CHAPTER IV

RESULTS AND DISCUSSION

In this chapter the research findings of important parameters from physical properties such as , moisture content and basic density of oil palm trunk (OPT), and mechanical properties of strength between those of dry OPL and densified gum rosin-treated samples are reported. The studies were performed in order to assess the variability of physical properties within the trunk.

4.1 Physical Properties of Oil Palm Trunk

In general, OPT log is inherently an extremely variable material, and any consideration of its physical and mechanical properties, in wet and dry state, must take this fact into count. One of the criticism often levied is that results of yield recovery on lumber drying and mechanical test of strength tend to be highly variable.

4.1.1 Moisture content

Values of mean MC in pith towards periphery zone of fresh OPT log with tree heights is given in Table 4.1. In general, variations of MC among the samples (from group A, in subgroup A-1) in radial direction at 1-m to 6-m of tree heights are as follows: 1-m height, MC ranged between 202.65% and 292.09%; 2-m height, MC ranged between 154.64% and 92.11%; 3-m height, MC ranged between 178.75% and 349.64%; 4-m height, MC ranged between 168.51% and 349.42; 5-m height, MC ranged between 193.32% and 368.25.

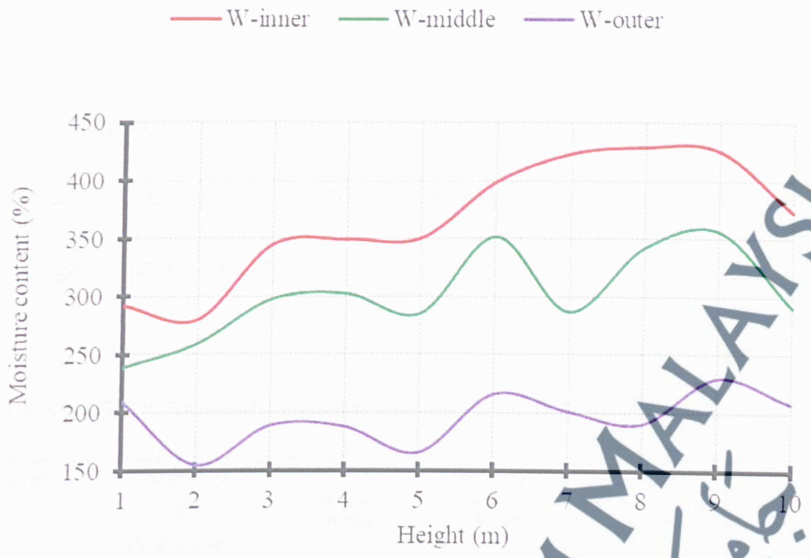
Table 4.1: Mean moisture content in pith to periphery zone of oil palm trunk with tree heights (%, based on oven-dry basis)

Height (m)	Positions of test sample in pith to periphery zone		
	Inner Zone	Middle Zone	Outer Zone
1	202.65 (24.18)	238.73 (23.99)	292.09 (7.17)
2	154.64 (12.82)	104.23 (16.02)	92.11 (15.53)
3	178.75 (8.38)	297.61 (16.42)	349.64 (18.67)
4	168.51 (10.38)	302.34 (15.64)	349.42 (19.01)
5	193.32 (12.28)	285.17 (9.49)	368.25 (16.17)
6	177.26 (10.23)	351.72 (15.26)	399.06 (26.41)
7	198.61 (26.30)	286.70 (22.45)	423.40 (25.02)
8	190.12 (26.92)	341.99 (18.56)	429.12 (10.23)
9	210.61 (17.74)	356.47 (20.44)	425.82 (18.54)
10	208.23 (20.26)	290.61 (12.89)	373.30 (16.96)

Standard error of the mean is shown in parenthesis, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

The MC value at 6-m height ranged between 177.26% and 399.06%; MC at 7-m height ranged between 198.61% and 423.40%; MC at 8-m height ranged between 190.12% and 429.12%; MC at 9-m height ranged from 210.61% and 425.82% while the MC at 10-m height ranged between 208.23% and 373.30%.

Figure 4.1 illustrates the MC distribution in pith towards periphery zone with tree heights. The curves indicate changes observed in the MC values for test samples of outer, middle and inner zones. As was seen for the sample position studies, these results suggest that all samples tend to show a slow gradual increase in MC as they move from the peripheral towards the inner zone with tree heights.



Outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius.

Figure 4.1: Spatial distribution of moisture content in pith to periphery zone of oil palm trunk with tree heights

These results suggest that it is likely the high MC at the inner and middle zones are due to the presence of parenchymatous tissues in large quantities than those of the outer zone (periphery) (Kamarudin, *et al.*, 1997). Killmann and Lim (1985), in their study observed an initial moisture content of similar magnitude (ranging from 100% to 500%), with the highest value near the pith and the lowest value at the periphery.

In the analysis of variance (ANOVA) results taken as a stem whole, the differences in MC were significant among positions along the radial direction, F(5, 534) = 145.76, $p<.05$. From Table 4.2, it was clearly showed that the MC was highest in pith ranged from 359.31% to 366.73% and lowest at the periphery zone ranged from 192.03% to 195.11% while MC at the intermediate zone ranged between 290.66% and 301.06%.

A post-comparison analyses using the Scheffe post hoc criterion for significance indicated that the zone effect between the inner, middle and outer zones proved to be highly significant (p<.05).

Table 4.2: Variations of moisture content in pith to periphery zone of oil palm trunk

Zone	Number of specimens	Moisture content (%)			
		Min	Mean*	Max	SE
Inner	90	359.31	363.77^{a}	366.73	7.56
Middle	90	290.66	295.36^{b}	301.06	6.66
Outer	90	192.03	193.49^{c}	195.11	4.92

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean. outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Table 4.3 shows the correlation of MC to the sample positions and height. The MC distribution and height level was positively correlated, r (540) = .28, *p*<.01, two-tailed. Pearson's correlation between the MC within OPT bole proved that the mean value of MC increased with an increase in heights. There was no significant correlation when comparing the respective value for the MC from the same spatial position and heights. However, when the variation in radial direction is considered, the MC was negatively related with sample position. These results suggest that it is likely the MC value decreases with an increase in the distance from the pith to periphery zone.

Table 4.3: Correlations of moisture content to sample positions and tree heights

	Moisture Content	Sample Position	Heights
Moisture content	—	-.03 n.s	.28**
Sample positions	-.03 n.s	—	.00 n.s
Heights	.28**	.00 n.s	—

** Correlation is significant at the 0.01 level (2-tailed); n.s denotes not statistically significant

4.1.2 Basic density

Table 4.4 gives the mean of BD values, in pith towards periphery zone of freshly felled OPT with tree heights. In general, variations of BD among the test samples (from group A, in subgroup A-2) in radial direction at different heights are as follows: 1-m height, BD ranged between 222.55 and 293.76 kg m^{-3}; 2-m height, BD ranged between 224.17 and 381.14 kg m^{-3}; 3-m height, BD ranged between 191.48 and 327.48 kg m^{-3}; 4-m height, BD ranged between 196.88 and 344.66 kg m^{-3}; 5-m height, BD ranged between 185.80 and 354.37 kg m^{-3}; 6-m height, BD ranged between 174.11 and 317.77 kg m^{-3}; 7-m height, BD ranged between 168.15 and 307.41 kg m^{-3}; 8-m height, BD ranged between 164.31 and 306.89 kg m^{-3}; 9-m height, BD ranged from 164.14 and 274.21 kg m^{-3} while the BD of 195.60 and 289.90 kg m^{-3} was located at the 10-m height level.

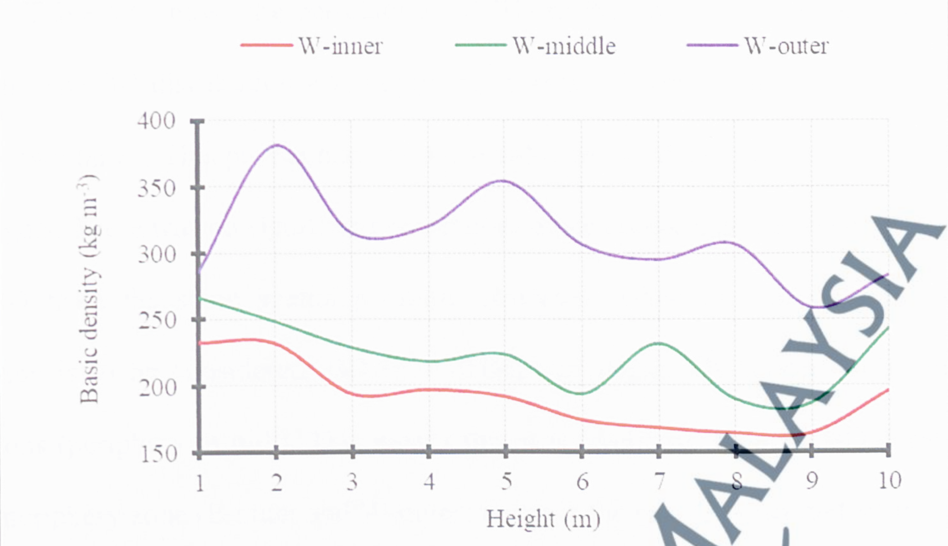
The BD distributions in pith towards periphery zone of OPT with heights is shown in Figure 4.2. The curves indicate that test samples obtained from the pith seemed to having the highest value at periphery zone and the lowest value in pith.

Table 4.4: Mean basic density in pith to periphery zone of oil palm trunk with tree heights (kg m^{-3})

Height (m)	**Positions of Test Sample, in Pith to Periphery Zone**		
	Inner Zone	**Middle Zone**	**Outer Zone**
1	222.55 (16.31)	266.65 (21.74)	293.76 (15.95)
2	224.17 (5.53)	248.35 (11.57)	381.14 (31.73)
3	191.48 (2.28)	228.57 (11.97)	327.48 (19.10)
4	196.88 (3.42)	218.04 (6.14)	344.66 (19.94)
5	185.80 (5.51)	223.34 (3.87)	354.37 (23.31)
6	174.11 (4.16)	193.57 (7.79)	317.77 (38.72)
7	168.15 (10.34)	231.46 (17.98)	307.41 (6.88)
8	164.31 (7.98)	189.80 (11.69)	306.89 (14.93)
9	164.14 (6.02)	186.80 (9.23)	274.21 (8.86)
10	195.60 (9.75)	242.78 (13.86)	289.90 (6.37)

Standard error of the mean is shown in parenthesis, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

As was seen for the sample position studies (Figure 4.2), these results suggest that all samples tend to show a gradual decrease in BD as the sample positions move from peripheral towards inner zone with tree heights. These results suggest that it is likely the high BD at the outer and middle zones are associated with the presence of parenchymatous tissues in lower amounts compared to the inner zone.



Outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Figure 4.2: Spatial distribution of basic density in pith to periphery zone of oil palm trunk with tree heights

Table 4.5 shows the mean BD value in pith to periphery of OPT. These results suggest that the BD was highest at the periphery zone ranging between 311.78 and 314.43 kg m^{-3} and lowest in pith ranging between 191.12 and 103.34 kg m^{-3}, while BD at the middle zone ranged between 222.25 and 230.23 kg m^{-3}.

Table 4.5: Variations of basic density in pith to periphery zone of oil palm trunk

Zone	**Number of Specimens**	**Basic Density (kg m^{-3})**			
		Min	**Mean***	**Max**	**SE**
Inner	87	191.12	103.34^{a}	299.75	3.56
Middle	87	222.25	227.11^{b}	230.23	4.67
Outer	87	311.78	312.59^{c}	314.43	7.21

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Table 4.6 shows the correlations of BD to the position of test samples and heights. The BD distribution was negatively correlated with heights, r (522) = -.26, p<.01, two tailed. This proves that the mean value of BD decreased with an increase in heights. There was no significant correlation when comparing the respective value for BD from the same spatial position. However, when the variation in radial direction is to be considered, BD (r = -0.04) was negatively related with sample positions (periphery to pith). This means that it is likely the value of BD decreases from periphery zone (E-outer and W-outer) towards the pith (E-inner and W-inner).

Table 4.6: Correlations of basic density to sample positions and tree heights

	Basic Density	**Sample Positions**	**Heights**
Basic Density	—	-.04 n.s	-.26**
Sample positions	-.04 n.s	—	.00 n.s
Heights	-.26**	.00 n.s	—

** Correlation is significant at the 0.01 level (2-tailed); n.s denotes not statistically significant

In general, the mean value of BD ranges from 191.12 to 314.43 kg m^{-3} with no defined zones of increasing or decreasing densities in radial direction. It is rather apparent that the OPT is composed of the so-called juvenile woody materials (densities of 250 kg m^{-3} and below), which is generally defined as a zone developing around the pith continuing towards the outer perimeters where its characteristics and properties are subject to gradual changes (Zobel and Sprague, 1998). The woody section of higher densities was concentrated in the periphery zone and partly in the intermediate zone. Depending on tree heights, the OPT log with the BD of 250 kg

m^{-3} and above, is mainly located outside a distance of 86 to 139 mm radius from its pith.

4.2 Impregnation of Oil Palm Lumber with a Gum Rosin

The successful performance of a bonded OPL product is the degree of wetting of gum rosin used. Like other types of wood adhesive, the gum rosin will stay bound together if the degree surface tension value of the gum rosin is greater than the surface-free energy value of OPL substrate. Conversely, when the surface-free energy value of the OPL substrate is higher than that of the gum rosin it allows the gum rosin to uniformly wet the OPL surfaces.

Sulaiman and co-workers (2009) mentioned that the contact angle on the surface of oil palm veneer was lower than the rubberwood. High wettability for OPL is partly due to high content of ground parenchyma cells, which will result in better penetration of gum rosin. A positive linear relationship was developed between the surface wettability and glue bond strength for bond integrity (Chen *et al.*, 1970).

4.2.1 Penetration of gum rosin into the lumber matrix

The vacuum infusion (VI) process used seemed to work well for the impregnation of OPL with gum rosin and it entered the lumber sample at a fixed point where the path resistance of gum rosin flow was minimum. The sample surface caused in micro-flow which progress between the vascular bundles and its parenchyma tissues, resulting in a non-homogenous flow front at the sample ends to that of the gum rosin. The resulting distance between the flow fronts is called lead-lag, is shown in Figure 4.3. The length of the lead-lag depends mainly on the permeability and the surface area of the sample used (Gabrielli and Kamke, 2010).

Permeability is a geometric parameter of OPL, which quantify how easily the gum rosin will flow through it. This geometric parameter is taken into account the porosity, which is the amount of void space in the OPL and is related to fibre volume fraction (Lopatnikov *et al.*, 2004). In resin infusion process, the higher the permeability suggests relatively shorter vacuum suction time is required, which may impose some limitations particularly if the gum rosin used is viscous.

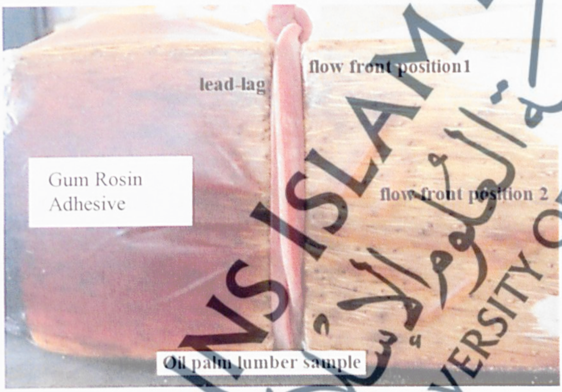


Figure 4.3: Creation of a lead-lag within the matrix of oil palm lumber during the resin impregnation process

For the VI process, the OPL sample (dimension: 100 mm wide by 100 mm thick by 400 mm long) took approximately two hours for wetting of the lumber matrix completely with the gum rosin. Too shorter the vacuum time would result in insufficient penetration and transfer of gum rosin whilst too long would cause the resin to pre-cure. One problem encountered with the presence of a lead-lag (Lee and Wei, 2000) is that the sample ends in contact with the gum rosin is fully filled before the rest of parts. If gum rosin gelation occurs before the sample is fully impregnated, a dry patch remain in the sample.

The precise reason for resin impregnation was not clearly understood. It was difficult to apply the Darcy's equation to directly predict and measure permeability because of the challenges in controlling all the variables (Patel *et al.*, 1995). For instance, OPL sawn from the same positions and heights of OPT possessed a significantly different microstructure, and therefore, will influence the permeability of the lumber sample (Waterhouse and Quinn, 1978).

Initially, problems of continuous resin flow within the matrix of dried lumber seemed unavoidable. It was noted that drying of OPL causes its surfaces to be 'inactivated' to resin flow due to (a) exudation of extractives to the surface, which lowers the wettability or hides the surface, (b) reorientation of wood surface molecules, which reduces wettability or bonding sites, and (c) irreversible closure of large micropores in cell walls (Christiansen, 1990).

Moreover, at the beginning of resin infusion, the stiffness of lumber sample could resist the compressive force of atmospheric pressure. The internal pressure, however, changes during the course of infusion, which in turn, will indirectly lead to changes in the permeability of the lumber sample due to compaction of the sample under vacuum (Barraza *et al.*, 2004).

One approach to direct the flow of resin homogenously within the lumber sample is to incise its surfaces with narrow grooves and channels (10 mm long) at the sample ends is shown in Figure 4.4. Provided the incisions are not too frequent the lumber is not weakened and the gum rosin can enter the lumber through the exposed ends in each incisions under vacuum treatment, and form an envelope of treated wood, which is slightly deeper than the incisions.

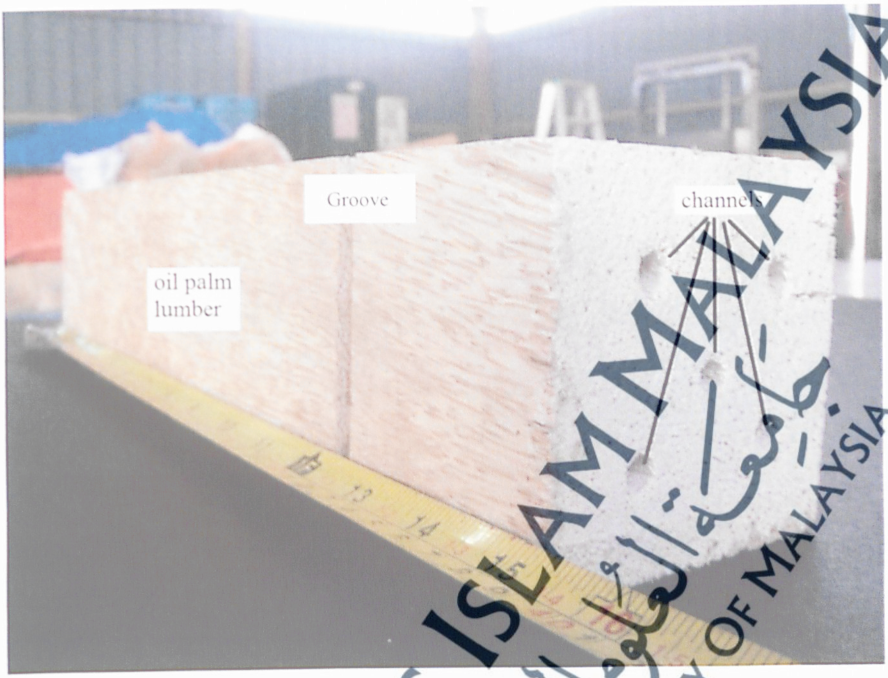


Figure 4.4: Positions of groove and channel to ease the flow of resin used into the matrix of oil palm lumber

It was noted that the gum rosin used was dispersed homogenously within the matrix of lumber sample. Such technique tended to eliminate the formation of resin-rich or starved areas and dry patches within the sample, and therefore leads to the success of resin infusion. For the OPL samples, mean amount of gum rosin absorbed and the time taken to infuse the resin per unit volume of the lumber sample was 0.69 g cm^{-3} and 1.5 s cm^{-3}, respectively.

4.2.2 Effect of gum rosin and densification treatments on dimensional stability

The antiswelling efficiency (ASE) values, which was calculated on a volumetric basis and represent the amount of swelling that gum rosin resin treatment prevents when compared to the swelling of a control samples, show that the low molecular weight gum rosin resin was able to impart a degrees of stability to the densified gum rosin -treated OPL. The densified gum rosin -treated OPL yielded ASE values (Table 4.7), are as follows: Outer zone ranged from 3.58% to 26.11%; Inner zone ranged from 0.96% to 10.07% while ASE values ranged between 1.20% and 10.02% for Middle zone.

Table 4.7: Variations of dimensional stability in pith to periphery zone of densified gum rosin-treated oil palm lumber

Zone	**Number of Specimens**	**Antiswelling Efficiency (%)**			
		Min	**Mean***	**Max**	**SE**
Outer	9	3.58	8.53^a	26.11	2.46
Inner	9	0.96	4.75^b	10.07	1.07
Middle	9	1.20	6.48^b	10.02	1.04

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius.

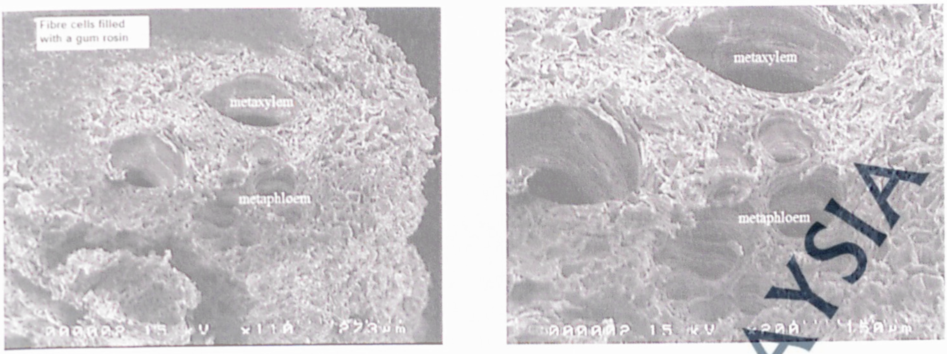
The positive ASE value indicates that the gum rosin had penetrated into the cell wall and subsequently cross-linked, leading to bulking along interstitial spaces (Loh *et al.*, 2010) created when thin-wall parenchyma cell collapse during drying (Obataya *et al.*, 2004). Gum rosin is located mostly in the cell wall of vascular bundles and yields dimensionally stable composites (Kumar, 1994).

The amount of water absorption was reduced by 75.22% to 79.09% (Table 4.8). It was noted that polymer grafting may have been taken place with reactive group on OPL component within the cell wall while ungrafted bulk polymer was formed in the OPL voids (Rowell *et al*., 1982). The gum rosin used was deposited either in cell-lumen (Schneider, 1995), in cell-wall (Furano *et al*., 1992) or a combination of cell-lumen and cell-wall types (Schneider *et al*., 1991). A typical SEM image of the vascular bundles of gum rosin-treated sample is shown in Figure 4.5.

Table 4.8: Variations of water reduction in pith to periphery zone of densified gum rosin-treated oil palm lumber

Zone	**Number of Specimens**	**Amount (%)**			
		Min	**Mean***	**Max**	**SE**
Outer	9	60.25	75.22^{a}	90.24	3.79
Inner	9	65.24	80.33^{a}	97.95	3.47
Middle	9	68.42	79.09^{a}	98.92	3.54

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE = standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius



(a) VB filled with a gum rosin (X80) (b) VB filled with a gum rosin (X150)

Figure 4.5: Typical SEM photomicrographs showing the distribution of gum rosin within the vascular bundles of densified gum rosin-treated oil palm lumber

4.3 Flexural Strength of Oil Palm Lumber

4.3.1 Dried oil palm lumber

Table 4.9 gives the mean values of MOR and MOE, in pith towards periphery zone of matched dried OPL samples (from group B, in subgroup B-1). In general, variations of the MOR and MOE among the samples in radial direction with height are as follows: 2-m height, MOR ranged between 13.13 to 24.68 MPa and MOE ranged between 2,131.54 to 4,007.32 MPa; 4-m height, MOR ranged between 10.97 to 20.29 MPa and MOE ranged between 1,781.61 to 3,295.09 MPa while the MOR and MOE at 6-m height ranged between 7.26 to 19.22 MPa, and 1,178.23 to 3,120.83 MPa, respectively.

Table 4.9: Mean flexural strength in pith to periphery zone of dry untreated oil palm lumber with tree heights

Height (m)	Sample positions					
	Outer Zone		Pith		Middle Zone	
	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)
2	24.68 (2.68)	4,007.32 (435.67)	13.13 (1.04)	2,131.54 (168.11)	20.65 (1.16)	3,352.19 (187.73)
4	20.29 (1.86)	3,295.09 (302.06)	10.97 (1.04)	1,781.61 (162.69)	18.78 (1.27)	3,049.12 (206.14)
6	19.22 (2.55)	3,120.83 (414.28)	7.26 (0.31)	1,178.23 (49.92)	16.75 (1.31)	2,719.53 (212.05)

Standard error of the mean is shown in parenthesis, MOR is modulus of rupture, and MOE is modulus of elasticity, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

In general, mean MOR and MOE values were higher at the periphery zone and lower in pith. This indicates that the OPL from woody portion at 100 mm from the periphery was significantly stronger than those woody portion located in pith.

For OPT log, a decreasing trend in flexural strength properties was apparently going from the outer regions towards the pith. This proved that the strength of woody portion was highly dependent on the variation in moisture content and their basic density values (Kamarudin *et al.*, 2011). The result highlighted the need to effectively grade to ensure the desired strength properties specific to product needs are capitalised upon in order to determine structure serviceability.

4.3.2 Densified gum rosin-treated oil palm lumber

Mean values for MOR and MOE of OPL scantling (from group B, in subgroup B-2), taken in pith towards periphery zone in east and west directions with tree heights, and treated with gum rosin is given in Table 4.10. In general, variations of the MOR and MOE among the samples in radial direction with height are as follows: 2-m height, MOR ranged between 18.31 to 43.21 MPa and MOE ranged between 2,972.41 to 7,015.85 MPa; 4-m height, MOR ranged between 14.98 to 39.89 MPa and MOE ranged between 2,432.63 to 6,476.53 MPa while the MOR and MOE at 6-m height ranged between 15.08 to 34.15 MPa, and 2,448.75 to 5,544.52 MPa, respectively.

Table 4.10: Mean flexural strength in pith to periphery zone of densified gum rosin-treated oil palm lumber with tree heights

Height (m)	Sample positions					
	Outer		Pith		Middle	
	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)
2	43.21 (3.34)	7,015.85 (541.59)	18.31 (1.83)	2,972.41 (297.89)	42.68 (2.77)	6,930.23 (449.56)
4	39.89 (4.13)	6,476.53 (670.69)	14.98 (1.75)	2,432.63 (283.33)	31.47 (1.24)	5,109.91 (201.74)
6	34.15 (2.63)	5,544.52 (427.63)	15.08 (1.33)	2,448.75 (216.19)	32.92 (3.17)	5,344.33 (515.70)

Standard error of the mean is shown in parenthesis. MOR is modulus of rupture, and MOE is modulus of elasticity, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Based on results, the strength of densified gum rosin-treated OPL had increased by approximately 66% more than those of the same matched dry OPL samples. This indicates that sufficient amount of gum rosin had penetrated and bulked into the OPL using the vacuum infusion technique, and followed by a densification process. It was noted that most of bending samples failed normally, first in compression followed by a simple tension. It is believed that the presence of gum rosin (which is either cross-linked with the cellulose or bulked the fibre walls), increased the support of the samples and reduced their buckling under the compressive load (Fry, 1976).

The histogram (Figure 4.6) serves to reduce and consolidated the data collected of MOR and MOE values of dry-versus densified gum rosin-treated samples of OPL scantling with tree heights, in this series of mechanical properties of strength studies. The lengths of the bars shown indicate the distance of respective strength value in terms of the geometric mean measurements, from the pith to periphery zones, expressed as a unit.

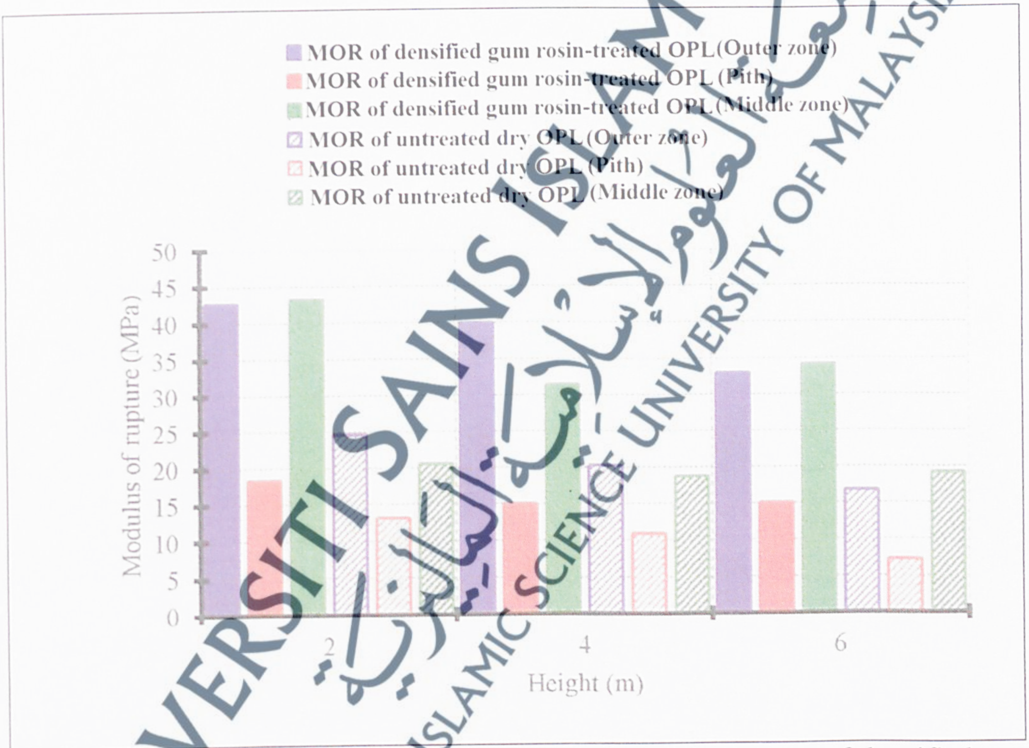


Figure 4.6: Values of modulus of rupture in pith to periphery zone of densified gum rosin-treated and matched dry oil palm lumber with tree heights

Treating the data in this manner makes it possible to compare the degree of variations to which the various OPL scantlings retain each of the observed mechanical properties of strength. Hence, the need to portray the results of variation in strength properties more than just one style. From this histogram, the expected mechanical properties of strength for each individual test samples in relation to treatment types could be identified. This data was recorded in the summary table, which appear in Tables 4.9 and 4.10. It was then possible to use these values to calculate the changes in strength properties of interest, in order to facilitate comparison of within-treatment types in a more quantitative approach.