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Developing structural sandwich panels for energy-efficient wall applications using laminated oil palm wood and rubberwood-based plywood/oriented strand board

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Abstract

In this work, a new type of structural sandwich panels made with laminated oil palm wood core and rubberwood-based oriented strand board (OSB)/plywood faces were introduced for energy-efficient wall applications in Thailand. Effect of the manufacturing process and material parameters including adhesive content (250 g/m^2 and 500 g/m^2), core configuration (cross or parallel laminated oil palm lumber) and density (low and medium) and face material type (rubberwood-based OSB/plywood) on panel's properties were explored. The panels were produced using two-component polyurethane adhesive and a constant clamping pressure of 0.6 MPa. Adhesive content of 250 g/m^2 was found to be sufficient for gluing all layers, with wood failure percentage of more than 80% as required by the standard. In-plane dimensional stability of the panels was mainly affected by the core configuration; it was better for cross laminated oil palm wood core sandwich panel. Higher core density resulted in increased density, thermal conductivity and compressive strength in the major direction but lower thermal resistance of the panel. The plywood face sandwich panels provided slightly higher compressive strength than OSB face sandwich panel, and their failure mechanisms were also different. The heat loss of these panels was about one-third of concrete and brick walls, hence, they can provide better insulation for indoor space. Based on the measured thermal conductivity, it was expected that these panels would pass the energy criteria according to Building Energy Code of Thailand. Thus, from the energy saving and sustainability perspectives, these panels can potentially be used as energy efficient wall panels for buildings, not only for Thailand but also for other tropical countries, where the oil palm wood and rubberwood resource is available.

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Introduction

Since the international agreement on climate change, or Paris Agreement, has been announced in 2015, many attentions have been given to the construction industry, because most of the global greenhouse gas emission, a major cause of global warming crisis, are generated by this sector [1]. Recently, the International Energy Agency [1] in accordance with EU directives has launched a roadmap for the carbon neutral building sector by 2050. In Thailand, the law called building energy code [2] has just been revised and implemented to control the energy consumption of the new buildings with the aim to reduce the carbon emission generated by electricity usage during building operation [2]. In this regard, some energy performance indexes have been designated as a technical guideline for the design of building envelops planned to be constructed for energy saving. For example, an overall thermal transfer value (OTTV) index of 30–50 W/sq.m is required to control the heat transfer through the external walls in buildings [2].

To meet the energy criteria based on BEC, some researchers have considered using wood instead of steel or brick as a main component of building walls because of its superior insulation performance and positive impact to environment [3, 4]. Due to the availability of oil palm trees, oil palm trunk waste could be considered as a potential source to produce wood-based products. Since the density range of oil palm wood, from 200 to 600 kg/m^3 [5–7], is relatively low compared to common wood species, it is expected that this wood material might have better insulation performance than other wood species [8]. However, use of this wood material as structural timber is not recommended due to its relatively low strength [5–7]. Thus, it is necessary to conduct further research and experimentation to explore the potential applications and limitations of oil palm trunk waste as a wood-based product for building construction. Some possible areas of investigation include testing the insulation properties of different forms and compositions of oil palm trunk waste, as well as exploring the feasibility of combining it with other materials to improve its structural properties.

The use of low strength material in the form of sandwich panel for wall applications has been proposed by several researchers [9–15]. Structurally, a sandwich panel typically consists of two stiff and strong face sheets and a light weight core made by low strength materials. The face sheets carry most of the structural loads, while the core material mainly resists shear forces while also contributing to the stiffness of the panel with little increase in weight [16, 17]. In general, the sandwich panel could be designed and used as a non-load bearing or load bearing wall by considering various factors, such as the face and core thicknesses, material properties, joint design, and other end-use considerations [10, 17, 18]. While a thicker face is generally required for a sandwich panel to be used as a load-bearing wall, the design of sandwich panel walls should not be based solely on the thickness of the face or core, but rather consider all relevant factors to ensure the effective use of the panel in the intended application. Thus, where the environmental impact such as energy consumption is concerned, the utilization of oil palm wood in sandwich panel systems for wall applications is an attractive option in Thailand due to its low-density, availability, and cost efficiency. Previously, we have successfully produced a 20 mm thick sandwich panel with a single layer of oil palm wood core overlaid with rubberwood veneer faces [19], which is limited to nonstructural applications due to its thickness. This sandwich panel concept can be expanded to structural applications, such as load-bearing walls; the manufacturing process of a panel with a thicker core and faces and its structural performance evaluation, such as in-plane compressive strength, will need to be explored.

The objective of this research was to develop sandwich panels made with oil palm wood core as energy-efficient-load-bearing component of a wall system in building construction in Thailand; a wall system also consists finishing materials, such as cladding, vapor barrier, air barrier. Commercial rubberwood-based plywood or oriented strand board (OSB) sheets were selected as face materials due to their wide availability in Thailand. The optimal adhesive content for bonding the face-to-core and core-to-core layers was determined before the sandwich panel production. Subsequently, various sandwich panel configurations were produced using cold pressing (no heat is required) to explore the effects of the core density (low- and medium-density) and layups (cross or parallel laminated lumber) and face material type on the final products' properties.

Materials and methods

Preparation of OSB/plywood faces and oil palm wood core materials

OSB/plywood face materials

Five 9 mm thick rubberwood OSB sheets and five 8 mm thick rubberwood plywood sheets sourced from commercial suppliers in Thailand were used as face materials for the sandwich panel production in this study. These plywood and OSB sheets had a standard size of 1.2 m (width) × 2.4 m (length). Both face materials were cut into specimens with the dimensions of 24 cm × 24 cm × thickness and kept in a conditioning room at a temperature of 20 °C and relative humidity of 65% for about 1 month before the sandwich panel production. The fundamental material properties including density, swelling in major (parallel to the surface veneer or strand longitudinal), minor (perpendicular to the surface veneer or strand longitudinal) and thickness directions, and compressive strength of both face materials were measured and expressed in Table 1. Density and swelling in major and minor directions of rubberwood-based OSB and plywood face materials were roughly similar. However, thickness swelling of OSB was found to be significantly higher than that of plywood but its compressive strength parallel to grain was lower. Compared to OSB material used in structural sandwich panel, compressive strength of rubberwood-based OSB (10.6 ± 3.2 MPa) and plywood (21.0 ± 5.6 MPa) were slightly lower and higher, respectively, compared with that of OSB type 3 (15.4 MPa, [10]). This indicates that both face types could be potentially used as a face for structural sandwich panel.

Preparation of oil palm wood raw material

Oil palm trees of approximately 30 years from the plantation area of Thasala district, Nakhon Si Thammarat province, Thailand were felled and converted into lumber with the dimensions of 120 mm (width) × 50 mm (thick) × 700 mm (length) using circular saw. The lumber was dried with a laboratory drying kiln at dry-bulb and wet-bulb temperature of 60 °C and 55 °C, respectively, for 4 days and the drying schedule was then changed to 60 °C dry-bulb temperature and 50 °C wet-bulb temperature for 14 days. After the drying process, the kiln dried lumber was kept in a conditioning room at temperature and relative humidity of 20 °C and 65%, respectively, for about 1 month. The conditioned lumber was then cut and sanded with 100 grid sand papers to obtain specimens with the dimensions of 20 mm (thick) × 80 mm (width) × 300 mm (length). These specimens were then kept in a conditioning room at temperature and relative humidity of 20 °C and 65%, respectively, for about 1 month. The final moisture content of the lumber measured from 30 randomly selected samples was 12 ± 0.5%. The density of the lumber at this moisture content was determined and the lumber was then classified into two groups based on their densities; low (LD) and medium (MD) density groups. The average density for LD and MD were 323 ± 43 kg/m^3 and 478 ± 46 kg/m^3, respectively. The fundamental material properties (swelling in tangential, radial and longitudinal directions and shear strength parallel to grain) of LD and MD were measured on the randomly selected specimens. The swelling in each grain direction was calculated from the dimension of the sample before and after soaking in distilled water at 20 °C in accordance with the referenced standard. The dimensions of the specimens for each property test are summarized in Table 2.

Evaluation of bonding performance

A total of 12 pairs of 6 configurations (LD oil palm wood/LD oil palm wood, LD oil palm wood/OSB, LD oil palm wood/plywood, MD oil palm wood/MD oil palm wood, MD oil palm wood/OSB, MD oil palm wood/plywood, as shown in Fig. 1 and Table 3), two pairs for each configuration, were prepared using two-part polyurethane adhesive (GSP PU 902H and GSP PU 902). The GSP PU 902H: GSP PU 902 ratio of 1:5 was used to prepare the adhesive as recommended by the manufacturer (GSP Products Co., LTD, Bangkok, Thailand). The surface of all wood materials was sanded with 100 grid sandpaper before application of two

Table 2 Property testing of oil palm wood raw material

Properties	Dimensions of the test specimen *W* (mm) × *L* (mm) × *t* (mm)	Testing standard
Swelling (*n* = 10)	20 × 20 × 20	[23]
Shear strength parallel to grain (*n* = 30)	20 × 20 × 20	[24]
Compressive strength parallel to grain (*n* = 30)	20 × 20 × 60	[25]

Table 1 Fundamental properties of rubberwood-based plywood/OSB used for this experiment

Properties	Face materials		Testing standard
	Plywood	OSB	
Density (kg/m^3)	695 ± 45 (*n* = 40) (DS = 50 × 50 × 8)	738 ± 61 (*n* = 40) (DS = 50 × 50 × 9)	[20]
Swelling (%)			[21]
Major direction	0.42 ± 0.29 (*n* = 10)	0.29 ± 0.31(*n* = 10)	
Minor direction	0.32 ± 0.28 (*n* = 10)	0.44 ± 0.31(*n* = 10)	
Thickness direction	1.30 ± 0.25 (*n* = 10) (DS = 50 × 50 × 8)	15.39 ± 2.39 (*n* = 10) (DS = 50 × 50 × 9)	
Compression parallel to surface (along major direction) (MPa)	21.0 ± 5.6 (*n* = 30) (DS = 25 × 32 × 8)	10.6 ± 3.2 (*n* = 30) (DS = 25 × 36 × 9)	[22]

DS dimensions of the test specimen, *W* (mm) × *L* (mm) × *t* (mm) levels of spread rates (250 g/m^2 and 500 g/m^2, [26, 27]) using single-face gluing and the assembly was then cold pressed at pressure of 0.6 MPa for about 60 min. Block shear test specimen (10 replicates for each configuration) was then prepared from the laminated specimens with the dimensions of 30 mm deep for oil palm wood–oil palm wood lamination or 23 mm deep for oil palm wood–plywood lamination or 24 mm deep for oil palm wood–OSB lamination, 300 mm long, and 80 mm wide to evaluate bonding performance of the assembly, as shown in Fig. 1. To obtain the bonding shear strength, the block shear test specimen was loaded using the cross-head speed of 5 mm/min to failure as recommended in ASTMD 905 [28]. Block shear strength was then calculated by dividing the maximum shear force by the shear plane area. Wood failure percentage of the test specimen was also examined, by diving the wood failure area on the shear plane area of the test specimen by shear plane area.

Table 3 Six configurations of a pair of either oil palm wood bonded to oil palm wood or OSB/plywood bonded to low (LD) or medium (MD) density oil palm wood

Assembly of a pair	Number of assemblies produced in this work
LD–LD	2
MD–MD	2
LD–OSB	2
LD–plywood	2
MD–OSB	2
MD–plywood	2

Sandwich panel production and property tests

Sandwich panel production

Three oil palm wood lumber of the same density range with the dimensions of 20 mm (thick) × 80 mm (width) × 240 mm (length) were edge bonded with polyvinyl acetate adhesive to prepare a single layer panel with the dimensions of 20 mm (thick) × 240 mm (width) × 240 mm (length). This panel was then sanded with 100 grid sandpaper on both flat plane sides to achieve the panel with the final thickness of 15 mm. Various sandwich panel configurations with three-layer oil palm wood core either cross laminated (CLT core) or parallel laminated (GLT core) and OSB/plywood faces (see Fig. 2) were then produced using the adhesive amount of 250 g/m^2 determined in the study Sect. "Evaluation of bonding performance" and clamping pressure of 0.6 MPa. Total 8 configurations were produced, as shown in Table 4. Five panels for each configuration were produced.

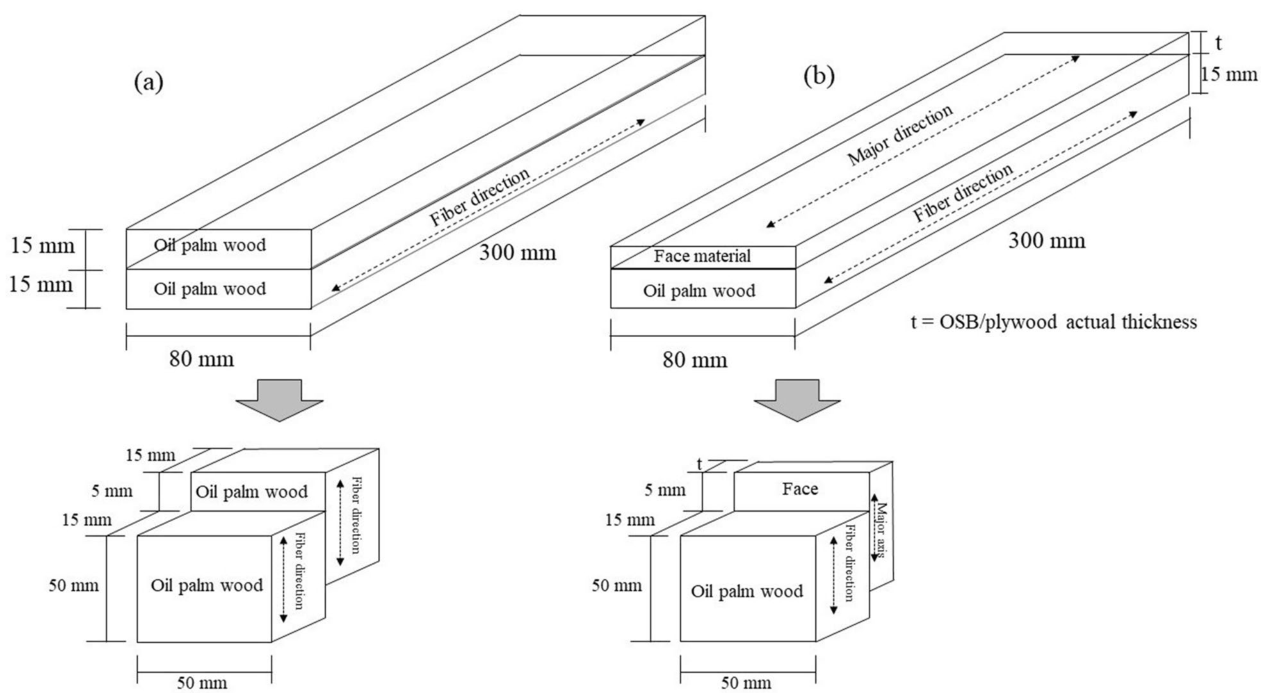

Fig. 1 Assembly of a pair of (**a**) oil palm wood to oil palm wood and (**b**) OSB/plywood to low or medium density oil palm wood, and preparation of the test specimen for block shear test

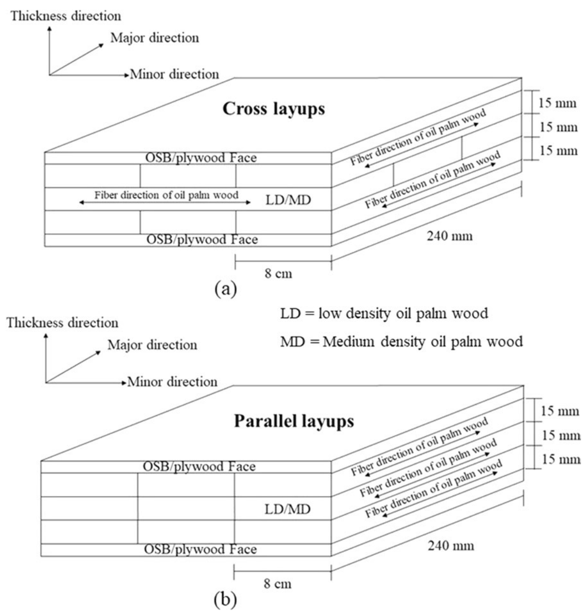

Fig. 2 Three-dimensional view of sandwich panel configurations, (**a**) OSB/plywood face with three-layer cross laminated low (LD) or medium (MD) density-oil palm wood core, (**b**) OSB or plywood face with three-layer parallel laminated low (LD) or medium (MD) density-oil palm wood core

Table 4 Eight configurations of sandwich panel produced in this work

Configurations of sandwich panel (Face–Core–Face)	Number of panels
OSB–LDCLT–OSB	5
OSB–MDCLT–OSB	5
Plywood–LDCLT–Plywood	5
Plywood–MDCLT–Plywood	5
OSB–LDGLT–OSB	5
OSB–MDGLT–OSB	5
Plywood–LDGLT–Plywood	5
Plywood–MDGLT–Plywood	5

LDCLT low-density oil palm wood CLT core, *MDCLT* medium-density oil palm wood CLT core, *LDGLT* low-density oil palm wood GLT core, *MDGLT* medium-density oil palm wood GLT core

Sandwich panel property testing

The produced sandwich panels were cut into the test specimens for determination of physical (density and swelling), thermal and mechanical properties. Prior the test, all samples were kept in conditioning room at 20 °C and 65% relative humidity for about 1 month to ensure that the equilibrium moisture content of 12% was attained. The detailed information for each property test is described below.

Physical properties Density and swelling (in major, minor and thickness directions of the panel, as indicated in Fig. 2) were conducted on the specimen with the dimensions of $50 \times 50 \times$ thickness in accordance with the test method described in EN 323 [20] and EN 317 [21], respectively. For swelling measurement, the specimen was soaked in distilled water at 20 °C for 24 h. Dimensions in all direction of the specimen before and after soaking in water were measured to calculate the swelling of the panel. Sixteen samples were used for each configuration of density measurement, and three samples were used for each configuration of swelling measurement.

Thermal properties Thermal conductivity of wood is generally dependent on grain direction [8]. As the heat would transfer though both CLT and GLT cores in radial direction (i.e., thicknesswise direction), ideally, both core configurations should have nearly the same thermal conductivity value. Based on the result of dimensional stability (see Sect. "Dimensional stability") which showed that the CLT core sandwich panel had better and more uniform dimensional stability in transverse direction which should be more preferred for structural use, the CLT panel type was, therefore, selected for the measurement of thermal conductivity. Thermal conductivity was measured across the thickness of the panel with the dimensions of 210 mm × 210 mm × thickness using a heat flow meter by a guarded custom made hot-plate apparatus. During the measurement, the temperature difference between the hot and cold plate was set to be 10 °C (the hot side temperature was 20 °C, and the cold side temperature was 10 °C). Thus, the mean temperature was 15 °C. All four edge sides of the sample were covered with 250 mm thick insulation materials to prevent the heat transfer in horizontal plane of the panel. The thermal conductivity was calculated at steady state conditions by measuring the heat flux at the center of the panel, on the 120 mm by 120 mm area, as described by Fourier's law as the following equation:

$$\lambda = \frac{d \cdot \phi_q}{\Delta T} \tag{1}$$

where λ is the thermal conductivity measured in Watts per meter Kelvin (W m^{-1} K^{-1}), ϕ_q is the measured heat flux (W m^{-2}), ΔT is the temperature difference across the specimen (Kelvin) and d is the thickness of the specimen (m). Three samples were tested for each panel type.

To compare the insulation performance of the produced sandwich panel with common construction materials (concrete and brick wall), the thermal resistance (R value) of all panels (including concrete and brick walls) of the same thickness was calculated using the following equation:

$$R = \frac{x}{\lambda} \tag{2}$$

where x is the sample thickness. The thermal resistance coefficient when the heat transfers from the air to the solid wall (=1/24 m^2·K/W) and from the solid wall to the air (=1/8 m^2·K/W) was also included in the calculation of R value according to the standard [24].

Compressive strength For wall applications, moisture-driven dimensional changes in the minor direction may apply in-plane tress to the adjacent walls and lateral force to the horizontal diaphragms or foundation. As the swelling in the minor direction of the CLT core sandwich panel was better (see Sect. "Physical properties"), the edgewise compressive strength in the major direction of the panel test was, therefore, conducted only on CLT core sandwich panel using universal testing machine (Lloy, UK) to estimate its vertical load capacity as a potential wall system. The load was applied at a constant crosshead speed of 0.25 mm/min until fracture in accordance with [22]. Eight samples were used for each configuration.

Data analysis

One-way analysis of variance (ANOVA) at 0.05 level of significance was used to evaluate the statistical difference between the mean values of each property.

Results and discussion

Fundamental properties of core materials

Table 5 shows the fundamental material properties of oil palm wood. Swelling in radial was rather larger than the tangential directions for both density ranges, and the values of MD specimen were higher. This trend is different from that of typical softwood and hardwoods in which the dimensional stability (shrinkage) in tangential direction is basically lower [8]. This should be a result of the absence of annual ring and the ray cells of oil palm wood [6, 29] that makes its properties in transverse direction to be more isotropic compared with that of softwoods and hardwoods. However, swelling in longitudinal direction of oil palm wood showed a similar trend as softwoods and hardwoods, in which the value in this direction was lower than in transverse direction. Shear and compressive strength parallel to grain of oil palm wood appeared to be dependent on wood density, which corresponded well to other works reported in literature [6, 7].

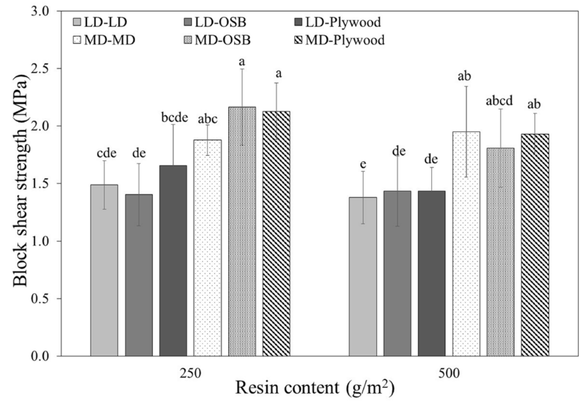

Fig. 3 Bonding shear strength of low-density oil palm wood bonded low density oil palm wood (LD–LD) specimen, low density oil palm wood bonded OSB (LD–OSB), low-density oil palm wood bonded plywood (LD–plywood), bonding shear strength of medium density oil palm wood bonded medium density oil palm wood (MD–MD), medium density oil palm wood bonded OSB (MD–OSB) and medium density oil palm wood bonded plywood (MD–plywood). The different between the mean value was determined by One-way-ANOVA analysis at 0.05 level of significance. Items with the same letter indicate that there is no difference between their mean values

Bonding performance

Figure 3 shows the bonding shear strength tests of oil palm wood to oil palm wood, oil palm wood to OSB and oil palm wood to plywood at two levels of resin contents (250 g/m^2 and 500 g/m^2). It was found that the bonding shear strength tended to be dependent on original oil palm wood used to prepare the block shear test specimens. As can be seen in Fig. 3, bonding shear strength of MD bonded specimen appeared to be higher than that of LD-bonded specimen. Visual inspection of the shear plane surface of the specimen after block shear

Table 5 Fundamental properties of oil palm wood

Properties	Density of oil palm wood	
	LD	MD
Swelling (%)		
Tangential direction	3.8 ± 0.9 (n = 10)	7.6 ± 3.5 (n = 10)
Radial direction	3.9 ± 1.3 (n = 10)	8.4 ± 3.6 (n = 10)
Longitudinal direction	1.4 ± 0.5 (n = 10)	1.4 ± 0.6 (n = 10)
Shear strength parallel to grain (MPa)	1.6 ± 0.6 (n = 30)	2.0 ± 0.9 (n = 30)
Compressive strength parallel to grain (MPa)	4.8 ± 2.7 (n = 30)	12.1 ± 3.6 (n = 30)

test revealed that the specimen failed due to shearing in oil palm wood tissue in all cases (see Fig. 4), implying that the block shear strength was governed by the shear strength of oil palm wood. It should also be noticed that the block shear strength value was very close to the shear strength parallel to grain of original oil palm wood of the same density (see Table 5), indicating that the bonding was nearly perfect. Examination of wood failure percentage of the test specimen also confirmed this result, as shown in Fig. 5. It was found that wood failure percentage of all specimen was more than 80% as required by the standard [30]. Note that, resin content did not affect the bonding shear strength for all test specimens. This indicates that the amount of adhesive of 250 g/m^2 is sufficient for boding all layers and this resin content was used to produce sandwich panels in the next section.

Properties of the sandwich panels

Physical properties

Panel's density Densities of the produced panels are shown in Fig. 6. As expected, density of the panel was strongly dependent on density of wood raw materials used in the production of sandwich panels in accordance with the rule of mixtures regardless of the core configuration and face material type. Since, densities of OSB and plywood were roughly similar (see Table 1), density of the produced sandwich panel was solely dependent on density of oil palm core material. As shown in Fig. 6, sandwich panels with higher core density had higher panel's density. Densities of the produced sandwich panels, which ranged from 440 to 471 kg/m^3 (Averaged density = 463 ± 24 kg/m^3) and 543 to 580 kg/m^3 (Averaged density = 562 ± 27 kg/m^3) for LD and MD cores, respectively, were found to be

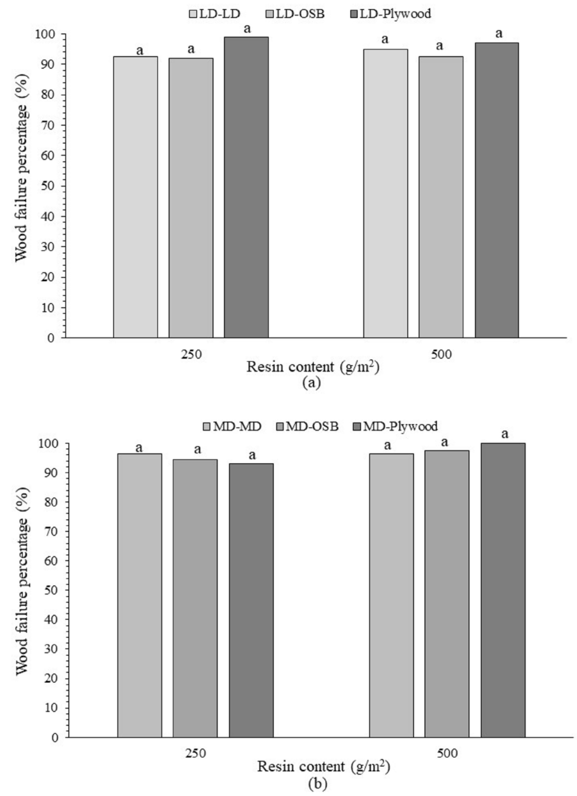

Fig. 5 Wood failure percentage of the produced sandwich panels (**a**) Low density oil palm core sandwich panel and (**b**) medium density oil palm core sandwich panel. Items with the same letter indicate that there is no difference between their mean values

lower compared with that of typical building materials currently used as a wall component in building structure, such as concrete (Density ~ 2400 kg/m^3, [2]), light weight

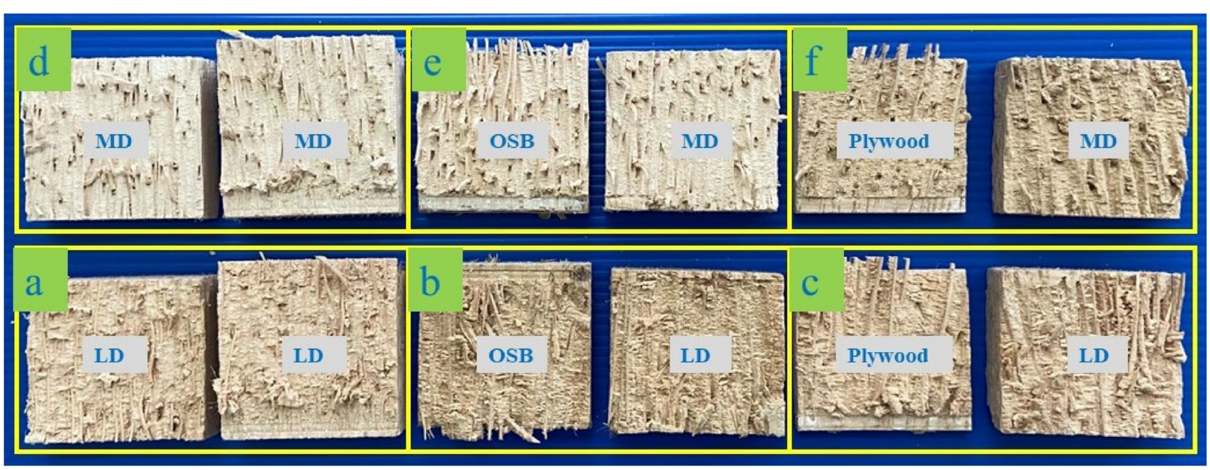

Fig. 4 Shear plane surface of the specimen after block shear test (**a**) low density oil palm wood bonded with low density oil palm wood, (**b**) low density oil palm wood bonded with OSB, (**c**) low density oil palm wood bonded with plywood, (**d**) medium density oil palm wood bonded with medium density oil palm wood, (**e**) medium density oil palm wood bonded with OSB and (**f**) medium density oil palm wood bonded with plywood

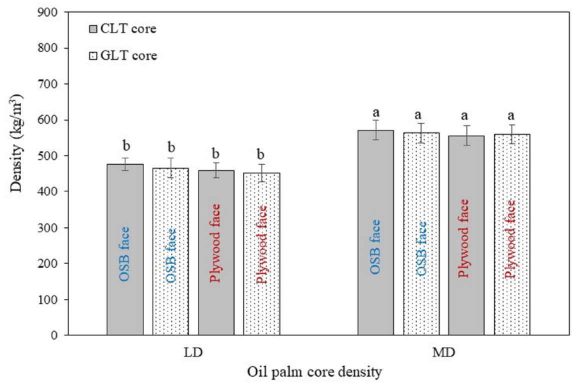

Fig. 6 Density of oil palm core sandwich panels. The different between the mean value was determined by One-way-ANOVA analysis at 0.05 level of significance. Items with the same letter indicate that there is no difference between their mean values

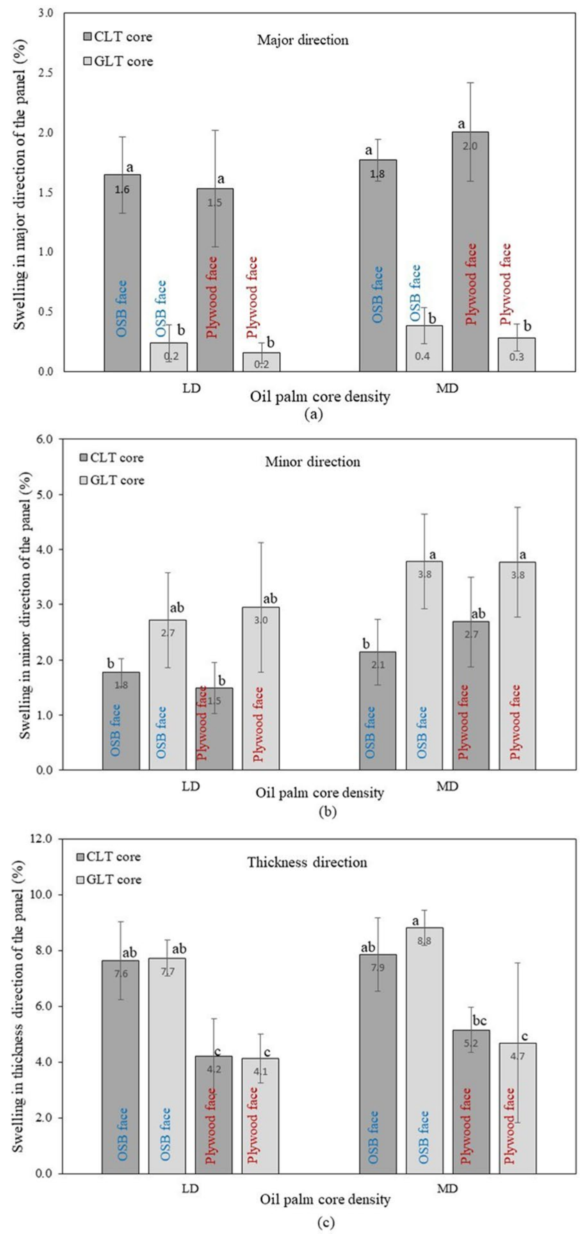

Fig. 7 Swelling in major (**a**), minor (**b**) and thickness (**c**) directions of the oil palm core sandwich panel. The different between the mean value was determined by One-way-ANOVA test at 0.05 level of significance. The same letter indicates that there is no difference between the mean values

concrete (Density- 1600–1800 kg/m^3, [31]), and brick (Density - 1600–1700 kg/m^3, [2]) walls. Thus, this panel could be considered as lightweight structure.

Dimensional stability Figure 7 shows swelling in major, minor and thickness directions of the sandwich panel. Core configurations seemed to significantly affect the swelling in major and minor directions of the panel. As shown in Fig. 7a, and b, sandwich panel with CLT core had higher swelling in major direction of the panel but lower swelling in the minor direction compared with that of GLT core. This should be a result of different swelling in tangential and longitudinal directions of oil palm wood raw materials, as shown in Table 5. It should also be noticed that although the MD oil palm wood swelled almost twice as much as LD oil palm wood in the tangential direction, however, this contribution of the oil palm's tangential swelling properties was abated by composite action between layers, including the surface sheathing materials, in the sandwich panel. It is interesting to note that the ratio of swelling in minor to major directions of CLT core sandwich panel was nearly to one, but they were more than 10 times for GLT core sandwich panel for both density group, implying that CLT core sandwich panel provided more uniform dimensional stability in the transverse directions. However, core configuration did not affect the swelling in the thickness direction of the panel. Thickness swelling tended to be dependent on the face materials. As shown in Fig. 7c, thickness swelling of OSB face sandwich panel was significantly higher than that of plywood face due to higher thickness swelling of OSB material (see Table 1). Although, higher core density seemed to slightly increase the swelling of the panel, but it had no significant effect based on One-way-ANOVA test at 0.05 level of significance.

Thermal properties

Thermal properties Figure 8 shows the thermal conductivity of the produced sandwich panels. It was found that thermal conductivity of the panel of the same core type seemed to be similar. Statistical analysis also confirmed this trend, as shown in Fig. 8. Examination of thermal conductivity of the plywood ($\lambda = 0.1229 \pm 0.0096$ W/m·K)

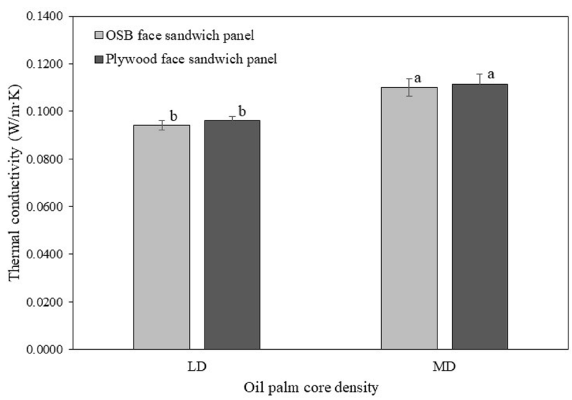

Fig. 8 Thermal conductivity of CLT core sandwich panels. The different between the mean value was determined by One-way-ANOVA test at 0.05 level of significance. Items with the same letter indicate that there is no difference between their mean values

Table 6 Calculated thermal resistance (*R*) of the produced sandwich panel compared with that of brick and concrete with the similar thickness (62 mm)

Type of wall	Thermal resistance (R) (m^2 K/W)
Sandwich panel	
Plywood face	
Low density core	0.8151 ± 0.0101^a
Medium density core	0.7257 ± 0.0191^b
OSB face	
Low density core	0.8260 ± 0.0140^a
Medium density core	0.7405 ± 0.0162^b
Brick	0.2355
Concrete	0.2201

[a, b] Items with the same letter indicate that there is no difference between their mean values

and OSB ($\lambda = 0.1175 \pm 0.0044$ W/m·K) faces revealed that both values were roughly similar, implying that the difference of thermal conductivity of the sandwich panel was mainly a result of different thermal conductivity of oil palm core materials. In general, this property of wood material is strongly dependent on its density [8, 9]. Higher density wood has higher amount of wood substance to conduct heat, and, therefore, higher thermal conductivity. Thus, higher oil palm core density sandwich panel gave higher thermal conductivity, as shown in Fig. 8.

Table 6 shows the calculated thermal resistance (*R* value) of the produced sandwich panels compared with that of concrete and brick walls at the same panel thickness of 62 mm. Thermal conductivity values of 0.9 W/m K (density 1788 kg/m^3) and 1.16 W/m K (density 2350 kg/m^3) for brick and concrete [32, 33], respectively, were used to calculate their *R* value according to Eq. 4. The *R* value of the produced sandwich panels showed the opposite trend as thermal conductivity with respect to oil palm core density. The *R* value of sandwich panel with LD core was highest followed by that of MD core sandwich panel, brick and concrete, respectively. This indicates that the low-density oil palm wood core sandwich panel could resist the heat flow through its thickness better than others. In other words, heat loss of LD core sandwich panel was lowest. On average, heat loss of all produced sandwich panel was about one-third of concrete and brick wall. This indicates that the produced sandwich panel had superior insulation performance than typical walls made of concrete and brick materials. Thus, it is expected that the OTTV index, which is directly related to thermal conductivity of material, of the produced sandwich panel would be lower as required by BEC standard of Thailand [2]. This implies that the wall structure made of oil palm core sandwich panel would provide much better insulation to the indoor space, hence more energy saving from air conditioning could be achieved.

Compressive strength

Compressive strength values in the major direction of the sandwich panels are shown in Fig. 9. It was found that oil palm wood core density and face material types significantly affected the compressive strength of the sandwich panels. As shown in Fig. 9, compressive strength tended to increase with core density for both face types and the values of plywood face sandwich panel seemed to be higher. This could be described by different failure modes observed in sandwich panels of different face materials. For OSB face sandwich panels, it was visually observed that the first crack always started in the OSB face material and subsequently progressed to oil palm wood core lamination whose grain oriented parallel to the applied load for both density group (Fig. 10). Thus, the loss of effective cross section due to OSB fracture contributed to the OSB face sandwich panel's compressive strength. For plywood face sandwich panels, however, the first crack was always observed in the oil palm wood core whose grain was oriented parallel to the applied load (major direction), and the face subsequently bent outward in the vertical direction. These observations indicate that both the face and core materials contributed to the load-carrying capability of this type of sandwich panel.

The compressive strength of the produced sandwich panels ranged from 8.0 to 13.1 MPa and 11.9 to 15.8 MPa for OSB and plywood face sandwich panels, respectively. Given that the plywood's compressive strength is double that of OSB, as presented in Table 1, its contribution to the overall sandwich panel's compressive strength was significant when the panel core material was the same.

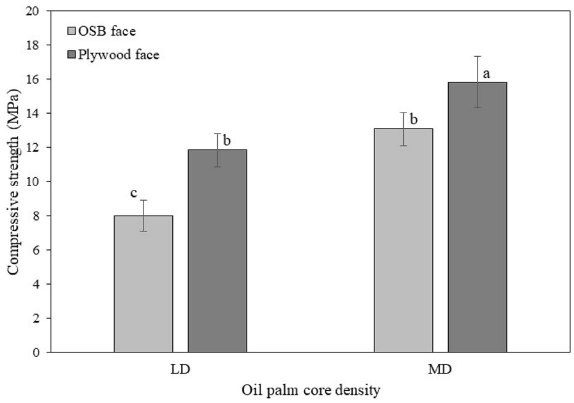

Fig. 9 Compressive strength of sandwich panel in parallel direction to the major axis of the face. The different between the mean value was determined by One-way-ANOVA test at 0.05 level of significance. Items with the same letter indicate that there is no difference between their mean values

Fig. 10 Representatives of failure modes observed in the test specimen after compression test (**a**) OSB face sandwich panel with low density core, (**b**) plywood face sandwich panel with low density core

Unlike a typical structural sandwich panel whose compressive strength is determined by the face materials, the core density also significantly contributes to the compressive strength of the presented sandwich panel type. Moreover, this core density's contribution to the panel's compressive strength became more critical for the MD core panel, as the face materials' contributions were reduced in comparison with that of the LD core panel, as shown in Fig. 9. Thus, the core's compressive strength can govern the proposed sandwich panel's compressive strength. In case a higher vertical load is required, the load-carrying capacity of the proposed panel could be increased not only by increasing the face thickness like a typical structural sandwich panel [10], but also by increasing the thickness of the core.

Conclusions

Based on the experimental result, it was concluded that adhesive content of 250 g/m^2 was sufficient to bond all layers (face to face/face to core/core to core). Core configuration mainly affected the dimensional stability of the panels. Swelling in transverse directions of cross laminated core sandwich panel was more uniform than that of parallel laminated core sandwich panel. Core density affected the overall density, thermal and compressive strength properties of the sandwich panels. The panels with higher core density had higher panel density, thermal conductivity and compressive strength but lower thermal resistance. Face material type affected dimensional stability, compressive strength and failure mechanism of sandwich panel. Plywood face sandwich panel had better dimensional stability and higher compressive strength. The compressive failure of the OSB face sandwich panel was initiated in the OSB face, while that of the plywood face sandwich panel was initiated in the core. Based on the measured thermal conductivity value, these panels had lower overall thermal transfer value (OTTV) as required by the Building Energy Code (BEC) of Thailand. Thus, they can provide better insulation performance than concrete or brick walls typically used in building construction in Thailand. In addition, the proposed sandwich panels also have the potential to be used as load-bearing walls. For practical applications of these sandwich panels, further structural performance evaluations considering the panel parameters (face/core thickness and panel size) are recommended for future work.

Abbreviations

OSB	Oriented strand board
OTTV	Overall thermal transfer value
LD	Low density
MD	Medium density
CLT	Cross laminated core
GLT	Parallel laminated core
ANOVA	Analysis of variance
BEC	Building energy code

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Author contributions

SJ: conceptualization, design of the work, performing the experiment, data analysis, interpretation of data, discussion of the result, drafting the manuscript, writing—review and editing. HL: design of the work, interpretation of data, discussion of the result, drafting the manuscript, writing—review and editing. ML: design of the work, interpretation of data, discussion of the result, drafting the manuscript, writing—review and editing. JKO: design of the work, interpretation of data, discussion of the result, writing—review and editing. ZP: design of the work, performing the experiment, interpretation of data, discussion of the result, writing—review and editing. HC: design of the work, interpretation of data, discussion of the result, writing—review and editing. SS: funding acquisition, Project administration, Conceptualization, design of the work, performing the experiment, data analysis, interpretation of data, discussion of the result, drafting the manuscript, writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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