PROPERTIES OF COMPOSITE BOARDS FROM OIL PALM FROND AGRICULTURAL WASTE

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Properties of composite boards from oil palm frond agricultural waste were researched. Phenol and urea formaldehyde resins were used as the binders. The oil palm fronds were obtained from 20 year-old trees in an oil palm plantation in Kota Belud, Sabah. The fronds were segregated into three groups of matured, intermediate, and young oil palm fronds and further subdivided into bottom, middle, and top sections. The leaflets and the epidermis were removed from the fronds before they were sliced longitudinally into thin layers. The layers were then compressed into uniform thickness of 2 to 3 mm. The layers were air-dried and later mixed with resins using 12 to 15% of phenol and urea formaldehyde and recompressed with other layers, forming composite boards. The composite boards samples were then tested for their physical and mechanical properties. Testing was conducted in accordance with the International Organization for Standardization (ISO) standard. The results for physical and mechanical properties showed that the oil palm composite boards were better than composite boards from oil palm trunks and slightly worse than the rubberwood. Statistical analysis indicated significant differences between composite boards made from each group and section, but no differences were observed in the type of resin used. The composite boards from oil palm fronds agricultural residues has the potential to be used as an alternative to wood to overcome the shortage in materials in the wood industry.

Keywords: Oil palm fronds; Composite boards; Physical properties; Mechanical strength

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INTRODUCTION

The rapid increase in the world's population has caused a rise in demand for wood and wood products (Uysal 2005). The increasing prices of timber and its shortage have affected the wood-based industries in the world. The ever-increasing manufacturing costs and uncertainty in wood supply in some regions, due to restrictions on logging and inadequate forest resources, has raised concerns over future wood supplies. The forest may no longer be able to supply the wood in a sustainable way anymore. To overcome this problem, research and development activities in many countries around the world, including Malaysia, have focused on composites, using non-wood resources from agricultural residues as the alternative source for raw material. Non-wood lignocellulosic composites are becoming attractive in both commercial and non-commercial applications.

Organic natural fibres are increasingly being investigated for various usages in many structural and non-structural applications. Malaysia produces a large quantity of agricultural waste such as coir–fibre (*Cocos nucifera*), rice husk (*Oryza sativa*), and oil palm fibre (*Elaeis guinnesis*) (Zulkifli *et al*. 2008). The advantages of these fibres are that they are renewable, non-abrasive, cheaper, abundant, and raise less health and safety concerns during handling and processing in comparison to the conventional reinforcing materials. Many agro-residues are combined with other materials such as metals, plastics, glass, and synthetic fibres, and the properties of these composites are still being studied (Hill *et al*. 1998).

Oil palm fronds, which can be obtained all year around, can be an answer to overcome the problem of a raw material because they appear to be the most viable alternative to be utilized as value-added products for the wood-based industry (Mohamad *et al*. 2003). Malaysia is currently the world's largest producer and exporter of palm oil. Malaysia produces about 47% of the world's supply for palm oil (Wahid *et al*. 2004). The Malaysian palm oil industry generates a huge quantity of oil palm biomass, including oil palm trunk, oil palm frond, empty fruit bunch, shell, and fibre in the production of palm oil. The oil palm fronds can be found in abundance year round.

Numerous research and development efforts have been undertaken to utilize empty fruit bunches, concentrating mainly on the production of pulp for paper making (Astimar *et al*. 2002; Tanaka *et al*. 2002), while a handful can also be found on the production of medium density fibreboards (Ridzuan *et al*., 2002), oil palm fibre mattress and agricultural mats, high quality organic fertilizer, charcoal briquette, and roof tiles (Mohamad *et al*. 2002). The production of medium density fibreboards (Laemsak and Okuma 2000), particleboards (Chew 1987), cement-bonded particleboards (Kochummen *et al*. 1990), fibre reinforced cement boards (Abraham *et al*. 1998; Schwarz 1985), fibre plastic composite (Liew *et al*. 2000), and plywood (Ho *et al*. 1985; Othman *et al*. 2008) from oil palm trunk, besides laminated veneer boards (Razak *et al*. 2008) and oil palm frond, have been shown to be technically feasible. Not many researchers, however, are currently focusing on the potential uses of oil palm fronds as an alternative to wood.

The general objective of this study was to investigate the properties of the compressed oil palm fronds composite boards (COPaF). This was achieved by assessing the physical and mechanical properties of COPaF in different stages of maturity and various sections of boards with phenol and urea formaldehyde resin and by investigating the suitability of using oil palm fronds from different maturity and sections in manufacturing COPaF for structural and non-structural applications using synthetic resins.

EXPERIMENTAL

Sourcing of Oil Palm Fronds

The oil palm fronds were obtained from a private plantation in Kota Belud, in Sabah. The oil palm fronds were selected from 20-year-old decay- and defect-free trees. The selected oil palm fronds were divided into three groups, namely mature, intermediate, and young oil palm fronds. Within these groups, they were further sub-divided into bottom, middle, and top sections. The selected fronds were then transported to Universiti Malaysia Sabah (UMS) for subsequent processing. Leaflets were removed from the fronds. A disc of length 10 cm was cut in the middle from every section for the physical properties study. The rests of the fronds were sliced in a longitudinal direction after removing their skins. The fronds were then sliced longitudinally with thickness varying in the range 2 to 4 mm, and length of approximately 1 m each. The sliced fronds were later flattened longitudinally and compressed using mechanical rollers to increase their density before undergoing air-drying.

Air Drying

All the compressed oil palm fronds then underwent an air-drying process for 12 hours to remove moisture in them. Compressed fronds were air dried to prevent fungi and insect attacks. The drying process ended once the moisture content of these compressed fronds reached the equilibrium moisture content (14% in Malaysia).

Resin

Two types of resin were used in this study to produce the composite boards; phenol formaldehyde (PF) and urea formaldehyde (UF) resin. Both types of resin were obtained from Sepanggar Chemical Sdn. Bhd. The viscosity, specific gravity, pH value and solid content of the resins are shown in Table 1.

Table 1. Properties of Phenol and Urea Formaldehyde Resin

Characteristic	Unit	Urea Formaldehyde	Phenol Formaldehyde
Viscosity	cps	95	64
Specific Gravity	-	1.193	1.189
pH Value	-	7.5	12.0
Solid Content	%	50.8	43.7

COPaF Boards

After undergoing an air-drying process in sunlight, the compressed oil palm fronds were then glued together with 12 to 15% of resins and adding 1% of hardener (NH_4Cl). Forming layers were manually laid using a forming box that compressed oil palm fronds into 350 x 350 mm pieces. After laying forming layers, the compressed oil palm fronds were pre-pressed by hand and then transferred to a single-opening hydraulic hot-pressed machine with a platen temperature of 125±5ºC for phenol formaldehyde resin or 100±5ºC for urea formaldehyde resin. The oil palm fronds were pressed into the shape of boards for testing. The compressed oil palm frond composite boards were manufac-tured to 20 mm in thickness. The compressed oil palm frond composite boards were pressed, following a three-step-down method with pressing time of 40 sec/mm for phenol-formaldehyde resin, and 30 sec/mm for urea-formaldehyde resin boards. Stop-bars 20 mm in thickness were inserted between the hot platens during hot pressing. All composite boards pieces were trimmed and cut into various size test specimens and then conditioned at 20±3ºC and 65±3% relative humidity (RH) for 72 hours prior to attaining an equilibrium moisture content of about 12±1% before testing.

Physical Properties of Oil Palm Frond and COPaF Boards

Physical properties were tested and evaluated in accordance with International Organization for Standardization (ISO) standards. The physical properties of oil palm fronds studied were the air-dried density and oven-dried density.

Air-dried density

The air-dried density was determined by measuring the mass at 12% moisture content and volume of each sample. Each test sample was weighed to a precision of 0.01 g by using an analytical balance, and the volume was determined using a water displacement method. The determination of density of each test sample was done in accordance with ISO 3131-1975. The initial weight of specimens was taken, and then the samples were oven dried at 103±2ºC until their moisture content reached 12%. The oven-dried weight was determined, and the specimens were dipped slightly into melting wax. Using the water displacement method, the initial level of a volumetric cylinder was recorded and the weighing equipment was set up to two decimal places. The specimens were then immersed in the water. The weight and the latest water level of the volumetric cylinder were recorded.

Oven-dried density

The oven-dried density was determined by measuring the oven-dried weight and green volume of each sample. Each test sample was weighed to an accuracy of 0.01 g by using an analytical balance, while the volume was determined by using a water displacement method. The determination of oven-dried density of each test samples was done in accordance with ISO 3131-1975. The initial weights of specimens were taken before undergoing to oven-dried-drying at 103±2ºC until their weights were constant. After the oven-dried weight was determined, the specimens were dipped slightly into melting wax. By using a water displacement method, the initial level of volumetric cylinder was recorded and the weighing equipment was set up at two decimal places. The specimens were then immersed in the water. The weights were recorded.

Mechanical Properties of COPaF Boards

Mechanical properties of compressed oil palm fronds were evaluated according to International Organization for Standardization (ISO) standards 3349-1975, 3133-1975, and 3787-1976. The COPaF boards were tested for the following properties: static bending strength, including modulus of elasticity (MOE), modulus of rupture (MOR), and compression strength.

Static bending strength

The static bending test was conducted using a Universal Testing Machine. The dimensions of the COPaF boards sample for the static bending test were decided according to ISO 3349-1975 for MOE and ISO 3133-1975 for MOR. The span used was 280 mm, and the force was applied at mid-span using a loading head. The test was stopped when the samples broke. The pro-sectional limit with ultimate load and deflection was recorded, the values for the MOE and MOR were calculated by the computer connected to the machine automatically.

Compression strength parallel to the grain

The compression strength test was performed according to ISO 3787-1976 for MOR using a Universal Testing Machine. This test was conducted with a constant rate of loading until the test piece was broken.

RESULTS AND DISCUSSION

Physical Properties of COPaF Boards

The density and oven-dried density were determined for the compressed oil palm frond composite boards because they greatly influenced the mechanical properties of the composite boards. The investigations were conducted on COPaF boards made of varying maturity levels, two different resins, and from different sections of the boards.

Air-dried density of COPaF boards

Table 1 shows the results of mean value for air-dried density of the COPaF boards. The air-dried density of the COPaF boards was dependent on the maturity of oil palm fronds, section of the wood tested, and types of the resin that have been used for bonding the COPaF boards. From the different levels of maturity, the matured fronds gave rise to the highest air-dried density, followed by the intermediate and young fronds. The highest air-dried densities for the COPaF boards were those produced from the matured bottom section, followed by the intermediate, middle, and young top sections. The air-dried density values decreased from the bottom to top sections for each maturity group, and from matured to young fronds for both types of resin used.

Table 2. Mean Value for Air-Dried Density of COPaF Boards

		Air-Dried Density (g/cm^3) of sections at 12% MC		
Oil palm fronds	Resin used	Bottom	Middle	Top
MATURED	Phenol formaldehyde	0.45	0.44	0.42
	Urea formaldehyde	0.46	0.43	0.42
INTERMEDIATE	Phenol formaldehyde	0.43	0.42	0.40
	Urea formaldehyde	0.44	0.42	0.41
YOUNG	Phenol formaldehyde	0.42	0.41	0.40
	Urea formaldehyde	0.42	0.41	0.40

Note : Number of replicates for each parameter = 5, Total number of replicates = 90
COPaF = compressed oil palm frond composite boards, MC = moisture content

Oven-dried density of COPaF boards

The oven-dried density for the COPaF boards was similar to the air-dried density. The mean values of oven-dried density for the COPaF boards for each maturity group, section, and resin type are shown in Table 3. The results showed that all the oven-dried density values decreased from the bottom to top sections for each maturity group, and from matured to young maturity groups, where the mature group possessed the highest oven-dried density values for every section compared to others, followed by the intermediate and young groups.

The high concentration of fibrous vascular bundles, especially at the bottom section of the oil palm fronds, gives a higher oven-dried density value compared to other sections (Mohamad *et al*., 1985). This finding is further supported by Rowell (1994), who stated that oven-dried density values for wood are different according to their cell size, cell wall thickness, and relative amount of solid cell wall material. He mentioned that more mature and thick cells are on the bottom part of wood, thus exhibiting higher oven-dried density values than other parts. This statement is in agreement with oven-dried density values that were recorded in this study, where the bottom section of the COPaF boards had higher oven-dried density value than other sections. Haygreen and Bowyer (1930) also noted that the oven-dried density values decrease from the bottom part of a wood to the top part because of differences in growing rate that affect the anatomical cell maturity development. Density and oven-dried density are the main physical properties that affect the mechanical properties of wood.

The matured bottom section of oil palm fronds has the highest oven-dried density, followed by the intermediate middle and young top sections.

Table 3. Mean Value for Oven-dried Density of COPaF Composite Boards

		Oven-dried density (g/cm^3) of sections		
Oil palm fronds	Resin used	Bottom	Middle	Top
MATURED	Phenol formaldehyde	0.38	0.36	0.33
	Urea formaldehyde	0.39	0.35	0.32
INTERMEDIATE	Phenol formaldehyde	0.36	0.35	0.32
	Urea formaldehyde	0.37	0.34	0.31
YOUNG	Phenol formaldehyde	0.34	0.33	0.30
	Urea formaldehyde	0.34	0.32	0.30

Note : Number of replicates for each parameter = 5, Total number of replicates = 90
COPaF = compressed oil palm fronds composite boards

Mechanical Properties of COPaF Boards

The mechanical properties of the COPaF boards were tested in this study, including the static bending strength (MOE and MOR) and compression strength parallel to the grain (MOR). The mechanical properties were evaluated on the basis of standards from the International Organization for Standardization (ISO). The mechanical properties of the COPaF boards were more thoroughly investigated in order to see the effect of oil palm fronds of different levels of maturity, sections, and types of resin on the strength properties.

Static bending strength of the COPaF boards

Table 4 shows the results of the MOE static bending tests carried out on the COPaF boards. The MOE strength decreased from the bottom to top section for matured oil palm fronds with either phenol or urea formaldehyde resins. The MOE strength also decreased with a decrease in the level of maturity of the oil palm fronds.

The average value of MOE strength for the bottom section from the mature, intermediate, and young groups of phenol formaldehyde COPaF boards were 999.61, 979.15, and 935.36 N/mm^2, respectively. The mean values of MOE strength for the bottom section of urea formaldehyde composite boards were 980.31, 953.93, and 936.24 N/mm^2 from the matured, intermediate, and young oil palm fronds. These results show that the average value of MOE strength decreased from the matured to young maturity levels for the bottom section both for phenol and urea formaldehyde COPaF boards.

Corresponding results also were obtained when using frond material from the middle and top sections too, when comparing results for the mature, intermediate, and young groups.

Table 4. Modulus of Elasticity (MOE) Static Bending Strength of COPaF Boards

		Static bending MOE (N/mm^2) of sections		
Oil palm fronds	Resin used	Bottom	Middle	Top
MATURED	Phenol formaldehyde	999.61	952.29	844.18
	Urea formaldehyde	980.31	949.40	840.40
INTERMEDIATE	Phenol formaldehyde	979.15	942.44	817.29
	Urea formaldehyde	953.93	928.34	776.04
YOUNG	Phenol formaldehyde	935.36	837.24	761.14
	Urea formaldehyde	936.24	836.67	666.30

Note : Number of replicates for each parameter = 5, Total number of replicates = 90
COPaF = compressed oil palm fronds composite boards

Based on the results in Table 5, the MOR of the COPaF boards decreased from the bottom to top sections for each maturity level and from mature to young levels for every section. This includes both types of the resins used to produce the composite boards. This trend was also similar to the intermediate and young maturity groups going from the bottom towards top sections of boards.

Table 5. Modulus of Rupture (MOR) Static Bending Strength of COPaF Boards

		Static bending MOR (N/mm^2) of sections		
Oil palm fronds	Resin used	Bottom	Middle	Top
MATURED	Phenol formaldehyde	16.66	12.55	11.72
	Urea formaldehyde	15.40	12.38	11.63
INTERMEDIATE	Phenol formaldehyde	14.38	12.37	10.87
	Urea formaldehyde	12.62	12.07	10.51
YOUNG	Phenol formaldehyde	12.16	11.62	10.27
	Urea formaldehyde	12.25	11.19	9.10

Note : Number of replicates for each parameter = 5, Total number of replicates = 90,
COPaF = compressed oil palm fronds composite boards

The strength values presented in Table 4 decreased from the matured to young oil palm fronds for the bottom section of COPaF boards with both of resin types that were used to make the composite boards. The MOR values also decreased in the other two sections as the maturity level of the oil palm fronds decreased. This trend is similar to MOE value effect by sections, in which the MOR values decrease from bottom to top sections for each maturity level as well as from mature towards young maturity levels for every section.

It was clearly observed that the values of both MOE and MOR for the COPaF boards decreased from the bottom to top sections of boards as well as from the mature to the young oil palm fronds. This occurred both in the COPaF boards made from phenol and urea formaldehyde resin. The trend of variations in MOE and MOR values along a tree's height can be explained by the decrease in maturity of the wood and fibre length from the bottom to the top of the tree (Rulliarty and America 1995). This statement was logically accepted due to the presence of vascular bundles, which decrease from the bottom to top sections along the oil palm fronds, as well as from the mature to young oil palm fronds. The presence of vascular bundles will affect the quantity of fibre cells, which that causes increases in density and oven-dried density values.

The strength properties of wood have a close and significant correlation with air-dried density and oven-dried density (Desh 1968). This is reinforced by the ANOVA in Table 7, which shows a significant difference between MOE and MOR of static bending across different maturity levels and sections of boards.

The obtained results show that the COPaF boards made with phenol-formaldehyde resin possessed slightly higher values both for MOE and MOR tests than the boards made with urea-formaldehyde resin. This might be due to the fact that urea-formaldehyde has a higher solids content than phenol-formaldehyde resin. Abdullah (2010) found that the distribution of phenol formaldehyde resin were located irregularly in the structures of composite boards. When stresses were applied during testing, the stresses could not be transferred consistently between the fibre and matrix. The penetration of the high viscosity urea-formaldehyde resin probably breaks the cell walls of the compressed oil palm frond composite boards (Abdullah 2010). This action would make it impossible for the fibre and matrix to withstand greater loads. However, the results of MOE and MOR of static bending did not show significant differences between resin types (ANOVA in Table 8). The type of resin does not significantly influence the density value of the composite boards.

Table 6. Bending Strength between COPaF boards, Composite Oil Palm Stem and Rubberwood

Composite Boards	MOR (N/mm^2)	MOE (N/mm^2)
Oil Palm Fronds	16.66 (70%)	999.61 (61%)
Oil Palm Stem	15.13 (-73%)	480.06 (-81%)
Rubberwood	56.57 (-00%)	2543.34 (-00%)

(values in brackets indicate % difference from rubberwood)

Table 6 shows the strength comparison between composite oil palm boards from trunk, fronds, and rubberwood. The strength of the COPaF boards was slightly higher than the composite made from the oil palm trunks (Razak *et al*. 2008).

Compression strength parallel to the grain of COPaF boards

The compression tests were carried out using a Universal Testing Machine. Compression strength is defined as the maximum stress sustained by compressing a specimen, with the specimen having a specified ratio of length to smallest dimension (Thanate *et al*. 2006). The characteristics of the compression load deformation curve are similar to those for static bending strength (Ronald and Gjinoli 1997). The compression strength of a composite is highly dependent on the effectiveness of the matrix in supporting the fibre against buckling (John and Reid 1969).

Tests of mechanical properties were conducted in accordance with ISO 3787-1976. The obtained data were examined using statistical analysis to determine the effect of three parameters, maturity levels (matured, intermediate, and young), sections of boards (bottom, middle, and top), and types of resin (phenol and urea formaldehyde), on the compression strength of the COPaF boards.

Table 6 shows the compression strength value of mature group from bottom to top sections for phenol formaldehyde composite boards and urea formaldehyde composite boards. It was observed that the compression strength decreased from bottom section towards to middle and top sections for the mature group, and section from bottom, middle, and top. The table clearly shows the decrement from mature towards intermediate and young maturity groups for the bottom section, and this trend was also apparent for the other two sections (middle and top).

Table 7. Modulus of Rupture (MOR) Compression Strength Parallel to the Grain of COPaF Boards

		Compression MOR (N/mm^2) of sections		
Oil palm fronds	Resin used	Bottom	Middle	Top
MATURED	Phenol formaldehyde	473.17	395.93	260.22
	Urea formaldehyde	459.52	344.60	260.00
INTERMEDIATE	Phenol formaldehyde	453.67	318.88	196.71
	Urea formaldehyde	431.88	274.90	190.70
YOUNG	Phenol formaldehyde	301.46	235.60	183.48
	Urea formaldehyde	312.94	198.79	181.06

Note : Number of replicates for each parameter = 5, Total number of replicates = 90,
COPaF = compressed oil palm fronds composite boards

The compression strength (MOR) of the COPaF boards displayed a similar trend to that of the static bending strength (MOR). Oyagade and Fasulu (2005) reported that for each species, wood density and mechanical properties decrease with the height of the tree. This can be applied along the oil palm fronds from the bottom to the top sections and from matured to young oil palm fronds. According to Nordahlia (2008), some strength properties of wood indicate that compression failure typically occurs in regions of low density. The ANOVA in Table 7 shows there was a significant difference between compression strength across different maturity levels and sections of boards.

The obtained results show that the average compression strength value for each section of phenol formaldehyde composite boards was higher than urea formaldehyde composite boards. The higher compression strength of compressed oil palm frond composite boards with phenol formaldehyde resin could be due to the fact that phenol formaldehyde resin, when properly cured, is often tougher than the wood itself (Baldwin 1995).

The effectiveness of phenol- and urea-formaldehyde resins in enhancing compression properties showed a similar trend to static bending strength, where the phenol-formaldehyde composite boards possessed slightly higher values of compression strength compared to urea-formaldehyde composite boards. However, the differences were not significant (ANOVA in Table 8).

Analysis of Variance (ANOVA) on Physical and Mechanical Properties of COPaF Boards

Table 8 shows the ANOVA for physical and mechanical properties of the compressed oil palm frond composite boards. The analysis was conducted to determine whether a significant difference exists between physical and mechanical properties of the composite boards.

Significant differences existed between physical properties (air-dried density and oven-dried density) and mechanical properties (static bending strength (MOE^b and MOR^b) and compression strength (MOR^c)) across varying levels of maturity and different sections of boards.

The air-dried density was affected by the anatomical structure in the oil palm fronds, which are composed of vascular bundles and parenchymatous tissues. This is reinforced by the ANOVA in Table 8, which shows significant difference between density in boards made from oil palm fronds of different maturity level and different sections of the boards, but no significant difference for the type of resins used to produce the composite boards. The type of resin does not influence the density value of the composite boards. The presence of both resins however, increases the density of the compressed oil palm frond composite boards (Razak *et al*. 2008).

Table 8. ANOVA of Physical and Mechanical Properties of COPaF Boards

Source of Variance	Dependent Variable	Sum of Square	DF	Mean Square	F-Ratio
Maturity	AD	0.0108	2	0.0054	7.94 **
	OD	0.0180	2	0.0197	28.75**
	MOEb	155675.0000	2	77837.5000	57.05 **
	MORb	79.0218	2	39.5109	40.39 **
	MORc	255794.0000	2	127897.0000	63.81**
Section	AD	0.0112	2	0.0056	8.26 **
	OD	0.0394	2	0.0090	28.75 **
	MOEb	507856.0000	2	253928.0000	186.12 **
	MORb	157.7170	2	78.8586	80.62 **
	MORc	565023.0000	2	282512.0000	140.95 **
Resin	AD	0.0001	1	0.0001	0.20 ns
	OD	0.0004	1	0.0004	1.28 ns
	MOEb	11232.8000	1	11232.8000	8.23 ns
	MORb	8.2313	1	8.2313	8.41 ns
	MORc	7538.0100	1	7538.0100	3.76 ns

** = significant at $p \leq 0.01$, ns = not significant, AD = Air-Dried Density,
OD = Oven-dried Density, MOE^b = Modulus of elasticity for static bending strength,
MOR^b = Modulus of rupture for static bending strength, MOR^c = Modulus of rupture for compression strength, COPaF = compressed oil palm fronds composite boards,
Total number of samples for each testing = 90.

Table 8 shows that there was a significant difference between oven-dried densities of the different levels of maturity and sections of boards, but there was no significant difference in the resin types that had been used to produce the composite boards. The type of resin did not influence the oven-dried density value of the composite boards. However, the oven-dried density of compressed oil palm fronds composite boards was higher than the oil palm frond oven-dried density because of the use of resin in producing the composite boards. The increase in oven-dried density of compressed oil palm fronds composite boards is probably related to resin penetration into the composite boards. A previous study by Paridah and Anis reported that parenchyma behaves like a sponge and can easily absorb moisture (2008). Therefore, the composite boards can easily absorb phenol and urea formaldehyde resin, increasing the oven-dried density of the compressed oil palm fronds composite boards. It is assumed that the resin enhanced the strength of the composite boards.

There were no significant differences between physical properties (air-dried density and oven-dried density) and mechanical properties (static bending strength (MOE and MOR) and compression strength (MOR)) using different types of resins. Slight differences were noted, but these had no significance.

Correlation Coefficient between Physical and Mechanical Properties of COPaF Boards

The correlation between the physical and mechanical properties of the COPaF boards is presented in Table 8. There was a correlation between the fronds' maturity and the section of boards tested in terms of the physical properties and strength of the composite boards. Negative correlations were observed between air-dried density and maturity level (r = -0.3657) and sections of boards (r = -0.3748). Meanwhile, oven-dried density values for the composite boards (r = -0.4435, r = -0.6588) were negatively correlated with frond maturity level and section of boards.

Table 9 shows the negative correlation between the air-dried density values and the maturity levels of oil palm fronds of the various sections of boards tested. They also show significant differences in the ANOVA displayed in Table 8. There was also a correlation coefficient between air-dried density and oven-dried density (r = 0.5611) in this study. A positive correlation was observed between them, and there was a significant difference at P-value ≤ 0.01. A positive correlation existed between resin types and air-dried density value (r = 0.0411), while a negative correlation existed between resin types and oven-dried density value (r = -0.0668). However, these correlations were not significant (ANOVA in Table 7), indicating that it was not possible to demonstrate an effect of the type of resin on the air-dried density as well as oven-dried density value of the COPaF boards.

The correlation coefficients between the strength properties (MOE^b for static bending strength and MOR^b for static bending compression strength) and other composite boards properties are presented in Table 8. There was a correlation between maturity levels and the mechanical property values. Negative correlations were obtained between maturity levels and MOE^b of static bending strength (r = -0.4321), MOR^b of static bending strength (r = -0.4927), and MOR^c of compression strength (r = -0.5029). Similar correlation trends were obtained from different sections of boards in relation to MOE of static bending strength (r = -0.7862), MOR^b of static bending strength (r = -0.6939), and MOR^c of compression strength (r = -0.7481).

The negative correlation between maturity groups and strength properties, as well as the negative correlation between sections of boards and strength properties means that the strength of the compressed oil palm fronds composite boards decreases from the bottom to the top sections of boards as well as from old to young maturity levels in each section. The ANOVA presented in Table 8 shows a significant difference at P-value ≤ 0.01. The strength properties of wood have a close and significant correlation with air-dried density as well as oven-dried density (Desh 1968). An increase in density and oven-dried density values increases the mechanical properties of wood, including static bending and compression strength. This statement is supported in the correlation analysis shown in Table 8. Positive correlations were obtained between air-dried density with MOE^b of static bending strength (r = 0.3750), MOR^b of static bending strength (r = 0.4045), and MOR^c of compression strength (r = 0.5339), while the correlation between oven-dried density with these three mechanical tests were r = 0.7241 for MOE, r = 0.6669 for MOR^b of static bending strength, and r = 0.7356 for MOR^c of compression strength. All of these correlations possessed significant differences at P-value ≤ 0.01 according to the ANOVA in Table 8.

Table 9: Correlation Analysis between Physical and Mechanical Properties of COPaF Boards

	Maturity	Section	Resin	AD	OD	MOEb	MORb	MORc
Maturity	1.0000	0.0000ns	0.0000ns	-0.3657**	-0.4435**	-0.4321**	-0.4927**	-0.5029**
Section		1.0000	0.0000ns	-0.3748**	-0.6588**	-0.7862**	-0.6939**	-0.7481**
Resin			1.0000	0.0411ns	-0.0668ns	-0.1196ns	-0.1592ns	-0.0867ns
AD				1.0000	0.5611**	0.3750**	0.4045**	0.5339**
OD					1.0000	0.7241**	0.6669**	0.7356**
MOEb						1.0000	0.7673**	0.7870**
MORb							1.0000	0.7889**
MORc								1.0000

** = significant at p≤ 0.01, ns = not significant, AD = Density, OD = Oven-dried Density, MOEb = Modulus of elasticity for static bending strength, MORb = Modulus of rupture for static bending strength, MORc = Modulus of rupture for compression strength, Note: Total number of samples for each testing = 90, COPaF = compressed oil palm fronds composite boards

The effect of resin type on the mechanical properties of compressed oil palm frond composite boards showed a negative correlation, where r = -0.1196 and r = -0.1592 for MOE^b and MOR^b of static bending strength, and r = -0.0867 for MOR^c of compression strength. A similar trend was observed in the correlation between physical properties (air-dried density and oven-dried density) of the composite boards and types of resin. Although they showed correlation, but there were no significant differences between them (see ANOVA in Table 8). This shows that the type of resin does not have a demonstratable effect on the mechanical properties of the composite boards. A positive correlation was observed among these three mechanical properties, where r = 0.7673 and r = 0.7870 between MOE^b of static bending strength and MOR^b of static bending and compression strength, while r = 0.7889 between MOR^b of static bending strength and MOR^c of compression strength. These correlation coefficients possessed significant differences at P-value ≤ 0.01.

CONCLUSIONS

1. There was a correlation between the fronds' maturity and the section of the COPaF boards tested in terms of the physical properties and strength of the composite boards.
2. The highest air-dried density for the COPaF boards were those produced from the matured bottom section, followed by the intermediate, middle, and young top sections.

3. The oven-dried density values decreased from the bottom to top sections for each maturity group, and from mature to young maturity groups, where the mature group possessed the highest oven-dried density values for every section compared to others, followed by the intermediate and young maturity groups.
4. The MOE strength decreased from the bottom to top section for mature oil palm fronds with either phenol or urea formaldehyde resins. The MOE strength also decreased with a decrease in the level of maturity of the oil palm fronds.
5. The MOR of the COPaF boards decreased from the bottom to top sections for each maturity level and from matured to young maturity levels for every section. This includes both types of the resins used to produce the composite boards.
6. The compression strength decreases from bottom section towards to middle and top sections for matured maturity group, and section from bottom, middle, and top. The decrement was from mature towards intermediate and young maturity groups for the bottom section, and this trend was also observed for the other two sections (middle and top).
7. Significant differences exist between physical properties (air-dried density and oven-dried density) and mechanical properties (static bending strength (MOE^b and MOR^b) and compression strength (MOR^c)) across varying levels of maturity and different sections of boards.
8. The COPaF boards have potential to be used for furniture manufacturing, based on their physical and strength properties.
9. The oil palm fronds can be used to produce quality composite boards that possess the physical and mechanical strength values that are better than the composite boards made from oil palm stem and less than rubberwood.

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