Published paper

Panyakaew, S., Fotios, S. (2011) *New thermal insulation boards made from coconut husk and bagasse*, Energy and Buildings, 43 (7), pp. 1732-1739
http://dx.doi.org/10.1016/j.enbuild.2011.03.015

New thermal insulation boards made from coconut husk and bagasse

Satta Panyakaew and Steve Fotios

School of Architecture, University of Sheffield, Crookesmoor Building, Conduit Rd., Sheffield, S10 1FL, United Kingdom.

Abstract

This study describes the production of low density thermal insulation boards made from coconut husk and bagasse without the use of chemical binding additives. Dwelling in Thailand use thermal insulation to reduce air conditioning loads; the aim of this study was to develop a thermal insulation with lower environmental footprint than conventional materials. The hot pressing method was used and this article reports on the effect of board density and pressing conditions on the properties of the insulation boards. Mechanical properties of the coconut husk and bagasse insulation boards were measured for comparison with the standard employed in Thailand: *JIS A 5905: 2003 Insulation Fibreboards*. It was found that the bagasse insulation board with a density of 350 kg/m^3, using a 13 minute pressing time at a temperature of 200ºC, met all of the requirements except for swelling thickness. Thermal conductivity of the coconut husk and bagasse insulation boards was measured according to *ISO 8301* and this suggested that both insulation boards have thermal conductivity values ranging from 0.046 to 0.068 W/mK which were close to those of conventional insulation materials such as cellulose fibres and mineral wool.

Keywords

Thermal insulation; Binderless board; Coconut husk; Bagasse

1. Introduction

The design of residential buildings in Thailand has tended to move away from traditional, climate responsive architecture, towards a design influenced by western architecture. This trend means that dwellings are less able to control the internal environment to comfortable conditions and mechanical air conditioning systems are needed. Energy consumption in the residential sector accounts for approximately 20-25% of annual energy use in Thailand [1] and 65% of this is consumed by mechanical space cooling [2]. Thermal insulation of the building envelope is one of techniques that have been adopted to reduce energy consumed by air conditioning.

Thermal insulation products available in Thailand tend to be manufactured from fibreglass, mineral wool or polyurethane foams. Although these materials have good physical properties, e.g. low thermal conductivity, good moisture protection and fire resistance, they can be hazardous to human health and to the environment [3-5]. For example, exposure to the small particles from fibreglass and glass wool insulation can cause respiratory or skin irritation [3]. In addition, these materials cannot be found locally; they need to be imported from overseas, primarily the United States [6], which makes them expensive to use in Thailand.

Thailand is an agricultural country: 41% of the total area is used for agriculture [7] and the waste and disposal produced by agricultural industry can be a major problem [8-9]. One solution to the problem of waste management is reuse rather than disposal or combustion. This article discusses the manufacture of thermal insulation from agricultural waste, thus creating a useful building material [10,11]. Coconut husk and bagasse were considered to be the raw materials offering greatest potential for manufacture of thermal insulation [12], particularly in the context of Thailand [13]. This is because these raw materials are available within Thailand, and reducing the transportation component of embodied energy gives the potential for an improved environmental profile compared with those that are imported from overseas. In addition the production of insulation materials tends to require use of chemical binders such as formaldehyde or phenolic resins which are toxic to humans; coconut husk and bagasse can be used to manufacture thermal insulation without a binder, a benefit in terms of environmental and health impacts [14-18].

Coconuts are abundant in coastal areas of tropical countries. The coconut husk is available in large quantities as residue from coconut-fibre mattress production in many areas, which yields the coarse coir fibre. The husk consists of 30% fibre and 70% pith. Both fibre and pith are extremely high in lignin and phenolic content and it has been found that the coconut husk lignin can be used as intrinsic resin in board production [15]. Bagasse, the by-product of sugar production, is now considered to be one of the most promising non-wood lignocellulosic raw materials [19]. Large quantities of this waste are still left unused or burnt in developing countries. Bagasse is rich in celluloses which may act as a binder when making a board [16,18] and thus bagasse has good potential for the manufacture of binderless thermal insulation boards.

Synthetic binders[1] (e.g. formaldehyde resins) are normally used for the production of boards such as particleboard and fibreboard. These raw materials are expensive particularly for developing countries like Thailand where the supply of chemical products are limited. It is therefore considered that in the context of Thailand with a surplus of agricultural waste materials, the production of binderless board is the preferred option [17]. While efforts have been made to develop binderless boards by using a high-temperature hot pressing process, it appears that the process can only produce binderless board with high densities [14-18] whereas thermal insulation requires a low density.

The objective of this study is to develop low density, binderless boards using coconut husk and bagasse as the raw material. Low density boards tend to have lower thermal conductivity than boards with higher density, which makes them more suitable for use as thermal insulation boards. Binderless boards were made using the hot pressing method to investigate the effects of board density, hot pressing conditions (temperatures and times), proportion and size of the raw materials on the properties of the insulation board. The target board densities were relatively low, ranging from 250 to 450 kg/m^3.

[1] Board production typically uses thermosetting resins as binders. These synthetic binders include urea-formaldehyde, phenol-formaldehyde, resorcinol-formaldehyde, condensed furfuryl alcohol resins or organic poly-ioscyanates. To bond the raw materials together, a binder is mixed with the raw materials or fibres and then compressed with heat.

2. Materials and Test Methods

2.1. Raw materials

Both coconut husk and bagasse are rich in cellulose and lignin, which are two major compositions for producing binderless boards [14-18]. The chemical components of coconut husk (fibre and pith) and bagasse using for the production of binderless boards in this study are shown in Table 1 and these were measured according to the procedures in TAPPI standard[2] [20].

For this project, coconut fibre and pith were directly obtained from the waste of a coconut-fibre mattresses factory in Bangkok while bagasse was obtained from the waste of the sugar factory in Rajchaburi province.

Table 1

Chemical components of coconut fibre, coconut pith and bagasse

Chemical component	Results (%)			Test method
	Coconut fibre	Coconut pith	Bagasse	
Lignin	36.73	45.12	19.19	TAPPI-T222-cm-98
Holocellulose	67.63	58.82	76.31	Acid chlorite's Browing
A Cellulose	51.12	48.21	56.94	TAPPI-T203-cm-93

Note: All measurements carried out by Kasetsart Agricultural and Agro-Industrial Product Improvement Institute (KAPI), Bangkok, Thailand.

[2] TAPPI (Technical Association of Pulp and Paper Industry) prescribes standard testing procedures and related practices used in the measurement, evaluation, and description of pulp, paper, and related products. The standard also applies to the raw materials used in the manufacture of these products. The standards in TAPPI T 1-200 series are for fibrous materials and pulp testing.

2.2. Preparation of raw materials

According to JIS A 5905 – 2003, the Japanese standard for fibreboards, the moisture content of insulation board should be around 5-13%. In order to produce insulation boards with a moisture content within this range, coconut husks (fibre and pith) were oven dried at 80°C to a moisture content of 11-13%. Bagasse is more porous and easily absorbs moisture during storage before the production and thus bagasse was dried to lower moisture content: firstly being sun dried for three days to a moisture content of 10% and then further oven dried at 80°C to a moisture content of 6-7%.

The coconut fibres were cut to lengths of 8-10mm. The fibre to pith ratio for the production of coconut husk insulation boards was 80:20 by weight. For the production of bagasse insulation boards, the average length of large particles was around 20 - 40mm and the average length of small particles was around 8-9mm, and the ratio of large particles to small particles was 50:50 by mass.

2.3. Hot pressing process

Hot pressing is the process in which heat and pressure is applied to a mattress composed of fibres and resin to mould the final product [21]. In this study, binderless insulation boards made from coconut husk and bagasse were manufactured using hot pressing with pressure of 14.7 MPa.

Previous studies suggested that the coconut husk and bagasse binderless boards can be made by using hot pressing method at temperatures above 180ºC for 10 min [14-18]. Therefore, to investigate the effect of pressing temperature on physical properties of the insulation boards, three temperature settings (180 °C, 200 °C and 220°C) were used for pressing coconut husk and three temperature settings (160 °C, 180 °C and 200°C) for bagasse. The lower temperatures for bagasse follow previous study [22-24] which suggested that sugar containing lignocellulosic materials such as oil palm frond and kenaf core can be made into binderless boards using lower temperatures (140 °C -180 °C) due to their high hemicellulose content. It was expected that bagasse, also with high hemicellulose content, could be made into binderless boards using the similar lower temperature setting. In order to investigate the effect of pressing duration, three pressing durations were used (7, 10 and 13 minutes) for both coconut husk and bagasse.

2.4. Board preparation

The test boards were produced in a laboratory at the Royal Department of Forestry, Bangkok, Thailand. To study the effect of board density on physical properties of the insulation boards, the 25mm thick test boards were manufactured at the target board densities of 250, 350 and 450 kg/m^3. Coconut fibre and pith as well as bagasse particles were formed manually using a forming box into a mat of size 450 x 450mm. After forming, the mats were pre-pressed by hand to compact the materials without heat transfer. Two Teflon (polytetrafluoroethylene: PTFE) sheets were used on both the top and bottom surfaces of the mat to prevent the produced boards from sticking onto the hot plates during hot pressing process. The mat was then transferred to a single-opening hydraulic hot press. Bars of 25mm thickness were inserted between the hot plates before pressing to maintain a uniform thickness for all samples.

A total of 81 binderless coconut husk insulation boards were made, three boards being made for each of the 27 different manufacturing conditions. These manufacturing conditions were the 27 combinations of target board density (3 levels: 250, 350 and 450 kg/m^3), hot pressing temperature (3 levels: 180, 200, 220°C) and hot pressing duration (3 levels: 7, 10 and 13 min). Similarly, 81 binderless bagasse insulation boards were made, again corresponding to three boards for each of the 27 manufacturing conditions, combinations of target board density (3 levels: 250, 350 and 450 kg/m^3), hot pressing temperature (3 levels: 160, 180, 200°C) and hot pressing duration (3 levels: 7, 10 and 13 min).

2.5. Board testing

All produced boards were cut and trimmed into various test specimens. Since there is no standard testing procedures for fibreboard in Thailand, other industrial standards were used instead when testing the specimens. Japanese Industrial Standard: Insulation Fibreboards (JIS A 5905 – 2003) [25] was used for testing mechanical properties and dimensional stability: modulus of rupture (MOR), modulus of elasticity (MOE), internal bonding (IB) strength, and thickness swelling (TS) after water immersion. All tests for mechanical properties were carried out on a universal testing machine (Testometric M500-50kN). ISO 8301 [26] was followed in the measurement of thermal conductivity of the binderless boards using a Heat Flow Meter.

Bending strength test or MOR test is a three-point bending test conducted over a span of 375 mm at a loading speed of 10mm/min from the surface of test specimen. The test requires two specimens with the dimension of 425x100x25mm from each board. The load is increased onto the specimen until the specimen cracks. The maximum load (P) is measured and the bending strength of individual test piece is calculated using Equation 1.

$$\text{Bending strength (N/mm}^2\text{)} = 3PL/2bt^2 \qquad (1)$$

Where P is maximum load (N), L the span (mm), b the width of the test piece (mm) and t is the thickness of the test piece (mm).

Breaking load test or MOE test is based on the result from the MOR test. After the maximum load is measured, a graph between the load and the increasing bending distance is plotted. The values of bending strength test can be determined using Equation 2.

$$\text{MOE (N/mm}^2\text{)} = L^3\Delta W/4bd^3\Delta S \qquad (2)$$

Where L is the span (mm), ΔW the increasing load in the range of linear line of graph (N), ΔS the increasing bending distance in the range of linear line of graph (N), b the width of the test piece (mm) and d is the thickness of the test piece (mm).

Internal Bond (IB) test is carried out using two test specimens with the dimension of 50x50x25mm from each board. Each test specimen was adhered to aluminium blocks. Then, a tensile load was applied vertically to surface of the test specimen. In this study, the tensile load speed was about 2 mm/min. The maximum load (*P'*) at the time of the fracture of the adhesion part was measured. The internal bond can be calculated by the Equation 3.

$$\text{Internal bond } (N/mm^2) = P'/bL \quad (3)$$

Where P' is the maximum load (N), *b* the width of the test piece (mm), and L is the length (mm) of the test piece.

Thickness Swelling test (TS) examines the expansion of the board after immersion in water after two hours. Two specimens with the dimension of 100x100x25mm from each board were used. First, the thickness in the centre of a test specimen (t_1) was measured to the nearest 0.05 mm using a micrometer. Then, the specimen was immersed in water of temperature 24±1ºC, in the horizontal plane about 3 cm below the water surface for two hours. After that, the specimen was removed from the water, wiped to remove surface water, and its thickness measured again (t_2). Equation 4 is used for the calculation of the expansion ratio in thickness due to water absorption.

$$\text{Swelling in thickness after immersion in water } (\%) = (t_2/t_1 - 1) \times 100 \quad (4)$$

Thermal conductivity was measured at room temperature using a Heat Flow Meter under a steady-state one-dimensional test condition with upward heat flow [26]. Test boards were sandwiched between two plates, the hot plate and cold plate. At the centre of both plates within the measuring area of 100x100mm, two temperature sensors and two heat flux transducers were placed, one for each plate. Measurements of heat flux (W/m^2) and temperature difference (K) across the board thickness were used to calculate its thermal conductivity. The Heat Flow Meter can provide the measurements of thermal conductivity ranging from 0.005 to 0.35 W/mk. Twelve boards with the dimension of 300x300x25mm were tested, these being two of each material (BBI and BCI) at each of the three target densities.

2.6. Data Analysis

Mechanical properties and dimensional stability of the insulation boards produced in the current study were statistically analysed. The effects of different variables including board density, hot pressing temperatures and times on the mechanical properties and dimensional stability of the board were evaluated using the analysis of variance (ANOVA), a statistical technique for testing differences among experimental group means. ANOVA tests the null hypothesis that all group means are the same. Significant differences between groups would suggest that the experimental manipulation had some effects on the dependent variables [27].

3. Results and discussions

3.1. Board appearance

All the binderless boards were dark brown and had a peculiar smell, especially those boards made from bagasse at high temperature. The dark colour and smell indicate a modification of the chemical components during hot pressing. The binderless bagasse insulation boards had smooth surfaces similar to those of typical MDF board, as a result of the fineness of particles and the strong bonding generated by chemical reaction of the particles.

The actual densities of the test boards were in the range of 230-270 kg/m^3, 340-360 kg/m^3 and 440-480 kg/m^3 for the target board densities of 250, 350 and 450 kg/m^3 respectively. The average moisture contents of the test boards were between 6.3 and 9.3 %. Some of the coconut boards of density 230-270 kg/m^3 were slightly delaminated after hot pressing at a temperature of 180ºC and pressing times of 7 and 10 min.

3.2 Bending strength

The effects of materials type and board density on the modulus of rupture (MOR) of binderless boards produced using various pressing conditions are shown in Fig. 1. The results show that the binderless bagasse insulation boards have higher MOR values than the binderless coconut husk insulation boards. Some of the 230-270 kg/m^3 of binderless coconut husk insulation boards were brittle and broke during cutting.

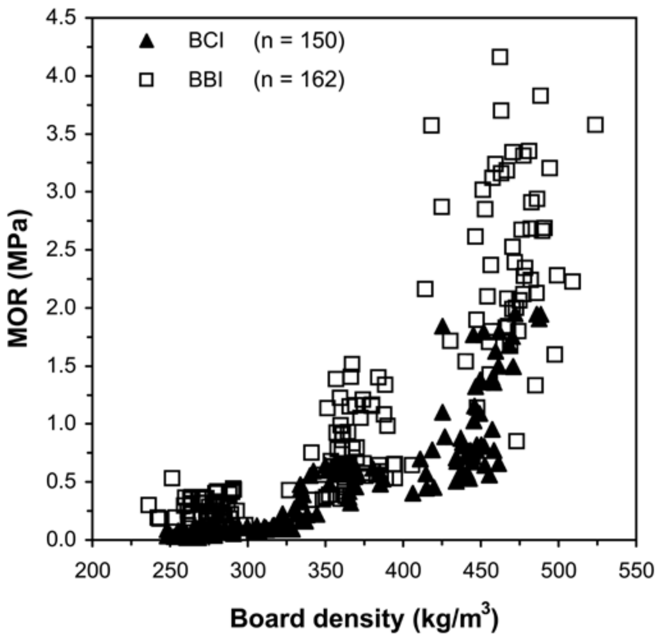

Fig.1. The effect of board density on MOR of binderless coconut husk insulation board (BCI) and binderless bagasse insulation board (BBI). (n = number of samples tested)

The maximum value of MOR for the binderless coconut husk insulation boards was 0.12 MPa at the board density of 250 kg/m^3, 0.68 MPa at the board density of 350 kg/m^3 and 1.94 MPa at the board density of 450 kg/m^3. The maximum value of MOR for the binderless bagasse insulation boards was 0.43 MPa at the board density of 250 kg/m^3, 1.51 MPa at the board density of 350 kg/m^3 and 4.16 MPa at the board density of 450 kg/m^3.

It can be seen that MOR increased with increasing board density, similar to common fibreboards (Fig. 1). The MOR of bagasse insulation boards was about two times higher than those of coconut husk insulation boards. The inferior bending strength of the binderless coconut husk insulation boards may be due to the chemical and physical properties of the coconut fibre. MOR not only depends on the bonding strength among fibres, but also the individual fibre strength and fibre geometry. The length of fibres using in this study could also contribute to a low MOR.

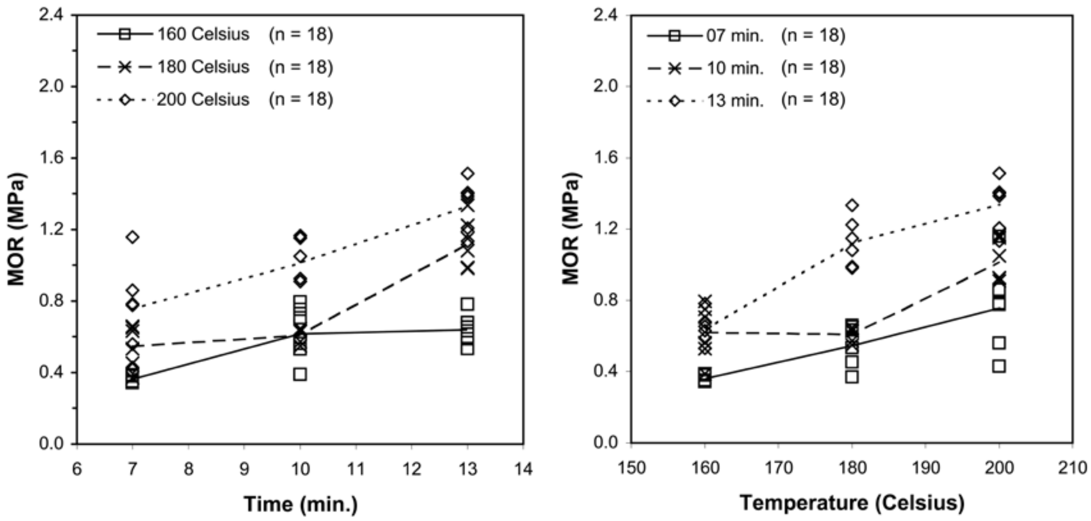

Fig.2. The effect of hot pressing times and temperatures on MOR of binderless bagasse insulation boards at the density of 350 kg/m^3. (n = number of samples tested)

Fig. 2 shows the relationship between hot pressing conditions (duration and temperature) on the MOR of binderless boards. It is obvious that the MOR values increase with increasing pressing time and temperature.

JIS A 5905 – 2003 recommends the minimum MOR of 1 MPa for insulation fibreboards (boards with density under 400 kg/m^3). It is apparent that only the binderless bagasse insulation boards at a density of 350 kg/m^3 with 200ºC/13 min pressing condition could meet this requirement. It is obvious that a certain pressing condition is required to produce insulation boards with good bending strength.

The results of the modulus of elasticity (MOE) for all boards are shown in Fig.3. It is clear that MOE of both bagasse insulation boards and coconut husk insulation boards follows the same trend as the MOR; MOE increased with increasing board density. The maximum value of MOE for binderless bagasse insulation boards was 102 MPa at the board density of 250 kg/m^3, 392 MPa at the board density of 350 kg/m^3 and 957 MPa at the board density of 450 kg/m^3. The maximum value of MOR for binderless coconut husk insulation boards was 88 MPa at the board density of 350 kg/m^3 and 365 MPa at the board density of 450 kg/m^3. Due to the brittleness of the coconut insulation boards at the target density of 250 kg/m^3, it was not possible to determine MOE for these boards.

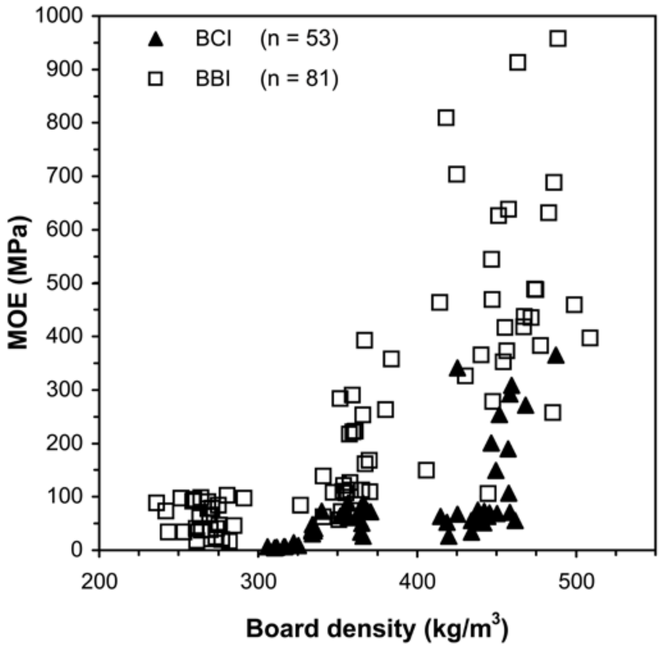

Fig.3. The effect of board density on MOE of binderless coconut husk insulation board (BCI) and binderless bagasse insulation board (BBI). (n = number of samples tested)

It should be noted that JIS A 5905 – 2003 does not specify a minimum MOE value for insulation boards. Nevertheless, the MOE values of binderless bagasse insulation boards at density of 450 kg/m^3 with 200ºC/13 min pressing condition exceeded 800 MPa at which JIS A 5905 – 2003 recommends for type 5 Medium Density Fibreboard (MDF).

3.3. Internal bond

The effects of materials type and board density on the internal bond (IB) of binderless boards produced using various pressing conditions are shown in Fig. 4. The results showed that the IB values of binderless coconut husk insulation boards were much lower than those of binderless bagasse insulation boards of the same board densities. For example, at the board density of 350 kg/m^3, the maximum value of IB for the binderless coconut husk insulation boards was only 0.002

MPa whereas the maximum value of IB for the binderless bagasse insulation boards was 0.014 MPa.

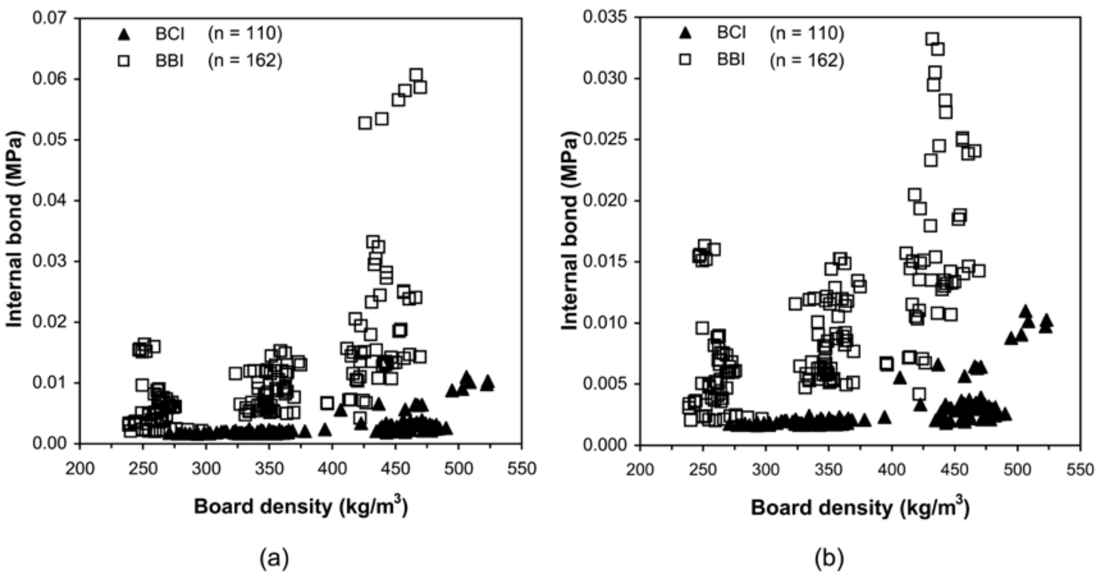

Fig.4. The effect of board density on IB of binderless coconut husk insulation board (BCI) and binderless bagasse insulation board (BBI). Figure 4a shows the whole set of results: Figure 4b omits the BBI boards of internal bond 0.05-0.06 MPa to improve clarity of data at lower regions. (n = number of samples tested)

Fig.5 shows IB for binderless bagasse insulation boards at the board density of 350 kg/m^3 using different pressing time of 7, 10 and 13 min, and different pressing temperature of 160, 180 and 200ºC. It is obvious that the IB value increased with increasing pressing time. An increase of pressing time from 10 to 13 min improved the IB by 30-50% for binderless coconut husk insulation boards and by 60-80% for binderless bagasse insulation boards. The trend of the relationship between hot pressing temperature and IB value was different for the three pressing times.

According to JIS A 5905 – 2003, IB test is not required for insulation board. However, the results of IB values of both binderless coconut husk and binderless bagasse insulation boards could be used for comparison with the conventional insulation materials. Fibreglass and rock wool insulation boards generally have IB values ranging from 0.003 to 0.08 MPa [28]. The IB values of both binderless coconut husk and binderless bagasse insulation boards were within or slightly lower than this range.

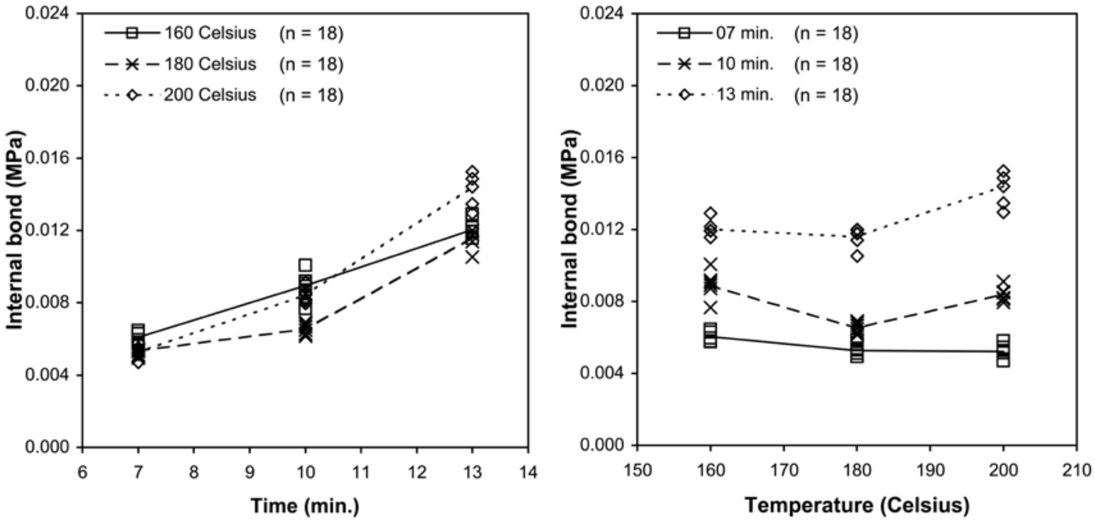

Fig.5. The effect of hot pressing times and temperatures on IB of binderless bagasse insulation board at the density of 350 kg/m^3. (n = number of samples tested)

3.4. Dimensional stability

The percentage thickness of swelling (TS) after water-soaking for different board densities are shown in Fig. 6. The plotted values are scattered and suggest the unexpected non-linear relationship between density and TS. This is believed to be due to the density gradient across the thickness of the board and is being further investigated.

The TS values of the binderless coconut husk insulation boards decreased with increasing temperature and pressing time. This trend is similar to the previous studies [23, 24]. In contrast, the TS values of the binderless bagasse insulation boards increased with increasing temperature and pressing time. At the board density of 350 kg/m^3, the binderless coconut husk insulation board gave the lowest TS value of 21.7% with pressing temperature of 220ºC/13 min whereas the binderless bagasse insulation board gave the lowest TS value of 42.7% with pressing temperature of 160ºC/7 min. It should be noted that thickness swelling of both insulation boards exceeds the maximum permitted levels (10%) for insulation boards in JIS A 5905: 2003.

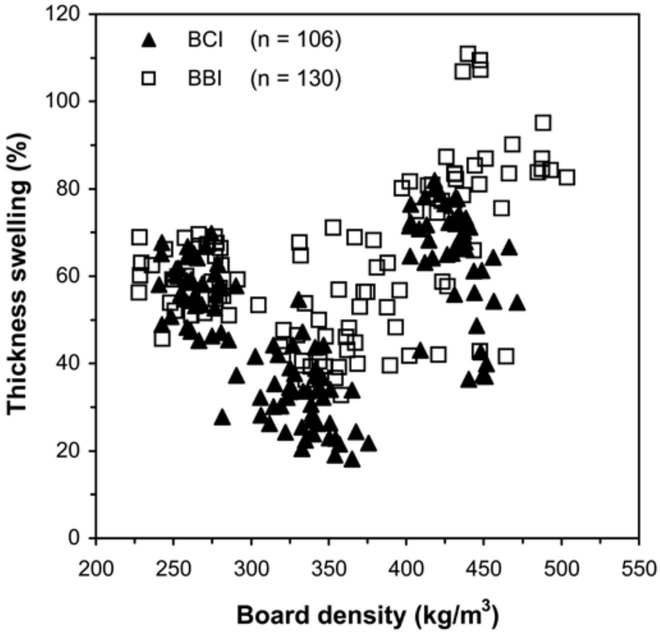

Fig.6. The effect of board density on thickness swelling after water-soaking tests for 2 h of binderless coconut husk insulation board (BCI) and binderless bagasse insulation board (BBI). (n = number of samples tested)

3.5 Thermal conductivity

The thermal conductivity values of binderless boards made from coconut husk and bagasse plotted against board density are shown in Fig. 7. The data indicate a positive relationship between thermal conductivity and density. The thermal conductivity values of binderless coconut husk and bagasse insulation boards with the density of 250-350 kg/m^3 range from 0.046 to 0.068 W/mK. Table 2 compares the thermal conductivity of both boards with other insulation materials. It can be seen that the thermal conductivity values of both boards are lower than those of kenaf and cotton stalk insulation boards [29, 30], in the same range as those of expanded perlite and vermiculite and close to those of synthetic fibrous and cellular materials (e.g., cellulose fibres, mineral wool, polyethylene foam and extruded polystylene foam) [28].

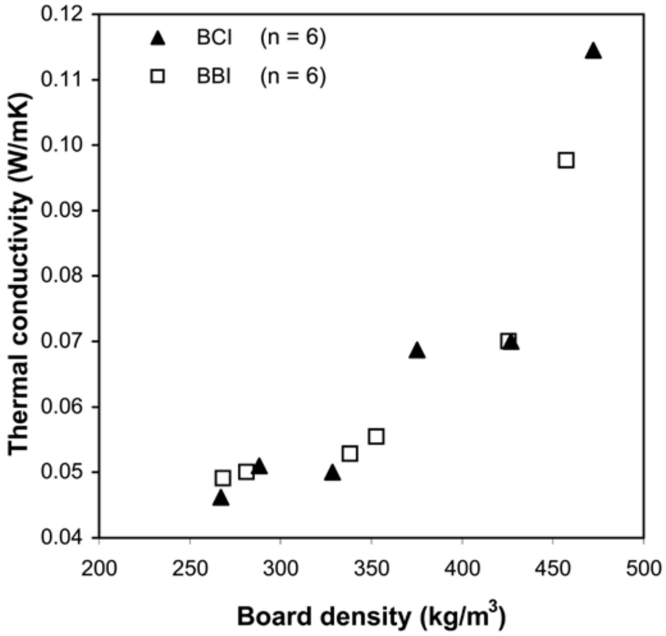

Fig.7. The effect of board density on thermal conductivity of binderless coconut husk insulation board and binderless bagasse insulation board. (n = number of samples tested)

Table 2

Thermal conductivity of binderless coconut husk insulation board (BCI) and binderless bagasse insulation board (BBI) compare with other insulation materials.

Materials	Density (kg/m^3)	Thermal conductivity (W/mK)	Source
BCI	250-350	0.046-0.068	
BBI	250-350	0.049-0.055	
Kenaf insulation board	150-200	0.051-0.058	[29]
Cotton stalk insulation board	150-450	0.058-0.081	[30]
Cellulose fibres	30-80	0.040-0.045	[28]
Mineral Wool (fibreglass & Rockwool)	20-200	0.035-0.045	[28]
Polyethylene foam (PE)	50-100	0.035-0.045	[28]
Extruded polystylene foam (XPS)	25-45	0.030-0.040	[28]
Expanded perlite boards (EPB)	90-490	0.045-0.070	[28]
Vermiculite	70-160	0.046-0.070	[28]

3.6. Statistical Analysis

ANOVA was carried out to determine the effects of board density, hot pressing temperature and time on mechanical properties and dimensional stability of binderless coconut husk and bagasse insulation boards. Note that analysis of the data suggested they were drawn from a normally distributed population. The ANOVA results are shown in Table 3 and Table 4. Overall, the results for binderless coconut husk and bagasse insulation boards were similar: there were the significant main effects of density, temperature, and time on board properties at the probability level of 0.001, for all board properties being analysed (MOR, MOE, IB and TS). Also there were significant interaction effects between density and temperature, density and time, temperature and time on all board properties. The interaction effect among density, temperature and time was also significant on some board properties (MOR, MOE and IB for binderless coconut husk insulation boards, and MOE, IB and TS for binderless bagasse insulation boards).

Table 3

The result of ANOVA test on the effect of variables on binderless insulation board properties made from coconut husk. (n = number of samples tested)

Between-subject effects	MOR (n=150)		MOE (n= 53)		IB (n=110)		TS (n=106)	
	F	Sig	F	Sig	F	Sig	F	Sig
Density	1961.24	p<0.001	297.41	p<0.001	1006.23	p<0.001	612.17	p<0.001
Temperature	291.50	p<0.001	123.46	p<0.001	437.39	p<0.001	90.69	p<0.001
Time	188.20	p<0.001	92.60	p<0.001	186.00	p<0.001	65.03	p<0.001
Density*Temperature	167.22	p<0.001	83.70	p<0.001	431.21	p<0.001	4.34	p<0.001
Density*Time	39.54	p<0.001	27.11	p<0.001	154.98	p<0.001	6.02	p<0.001
Temperature*Time	21.36	p<0.001	26.63	p<0.001	83.45	p<0.001	3.17	p<0.05
Density*Temperature*Time	19.68	p<0.001	19.89	p<0.05	68.95	p<0.001	1.65	p=0.12

Table 4

The result of ANOVA test on the effect of variables on binderless insulation board properties made from bagasse. (n = number of samples tested)

Between-subject effects	MOR (n=162)		MOE (n=81)		IB (n=162)		TS (n=130)	
	F	Sig	F	Sig	F	Sig	F	Sig
Density	1634.83	$p<0.001$	614.32	$p<0.001$	1562.82	$p<0.001$	359.47	$p<0.001$
Temperature	143.53	$p<0.001$	72.84	$p<0.001$	615.59	$p<0.001$	41.75	$p<0.001$
Time	96.11	$p<0.001$	80.42	$p<0.001$	817.95	$p<0.001$	111.61	$p<0.001$
Density*Temperature	40.32	$p<0.001$	17.05	$p<0.001$	338.66	$p<0.001$	19.62	$p<0.001$
Density*Time	24.37	$p<0.001$	19.33	$p<0.001$	122.45	$p<0.001$	4.46	$p<0.01$
Temperature*Time	4.04	$p<0.01$	6.28	$p<0.001$	153.69	$p<0.001$	5.48	$p<0.01$
Density*Temperature*Time	1.27	$p=0.26$	2.20	$p<0.05$	50.73	$p<0.001$	4.35	$p<0.001$

4. Conclusions

Binderless insulation boards with a low density of 250-450 kg/m^3 were made from coconut husk and bagasse using the hot pressing method. The effects of board density and pressing conditions on the physical properties of the board were evaluated. The result show that the mechanical properties (MOR, MOE and IB strength) of the boards increased with increasing board density, pressing time and temperature. The binderless insulation boards made from bagasse at density of 350 kg/m^3 treated at a hot press temperature of 200^{o}C for 13 min show greater mechanical properties and meet the requirements of insulation fibreboards according to JIS A 5905: 2003. For dimensional properties, the binderless coconut husk insulation boards showed greater stability against water than the binderless bagasse insulation boards. However, the TS values of both boards are higher than the requirements. Thermal conductivity of the binderless insulation boards made from coconut husk and bagasse showed values close to those of conventional insulation materials (e.g., cellulose fibre, mineral wool).

The binderless bagasse insulation boards provided properties that were superior to those of coconut husk boards. The results showed that the binderless bagasse insulation boards at density of 350 kg/m^3 satisfying the requirement of the relevant standards (except the thickness swelling) can be used as building materials for thermal insulation applications. Since the binderless boards are made from waste materials and without any chemical binders, it is environmental friendly and can possibly compete with conventional insulation materials. Furthermore, the manufacturing process of binderless boards is very simple; no special equipment is needed so it can easily be applied to commercial production. Nevertheless, the application of insulation boards in hot and humid climate like Thailand involves some complications, in particular for organic materials. Before new insulation boards can be introduced to the market there are further issues that need to be examined including resistance to fungal growth, insect protection, moisture control and water sorption. Regarding to the problem of swelling, a possible solution is to wrap the insulation board in waterproof materials like plastic (Polypropylene, PP) and is being further investigated.

The next stage of this study involves the evaluation of environmental and health impacts of the binderless insulation boards made from coconut husk and bagasse using Life Cycle Assessment (LCA) in accordance with the standard of ISO 14040 series. This evaluation will use the IMPACT 2002+ method for impact assessment and Simapro 7.1 as the LCA software tool. The results will provide information for comparing the environmental profile of the boards with conventional insulation materials.

Acknowledgments

The authors thank the laboratory at the Royal Department of Forestry, Bangkok, Thailand for providing equipment for this study, and Victory Industrial Co. Ltd. and Baan Pong sugar factory for supplying the raw materials.

References

[1] V. Yungchareon, B. Limmeechokchai, Energy Analysis of the Commercial Sector in Thailand: Potential Saving of Selected Options in Commercial Buildings, In The Joint International Conference on "Sustainable Energy and Environment (SEE)", 1-3 December 2004, Hua Hin, Thailand, 2004, pp. 496-501.

[2] H. Nakagami, International Comparison of Residential Energy Consumption, In 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Building – IAQVEC 2007, 28 – 31 October 2007, Sendai, Japan, 2007.

[3] Agency for Toxic Substances and Disease Registry (ATSDR), Toxicological profile for Synthetic Vitreous Fibers, Atlanta: U.S. Department of Health and Human Services, 2004.

[4] P.F. Infante, L. Schuman, J. Dement, J. Huff, Fibrous glass and cancer, American Journal of Industrial Medicine 26 (1994) 559-584.

[5] U.S. Environmental Protection Agency, Health and Environmental Effect Profile for Formaldehyde, Cincinnati: Environmental Criteria and Assessment Office, Office of Health and Environment Assessment, Office of Research and Development, 1988.

[6] Thai Environment Institute (TEI), Building Materials: Thermal Insulation, Bangkok: Ministry of Industry Report No.: TGL-14-97, 1997.

[7] Office of Agricultural Economics (OAE), Agricultural statistics of Thailand, Ministry of Agriculture and Cooperatives, Bangkok, Thailand, 2004.

[8] D.S. Lee, D.H.F. Atkins, Atmospheric ammonia emissions from agricultural waste combustion, Geophysical Research letters 21 (4) (1994) 281-284.

[9] J. Webb, N. Hutchings, B. Amon, Field burning of agricultural wastes, EMEP/EEA emission inventory guidebook 2009, Copenhagen: EEA (European Environment Agency), 2009.

[10] R.M. Rowell, R.A. Young, J.K. Rowell, Paper and Composites from Agro-based Resources, New York: CRC Press, 1996.

[11] A. Sampathrajan, N.C. Vijayaraghavan, K.R. Swaminathan, Mechanical and Thermal Properties of Particle Boards Made from Farm Residues, Bioresource Technology 40 (3) (1992) 249-251.

[12] K. Manohar, D. Ramlakhan, G. Kochhar, S. Haldar, Biodegradable Fibrous Thermal Insulation, Journal of the Brazilian Society of Mechanical Sciences and Engineering 28 (1) (2006) 45-47.

[13] S. Panyakaew, S. Fotios, Agricultural waste materials as thermal insulation for dwellings in Thailand: Preliminary results, In PLEA 2008 – 25th Conference on Passive and Low Enegy Architecture, 22 – 24 October 2008, Dublin, 2008

[14] E.L. Mari, Binderless board from coconut (Cocos nucifera L.) coir dust, Forest Products Research and Development Institute Journal (FPRDI J) 22 (1) (1996) 45-54.

[15] J.E.G. van Dam, M.J.A. van den Oever, W. Teunissen, E.R.P. Keijsers, A.G. Peralta, Process for production of high density/high performance binderless boards from whole coconut husk, Industrial Crops and Products 19 (2004) 207-216.

[16] R. Widyorini, J.Y. Xu, K. Umemura, S. Kawai, Manufacture and properties of binderless particleboard from bagasse I: effects of raw material type, storage methods, and manufacturing process, Journal of Wood Science 51 (2005) 648-654.

[17] F. Mobarak, Y. Fahmy, H. Augustin, Binderless lignocellulose composite from bagasse and machanism of self-bonding, Holzforschung 36 (1982) 131-135.

[18] K. Shen, Process for manufacturing composite products from lignocellulosic materials, United Stated Patent 4627951, 1986.

[19] A. Ashori, A. Nourbakhsh, A. Karegarfard, Properties of Medium Density Fiberboard Based on Bagasse Fibers, Journal of Composite Materials 43 (18) (2009) 1927-1934.

[20] Technical Association of Pulp and Paper Industry, TAPPI Standard Test Method: Fibrous Materials and Pulp Testing T 1-200 Series, New York: TAPPI, 1998.

[21] N. Norberto, S Mario, Hot-pressing Process Modeling for Medium Density Fiberboard (MDF), International Journal of Mathematics and Mathematical Sciences 26 (12) (2001) 713-729.

[22] N. Laemsak, M. Okuma, Development of boards made from oil palm frond I: Manufacturing and fundamental properties of oil palm frond particleboard, In FORTROP '96 International Conference, November 29-30, Bangkok, Thailand, 1996, pp. 71-83.

[23] N. Okuda, M. Sato, Manufacture and mechanical properties of binderless boards from kenaf core, Journal of Wood Science 50 (2004) 53-61.

[24] J. Xu, R. Widyorini, H. Yamauchi, S. Kawai S, Development of binderless fiberboard from kenaf core, Journal of Wood Science 52 (2006) 236-243.

[25] Japanese Industrial Standard, JIS A 5905-2003 Fibreboards, Tokyo: Japanese Standard Association, 2003.

[26] ISO, ISO 8301, Thermal insulation – Determination of steady-state thermal resistance and properties – Heat flow meter apparatus, International Organization for Standardization, 1991.

[27] A. Field, Discovering Statistic Using SPSS, SAGA Publications Ltd, London, 2005.

[28] M. Pfundstein, R. Gellert, H.M. Spitzner, A. Rudolphi, Insulating Materials – Principles, Materials, Applications, in: C. Schulz (Eds.), DETAIL Practice, Architektur-Dokumentation GmbH & Co., Munich, 2008.

[29] J.Y. Xu, R. Sugawara, R. Widyorini, G.P. Han, S. Kawai, Manufacture and properties of low-denstiy binderless particleboard from kenaf core, Journal of Wood Science 50 (2004) 62-67.

[30] X. Zhou, F. Zheng, H. Li, C. Lu, An environmental-friendly thermal insulation material from cotton stalk fibers, Energy and Buildings 42 (2010) 1070-1074.