Chapter 3

Results and discussion

3.1 Preparation of palm oil based polyester polyol

Palm oil based polyester polyol was synthesized from palm kernel oil (PKO), which involves two steps of reaction. First stage was alcoholysis of the oil by a part of the polyol and second stage was esterification of the free hydroxyls by a polyacid [34]. The related reactions are schematically represented in Figure 3.0 and Figure 3.1.

3.1.1 Alcoholysis

PKO is a triglyceride. In alcoholysis, triglyceride was converted to monoglycerides in the presence of glycerol and potassium hydroxide catalyst as shown in Figure 3.0.

CH2OCOR	CH ₂ OH	КОН	CH2-OCO-R
CH-OCOR +	2 сн-он		з сн-он
CH2OCOR	 Сн ₂ он		Г СН ₂ ОН
Triglyceride Oil	Glycerol		Monoglyceride



3.1.2 Esterification

In the second stage, in the presence of dicarboxylic acids, such as phthalate anhydride and fumaric acid, polycondensation reaction between diol of monoglyceride and dicarboxylic acid to the formation of polyester polyol. Figure 3.1 represents the reaction of (A) diol with PA and (B) diol with fumaric acid.



Figure 3.1: Suggested reaction pathway of esterification of (A) diol with PA and (B) diol

with fumaric acid

3.2 Characteristics of palm oil based polyester polyol

3.2.1 FTIR analysis

Figure 3.2 compares the spectra between palm kernel oil before and after undergoing alcoholysis to form the polyol. A strong OH peak at 3453 cm⁻¹ appeared as the PKO was converted to monoglyceride, polyester polyol. Table 3.0 summarizes the major absorption peaks of polyester polyol.



Figure 3.2: Comparison of IR spectra between refined palm kernel oil before and after

alcoholysis

Table 3.0: Major absorption peaks of polyester polyol

Bonding	Wave number (cm ⁻¹)	
O-H stretching	3453	
C-H stretching	2914, 2853	
C=O stretching	1734	

Figure 3.3 shows the FTIR spectrum of diphenylmethane-4,4-diisocyanate (MDI). The peaks at 2271 cm⁻¹ and 1473 cm⁻¹ show the NCO stretching of the diisocyanate. The major absorption peaks are shown in Table 3.1.



Figure 3.3: FTIR spectrum of diphenylmethane-4,4-diisocyanate (MDI)

Bonding	Wave number (cm ⁻¹)
NH	3395
CH ₃ stretching	2917
NCO stretching	2271, 1435
Aromatic C=C stretching	1608, 1577, 1524
CH ₃ Bending	1435, 1373

Table 3.1: Major absorption peaks of diphenylmethane-4,4-diisocyanate (MDI)

Figure 3.4 illustrates the FTIR spectra of diisocyanate terminated prepolymer (MDI) and polyester polyol. The NCO groups on the prepolymer were clearly indicated at 2269 cm^{-1} . The other major absorption peaks are shown in Table 3.2.



Figure 3.4: FTIR spectra of (A) diisocyanate terminated prepolymer and (B) polyester polyol

Bonding	Wave number (cm ⁻¹)
C-H stretching	2929, 2851
NCO stretching	2269
C=O stretching	1727
C-CH ₃ stretching	1374
C-O stretch	1271
C-O-C stretch	1116

Table 3.2: Major absorption peaks of diisocyanate terminated polyester polyol

3.2.2 Determination of acid value of palm oil based polyester polyol

The procedure is according to ASTM 1639-90 with minor modifications. The acid number is equal to mg of potassium hydroxide required to neutralize the free carboxylic groups in 1 g of sample. The KOH solution was standardized by titrating with known weight of potassium hydrogen phthalate. Normality can be calculated by using equation 3.1. Table 3.3 shows the results of standardization.

Normality =
$$\frac{W}{Vx0.2042}$$
 [3.1]

W = weight of potassium hydrogen phthalate (g)

V = volume of KOH solution required for titration of potassium hydrogen Phthalate (ml) Table 3.3: Results of standardization of KOH solution

Run	Weight of	Burette reading / ml			Normality
	sample/g	Before	After	Volume	
		titration	titration	used	
1	0.29	2.25	7.20	4.95	0.289
2	0.29	7.20	12.25	5.05	0.288
Average normality					0.289±0.001

Acid number can be calculated by using equation 3.2

Acid number =
$$\frac{Vx56.1xN}{S}$$
 [3.2]

V = volume of KOH solution for the titration of the sample (ml)

N = normality of KOH solution

S = weight of sample used (g)

Table 3.4:	Acid	number	deterr	ninatio	on
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Cook 1 (FA35-1)	First	Second
	determination	determination
Weight of sample, g	5.16	5.02
KOH required for titration for blank, ml (A)	0.10	0.10
KOH required for titration for sample, ml (B)	14.85	14.45
KOH required for titration, ml (B-A)	14.75	14.35
Normality	0.289	0.289
Acid value (mgKOH/g)	46.28	46.29
Average acid value	46.29	±0.01

Table 3.4 shows the final acid value of the polyester polyol was 46.29 mg KOH/g.

Weight (W) of pthalic anhydride (PA) was 251.84 g and fumaric acid (FA) is 106.14 g respectively

Equivalent weight of PA was 74.1 and FA was 58 respectively

Number of acid equivalent (e_a) of PA = W of PA / Equivalent weight of PA

= 251.84 / 74.1 = 3.40

Number of acid equivalent (e_a) of FA = W of FA / Equivalent weight of FA

The initial acid value = ([(e_a) of PA + (e_a) of FA] x 56100) / \sum (W of PA + W of FA)

$$= [(3.40 + 1.83)56100] / (251.84 + 106.14)$$
$$= 819.61$$

Therefore, the % conversion for the reaction

- = 100% [(final acid value/ initial acid value) 100%]
- = 100% [(46.29/819.61) 100%]
- = 100% 5.21%
- = 94.79%

Table 3.5 represents the acid value and % conversion of the acid value of the polyester polyol. From the results, the acid value of FA35-1 is 46.29±0.01and the % conversion of the acid value is 94.79%. Acid value of FA35-2 is 46.07±0.01 and the % conversion of the acid value is 94.38%.

Table 3.5: Acid values and % conversion of the acid values of the polyester polyols FA35-1 and FA35-2

Polyester Polyol	Acid Value (mgKOH/g)	% Conversion of the acid
		value (%)
FA35-1	46.29	94.79
FA35-2	46.07	94.38

3.2.3 Determination of hydroxyl value of palm oil based polyester polyol

The hydroxyl numbers were determined according to ASTM D4274-88. It is important to determine the hydroxyl content of polyester polyol for the purpose of formulating polyurethane in later stage. Normality of NaOH can be determined from equation 3.1 (refer page 49). Table 3.6 represents the standardization result of NaOH solution.

Table 3.6: Result of standardization of NaOH solution

Run	Weight	Burette reading / ml			Normality
	of sample /	Before titration	After titration	Volume used	
	g				
1	2.01	1.00	20.70	19.80	0.49
2	2.00	20.80	40.50	19.70	0.49
Average normality			0.49±0.01		

Determination of sample size

Size of sample can be calculated by using equation 3.3

Sample size =
$$\frac{561}{estimated hydroxyl value}$$
 [3.3]

$$= \frac{561}{112.26}$$

= 4.99 g

Hydroxyl value can be calculated by using equation 3.4

Hydroxyl value =
$$\frac{[(B-A)N \times 56.1]}{W}$$
 [3.4]
= $\frac{[(104.4 - 86.7)0.4976 \times 56.1]}{5.0023}$
= 98.77 mg KOH / g sample

A = KOH required for titration of the sample in ml

B =KOH required for titration of the blank in ml

N = Normality of KOH

W = Weight of sample in g

	Sample 1	Sample 2
Weight of sample, g	5.0023	4.9996
KOH required for titration for blank, ml (<i>B</i>)	104.10	104.40
KOH required for titration for sample, ml (A)	86.70	86.55
KOH required for titration, ml (<i>B</i> - <i>A</i>)	17.40	17.85
Normality	0.4976	0.4976
Hydroxyl value (mg KOH/g)	98.77	99.67
Average hydroxyl value	99.2±1.0	

Table 3.8: Comparison between the estimated and experimental hydroxyl values of both

Polyester Polyol	Expected Hydroxyl Value (mg KOH / g)	Hydroxyl Value (mg KOH / g)	Deviation (%)
FA35-1	112.3	99.2	11.6
FA35-2	112.3	100.2	10.8

polyester polyols

Table 3.7 shows the result of the hydroxyl value and Table 3.8 represents the estimated and experimental hydroxyl values of both polyester polyols. In general, the experimental hydroxyl values were found to be about 12% lower than the calculated values depending on the completion of the reaction conditions, such as reaction temperature and duration of the reaction. In this case under the same formulation of the

reaction, the difference between experimental and theoretical values was in the range of 10.78% to 11.63%. From the results of acid values and hydroxyl values, the values of both acid and hydroxyl were repeatable. Thus, the polyester polyol can be reproducible.

3.2.4 Themogravimetric analysis (TGA)

Thermogravimetric analysis was used to study the thermal stability of the palm oil based polyester polyol (FA35-1). Figure 3.5 shows thermogram of a single stage mass loss of polyol. The initial degradation started at 278.11°C, reached maximum at 379.17°C. and finally completed at 427.78°C.



Figure 3.5: Thermogram for palm oil based polyester polyol (FA35-1)

3.2.5 Gel Permeation Chromatography Analysis

Table 3.9 summarizes the GPC results on the number average molecular weight (M_n) and weight average molecular weight (M_w) of each of the palm oil based polyester polyols which were FA 35-1 and FA 35-2. From Figure 3.6 and Figure 3.7, the maximum peak of molecular weight distribution of FA 35-1 and FA 35-2 are 852 and 1106 respectively. The polydispersity indexs (Q) of two polyester polyols were 1.51 and 1.49 respectively.

Table 3.9: Number average molecular weight and weight average molecular weight of each of the palm oil based polyester polyols as determined by GPC

Polyester	Number Average	Weight Average	
Polyol	Molecular Weight	Molecular Weight	
	(M _n), g/mol ⁻¹	$(\mathbf{M}_{w}), \mathbf{g/mol}^{-1}$	
FA 35-1	1545	2333	
FA 35-2	1620	2407	



Figure 3.6: The maximum peak of molecular weight distribution of the palm oil based

polyester polyol (FA 35-1)



Figure 3.7: The maximum peak of molecular weight distribution of the palm oil based

polyester polyol (FA 35-2)

3.2.6 Water content of palm oil based polyester polyol

The water content was determined by Karl Fischer Titrator (Mattle Toledo). The amount of water present in palm oil based polyester polyol has to be accounted for in formulating the polyurethane binder since water can react with MDI. Table 3.10 shows the water content of the palm oil based polyester polyol (FA35-1). Generally the water content of polyester polyols was below 0.20%.

Polyester polyol	Water content (%)
1	0.19
2	0.19
3	0.19
Average	0.19

Table 3.10: Water content of palm oil based polyester polyol (FA35-1)

3.3 The mechanical properties of fiberboards made from palm fiber mat



Figure 3.8: Fiberboard made from palm fiber mat

3.3.1 Density

Figure 3.8 shows the fiberboard made from palm fiber mat. Density of the fiberboard was affected by two parameters which are binder content and curing pressure. In this study, the density of the fiberboard was in the range of 0.94 g/cm^3 to 1.26 g/cm^3 .

Figure 3.9 shows the effect of binder content on the density of the fiberboards. At the specified curing pressure, pressing time and temperature, the fiberboards were mixed with different amounts of the binder. It can be observed that the density of the fiberboard has increased when the content of binder was increased. This might be due to the presence of the voids in the matrix, fiber-matrix interface, or within the fiber lumens of the composite [16]. At higher binder content, the penetrations of binder into fiber mat more and filled up more voids. Thus the density of the fiberboard increased.



Figure 3.9: The effect of binder content on the density of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time

Figure 3.10 shows the effect of curing pressure on the density of the fiberboards at the specified binder content, curing time and temperature. As expected the density of the fiberboards increased as the curing pressure was raised due to the fact that under higher pressure the fiber mat became more compact.



Figure 3.10: The effect of curing pressure on the density of the fiberboards made from 30% binder content and cured at 100°C for 25 minutes curing time

3.3.2 Tensile strength of the fiberboards

3.3.2.1 The effect of binder content on the tensile strength of the fiberboards

Figure 3.11 shows the tensile strength of the fiberboards cured from 60° C to 100° C, pressed at 7 MPa for 25 minutes curing time. The tensile strength increased when PU binder content was increased. At curing temperature of 100° C, the tensile strength of fiberboard was 2.74±0.2 MPa at 10.63% binder content. When the PU binder content was increased to 16.41%, the tensile strength of the fiberboard was 3.56±0.3 MPa, almost 12% higher than the tensile strength of the fiberboard at 10.63% binder content. The tensile strength of the fiberboard was 4.57±0.3 MPa at 20.74% binder content, which was 28% higher than the tensile strength of the fiberboard at 16.41% binder content. The

tensile strength is 5.39 ± 0.3 MPa at 24.66% binder content, almost 18% higher than the tensile strength at 20.74% binder content. As the binder content was increased to 28.19%, the tensile strength of the fiberboard was 5.69 ± 0.2 MPa and 5.6% higher than the tensile strength at 24.66% binder content. The tensile strength of the fiberboard slightly increased to 5.76 ± 0.1 MPa as the binder content was increased to 31.42%, which was 1.2% higher than the tensile strength at 28.19% binder content. As the binder content was increased to 34.37%, the tensile strength increased to 5.81 ± 0.1 MPa. The difference of the tensile strength of the fiberboards between the 31.42% and 34.37% binder content was 0.86%. From the results, it can be seen that the increment of the tensile strength became less as the binder content goes up. This indicated that higher PU binder content can enhance the tensile strength to a certain limit. The tensile strengths of other fiberboards that were cured under same condition showed similar trend.



Figure 3.11: The effect of binder content on the tensile strength of the fiberboards cured from 60°C to 100°C, pressed at 7 MPa for 25 minutes curing time

The mechanical properties of the fiberboards are related to the compatibility between fiber matrix and PU binder. A good compatibility between fiber matrix and PU binder can contribute to a high tensile strength [35]. Palm fiber comprises mainly of cellulose, hemicellulose and lignin. There is possible reaction of OH groups of hydrophilic cellulose of palm fiber with NCO groups in the polyurethane chains (Figure 3.12). It has been reported that NCO can react with OH from lignocellulosic materials to form urethane linkages [36]. PU binder will penetrate into the pores of the fiber mat. In addition, hydrogen bonding may form between PU binder and cellulose fiber. At lower PU binder content, the distribution of PU binder among the cellulose may be insufficient. In the fiber mat, certain part of the fiber was thoroughly covered, whereas some parts might not be covered with sufficient PU binder. As a result, voids might be present between the binder and the fiber. On the other hand, as the PU binder content increases the distribution of PU binder into fiber become more even. Thus, voids between PU binder and fiber would be reduced [36].

The presence of voids would prevent the PU binder-fiber interface. Interface consists of the bond between fiber and matrix and the immediate region adjacent to this bond. The strength of interfacial bond in the composite would affect the mechanical properties of the composite. However, the interfacial bond in the composite depends on the chemical functionality between PU binder and fiber [37, 38]. Lignocellulosic fibers, being of natural origin, have a wide range of properties depending on the type, source and age of the lignocellulosic. Besides that, the condition of process will also affect the final fiber properties. Hence, it is difficult to obtain realistic fiber strength for a batch of fiber

and further estimate the theoretical strength [39]. The interface region in PU binder-fiber composite is very difficult to define and even more difficult to study [40].



Figure 3.12: The possible reaction of OH groups of hydrophilic cellulose of palm fiber

with NCO groups of isocyanate

3.3.2.2 The effect of curing temperature on the tensile strength of fiberboards

Figure 3.13 shows the tensile strength of the fiberboards made from 10.63% to 28.19% binder content, pressed at 7 MPa for 25 minutes curing time. The tensile strength increased with curing temperature. At 20.74% binder content, the tensile strength of fiberboard was 2.01±0.1 MPa at curing temperature of 60°C. When the curing temperature was increased to 70°C, the tensile strength of the fiberboard was 2.63±0.1 MPa, almost 31% higher than the tensile strength of the fiberboard cured at 60° C. The tensile strength of the fiberboards was 3.38±0.1 MPa, 29% higher than the tensile strength of the fiberboard cured at 80°C. The tensile strength is 3.96±0.2 MPa at curing temperature of 90°C, which is 17% higher than the tensile strength cured at 80°C. As the curing temperature was increased to 100°C, the tensile strength of the fiberboard was 4.57±0.3 MPa and 15% higher than the tensile strength cured at 90°C. The tensile strength of the fiberboard was slightly increased to 5.01±0.2 MPa as the curing temperature increased to 110°C, which is 9.6% higher than the tensile strength cured at 100°C. As the curing temperature goes up to 120°C, the tensile strength increased to 5.05 ± 0.3 MPa. The difference of the tensile strength of the fiberboards between the curing temperature of 110°C and 120°C was 0.79%. However, when the curing temperature was increased to more than 100°C, the tensile strength of the fiberboard increased less appreciably. Similarly, the effect of curing temperature on tensile strength of the fiberboard displays same trend at other binder content.

The mechanism of curing process could be very complicated due to the uncertainty of the rate of the heat transfer from the platens surface to the fiber mat, the phase change, convection effects and loss of water vapor from the edge of the fiber mat [38]. Heat transfer plays vital role in fabricating the fiberboard. The fiber mats in between the platens contain palm fiber, adhesive and trace amount of moisture. These substances might change their physical or chemical properties during molding process, which may affect the heat transfer. The heat transfer increases when the temperature is increased. During pressing, the heat from the hot platens must be transferred to a satisfactory amount into the whole volume of the fiber mat. Due to that, most of the heat transfer in fiberboard pressing is achieved. Thus, the higher curing temperature would enhance the distribution of heat among the fiber mat [41, 42].



Figure 3.13: The effect of curing temperature on the tensile strength of fiberboards made from 10.63% to 28.19% binder content, pressed at 7 MPa for 25 minutes curing time

3.3.2.3 The effect of curing pressure on the tensile strength of fiberboards

Figure 3.14 depicts the effect of the curing pressure on the tensile strength of the fiberboard from 28.19% binder content and cured from 60°C to 100°C for 25 minutes curing time. Generally, it can be seen that the tensile strength of fiberboards increased when the curing pressure was increased. At curing temperature of 60°C, the tensile strength of the fiberboard was 1.06±0.3 MPa with curing pressure of 3 MPa. When the curing pressure was increased to 4 MPa, the tensile strength increased rapidly to 1.77±0.2 MPa, which is 67% higher than the tensile strength of the fiberboard with curing pressure of 3 MPa. The tensile strength of the fiberboard was increased to 2.13±0.3 MPa with curing pressure of 5 MPa. It was 20% higher than curing pressure 4 MPa. As the curing pressure was increased to 6 MPa, the tensile strength of the fiberboard was 2.75±0.4 MPa, almost 62% higher than curing pressure of 5 MPa. As the curing pressure goes up to 7 MPa, the tensile strength of the fiberboard was 2.93 ± 0.2 MPa. It is approximately 18% higher than curing pressure of 6 MPa. The tensile strength slightly increased to 3.00±0.3 MPa with curing pressure of 8 MPa. The difference of the tensile strengths between specimens pressed at 7 MPa and 8 MPa was 2.3% only. Similarly, the effect of pressure on tensile strength displayed the same trend at other curing temperatures.



Figure 3.14: The effect of curing pressure on the tensile strength of the fiberboards made from 28.19% binder content, cured from 60°C to 100°C for 25 minutes curing time

During the making of the fiberboard, lower pressure might produce insufficient bonding between fiber and binder. As a result, the tensile strength of the fiberboard will be low. As the pressure goes up, it will give more intimate contact between fibers and between fiber and binder. Thus, it will enhance the heat conduction and the interfacial strength between fiber and binder. Consequently, the tensile strength of the fiberboard will be increased [43].

During pressing, differential thermal expansion of the fiber and the binder might create a tensile stress in the binder along the fiber axis, and this will lead to a shear stress at the fiber-binder interface. The compressive stress strengthens the fiber-binder interface but the tensile stress weakens the fiber-binder interface [44]. It is complicated and hard to predict actually what affects the interaction of all residual stresses on the overall interface strength. This might be due to the orientation of the fiber in the fiberboard that was disoriented and the stresses between fiber-binder that are not uniform.

3.3.2.4 The effect of curing time on the tensile strength of fiberboards

Figure 3.15 represents the effect of curing time on tensile strength of the fiberboards from 28.19% binder content and pressed at 7 MPa and cured at 100°C. The tensile strength increases with increase in curing time. At the 10 minutes curing time, the tensile strength is 3.09 ± 0.1 MPa. The tensile strength increased to 4.97 ± 0.2 MPa as the curing time was increased to 20 minutes. It is 61% higher than that at 10 minutes curing time. When the curing time was increased to 30 minutes, the tensile strength was 6.02 ± 0.4 MPa which is 21% higher than the curing time at 20 minutes. The tensile strengths were 6.42 ± 0.5 MPa and 6.84 ± 0.2 MPa respectively at 40 and 50 minutes curing times. The tensile strength at 40 minutes curing time was 6.6% higher than the tensile strength at 30 minutes curing time. The tensile strength at 50 minutes curing time, the tensile strength at 40 minutes curing time. At 60 minutes curing time, the tensile strength at 50 minutes curing time. It can be seen that longer curing time above 40 minutes does not increase the tensile strength significantly.

Temperature in fiber mat, vapor pressure and compaction stress are all related to the pressing process [45]. In the early stages of pressing, fiber mat is in an unsteady state, and this will cause poor bonding strength development throughout the fiber mat. A minimum pressing time is required to transfer the heat needed to cure the binder [46]. The continual compression state occurs in the whole fiber mat during the consolidation period. Although the continual compression state increases the contact area among the fiber mat and subsequently improves the bonding between fiber and binder, it may also destroy the bonding that has already been formed [47]. At short curing time, time might be insufficient to complete the chemical reaction between fiber and binder, hence the bonding is not strong. As curing time increases, fiber and binder will react more completely, thus resulting in stronger bond.



Figure 3.15: The effect of curing time on the tensile strength of the fiberboards made

from 28.19% binder content and pressed at 7 MPa at 100°C

3.3.2.5 The effect of NCO/OH ratio on the tensile strength of the fiberboards

Figure 3.16 illustrates the effect of the NCO/OH ratio on tensile strength of the fiberboard pressed at 7 MPa and cured at 100°C for 25 minutes curing time. The tensile strength increased with the increase in NCO/OH ratio. At NCO/OH ratio of 1.0, the tensile strength was 5.69±0.2 MPa. The tensile strength increased to 7.33±0.2 MPa at NCO/OH ratio of 1.2. It was 29% higher than that at NCO/OH ratio of 1.0. When the NCO/OH ratio of 1.4, the tensile strength was 12.47±0.3 MPa, which is 70% higher than NCO/OH ratio of 1.2. The tensile strength was 16.57±0.5 MPa at NCO/OH ratio of 1.6, which is 33% higher than NCO/OH ratio of 1.4. As the NCO/OH ratio increased to 1.8, the tensile strength was 21.73±0.1 MPa, almost 31% higher than NCO/OH ratio of 1.6. At NCO/OH ratio of 2.0, the tensile strength increased 14%, from 21.73±0.1 MPa to 24.67±0.7 MPa. The tensile strength slightly increased to 24.85±0.4 MPa at NCO/OH ratio of 2.2, which is 0.73% higher than tensile strength at NCO/OH ratio of 2.2. This indicated that increase in NCO/OH ratio will increase the tensile strength of the fiberboards to a certain limit.

MDI was premixed with polyester polyol and then poured on to the surface of the fiber mat. After that, the fiber mat was placed between the platens of the compression machine under certain pressure and temperature. During molding, the isocyanate groups (–NCO) from MDI will react with hydroxyl groups (–OH) from polyol, wood fiber such as cellulose, hemicellulose and lignin to form polyurethane linkage (as shown in Figure 3.12). This will lead to cross linking between the fiber and binder during curing [48, 49]. At lower NCO/OH ratio, the isocyanate groups (–NCO) might not be sufficient to react

with hydroxyl groups (-OH) from polyol and hydroxyl groups (-OH) from fiber. Therefore, the urethane linkages between fiber and binder become less and crosslink might not occur between fiber-binder matrix. As a result, the tensile strength was lower at lower NCO/OH ratios. In contrast, as the NCO/OH ratio was increased, the isocyanate groups (-NCO) is adequate to form urethane linkages and crosslink might occur between the fiber-binder matrix. This would enhance the covalent bonds in the PU chains and hence increased the tensile strength. However, if the NCO/OH ratio was too high, the urethane linkages would increase progressively and the PU chains become rigid due to the excess of the isocyanate groups (-NCO) [50]. This would make the PU binder brittle and the mechanical properties of the composite would be affected [51, 52]. Besides that, when an excess isocyanate was used, biuret and allophanate would be formed at higher temperatures (as shown in Figure 3.17). Thus, the network of the fiber-binder matrix might be influenced [50]. Figure 3.18 represents the possible crosslink between fiber-binder matrix.



Figure 3.16: The effect of NCO/OH ratio on the tensile strength of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time



Figure 3.17: Biuret and allophanate formation at higher temperatures [50].



Figure 3.18: The possible crosslink between fiber-binder matrix

3.3.3 The Young's modulus of fiberboards

3.3.3.1 The effect of binder content on the Young's modulus of fiberboards

Figure 3.19 represents the effect of the binder content on the Young's modulus of the fiberboards cured at 100°C at 0.7 GPa for 25 minutes curing time. It can be seen that the Young's modulus increased with the binder content. The Young's modulus of the fiberboard increased from 0.36 GPa to 0.53 GPa as the binder content was increased from 10.63% to 16.41%. The Young's modulus of the fiberboard was 0.65 GPa and 0.72 GPa respectively at 20.74% and 24.66% binder content. As the binder increased to 28.19%, the Young's modulus of the fiberboard was 0.78 GPa. The Young's modulus of the fiberboard increased to 820MPa at 31.42% binder content and slightly increased to 0.83 GPa at 34.37% binder content. The Young's modulus difference between the 35% binder content and the 40% binder content is only 1.2%.

This indicated that higher binder content would produce greater Young's modulus. Young's modulus is defined as ability of the material to resist deformation when external forces are applied [44]. Wood fiber is the main constituent of the fiberboard and could affect the Young's modulus of the fiberboard. Cellulose fiber has been shown by x-ray diffraction study that the constituent molecules exist in a definite crystal pattern in certain region of the fiber, the crystalline region. In the other region of the fiber, the molecular arrangement is more random and less compact and is referred to as amorphous. The ratio of the crystalline to amorphous cellulose has an appreciable effect on the Young's modulus of cellulose fibers [53]. The fibers have higher strength at

crystalline region compared to amorphous region. Moreover, the covalent bond between fiber and binder would affect the Young's modulus of the fiberboard significantly. At low binder content, the intermolecular forces will be less, and the amorphous region is more than the crystalline region, resulting in decrease of the Young's modulus due to the fiberbinder interface being easy to deform when the external load is applied. At high binder content, the intermolecular force is sufficiently strong and the crystalline region is increased, thus enhancing the fiber-binder interfaces and resists the deformation. Consequently, the Young's modulus of the fiberboard would be increased.



Figure 3.19: The effect of PU binder content on the Young's modulus of fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time

3.3.3.2 The effect of curing temperature on the Young's modulus of fiberboards

Figure 3.20 illustrates the effect of the temperature on the Young's modulus of the fiberboards made from 28.19% binder content and pressed at 7 MPa for 25 minutes curing time. It can be observed that the Young's modulus increased with the temperature. The Young's modulus of the fiberboards increased from 0.27 GPa to 0.41 GPa as the temperature was increased from 60°C to 70°C. The Young's modulus of the fiberboard was 0.67 GPa and 0.70 GPa respectively at 80°C and 90°C curing temperature. As the curing temperature increased to 100°C, the Young's modulus of the fiberboard was 0.78 GPa. The Young's modulus increased to 0.80 GPa at 110°C and only increased to 0.81 GPa at 120°C curing temperature. The Young's modulus difference between 110°C and 120°C curing temperatures was 1.3%. This could be attributed to the strong covalent bond formed between fiber and binder. The strong covalent bond might resist towards the deformation of the fiber-binder interface [16].



Figure 3.20: The effect of curing temperature on the Young's modulus of fiberboard made from 28.19% binder content and pressed at 7 MPa for 25 minutes curing time

3.3.3.3 The effect of curing pressure on the Young's modulus of fiberboards

Figure 3.21 shows the effect of the curing pressure on the Young's modulus of the fiberboards made from 28.19% binder content and cured at 100°C for 25 minutes curing time. It was obvious that the Young's modulus had increased with the curing pressure. The Young's modulus of the fiberboards increased from 0.21 GPa to 0.33 GPa as the curing pressure is increased from 3 MPa to 4 MPa. The Young's modulus of the fiberboards was 0.56 GPa and 0.74 GPa respectively at 5 MPa and 6 MPa. As the curing pressure increased to 7 MPa, the Young's modulus of the fiberboard was 780 MPa and remains the same as the curing pressure is increased to 8MPa. Initially, increasing the

curing pressure improves the Young's modulus of the fiberboard. However, above 6 MPa, the Young's modulus of the fiberboard increased more slowly and was almost constant at 8 MPa.



Figure 3.21: The effect of pressure on the Young's modulus of fiberboards made from 28.19% binder content and cured at 100°C for 25 minutes curing time

3.3.3.4 The effect of NCO/OH ratio on the Young's modulus of fiberboards

Figure 3.22 represents the relationship between NCO/OH ratio and Young's modulus of the fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time. It can be seen that the Young's modulus increased as the NCO/OH ratio was increased. The Young's modulus of the fiberboards increased from 0.71 GPa to 0.97 GPa as the NCO/OH ratio was increased from 1.0 to 1.2. The Young's modulus of the fiberboard was 1.21 GPa and 1.36 GPa respectively at 1.4 and 1.6 NCO/OH ratios. As the

NCO/OH ratio was increased to 1.8, the Young's modulus of the fiberboard was 1.57 GPa. The difference between the highest and the lowest Young's modulus was 36%. At 2.0 NCO/OH ratios, the Young's modulus was increased to 2.01 GPa and was slightly increased to 2.03 GPa at 2.2 NCO/OH ratio. These results indicated that the extent of cross-linkages between fiber-binder matrix interfaces increases the Young's modulus [50]. However, at higher NCO/OH ratio, the PU binder became brittle due to the excess of the isocyanate groups (– NCO) and thus affected the mechanical properties of the fiberboard.



Figure 3.22: The effect of NCO/OH ratio on the Young's modulus of fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time

3.3.4 Flexural strength of the fiberboards

3.3.4.1 The effect of binder content on the flexural strength of the fiberboards

Figure 3.23 illustrates the effect of the binder content on the flexural strength of the fiberboards cured from 60°C to 100°C and pressed at 7 MPa for 25 minutes curing time. It can be observed that the flexural strength increased with the binder content. At 80°C, the flexural strength of the fiberboards increased from 15.8 MPa to 17.6 MPa as the binder content is increased from 10.63% to 16.41%. The flexural strength of the fiberboards were 20 MPa and 21.5 MPa respectively at 20.74% and 24.66%. As the binder content increased to 28.19%, the flexural strength of the fiberboard was 22.7 MPa. The flexural strength of the fiberboard increased to 22.9 MPa at 31.42% binder content and slightly increased to 23.5 MPa as the binder content was increased to 34.37%. The flexural strength difference between the 31.42% and 34.37% of the binder content was 2.6%.

The effect of bending of the beam is to put the upper fibers on compression and the lower fibers in tension. As external forces were applied on the beam of the fiberboard, it could be seen that the beam failure occurred at the lower surface. This indicates that the tension has led to beam failure [54]. Besides that, at higher binder content, more covalent bonds would be formed and the bonding between fiber-binder matrices would be much stronger. Thereby, the efficiency of stress transfers between the fiber-binder matrix would be enhanced and finally increases the flexural strength of the fiberboard [55].



Figure 3.23: The effect of binder content on the flexural strength of the fiberboards cured from 60°C to 100°C and pressed at7 MPa for 25 minutes curing time

3.3.4.2 The effect of curing temperature on the flexural strength of the fiberboards

With reference to Figure 3.24, it can be seen that the flexural strength increased as the curing temperature was increased. At 28.19% binder content, the flexural strength was 18.8 MPa with curing temperature 60°C. The flexural strength of the fiberboard was slightly increased to 19.9 MPa at curing temperature 70°C. The flexural strengths of the fiberboards were 22.7 MPa and 24.7 MPa respectively at curing temperature 80°C and 90°C. As the curing temperature increased to 100°C, the flexural strength of the fiberboard was 26 MPa. The flexural strength of the fiberboard increased to 26.6 MPa at curing temperature 110°C and slightly increased to 26.9 MPa at curing temperature 120°C. This indicated that the increased of the curing temperature accelerated the reaction between fiber and binder and crosslinking between the polymer chains of PU



binder. Thus the crosslinks in the fiber-binder matrix would increase the flexural strength of the fiberboard [56].

Figure 3.24: The effect of temperature on the flexural strength of the fiberboards made from 10.63% to 28.19% binder content and pressed at 7 MPa for 25 minutes curing time

3.3.4.3 The effect of curing pressure on the flexural strength of the fiberboards

Figure 3.25 depicts the effect of the curing pressure on the flexural strength of the fiberboards made from 28.19% binder content and cured at 100°C for 25 minutes curing time. It is obvious that the flexural strength increasewa with the pressure. The flexural strength of the fiberboards increased from 20.2 MPa to 22.6 MPa as the curing pressure was increased from 3 MPa to 4 MPa. The flexural strengths of the fiberboards were 29.7 MPa and 35.8 MPa respectively at 5 MPa and 6 MPa curing pressure. As the curing

pressure increased to 7 MPa, the flexural strength of the fiberboard increased to 37.4 MPa and slightly increased to 37.6 MPa at 8 MPa curing pressure. However, above 6 MPa curing pressure, the flexural strength of the fiberboard increased less appreciably. This indicated that at higher curing pressure, the increased of the flexural strength of the fiberboard was less significant [16].



Figure 3.25: The effect of curing pressure on the flexural strength of the fiberboards made from 28.19% binder content and cured at 100°C for 25 minutes curing time

3.3.4.4 The effect of NCO/OH ratio on the flexural strength of the fiberboards

Figure 3.26 shows the effect of the NCO/OH ratio on the flexural strength of the fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time. The flexural strength increased with the NCO/OH ratio. The flexural strength of the fiberboards

increased from 37.4 MPa to 41.3 MPa as the NCO/OH ratio was increased from 1.0 to 1.2. The flexural strengths of the fiberboards were 67.1 MPa and 85.8 MPa respectively at 1.4 and 1.6 NCO/OH ratios. As the NCO/OH ratio increased to 1.8, the flexural strength of the fiberboard increased to 101MPa. The flexural strength of the fiberboard increased to 123.4 MPa at 2.0 NCO/OH ratio and slightly increased to 124.1 MPa at 2.2 NCO/OH ratio. From the results, it can be seen that an increased in NCO/OH ratio increased the flexural strength of the fiberboards only to a certain extent.



Figure 3.26: The effect of NCO/OH ratio on the flexural strength of the fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time

3.3.5 Impact strength of the fiberboards

3.3.5.1 The effect of binder content on the impact strength of the fiberboards

Figure 3.27 illustrates the effect of the binder content on the impact strength of the fiberboards cured at 100°C and pressed at 7 MPa for 25 minutes curing time. It can be observed that the impact strength increased with the binder content. At 100°C curing temperature, the impact strength of the fiberboard increased from 3.28 kJ/m^2 to 3.92 kJ/m^2 when the binder content was increased from 10.63% to 16.41%. The impact strengths of the fiberboards were 4.63 kJ/m² and 5.75 kJ/m² respectively at 20.74% and 24.66% binder content. As the binder content increased to 28.19%, the impact strength of the fiberboard was 6.12 kJ/m². The impact strength increased to 6.53 kJ/m² at 31.42% binder content and slightly increased to 6.59 kJ/m² at 34.37% binder content.

Impact strength is a measure of the energy required to cause the damage and the failure within the composite. The broken part may be thrown a significant distance during breaking; the energy associated with this process should be subtracted from the energy absorbed to yield the true absorbed energy to cause failure [57]. The toughness of the fiber composite is mainly dependent on the fiber stress-strain behavior and related to the mechanical properties of the fiber composite [58]. During the impact test, the fiber might be pulled out from the binder or broken by itself. This would affect the impact strength of the fiberboard. As the binder content is increased, more covalent bonds would be formed between the fiber-binder matrices and would improve the toughness of the fiberboard. In contrast, weak interface at low binder content would lead to an easy break at the fiber-

binder matrices. This indicates that binder content affects the impact strength of the fiberboard significantly. This explanation is similar to that given for flexural strength.



Figure 3.27: The effect of binder content on the impact strength of the fiberboards cured at100°C and pressed at 7 MPa for 25 minutes curing time

3.3.5.2 The effect of curing temperature on the impact strength of the fiberboards

Figure 3.28 shows the effect of the curing temperature on the impact strength of the fiberboards made from 28.19% binder content and pressed at 7 MPa for 25 minutes curing time. It can be seen that the impact strength increased as the curing temperature was increased. At 30% binder content, the impact strength is 3.53 kJ/m² for 60°C curing temperature. The impact strength of the fiberboard was increased to 4.25 kJ/m² for 70°C curing temperature. The impact strengths of the fiberboards were 5.47 kJ/m² and 5.81 kJ/m² respectively at of 80°C and 90°C curing temperatures. The impact strength of the fiberboard increased to 6.12 kJ/m² at 100°C curing temperature. The impact strength was increased to 6.25 kJ/m² at 110°C curing temperature and slightly increased to 6.29 kJ/m² 120°C curing temperature. This indicated that the increased of the curing temperature accelerated the reaction between fiber and binder and crosslinking between the polymer chains of PU binder. Thus the crosslinks in the fiber-binder matrix would increase the impact strength of the fiberboard [53].



Figure 3.28: The effect of curing temperature on the impact strength of the fiberboards made from 28.19% binder content and pressed at 7 MPa for 25 minutes curing time

3.3.5.3 The effect of NCO/OH ratio on the impact strength of the fiberboards

Figure 3.29 depicts the results of the effect of the NCO/OH ratio on the impact strength of the fiberboard cured at 100°C and pressed at 7MPa and for 25 minutes curing time. The impact strength increases with the NCO/OH ratio. The impact strength of the fiberboards increased from 6.12 kJ/m² to 7.54 kJ/m² as the NCO/OH ratio was increased from 1.0 to 1.2. The impact strength of the fiberboard increased to 9.45 kJ/m² at 1.4 NCO/OH ratio. The impact strength was 10.71 kJ/m² as the NCO/OH ratio increased to 1.6. As the NCO/OH ratio increased to 1.8, the impact strength of the fiberboard increased to 12.83 kJ/m². At 2.0 NCO/OH ratio, the impact strength was increased to 14.24 kJ/m² and was slightly increased to 14.32 kJ/m² at 2.2 NCO/OH ratio. These results

show that at higher NCO/OH ratio, the urethane linkages formed between the fiberbinder matrix can absorb more energy and distribute it more efficiently in the composite [30]. Thus, increase in the NCO/OH ratio would increase the impact strength of the fiberboard. However, at higher NCO/OH ratio, the excess isocyanate groups (–NCO) would make the PU binder brittle and thus affects the mechanical properties of the composite as mentioned earlier [51, 52].



Figure 3.29: The effect of NCO/OH ratio on the impact strength of the fiberboards cured at 100°C and pressed at 7 MPa and for 25 minutes curing time

3.3.6 Water absorption of fiberboards

3.3.6.1 The effect of the binder content on the water absorption of the fiberboards.

Table 3.11: Water absorption of fiberboards with different binder contents after soaking in water for 2 hours and 24 hours

Binder Content (%)	2 Hours	24 Hours
10.63	92.7%	109.2%
16.41	85.7%	90.3%
20.74	73.9%	85.6%
24.66	57.3%	68.5%
28.19	47.5%	55.8%
31.42	36.9%	44.8%
34.37	33.2%	39.5%

Table 3.11 shows the effect of the binder content on the water absorption of the fiberboards after soaking in water for 2 hours and 24 hours. The fiberboards were pressed at 7 MPa at 100°C for 25 minutes curing time. It can be seen that water absorption decreased as the binder content was increased. The water absorption increased rapidly for the first two hours and increased less appreciably until 24 hours. The main constituent of the fiberboard is wood fiber. Wood fiber is hydrophilic in nature because of an abundance of hydroxyl groups (–OH) so that the wood fiber has a very strong affinity for water [56]. In addition to that, the water absorption of the fiberboard may also be due to

the capillary action when fiber ends are exposed to water. The capillary action may contribute to the lumens of fiber [59, 60].

The improvement of water resistant of fiberboards could be explained by an improved fiber-binder matrix adhesion. During molding the fiberboards were under curing temperature and pressure and the hydroxyl groups of fiber will react with the isocyanate groups (NCO) of MDI and hydroxyl groups of polyester polyol to form urethane linkages. Thus, crosslinks might occur between the polymer chains of PU binder. At lower binder content, the penetration of PU binder is limited that it did not wet the fiber sufficiently. As a result, the hydroxyls groups of fiber could not react with binder completely and would make the fiberboard more susceptible to water absorption [60]. Besides that, voids might occur at the interface between the fiber and binder due to the insufficient PU binder. Thus, the adhesion between fiber and binder becomes poor and the water easily penetrates into voids when the fiberboard was exposed to water. Some hydroxyl groups of fiber could react with binder to form more urethane linkages and enhance the adhesion between the fiber and binder at higher binder content. Thus, the water absorption of fiberboard would be reduced. While the fiberboard was immersed in water, the free hydroxyl groups of fiber will form hydrogen bonding with water progressively within the first 2 hours. However, as the time goes on, there were no more hydroxyl groups to form hydrogen bonding. After certain time, the ability of fiberboard to absorb water would be saturated. This is why the water absorption of the fiberboard increased rapidly in the first 2 hours but tapered off as immersion in water reaached 24 hours.

3.3.6.2 The effect of NCO/OH ratio on the water absorption of the fiberboards.

Table 3.12: Water absorption of fiberboards with different ratios of NCO/OH after soaking in water for 2 hours and 24 hours

NCO/OH ratio	2 Hours	24 Hours
1.0	47.5%	64.1%
1.2	32.5%	33.9%
1.4	25.4%	27.2%
1.6	19.6%	20.3%
1.8	16.6%	17.4%
2.0	10.9%	11.1%
2.2	10.4%	10.6%

Table 3.12 illustrates the effect of NCO/OH ratio on the water absorption of the fiberboards after soaking in water for 2 hours and 24 hours. The fiberboards were pressed at 7 MPa at 100°C for 25 minutes curing time. It can be observed that water absorption decreases as NCO/OH ratio was increased. The water absorption of the fiberboard decreased from 47.5% to 10.4% as NCO/OH ratio was increased from 1.0 to 2.2. During pressing of the fiberboard, the isocyanate groups (–NCO) will react with hydroxyl groups (–OH) to form urethane linkages. Thus, crosslinks might occur between polymer chain and PU binder. This would reduce the availability of the hydroxyl groups for water interaction and would enhance the retain water nature of wood fiber. That is why the increase in the NCO/OH ratio would reduce the water absorption of the fiberboard [61].

3.3.7 The swelling thickness of the fiberboards

3.3.7.1 The effect of the binder content on the swelling thickness of the fiberboards

Table 3.13: Swelling thickness of fiberboards with different binder contents after soaking in water for 2 hours and 24 hours

Binder Content (%)	2 Hours	24 Hours
10.63	42.7%	58.3%
16.41	34.9%	48.5%
20.74	30.5%	45.7%
24.66	27.1%	39.2%
28.19	24.4%	34.8%
31.42	20.6%	27.9%
34.37	19.1%	25.3%

Table 3.13 shows the effect of the binder content on the swelling thickness of the fiberboards after soaking in water for 2 hours and 24 hours. The fiberboards were pressed at 7 MPa at 100°C for 25 minutes curing time. It was found that the thickness swelling decreased as the binder content was increased. Thickness swelling might be due to the expansion of the spaces existing between the concentric lamellae, between the fibrils and the fibers and also may be between the microfibrils themselves [62]. The cellulose wall comprises of primary wall and secondary wall. The secondary wall contains outer layer, middle layer and inner layer. The middle layer of the secondary wall contributes most to

the physical properties of cellulose fiber [63]. The main body of the middle layer displays orientation nearly parallel to the long axis of the cell. The orientation causes the cellulose fibers to swell appreciably in thickness but less appreciably in length [62]. When the fiberboard was immersed into water, it absorbed the water and the water swelled the fibers. Thus, the thickness of the fiberboard swelled significantly upon soaking in water for the first 2 hours and became less for the 24 hours.

3.3.7.2 The effect of NCO/OH ratio on the swelling thickness of the fiberboard

Table 3.14: Swelling thickness of fiberboards with different NCO/OH ratios of after soaking in water for 2 hours and 24 hours

NCO/OH ratio	2 Hours	24 Hours
1.0	34.9%	48.5%
1.2	13.5%	25.1%
1.4	5.5%	10.3%
1.6	4.8%	9.3%
1.8	4.1%	8.6%
2.0	2.2%	5.1%
2.2	2.2%	3.6%

Table 3.14 illustrates the swelling thickness of fiberboards with different NCO/OH ratios. After soaking in water for 2 hours and 24 hours, the fiberboards were pressed at 7 MPa at 100°C for 25 minutes curing time. The thickness swelling decreased

from 34.9% to 2.2% for the first 2 hours as NCO/OH ratio was increased from 1.0 to 2.2. This indicated that increase in NCO/OH ratio would enhance the fiber-binder matrix hence prevents the cell wall from swelling [64].

3.4 The mechanical properties of fiberboards made from fine palm fiber

The second set of the fiberboards were made from fine palm fiber. The fiberboards were cured at 100°C at 7 MPa for 25 curing time, similar conditions as those made from palm fiber mat. The length of fine palm fiber was from 3-5 mm whereas the length of palm fiber mat was from 50-100 mm. Figure 3.30 shows the fiberboard made from fine palm fiber. Size of the fiber mat is 150x150x6 in mm.



Figure 3.30: Fiberboard made from fine palm fiber

3.4.1 The tensile strength of the fiberboards

Figure 3.31 represents the tensile strength of two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time. It can be seen that the tensile strength of fiberboards made from fine palm fiber was higher than fiberboards made from palm fiber mat. This might be due to the fine fiber having larger surface area per volume for interaction of hydroxyl groups from palm fiber with isocyanate groups [64]. Besides that, the natural poor bonding between long fiber and binder also might reduce the mechanical properties of the fiberboard. The surface area of the fibers is also significantly increased resulting in a better bonding [65].

The fiber orientation is probably another factor that influences the tensile strength of the fiberboards besides curing temperature, curing pressure and curing time. Oriented fibers are strong as they are pulled in the fiber direction, but weak at transverse angles to the fiber direction. Fibers only have good tensile strength in the direction of the fibers [66, 67, and 68]. During molding, fine palm fiber is easier to form uniformly and directed in the direction of the fibers. Thus, the tensile strength of the fiberboard would be enhanced. However, as fibers in fiber mat are undirected, the external load may not be transferred uniformly among the fiber mat. In some region, the load may be larger than in other regions. Consequently, the tensile strength of the fiberboards will be reduced [35].



Figure 3.31: The effect of PU binder content on the tensile strength of two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time

3.4.2 The Young's modulus of the fiberboards

Figure 3.32 illustrates the Young's modulus of the two sets of fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time. It can be observed that the Young's modulus of the fine palm fiber fiberboards was higher than that of palm fiber mat fiberboard. The Young's modulus fine palm fiber fiberboards increased from 0.53 GPa to 1.06 GPa. The Young's modulus of fine palm fiber improved significantly if compared to palm fiber mat fiberboards. This could be attributed to the orientation of fine fiber which contributes towards the stiffness of the composite. Hence, the Young's modulus of the composite increases [64].



Figure 3.32: The effect of PU binder content on the Young's modulus of two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time

3.4.3 The flexural strength of the fiberboards

Figure 3.33 represents the flexural strength of the two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time. The impact strength of the fine palm fiber fiberboards was higher than that of palm fiber mat fiberboards. The impact strength of the fine palm fiber increased from 26.3 MPa to 56.8 MPa. It was almost 79% higher than palm fiber mat fiberboard. This is because the fine fiber would enhance the fiber-binder matrix (same as mentioned earlier on tensile strength), hence increases the ability of stress transfer [64].



Figure 3.33: The effect of PU binder content on the flexural strength of two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time

3.4.4 The impact strength of the fiberboards

Figure 3.34 depicts the impact strength of the two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time. The flexural strength of the fine palm fiber fiberboards was higher than that of palm fiber mat fiberboard. The flexural strength of the fine palm fiber increased from 4.24 kJ/m² to 7.02 kJ/m². This again shows similar trend as for tensile strength, MOE and flexural strength. This indicated that increase in the binder content can improve the mechanical properties of the composite.



Figure 3.34: The effect of PU binder content on the impact strength of two sets of the fiberboards pressed at 7 MPa and cured at 100°C for 25 minutes curing time

3.4.5 The water absorption of the fiberboards

Table 3.15: Comparison of the water absorption of two sets of fiberboards

Binder	2 H	lours	24 Hours		
Content	Palm fiber mat	Fine palm fiber	Palm fiber mat	Fine palm	
(%)	fiberboard fiberboard		fiberboard	berboard fiber	
				fiberboard	
10.63	92.7%	77.2%	109.2%	83.1%	
16.41	85.7%	60.9%	90.3%	73.7%	
20.74	73.9%	57.5%	85.6%	62.6%	
24.66	57.3%	42.6%	68.5%	51.5%	
28.19	47.5%	32.1%	55.8%	40.1%	

Table 3.15 shows the water absorption of the fiberboards made from palm fiber mat and fine palm fiber after soaking in water for 2 hours and 24 hours. It can be seen that the water absorption of the palm fiber mat fiberboards deceases from 92.7% to 47.5% as binder content was increased from 10% to 30% for the first 2 hours. At the same binder content, the water absorption of the fine palm fiber fiberboard decreased from 77.2% to 32.1% for the first 2 hours. This signifies that the fiberboards made from fine palm fiber could reduce the water absorption. This is because the fine fiber is in the fiber direction and this would enhance the fiber-binder matrix and thus resists absorption of water into the fiberboard.

3.4.6 The swelling thickness of the fiberboards

Table 3.16 Comparison of the swelling thickness of two sets of fiberboards

Binder	2 Hours		24 Hours	
Content	Palm fiber matFine palm fiber		Palm fiber mat	Fine palm fiber
(%)	fiberboard	fiberboard	fiberboard	fiberboard
10.63	42.7%	35.6%	58.3%	50.6%
16.41	34.9%	31.2%	48.5%	44.7%
20.74	30.5%	27.4%	45.7%	38.1%
24.66	27.1%	24.7%	39.2%	33.9%
28.19	24.4%	20.1%	34.8%	29.8%

The swelling thickness of two sets of the fiberboards is illustrated in Table 3.16. It can be observed that the thickness swelling of the palm fiber mat fiberboards decreased from 42.7% to 24.4% whereas the thickness swelling of the fine palm fiber fiberboards decreased from 35.6% to 20.1% for first 2 hours. This observation indicated that the fiber orientation does not improve the swelling thickness progressively.

3.5 The surface morphology of two sets of fiberboards

Figure 3.35 and Figure 3.36 show the surface morphology of two sets of fiberboards made from fine palm fiber and palm fiber mat respectively. Both fiberboards were made at 28.19% of binder content and pressed at 7 MPa at 100°C for 25 minutes curing time. It can be seen that more air bubbles are trapped inside the voids of the fiberboard made from fiber mat. This is because the fiberboards made from fine palm fiber are more compact than fiberboards made from palm fiber mat. Thus, the fiberboards made from fiber have better mechanical properties than the fiberboards made from fiber mat.



Figure 3.35: Fine fiber



Figure 3.36: Fiber mat (long fiber)

3.6 Comparison of the two sets of fiberboards with commercial fiberboards and commercial plywood

 Table 3.17: Mechanical properties of the commercial fiberboards, commercial plywood

 and the two sets of the palm fiberboards

Mechanical	Commercial	Commercial	Commercial	Commercial	Fine fiber	Fiber mat
properties	Plywood 1	Plywood 2	fiberboard 1	fiberboard 2	fiberboard	fiberboard
					(28.19%	(28.19%
					binder	binder
					content)	content)
Tensile	27.9	24.1	17.6	11.9	6.41	5.69
Strength (MPa)						
Modulus of	1301	1998	1991	1251	1060	780
elasticity						
(MPa)						
Flexural	17.9	10.33	21.2	20.9	56.8	26
Strength (MPa)						
Impact	2.73	3.59	8.71	3.86	7.02	6.12
Strength						
(kJ/m ²)						
Water	27.8	38.1	20.2	23.1	32.1	47.5
absorption						
after 2 hours						
(%)						
Thickness	15.8	17.9	20.8	22.9	20.1	24.4
swelling after 2						
hours (%)						

Table 3.17 shows the mechanical properties of the selected commercial fiberboards, plywoods and two sets of the palm fiberboards. Commercial plywood 1 was

bought from 'Jaya Do It Yourself Hardware Centre'. Commercial plywood 2 was bought from 'Meng Bingkai Cermin'. Commercial fiberboards were a kind gift from Mr Ng Kock Leong from Aura P.U Tech (M) Sdn Bhd. Commercial fiberboard 1 was made from recycled paper. Commercial fiberboard 2 was made from wood chips. All commercial boards and plywoods were tested under the same procedures as applied to the palm fiberboards. Each sample of commercial board and plywood was tested using five specimens and the average value was taken.

From Table 3.13, it can be seen that the tensile strength of the commercial plywoods and fiberboards covered a wide range of values; from the highest 27.9 MPa to the lowest 11.9 MPa. Among all the plywoods and the fiberboards, commercial plywood 2 has the highest modulus of elasticity. The commercial plywood 2 has the lowest flexural strength and the commercial plywood 1 has the lowest impact strength which is 10.33 MPa and 2.73 kJ/m² respectively. The commercial fiberboard 1 has the highest water absorption among all the fiberboards and plywoods. The commercial plywood 2. The fiber mat fiberboard has the highest water absorption and plywood 2. The fiberboards and plywoods.

Overall, both fine fiberboard and fiber mat fiberboard were comparable to other commercial plywoods and fiberboards.