et al.*, 2015; 2018), fibre reinforce cement board (Zhang *et al.*, 2020), fibre plastic composite (Liew *et al.*, 2000), plywood (Onoja

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et al., 2018), laminated-veneer lumber (Nordin *et al.*, 2004), biochar (Kong *et al.*, 2014), concrete (Zawawi *et al.*, 2020) and furniture (Ratnasingam and Ioras, 2010). Therefore, effective utilisation of these OPT could be beneficial to the wood-based industry in term of sustainability of raw materials supply.

Nevertheless, before oil palm wood (OPW) could be utilised effectively, drying of the materials is the utmost importance procedure. Minimisation of production costs could be achieved provided that an optimised drying process was adopted for woody materials. In addition, optimised drying process could also prevent productivity and quality lost. It was reported that moisture content (MC) is the highest at the core of oil palm stem and decreased when moving to the outer layer of the stem (Choo *et al.*, 2011; 2013). The MC of the oil palm stem could reach to an astonishing 500% as reported by previous studies (Lim and Khoo, 1986; Bakar *et al.*, 2008). Green MC of up to 300%-500% and density of 200-700 kg m⁻³ (Anis *et al.*, 2007) can be found mainly from the trunk. High MC found in oil palm lumbers (OPL) caused the drying process to be very time-consuming and higher energy is therefore needed to completely dried the lumber. In addition, the variation in MC across the oil palm stem make the drying of OPL have to be adjusted specifically according to lumbers obtained from different parts of the OPT. To date, an optimum drying schedule is yet to be developed for OPL. Thirty to 35 days is needed for drying OPL by using conventional drying method in kiln drier and resulted in many drying defects.

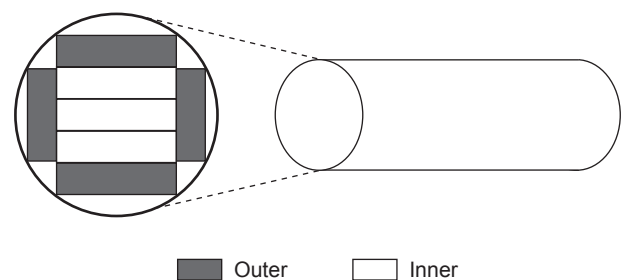
In order to resolve this matter, a drying method for OPL, called Oil Palm Lumber Drying Method and System Thereof, has been developed by Bakar *et al.* (2016). The concept of the method was to increase the evaporation rate of water from the material by using holing technique on the OPL. This method had successfully reduced the drying time of OPL from 30-35 days to approximately 3 hr. The method is called super-fast drying (SFD). The method involved drilling holes, or holing, on the OPL surface to accelerate the moisture reduction, followed by applying light compression to produce defect free board. This method requires high precision on the intermediate MC and therefore the drying process for inner and outer part of OPL are different. The inner portion of OPL requires two higher compressions cycle while the outer portion of OPL only undergoes one cycle with lower compression. Nevertheless, despite its effectiveness in drying OPL in a shorter time, the unattractive holes on the surface has repelled the manufacturers from using this OPL. To make the method more attractive to the wood industry, the drawback mentioned above needs to be solved in order to produce laminated products with two clear surfaces.

A preliminary study demonstrated that the OPL can be dried using SFD without holes provided the initial MC of the green OPW is lowered to less than 200%. Therefore, in this study, the initial MC of the outer and inner OPL were reduced by using forced-air drying (AFD) method prior to dried using SFD method. The new method, a combination of AFD and SFD methods, are called modified super-fast drying (MSFD) method. The MSFD method consist of two stages. The first stage involving the drying of OPL to intermediate MC of 60%, 80% and 100% using AFD method. The second stage involve the drying of OPL from intermediate MC to final target MC of <10% using SFD method. Using the MSFD method, the holing process in SFD method could be eliminated. Nevertheless, the drying rate and drying defects of the OPL using AFD method are still remained unknown. In addition, physical and mechanical properties of the OPL dried using MSFD in comparison to the conventional ai-dried method as well as SFD method have yet been documented. Therefore, the objectives of this study were to identify an optimum drying method without holing process for inner and outer OPL. Conventional air drying (AD) method was compared with the AFD method in terms of drying time, rate and defects.

MATERIALS AND METHOD

Material Preparation

Three 25-years old OPT with length of 4-5 m were purchased from a private company in Bandar Saujana Putra, Selangor, Malaysia. The OPT were cut into 200 cm in length and were sawn into planks of two different thicknesses, namely 3 cm and 5 cm, using modified cant sawing as shown in *Figure 1*. Modified cant sawing is a simpler method compared to polygon sawing and able to make sure a proper separation of inner and outer parts of OPL with higher recovery. The MC of the OPL were determined.



Source: Bakar *et al.* (2006).

Figure 1. Segregation of outer and inner portion of oil palm lumber using modified cant sawing.

Segregation Oil Palm Lumber (OPL)

Prior to drying, OPL were segregated based on the green MC. The OPL with green MC above 200% were regarded as inner part while OPL with green MC below 200% were regarded as outer part (Bakar *et al.*, 2016). The lumbers were sawn into two dimensions with different thicknesses, namely 3 cm x 15 cm x 200 cm and 5 cm x 15 cm x 200 cm (thickness x width x length) prior to drying process.

Drying Process

Air drying (AD) and forced-air drying (AFD) of OPL. The OPL samples were dried using AD and AFD method. The set-up of the AD method is shown in Figure 2. The set-up of the AFD method is shown in Figure 3. A fan was used to charge a direct air flow towards the OPL samples. The velocity of the air slow was set between 6-11 km hr⁻¹, measured by a thermos-anemometer. The OPL stacks dried with both AD and AFD method were consisted of two types of samples with different dimensions, namely 15 cm width x 150 cm length x 3 cm or 5 cm thick and 15 cm width x 40 cm length x 3 cm or 5 cm thick. The former was denoted as large samples while the latter were denoted as small samples.

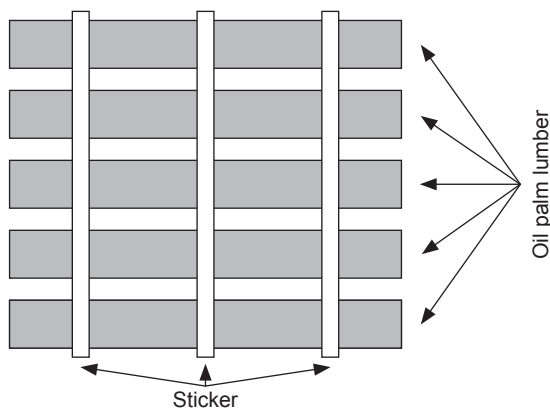


Figure 2. Top view diagram of air drying stacking of oil palm lumber.



Figure 3. Top view diagram of forced-air drying stacking of oil palm lumber.

Super-fast drying (SFD) of OPL. Figure 4 shows the drying procedure for inner and outer OPL, respectively. Both inner and outer plank of OPL were undergone holing process prior to Direct Contact Drying (DCD) processing. For outer part, the OPL were subjected to DCD with a compression of 20% at 180°C for 40 min and followed by a High Temperature Drying (HTD) at 100 ± 3°C for 3 hr. As for inner part, the inner OPL were subjected to two cycles of DCD instead of one as in outer OPL. The inner OPL were firstly subjected to 180°C for 40 min with a compression of 20% and then an additional cycle at the same temperature and compression for another 40 min before dried using HTD at 100 ± 3°C for 3 hr.

Modified super-fast drying (MSFD) of OPL. The MSFD method includes AFD in preliminary drying of the OPL where the holing process as in SFD method were omitted. The MSFD method consisted of three phases, namely, AFD process, DCD and HTD as shown in Figure 5. The OPL were underwent a preliminary drying of OPL using AFD method to achieve intermediate MC (100%, 80% and 60%). Then the OPL were subject to DCD method with a compression of 20% at 180°C for 40 min and followed by the HTD method at 100 ± 3°C for 3 hr.

Properties Evaluation

Moisture content (MC) and drying rate of OPL. The MC and drying rate of samples underwent AD, AFD and MSFD processes were recorded daily. The weight of the small samples was taken and recorded every day for the determination of MC and drying rate. In addition to that, the drying defects of the OPL under drying were recorded daily.

Drying defects of dried OPL. The drying defect of the AD, AFD and MSFD processes were recorded daily. The type of defects such as mechanical and physical defects were observed and recorded. Types of defects could include honey combing, warping and cracking as well as occurrence of stain and fungi.

Physical and mechanical properties of dried OPL. Physical and mechanical properties of the OPT dried using AD, SFD, MSFD at intermediate MC of 60%, 80% and 100% (MSFD 60, MSFD 80 and MSFD 100) were tested. The bending strength, modulus of rupture (MOR) and modulus of elasticity (MOE), of the lumbers were tested according to the procedures stipulated in EN 310:1993. As the bending strength of the samples are highly dependent on the final board density (Yano, 2001; Yano *et al.*, 2000; 1997), specific MOR and specific MOE were measured based on Equation (1) and

(2) to eliminate the effects of density (Garcia *et al.*, 2005; Xing *et al.*, 2007).

$$SMOR (Nmm^{-2}/g\ cm^{-3}) = \frac{MOR}{Density} \tag{1}$$

$$SMOE (Nmm^{-2}/g\ cm^{-3}) = \frac{MOE}{Density} \tag{2}$$

As for physical properties, water absorption (WA) and thickness swelling (TS) were evaluated in accordance with EN 317:1993. Samples with dimension of 50 mm width and 50 mm length were soaked into water for 24 hr. The TS and WA of the samples were expressed as a percentage increment of the initial thickness and weight of the sample after 24 hr immersion in the water.

RESULT AND DISCUSSION

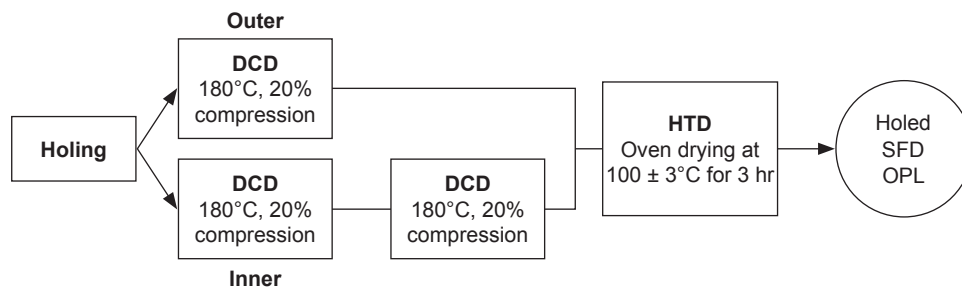
Drying Time of AFD and AD

Figure 6 illustrates the drying time of inner OPL using both AFD and AD. Inner parts of OPL with 3 cm and 5 cm thickness exhibits different drying times. Using AFD method, inner part with 3 cm thickness achieves MC of 100%, 80% and 60% at Days 8, 9 and 11, respectively. Meanwhile, 5 cm inner part attains intermediate MC of 100%, 80% and

60% at Days 11, 14 and 16, respectively. As for AD method, 3 cm inner part and 5 cm inner part achieve MC of 100% at Days 21 and 20, respectively and both achieve MC of 80% at Day 23.

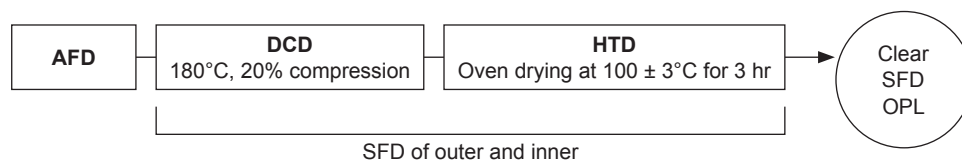
Figure 7 illustrates the drying time of OPL outer parts using both AFD and AD. Due to the fact that outer part has lower initial MC, it achieves targeted MC faster than that of the inner OPL for both AFD and AD method. Six, eight and 10 days were required for both the 3 cm and 5 cm outer OPL to be dried to 100%, 80% and 60%, respectively, using AFD method. As for AD method, the OPL with 5 cm thickness has a green MC of 150% and the 3 cm has lower green MC of 129%. A total of 5 cm OPL attain the targeted MC of 100% at Day 9 while the 3 cm OPL reach at Day 6. At Day 12, the MC of the 5 cm OPL reaches 80% and 60% at Day 18. Meanwhile, 3 cm OPL reaches MC of 80% and 60% at Days 9 and 16, respectively.

The findings were in agreement with Pfeiffer (1957) who recorded around 50% reduction in MC in lumber West Coast hemlock and Douglas fir after a two-weeks drying period using propeller fans. The OPL dried using AFD generally require shorter times to achieve targeted MC. Air flow is needed to transport the moisture away from the OPL. A constant air flow in AFD method gives the surrounding a uniform relative humidity and temperature (Eckelman and Baker, 1976). Equilibrium MC between surroundings and OPL could be achieved in an accelerated manner and making the drying process more efficient.



Note: DCD - direct contact drying; HTD - high temperature drying; OPL - oil palm lumber.

Figure 4. Procedure for super-fast drying (SFD) method.



Note: AFD - forced-air drying; DCD - direct contact drying; HTD - high temperature drying; SFD - super-fast drying; OPL - oil palm lumber.

Figure 5. Procedure for modified super-fast drying method.

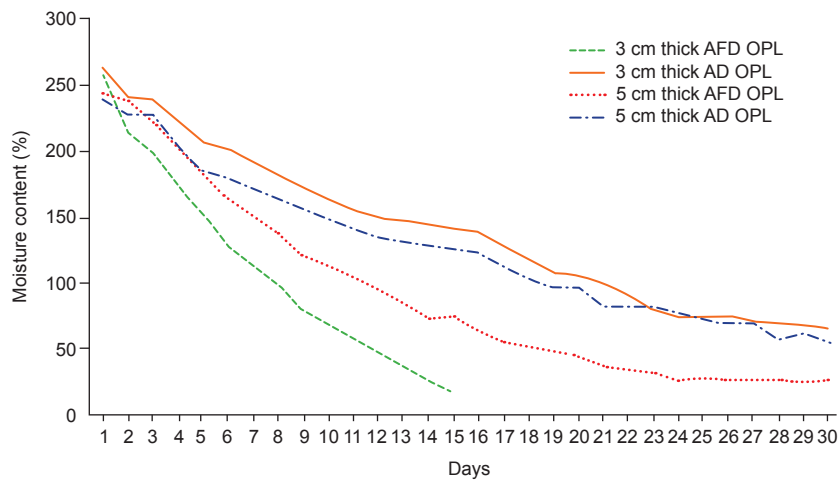


Figure 6. Moisture content reduction of inner oil palm lumber (OPL) dried using air drying (AD) and forced-air drying (AFD) method.

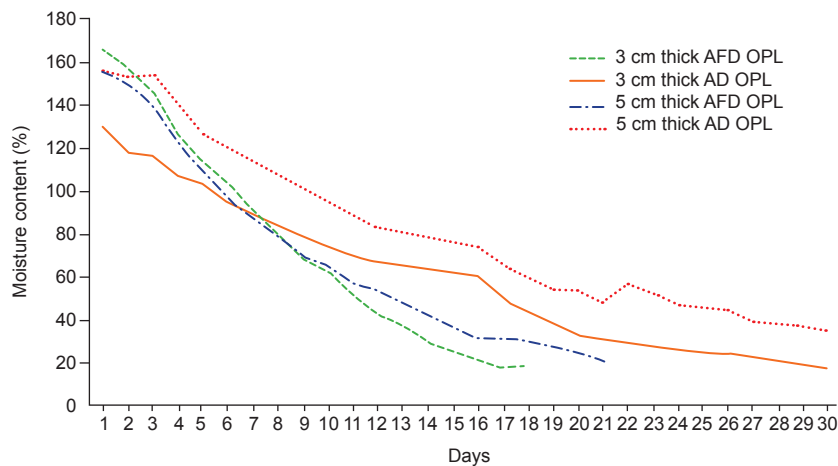


Figure 7. Moisture content reduction of outer oil palm lumber (OPL) dried using air drying (AD) and forced-air drying (AFD) method.

Drying Rate of AFD and AD

The drying rate of the AFD and AD methods are illustrated in *Figure 8*. It can be seen from the figure that AFD process accelerate the drying process significantly. The highest drying rate of 15.18% was recorded in 3 cm inner OPL when AFD was used. Thickness plays a significant role on the AFD method as 5 cm OPL samples generally have lower drying rate than that of the 3 cm OPL. In comparison to AFD, AD resulted in lower drying rate and the influence of thickness is not as significant as AFD. This observation might be due to the fact that AD is an uncontrolled drying where the moisture gradient in the samples is completely dependent on the temperature and relative humidity of the surroundings (Tschernitz and Simpson, 1979).

Table 1 summarises the drying time required for AFD and AD method to achieve target MC of 100%, 80% and 60%. Using AFD method, inner OPL with 3 cm and 5 cm thickness could attain target MC of 60% at Days 11 and 16, respectively. As for outer OPL, it required 10 days for both 3 cm and 5 cm OPL to achieve target MC of 60%. In comparison to the AD method, AFD greatly reduced the drying time needed. It would take 28 and 29 days for 3 cm and 5 cm inner OPL to achieve target MC of 60% using AD method. More than 16 days is needed for outer OPL to achieve 60% MC. In addition, AFD method also helps to decrease the drying defect when compared with AD method. Although some minor defects were also detected in AFD method, it is however, could be overcome during the SFD process where pressure was to be applied to the OPL.

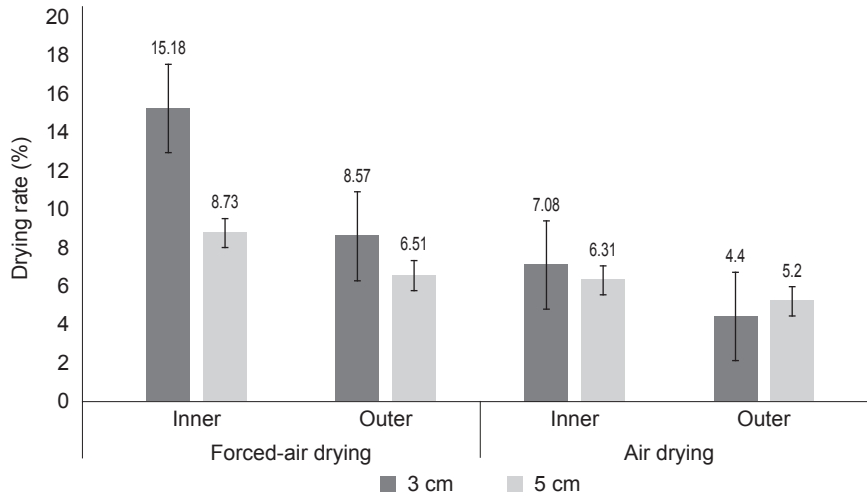


Figure 8. Drying rate of forced-air drying and air drying methods at different portions and thickness of oil palm lumber.

TABLE 1. DRYING TIME REQUIRED FOR FORCED-AIR DRYING AND AIR DRYING METHOD TO ACHIEVE TARGET MOISTURE CONTENT OF 100%, 80% AND 60% FOR THE INNER AND OUTER PORTIONS OF OIL PALM LUMBER (OPL)

| Treatments | Target moisture content (days) | | |
|--------------------------|--------------------------------|-----|-----|
| | 100% | 80% | 60% |
| Forced-air drying | | | |
| Inner OPL | | | |
| 3 cm | 8 | 9 | 11 |
| 5 cm | 11 | 14 | 16 |
| Outer OPL | | | |
| 3 cm | 6 | 8 | 10 |
| 5 cm | 6 | 8 | 10 |
| Air drying | | | |
| Inner OPL | | | |
| 3 cm | 21 | 23 | 28 |
| 5 cm | 20 | 23 | 29 |
| Outer OPL | | | |
| 3 cm | 6 | 9 | 16 |
| 5 cm | 9 | 12 | 18 |



Figure 9. Warping of inner oil palm lumber.



Figure 10. Cell wall collapse of inner oil palm lumber.

Drying Defect of AFD and AD of OPL

Drying defects could be observed from inner OPL on Day 3 using AFD method. However, the drying defects among samples were relatively low as only 9% of the total defected samples were identified. On the contrary, no defect was found on the outer OPL. From Figures 9 and 10, one can see that inner OPL experienced warping and cell wall collapse. Black moss was found on the surface of the OPL where these air-borne fungal spores are quite fine ($\leq 2.5 \mu\text{m}$) and settled on the OPL surface during the drying process.

On the other hand, AD method exhibited different observation compared to that of AFD method. Sap stain and fungal decay started to occur at Day 3 at the end butt and various places for both inner and outer OPL (Figure 11). The aforementioned defects were found to be more affected inner OPL than outer OPL. After a week, mechanical defect such as cell wall collapse started to be observed. At the end of the process, all the OPL samples were fully covered by the moss and unusable. These

findings are in agreement with Anis *et al.* (2016) who concluded that OPL has a low drying recovery due to high green MC and wide density variation.

Drying Rate of MSFD from Different Initial MC

Figures 12 and 13 exhibits the moisture reduction of outer and inner portion OPL dried using MSFD from three different intermediate MC, namely 100%, 80% and 60%. For outer OPL, it can be observed that MC are able to achieve less than 10% within 3 hr of drying. On the other hand, inner OPL with intermediate MC of 80% and 60% could be dried to less than 10% within 3 hr while inner OPL with intermediate MC of 100% required duration longer than 3 hr to reach MC of less than 10%. The MSFD method is a combination of DCD process and HTD process. The DCD process has facilitated the drying process by reducing the intermediate MC to more than half. Compression level of 20% applied during DCD has created some micro-cracks on the surface of the OPL. These micro-cracks accelerated the water evaporation process and making the entire drying process faster without compromising the quality of OPL. The HTD process were then ensued to bring

down the MC of the OPL to less than 10%. As a result, both inner and outer OPL with intermediate MC of 100%, 80% and 60% was able to achieve MC less than 10% within 3-4 hr.

Drying Defect of MSFD from Different Initial MC

Visual appearance of the OPL dried with SFD and MFSD methods are shown in Figures 14 and 15. From Figure 14, one can see that no visible drying defect was detected during the drying process for both inner and outer OPL. In addition, no spring back or physical alteration was observed from the samples.

Performance of Dried OPL

Physical properties of MSFD of OPL. In this section, the properties of the OPL samples dried with MSFD method at intermediate MC of 60%, 80% and 100% (denoted as MSFD 60, MSFD 80 and MSFD 100) were compared with the samples dried using SFD and AD. The TS and WA of both inner and outer OPL dried using AD, SFD and MSFD methods are shown in Table 2.

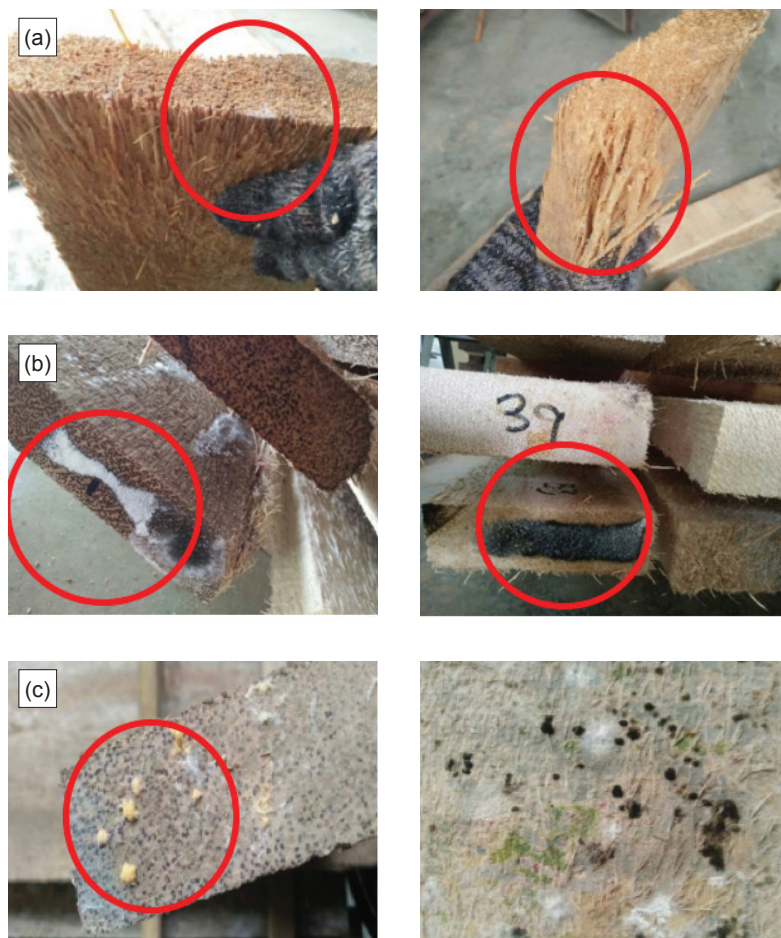
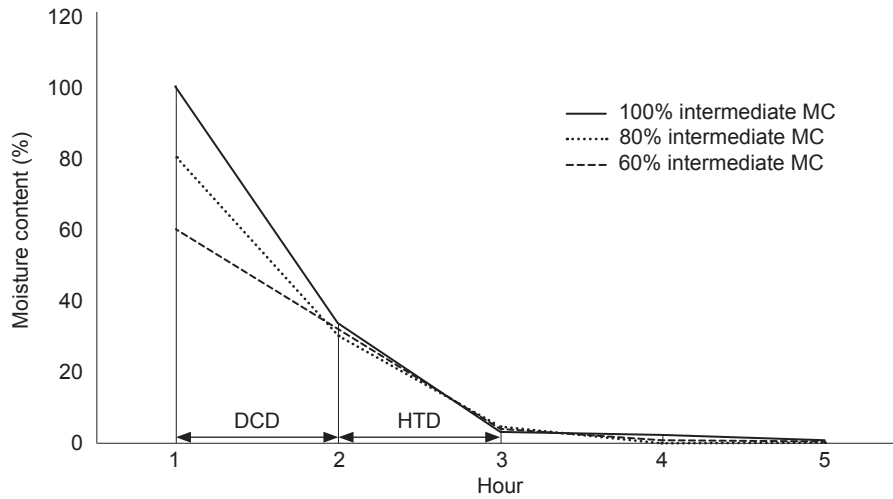
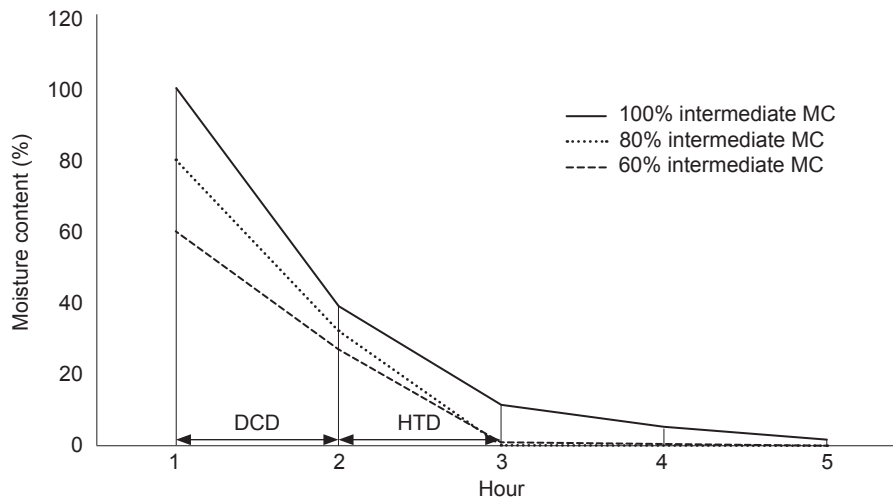


Figure 11. Types of drying defect of oil palm lumber dried with air drying method (a) cell wall collapse, (b) sap stain, and (c) fungal decay.



Note: DCD - direct contact drying; HTD - high temperature drying.

Figure 12. Moisture reduction of outer oil palm lumber using modified super-fast drying from intermediate moisture content (MC) of 100%, 80% and 60%.



Note: DCD - direct contact drying; HTD - high temperature drying.

Figure 13. Moisture reduction of inner oil palm lumber using modified super-fast drying from intermediate moisture content (MC) of 100%, 80% and 60%.



Figure 14. Visual appearance of oil palm lumber samples dried with super-fast drying method.



Figure 15. Visual appearance of oil palm lumber samples dried with modified super-fast drying method (top – outer portion; bottom – inner portion).

Inner OPL dried using AD method has TS and WA of 2.33% and 97.96%, respectively. However, when the inner OPL was dried using SFD, increment in TS (10.42%) and WA (141.10%) was recorded. This phenomenon could be attributed to the holes in the samples dried using SFD method. In order to remove excess MC, an additional step of holing was added to the SFD method. The existence of holes increased the surface area and enables more water to penetrate into the samples and resulted in higher TS and WA. As for MSFD method, samples that dried at intermediate MC of 100% and 80% exhibited lower TS compared to that of SFD but still significantly higher than that of the AD method. However, it is interesting to note that inner OPL samples that dried with MSFD method at intermediate MC of 60% displayed comparable TS value with AD method. The MSFD method has eliminated the holing process as in SFD method and therefore the surface area remained the same as original OPL samples. Nevertheless, pressure was applied to the samples during drying using MSFD method. Therefore, springback

might occur during the water immersion and resulted in higher TS compared to that of AD method. Similar trend was also observed for outer OPL.

Mechanical properties of MSFD of OPL. Tables 3 and 4 show the specific modulus of rupture (SMOR) and specific modulus of elasticity (SMOE) for inner and outer OPL, respectively. For inner OPL, the highest SMOR was recorded in the samples dried with MSFD at intermediate MC of 60%. Air-dried OPL has SMOR and SMOE of 53.73 MPa and 5900.88 MPa, respectively. Meanwhile, SFD samples was recorded to have SMOR of 55.45 MPa and SMOE of 6383 MPa. On the other hand, the highest SMOR was found in the samples dried with MSFD at intermediate MC of 100% for outer OPL. The OPL samples dried using MSFD involved a compression step during DCD. Therefore, the higher SMOR and SMOE could be attributed to the effect of densification. Hamzah *et al.* (2017) reported that the compression process is able to increase the density of the wood which in turn led to improved mechanical properties.

TABLE 2. PHYSICAL PROPERTIES OF OIL PALM LUMBER (OPL) DRIED USING SUPER-FAST DRYING (SFD), MODIFIED SUPER-FAST DRYING (MSFD) AT DIFFERENT PERCENTAGES OF MOISTURE CONTENT (MC) AND AIR DRYING (AD) METHOD

| Treatments | Inner OPL | | Outer OPL | |
|-----------------|------------------------|----------------------|------------------------|----------------------|
| | Thickness swelling (%) | Water absorption (%) | Thickness swelling (%) | Water absorption (%) |
| SFD | 10.42 ± 0.62a | 141.10 ± 18.49ab | 22.61 ± 2.91a | 151.69 ± 32.99a |
| MSFD at 100% MC | 8.66 ± 1.90ab | 183.05 ± 57.87a | 8.72.38 ± 4.07b | 88.66 ± 21.39bc |
| MSFD at 80% MC | 7.12 ± 3.02b | 136.29 ± 41.10ab | 6.46 ± 1.78b | 95.46 ± 27.89bc |
| MSFD at 60% MC | 2.73 ± 1.39c | 164.10 ± 79.18a | 6.14 ± 2.71b | 102.79 ± 17.79b |
| AD | 2.33 ± 1.50c | 97.96 ± 25.87b | 1.78 ± 0.71c | 73.25 ± 23.53c |

Note: Numbers after ± are standard deviation values; Means followed by the same letter in the same column are not significantly different at P≤0.05.

TABLE 3. SPECIFIC MODULUS OF RUPTURE (SMOR) AND SPECIFIC MODULUS OF ELASTICITY (SMOE) FOR INNER OIL PALM LUMBER (OPL) DRIED USING SUPER-FAST DRYING (SFD), MODIFIED SUPER-FAST DRYING (MSFD) AT DIFFERENT MOISTURE CONTENT (MC) AND AIR DRYING (AD) METHOD

| Treatments | Density | SMOR | SMOE |
|--------------|--------------|----------------|----------------------|
| SFD | 0.51 ± 0.27a | 55.45 ± 28.17a | 6 383.33 ± 2 744.32a |
| MSFD 100% MC | 0.24 ± 0.02b | 48.45 ± 14.23a | 4 906 ± 1 371.02a |
| MSFD 80% MC | 0.25 ± 0.01b | 41.71 ± 10.39a | 4 736.92 ± 1 538.47a |
| MSFD 60% MC | 0.26 ± 0.02b | 60.55 ± 10.66a | 6 376.47 ± 1 063.01a |
| AD | 0.29 ± 0.02b | 53.73 ± 8.89a | 5 900.88 ± 3 126.95a |

Note: Numbers after ± are standard deviation values; Means followed by the same letter in the same column are not significantly different at P≤0.05.

TABLE 4. SPECIFIC MODULUS OF RUPTURE (SMOR) AND SPECIFIC MODULUS OF ELASTICITY (SMOE) FOR OUTER OIL PALM LUMBER (OPL) DRIED USING SUPER-FAST DRYING (SFD), MODIFIED SUPER-FAST DRYING (MSFD) AT DIFFERENT MOISTURE CONTENT (MC) AND AIR DRYING (AD) METHOD

| Treatments | Density | SMOR | SMOE |
|--------------|---------------|-----------------|-----------------------|
| SFD | 0.43 ± 0.06ab | 29.63 ± 4.07c | 4 833.09 ± 1 282.84b |
| MSFD 100% MC | 0.45 ± 0.09a | 72.38 ± 24.81a | 8 450.27 ± 4 192.02a |
| MSFD 80% MC | 0.42 ± 0.07ab | 54.71 ± 13.71b | 7 056.25 ± 1 306.69ab |
| MSFD 60% MC | 0.38 ± 0.06ab | 63.07 ± 11.67ab | 7 919.40 ± 1 641.98a |
| AD | 0.34 ± 0.04b | 49.26 ± 8.09b | 6 271.67 ± 1 323.46ab |

Note: Numbers after ± are standard deviation values; Means followed by the same letter in the same column are not significantly different at P≤0.05.

CONCLUSION

Outer and inner OPL were dried using SFD and MSFD. The following conclusions could be drawn based on the current findings:

- i) Dissimilar to SFD, MSFD involves AFD at the beginning stage of drying instead of conventional AD method. The AFD method exhibited significantly effective drying rate compared to that of the AD method. Using AFD method, inner OPL achieved MC of 80% in nine days while AD method required 23 days for the inner OPL to attain MC of 80%. In the case of outer OPL, eight days are needed for the samples to be dried to around 80% MC. However, drying to 80% MC using AD method would require 12 days.
- ii) MSFD were found to be able to reduce the outer OPL with intermediate MC of 100%, 80% and 60% to less than 10% within 3 hr. As for inner OPL, OPL with intermediate MC of 80% and 60% could be dried to less than 10% within 3 hr while inner OPL with intermediate MC of 100% required longer duration, which is 3-4 hr to reach MC of less than 10%.
- iii) In term of physical properties, due to the application of pressure during drying and the springback effect after drying, OPL samples that dried using MSFD displayed higher TS and WA compared to samples dried using AD method. However, due to the inexistence of holes, MSFD has lower exposure area and consequently lower TS and WA in comparison to SFD method.
- iv) In term of mechanical properties, inner OPL dried using MSFD at intermediate MC of 60% has the highest SMOR. Meanwhile, outer OPL dried using MSFD at intermediate MC of 100% exhibited the highest SMOR and SMOE.

The findings suggested the MSFD method is an enhanced method compared to SFD method. Without the existence of holes in MSFD method, the dried OPL could be utilised for wider applications.

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