Effect of Surface Density on the Fire Performance of Wood and Wood-Based Materials

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Abstract

Surface density known as mass per unit area or as a product of density and thickness was analyzed as a key factor in predicting the fire performance of wood and wood based materials. Sawn timber of Mangium (*Acacia mangium* Willd) and Gmelina Arborea (*Gmelina arborea* Roxb.) in various thicknesses, manufactured particleboards and cement bonded particleboards of both species in various densities and thicknesses were used as the testing materials. Commercial particleboards, cement bonded particleboards and MDF were also tested. Boards were tested under ISO 5660 using cone calorimeter. Physical and mechanical properties were tested based on ASTM and JIS standards. The physical and mechanical properties of manufactured wood based panels could fulfil the JIS standard. Ignition time is affected by the surface density and effective surface area to the heat exposure of the boards. Boards reacted in different ways to the heat exposure but they needed similar time to the critical temperatures of 260 °C, in the similar surface density regardless of materials type. Surface density could be used as a key parameter in the fire resistant design process. The results of tested boards under ISO 5660 were about two third of those under JIS A 1304.

Key words: cone calorimeter, fire resistant performance, surface density, wood, wood based materials.

Introduction

Wood and wood based panels play an important role in housings and building constructions such as for siding, framing, sheathing, roofing, flooring, and interior finishing. It is frequently involved when fire occurs in building (Benedetti 1981). Fire performance characteristic is important information in building design and construction activities. Moreover, due to the declining of the supply of timber from natural forest, the use of fast growing species in the building construction will be increasing. *A. mangium* and *G. arborea* are the two major fast growing species planted one and two decades ago in Indonesia. Nowadays such timber species are abundantly available for constructions and raw materials of wood based products.

The fire performance characteristic of wood depends on its various characteristics. Some of the characteristics are density, moisture content, permeability, anatomy and chemical compositions. Surface density known as mass per unit area or a product of density and thickness has been reported as an important indicator for fire performance characteristic of wood. It was mentioned that the higher surface density, the longer time for the unexposed surface of wood to reach the critical temperature. The fire performance of sawn timber of Hinoki, Falcataria and *G. Arborea* was evaluated by using JIS A 1304 and cone calorimeter (Subyakto *et al.* 1998). The thickness variation of tested sawn timber was limited so that the results covered the narrow range of observed surface density. Another study reported the similar trend for low density particleboard and plywood (Kawai 1988, Ishihara & Kawai 1989). The new findings of such research are important in fire resistant design and it needs to be extended for other types of wood based products with various conditions.

In this paper, *A. mangium* and *G. arborea* timber were used as the target species to get a clear figure on the effect of surface density on the fire resistant performance of building materials. Beside plain-sawn and quarter-sawn timber, particleboard and cement bonded particleboard made of such species were produced in various thicknesses and densities in order to get wider range of observed surface densities. With organic and inorganic binder of wood based panels, the result of this research will be useful for designing both the fire resistance of interior as well as exterior part of buildings. Commercial wood based panels in the type of particleboard, cement bonded particleboard and medium density fibre board (MDF) was also tested to be compared with the data. The fire performance was tested under ISO 5660 with cone calorimeter. Since ISO 5660 is a newly developed testing procedure replacing the ISO 834 which was analogous to JIS A 1304 and ASTM E 117 testing procedure, the analysis is enriched with the testing results of JIS A 1304 for particleboard and other wood based panels. Statistical analysis was also applied to give clearer figure of the testing results.

Materials and Methods

Sawn timber

Sawn timber in the form of planks of *A. mangium* and *G. arborea* were produced from 10 years old plantation forest in Bandung, Indonesia. The size of the boards was (100 x 100) mm^2 with the thicknesses of 6, 12, 18 , 24, and 30 mm in the tangential (plain-sawn) and radial (quarter-sawn) directions. The boards for specimens were freshly cut and air-dried to the equilibrium moisture content of 15%. The density, moisture content, and the dimensions of the specimens were measured before the testing on fire performance was conducted.

Particleboard

Particleboards bonded with 10% urea formaldehyde (UF) adhesive resin were manufactured using wood particles of the same materials as sawn timber. The densities of the particleboard were 0.4, 0.6, and 0.8 g cm^{-3}. The size of the particleboard was 400 mm in square with the thicknesses of (12 and 24) mm. Three replications were made of each variable. Specimens were conditioned to air dry moisture content.

Cement bonded board

Cement bonded particleboards of *A. mangium* and *G. arborea* were manufactured with the target density of 1.15 g cm^{-3}. The size of the board was 500 mm in square with the thicknesses of 12, 15, 18, 24, and 27 mm. The ratio of wood to cement was 1:2.75. Three replications were made for each board thickness. Boards were conditioned in room temperature for about 2 months before testing to get the equilibrium moisture content.

Commercial boards

Commercial particleboards from Japan NOVOPAN Ind. Co. Ltd. bonded with UF and melamine-urea (MUF) adhesives in the density of 0.80 g cm^{-3} and with the thicknesses of 12, 15, 20, and 25 mm, cement bonded particleboards from NICHIHA Corporation with 0.9 C Type in the density of 1.40 g cm^{-3} and with the thicknesses of 12, 17, 18, and 24 mm, and medium density fibre boards (MDF) from HOKUSHIN Co. Ltd. with M-Type in the density range of 0.60-0.70 g cm^{-3} and with the thicknesses of 5.5, 12, 15, and 21 mm were used as testing materials.

Testing on the physical and mechanical properties

Physical and mechanical properties of the wood materials were tested based on the ASTM D – 143 (ASTM 1996) for small scale test of sawn timber and JIS A 5908 (JIS 1994) for particleboard, JIS A 5417 (JIS 1985) and ASTM D-1073 (ASTM 1990) for cement bonded particleboard, and JIS A 5906 (JIS 1983) for MDF to support the data on the fire performance. Five and three samples for timber and wood based materials, respectively, were tested for each condition.

Testing on the fire performance of boards using a cone calorimeter apparatus

The cone calorimeter test was done based on the ISO 5660 (ISO 1993) standard. The weight and the thickness of (100 x 100) mm^2 boards were determined before testing. The boards were wrapped with alumunium-foil sheet and left open for the exposed surface. Thermocouples connected to the data logger were attached at the center of unexposed and exposed surfaces to check the temperature change in both sides. After the specimen was attached to the equipment at a horizontal position, spark igniter was applied. The heat was maintained at a constant heat flux of 40 kW m^{-2}. The observed parameters were ignition time, mass loss rate and time-temperature gradient in unexposed surface of the boards. The weight of the tested boards was also measured just after the testing.

With five thickness variations and two cutting patterns of two timber species and three replications of each condition, 60 specimens of fire performance testing of sawn timber were prepared. For the wood based materials, three replications for each condition, i.e. total of 102 specimens were also prepared for fire performance testing.

Results and Discussion

Physical and mechanical properties of the boards

The physical and mechanical properties of small clear specimens of sawn timber of *A. mangium* and *G. arborea* were shown in Table 1. It showed that *A. mangium* had a slightly higher mechanical performance than *G. arborea* due to its higher density.

The manufactured particleboards made of *A. mangium* and *G. arborea* as well as the commercial ones conformed to the standard for base particleboard of JIS A 5908-1994. Particleboards in the density of 0.4 g cm^{-3}, 0.6 g cm^{-3} and 0.8 g cm^{-3} conformed to the quality 8-type, 13-type and 18-type, respectively. It is shown in Table 2 that the higher the densities of particleboards, the higher the mechanical properties of the boards.

All of the manufactured cement bonded particleboards and the commercial cement bonded particleboards conformed to the high quality cement bonded particleboard in the JIS A 5417-1994. With reference to the Table 2, the M-Type MDF samples with various thicknesses conformed to the requirement of JIS A 5906-1983 for the 300 Type MDF.

Ignition time

Wood products ignite when subjected to a certain condition of high temperature in surroundings that provide oxygen for combustion. Wood typically responds to these external exposures by decomposing, or pyrolyzing, into volatiles and a char residue. The ignition could be recognized from the flaming combustion after pyrolysis. For the smouldering materials, the evidence of thermal degradation may be the colour change accompanied by a weight loss over a matter of a few minutes in the affected region (Forest Product Laboratory 1990).

Surface density gives more clear effect of density and thickness of the specimen on the ignition time as shown in Fig. 1. The higher surface density, the longer it will take for the materials to be ignited. For sawn timber, the timber species obviously affected the ignition time as shown in the Figure 1. *A. mangium* with the average density of 0.61 g cm^{-3} need more time to be ignited than *G. arborea* with the average density of 0.50 g cm^{-3}. *G. arborea* has a coarse texture but *A. mangium* has fine texture (Soerianegara & Lemmens 1993, Lemmens *et al.* 1995). The former provides very thin cell walls of 2-3.5 μm while the latter provides thin to moderate thick cell walls. Such structure of wood might affect the surface area exposed to radiant heat energy.

Table 1 Physical-mechanical properties of tested *A. mangium* and *G. arborea* timber in small clear specimen

Physical-Mechanical Properties	*Acacia mangium*			*Gmelina arborea*		
	Average	SD	CV %	Average	SD	CV %
1. Density (g cm^{-3})	0.61	0.016	2.50	0.51	0.014	2.80
2. Moisture content (%)	14.94	0.21	1.38	15.21	0.34	1.65
3. Compression (MPa)						
- Parallel	29.8	2.3	7,71.8	23.2	1.8	7.76
- Perpendicular	16.5	0.89	5.39	9.85	0.76	7.70
4. Tension (MPa)						
- Parallel	158.9	14.17	8.91	120.2	10.04	8.35
- Perpendicular	5.29	0.53	9.10	2.76	0.11	3.9
5. Stiffness (GPa)	33.29	1.40	4.21	28.37	1.32	4.67
6. Flexural strength (MPa)	70.10	4.92	7.02	50.56	4.22	8.35
7.Shear strength (MPa)						
- Parallel	9.23	0.52	5.63	7.84	0.59	7.53
- Perpendicular	7.90	0.53	6.71	4.84	0.14	2.89

Note: SD, Standard Deviation; CV, Coefficient of Variation (%).

The thin cell wall with the wide cavity provided the larger apparent surface area than the thick cell wall with the narrow cavity. The larger apparent surface area provided higher effective surface area to the heat exposure. Effective surface area is the area of which was attacked by the heat on the surface of boards. There was no significant effect of cutting direction in one species to the ignition time.

The ignition time was significantly affected by the type of materials. Particleboard ignited earlier than the sawn timber of the same species with the same surface density. It may be due to the wider effective surface area to the heat exposure of particleboard than that of timber. Manufactured particleboards of *A. mangium* and *G. arborea* did not show any significant differences in the ignition time with each other due to the similar surface density and specific surface area. On the other hand, commercial particleboard with the same surface density as the manufactured particleboard needed longer time to ignite. The density distribution in the thickness direction (Hata 1989) and surface condition with the finishing process of the commercial particleboard is predicted as a factor affecting ignition time of particleboards. Medium density fiberboards tended to ignite earlier than particleboard and sawn timber. It might be affected by the smaller element size of MDF than that of particleboard and sawn timber. It should be noted that the moisture content of the tested MDF was relatively lower than those of the particleboard and sawn timber as shown in Tables 1 and 2.

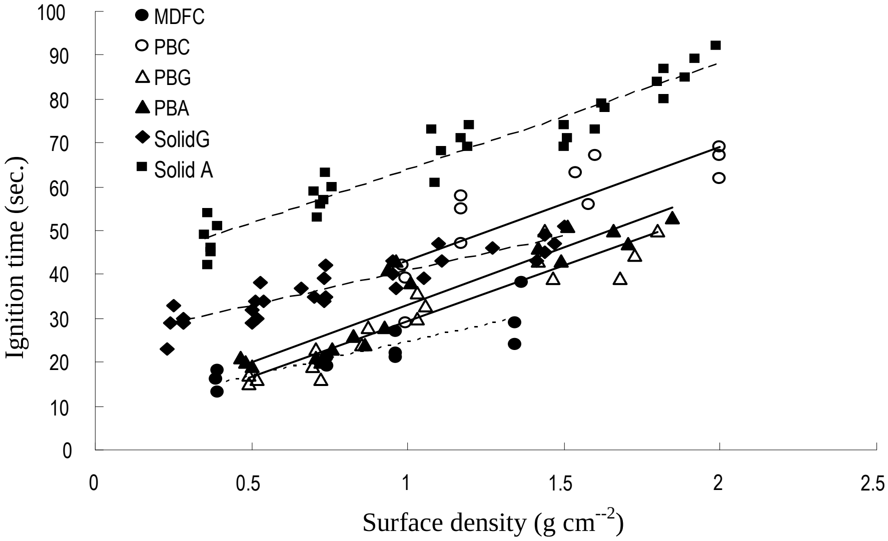

Figure 1 Relationship of surface density and ignition time of different type of boards (MDFC, Commercial MDF ,Y= 15.38X+9.11 r^2 =0.72; PBC, commercial particleboard, Y= 26.00X+17.22 r^2 =0.69; PBG, particleboard of *G. arborea*, Y= 25.55X+3.75 r^2 =0.89; PBA, particleboard of *A.mangium*, Y= 26.20X+6.77 r^2 =0.85; Solid *G. arborea*, sawn timber of *G. arborea*, Y= 15.77X+24.99 r^2 =0.84; Solid A, sawn timber of *A. mangium*, Y= 15.38X+9.11 r^2 =0.92). X=surface density, Y=ignition time.

Table 2 Physical and mechanical properties of wood based panels

Type of Boards	Density g cm^{-3}	Thickness mm	SD g cm^{-2}	MC %	TS %	WA %	IB Kgf cm^{-2}	MOR MPa	MOE GPa	SW Kgf
PBA	0.42	12	0.54	10.17	11.44	87.65	2.62	8.59	0.59	12.96
	0.40	24	0.96	10.70	9.75	78.68	2.54	8.09	0.75	18.14
	0.62	12	0.74	10.57	16.18	46.72	8.30	14.93	1.24	41.95
	0.61	24	1.46	10.40	14.79	52.23	8.98	16.62	1.76	40.65
	0.78	12	0.94	10.22	17.59	22.34	19.65	28.74	3.87	57.91
	0.80	24	1.92	10.35	13.54	15.76	15.50	25.98	3.82	67.55
PBG.	0.43	12	0.52	10.69	20.96	126.08	2.95	8.86	0.72	10.13
	0.42	24	1.01	10.77	18.93	93.76	2.92	8.42	0.68	10.05
	0.59	12	0.71	10.54	19.83	57.13	10.39	13.76	1.33	24.31
	0.61	24	1.46	10.68	15.21	38.39	5.63	13.36	1.65	37.05
	0.76	12	0.91	10.73	13.12	17.11	12.31	20.88	3.60	64.35
	0.78	24	1.87	10.82	12.80	14.22	11.08	24.76	3.01	66.97
CPBA	1.18	12	1.42	13.58	2.31	20.38	4.26	10.49	4.26	35.87
	1.15	15	1.73	13.83	2.48	16.79	8.81	10.51	3.51	36.35
	1.17	18	2.11	13.45	1.55	18.64	5.08	10.72	3.80	57.38
	1.15	24	2.76	13.52	1.86	16.92	4.24	10.23	3.92	47.21
	1.16	27	3.13	13.22	1.40	12.12	5.64	10.52	3.82	33.69
CPBG	1.14	12	1.39	14.20	0.86	17.18	6.30	11.67	3.65	34.97
	1.15	15	1.73	14.30	0.94	21.22	4.70	11.06	3.20	32.10
	1.16	18	2.09	14.34	1.30	15.73	5.82	11.38	3.58	31.50
	1.17	24	2.81	14.26	1.50	16.77	6.64	11.99	3.85	34.16
	1.18	27	3.19	14.36	2.44	11.98	6.65	10.77	3.52	32.60
PBC	0.80	12	0.96	10.40	7.91	11.49	13.80	24.20	3.54	57.82
	0.81	15	1.21	10.93	8.02	11.98	10.68	20.14	3.52	61.22
	0.81	20	1.62	10.57	7.54	10.90	10.58	27.36	3.71	59.54
	0.80	25	2.00	10.18	8.16	9.67	10.71	21.52	3.56	60.98
CPBC	1.40	12	1.68	9.40	1.88	13.21	12.60	16.76	5.92	45.67
	1.28	17	2.18	9.00	2.00	17.99	11.45	27.38	6.98	52.77
	1.40	18	2.52	10.11	1.32	10.22	11.83	24.24	6.17	32.89
	1.35	24	3.24	10.54	1.44	14.23	10.55	25.00	5.77	46.72
MDFC	0.70	5.5	0.39	6.55	9.64	23.12	11.69	36.14	3.20	67.21
	0.60	12	0.72	7.65	10.32	26.77	6.18	32.57	2.86	59.22
	0.60	15	0.90	7.63	10.45	24.78	9.06	35.60	3.35	64.22
	0.60	21	1.26	8.31	11.01	25.65	6.50	31.90	2.59	58.54

Notes: PBA, particleboard of *A. mangium*; PBG, particleboard of *G. arborea*; CPBA, cement bonded particleboard of *A. mangium*; CPBG, cement bonded particleboard of *G. arborea*; PBC, commercial particleboard; CPBC, commercial cement bonded particleboard; MDFC, commercial medium density fiberboard; SD, Surface Density; MC, Moisture Content; TS, thickness swelling ; WA, water absorption; IB, Internal Bond; MOE, Modulus of Rupture; MOE, Modulus of Elasticity; SW, Screw Withdraw.

The effects of surface density and effective surface area to the heat exposure on the ignition time could be explained as follows: "when heat attacks the surface of a semi transparent material, some of the heat flux is absorbed and some of it reflected through diffusion or speculative process and when a part of the material transparent, then some of the heat flux is transmitted to the inner part of the material" (Bardon 1977). The boards with higher surface density and/or effective surface area absorbed higher heat energy on the surface of the specimens than the boards with lower surface density and/or effective surface area. Since the heat flux was constant, in the beginning of the exposure the energy for ignition of boards with higher surface density and/or effective surface area was lower than that of boards with lower surface density and/or effective surface area.

Temperature change of the materials under heat exposure

Wood and wood based panels reacted in different characteristic to the radiant heat exposure as shown in Figure 2. In the all of tested boards, the heat energy was needed mostly for evaporating the moisture so that it took a long time for them to reach the temperature 100 °C. In the beginning of the exposure, the temperature rose in a constant gradient and levelled off at about 90 to 100 °C for a certain period. The moisture being evaporated took the path of lowest resistance to escapes through corners, arrays, joints, open pores, cracks, and shakes. The temperature did not increase until almost all the moisture had been evaporated (Hartl 1995). The temperature rose quickly again after 110 °C.

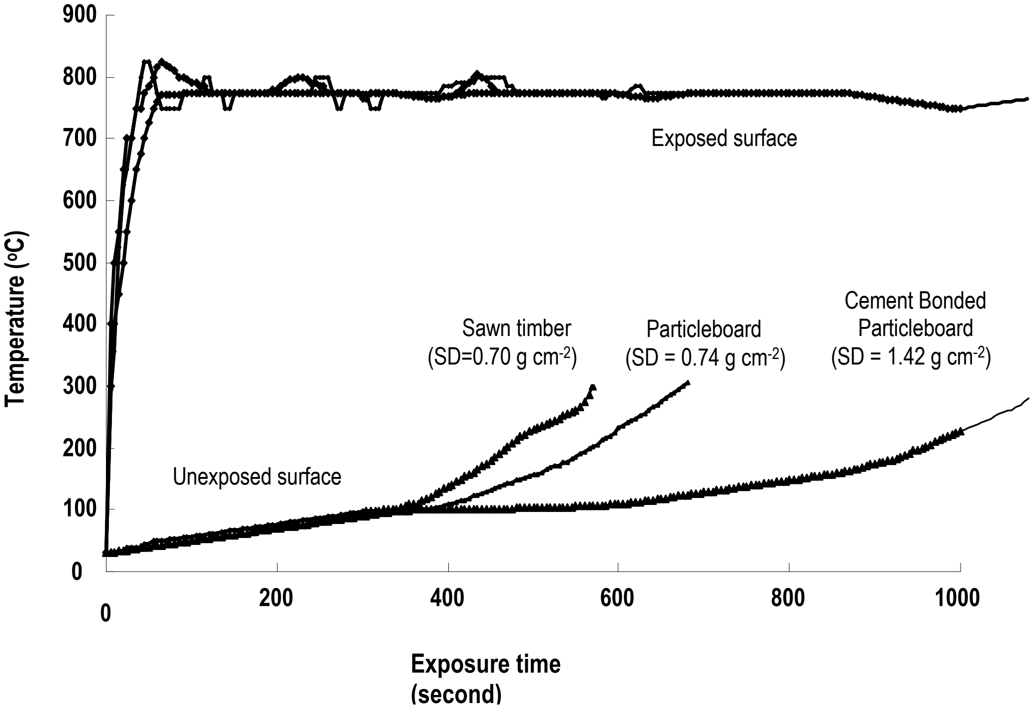

Figure 2 Fire resistance behavior at un-exposed surface and fire exposure condition at exposed surface for different type of boards from *A. mangium* wood with the thickness of 12 mm (SD, surface density).

Figure 2 showed that the temperature rising curve at unexposed surface near to the critical temperature of sawn timber was quite different from that of the particleboard. The presence of rays caused cracks, shrinks and other failures in the thickness direction of sawn timber which built up the new paths for the liquid and gaseous flow. The cracks and other failures generated shortened the time to reach the critical temperature in sawn timber. On the other hand, particleboard degraded constantly but no cracks were observed.

Cement bonded particleboard needed longer time to evaporate the moisture than particleboard and sawn timber due to the high surface density. It was also affected by the high moisture content in the form of cement hydrates. After the chemical decomposition the cement lost the bonding strength, and the wood particles were starting to be degraded. The moisture evaporation and wood particles degradation evoked the observed cracks in the tested boards.

As shown in Figure 2, temperature at the exposed surface was relatively stable especially for cement bonded boards. For resin bonded wood based panels and sawn timber, temperature at the exposed surface slightly increased when the ignition occurred. The ignition produced flame which affected the temperature gradient and when the flame disappeared temperature at the exposed surface became stable. No flame was found in cement bonded particleboard so that the temperature in exposed surface relatively stable during the testing.

Mass loss rate (MLR)

At the beginning of the test, condensed smoke was released from the boards before ignition occurred. High flame occurred just after ignition and the MLR became high to a peak called the first peak of MLR (first stage or MLRI). MLR gradually decreased as the flame decreased and the chars developed. The MLR remained the same for a certain period as the flame became constantly small (second stage). The flame then gradually increased again so did the MLR until it reached the second peak of MLR (third stage or MLR II). The flame gradually decreased and then distinguished when the boards burnt out, and the MLR also decreased gradually (Subyakto *et al*. 1998).

The MLR could indicate the reaction of boards to the heat exposure. Figure 3 showed the MLR of particleboard, sawn timber and cement bonded particleboard in first stage, second stage and third stage. The MLR I and MLR II and total mass loss of particleboard were higher than those of sawn timber and cement bonded particleboard. Particleboard has wider specific surface area that made higher possibility to be degraded than sawn timber. Particleboard also consists of more combustible components such as glue and wood particles than cement bonded particleboards. The burnt materials in particleboards tended to be degraded in the form of dust.

The MLR I of sawn timber was lower than that of particleboard. It happened due to its small effective surface area and the formation of char layer in the degraded area. After the ignition, the MLR of sawn timber was in constant condition. The presence of cracks in sawn timber after moisture evaporation might accelerate the time to reach the MLR.

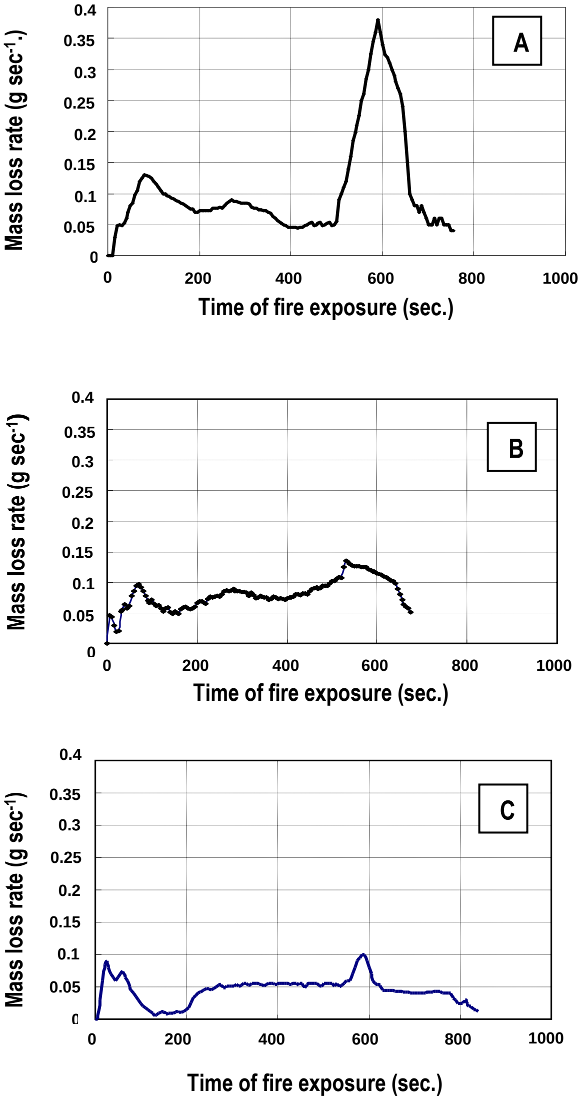

Figure 3 Mass loss rates during fire exposure of wood and wood based panels (SD, surface density).

Notes: A = Particleboard (SD=0.74 g cm^{-2});
B = Sawn timber (SD=0.70 g cm^{-2});
C = Cement bonded particleboard (SD=1.42 g cm^{-2})

The rapid time to reach MLR I of cement bonded particleboard might be affected by higher thermal conductivity of cement bonded particleboard than that of particleboard and sawn timber. With higher the thermal conductivity, faster the dehydration process in cement bonded particleboard than those in particleboard and sawn timber. In the cement bonded particleboard, the heat energy during the earlier heat exposure was absorbed for quick dehydration process so that after reached to the MLRI, the MLR drastically decreased to the lowest rate as shown in Figure 3. The dehydration process continued in a certain period. Due to the moisture evaporation and chemical decomposition as mentioned above, cracks were occurred. The presence of cracks promoted the presence of oxygen for degrading of high amount of wood particles in cement bonded particleboards which affected the MLR II. Since the amount of wood particles was about one fourth of the total cement bonded particleboards, the MLR II of cement bonded particleboards was relatively smaller than those of particleboards and sawn timber. After MLR II, the degradation was continued to the rest wood particles and inorganic parts of the board until the board totally burnt.

Figure 4 shows the effect of surface density on the time to reach the MLR II. The time to reach MLR II in sawn timber and resin bonded wood based panels increased with increasing of the surface density in the similar manner. The same trend was observed in the cement bonded particleboard, though the time to reach the MLR II was less than those of the sawn timber and resin bonded wood based panels as shown in Figure 4. It might be affected by the different reaction of the boards to the heat exposure as mentioned above. The presence of cracks accelerated the MLR II of cement bonded particleboard.

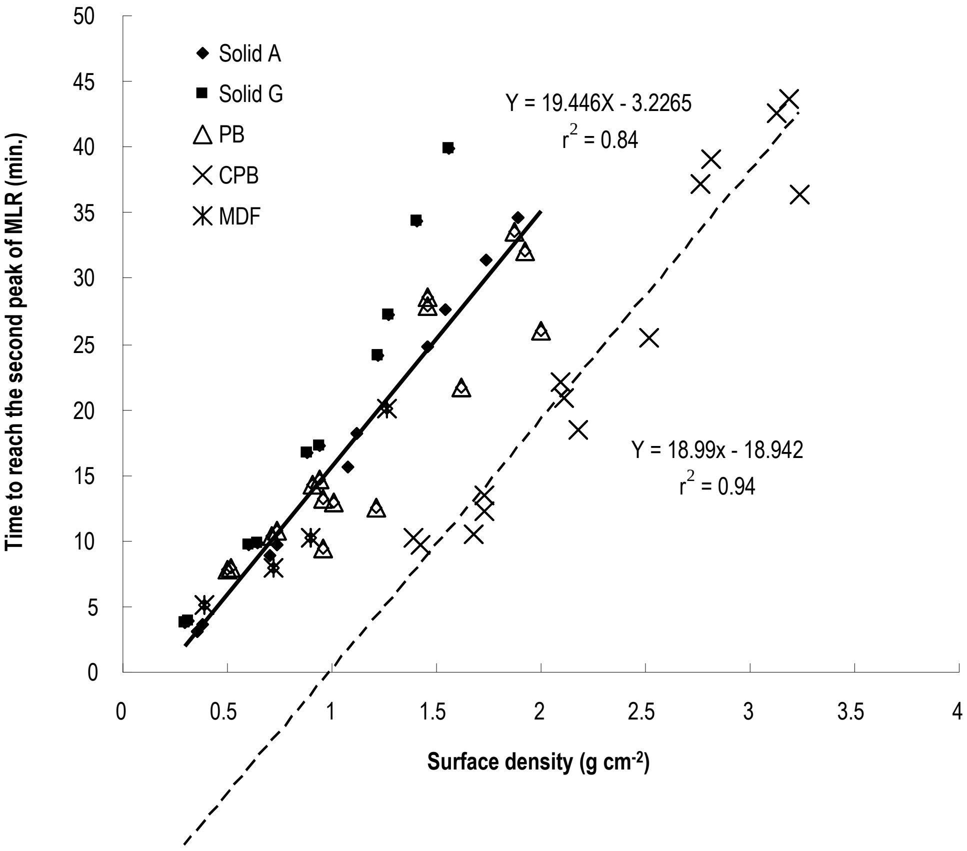

Figure 4 Relationship between surface density and time to reach the second peak of mass loss rate (Solid A, sawn timber of *A. mangium*; Solid G, sawn timber of *G. arborea*; PB, particleboard; CPB, cement bonded particleboard; MDF, medium density fiberboard).

Predicting the fire performance at the critical temperature through surface density

Figure 5 showed the plot of relationship between surface density and the time to reach the critical temperature of 260 °C for wood and wood based materials. The higher surface density the longer time to reach the critical temperature of 260 °C of any boards. The similar time to reach the critical temperature of wood and wood based materials could be expressed through the reaction of the materials to the heat exposure. Particleboards reacted with the production of dust but no cracks and sawn timber with the char layer but with the occurrence of cracks. The presence of cracks in cement bonded particleboard generated the decomposition of inorganic materials and wood particles. Due to the degradation of inorganic materials, cement bonded particleboard needed longer time to the critical temperature after MLR II than those of particleboards and sawn timber Statistical analysis of the data using linear regression and 5% exclusion limit had been conducted and the result as shown in Figure 5. The relationship between the surface density and the time to reach the critical temperature of 260 °C of any boards proved to have high correlation with the coefficient determination of 0.88 or coefficient correlation of 0.94. From the analysis of standard error and 5% exclusion limit, total excluded plots were 26 from 162 specimens.

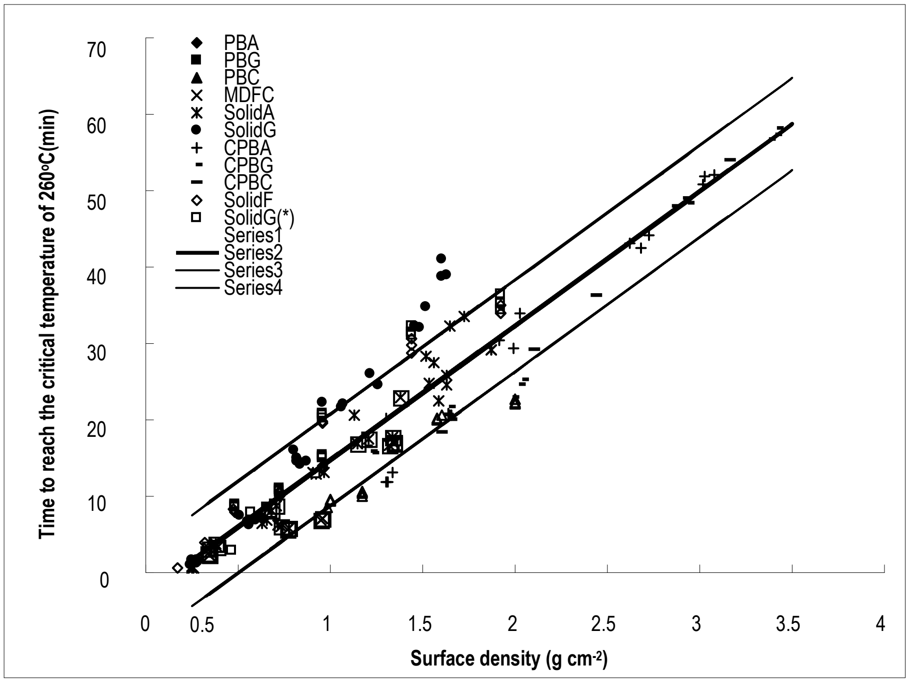

Figure 5 Relationship between surface density and time to reach the critical temperature of 260 °C. (EL, exclusion limit; CPBA, cement bonded particleboard of *A. mangium*; CPBG, cement bonded particleboard of *G. arborea*; CPBC, commercial cement bonded particleboard; Solid F, sawn timber of *P. falcataria*; Solid G(*), sawn timber of *G. arborea* tested in previous study; for other legends see Figure 1).

For the positive exclusion, sawn timber of *G. arborea* was dominantly found. The thermal conductivity of plain-sawn and quarter-sawn of *A. mangium* and *G. arborea* wood for 15% moisture content had been tested to support the analysis. The sample size for testing was (200 x 100 x 17) mm^3 under ASTM C-177-1997. The result showed that the average values of thermal conductivity of plain-sawn and quarter-saw timber of *A. mangium* were 2.06 and 1.86 Btu.in $h.ft^{-2}$. °F, respectively, and those of *G. arborea* were 1.35 and 0.94 Btu.in $h.ft^2$. °F, respectively. The range of standard deviation was from 0.01 to 0.12 Btu.in/$h.ft^{-2}$. °F and the coefficient of variation were from 0.93 to 8.53%. Such data showed that the thermal conductivity of *A. mangium* was higher than *G. arborea* and quarter-sawed of both species was higher than plain-sawed either. It is endorsed that higher the surface density, higher the thermal conductivity of the materials. The low thermal conductivity of *G. arborea* is predicted as the major factor for the positive exclusion especially for the thick boards.

In order to know whether the surface density could be a significant factor for predicting the fire resistant performance of wood and wood based panels especially for the time to the critical temperature, statistical analysis was done through "t" test with the equation as presented below:

$$t = r\sqrt{n-2} \Big/ \sqrt{(1-r^2)}$$

A number of 162 specimens were tested and 6 plots were taken from previous study[2] the total number of samples were 168. From the regression analysis, the r^2 was 0.88 as shown in Figure 6. Based on the above equation, the $t_{calculated}$ is 36.41. With the degree of freedom of 166 and level of significance of two-tail test of 0.05 and 0.01, the t_{table} are 1.960 and 2.576, respectively (Gomez & Gomez 1984). The higher value of $t_{calculated}$ than the t_{table} in 95% and 99% level of significance, means the surface density and time to the critical temperature of the boards in fire resistant performance test were in a significant correlation.

Predicting the fire performance based on surface density under ISO 5660 and JIS 1304

Testing on the fire performance of wood based materials had been conducted under JIS A 1304 for full-scale test of particleboards and plywood and lab-scale test of particleboards (Kawai 1988, Ishihara & Kawai 1989) as well as sawn timber of Falcataria and *G. arborea* (Subyakto 1998). The time to reach the critical temperature of 260 °C of the tested wood and wood based panels with cone calorimeter and data previously published (Kawai 1988) are shown in Figure 6. The time to reach the critical temperature of 260 °C of boards tested with cone calorimeter were slower than those tested with JIS A 1304 in the same surface density. This may be caused by the different heat exposure system between the cone calorimeter and burn through tests (JIS 1982). The initial exposure temperature of both systems was different. The heat exposure of cone calorimeter test was maintained at a constant heat flux of 40 kW m^{-2} during the test regardless the exothermic reaction of wood and wood based materials which were the combustible materials. On the other hand, the temperature of the specimens at exposed surface which controlled under JIS A 1304 with the standard fire curves; the temperature gradually increased to 730 °C at 10 min. 820 °C at 20 min. and slightly increased to 850-900 °C after 20 minute ahead (Subyakto *et al.* 1998).

It also should be noted that in the cone calorimeter test, the heat was applied as an irradiance heat without flame in contrast to the JIS A 1304 where heat was applied in the form of flames. The different type of heat applied might give different effects on the fire resistant performance of boards. From Figure 6 it is shown that the result of boards tested with cone calorimeter and under JIS A 1304 is in constant level of differences. With refer to the Figure 6 especially for the equation of the regression line of the plot of cone calorimeter test result and JIS A 1304 test result, it could be assumed that the time to reach the critical temperature of 260 °C of the cone calorimeter test is 2/3 of that of the JIS A 1304 test.

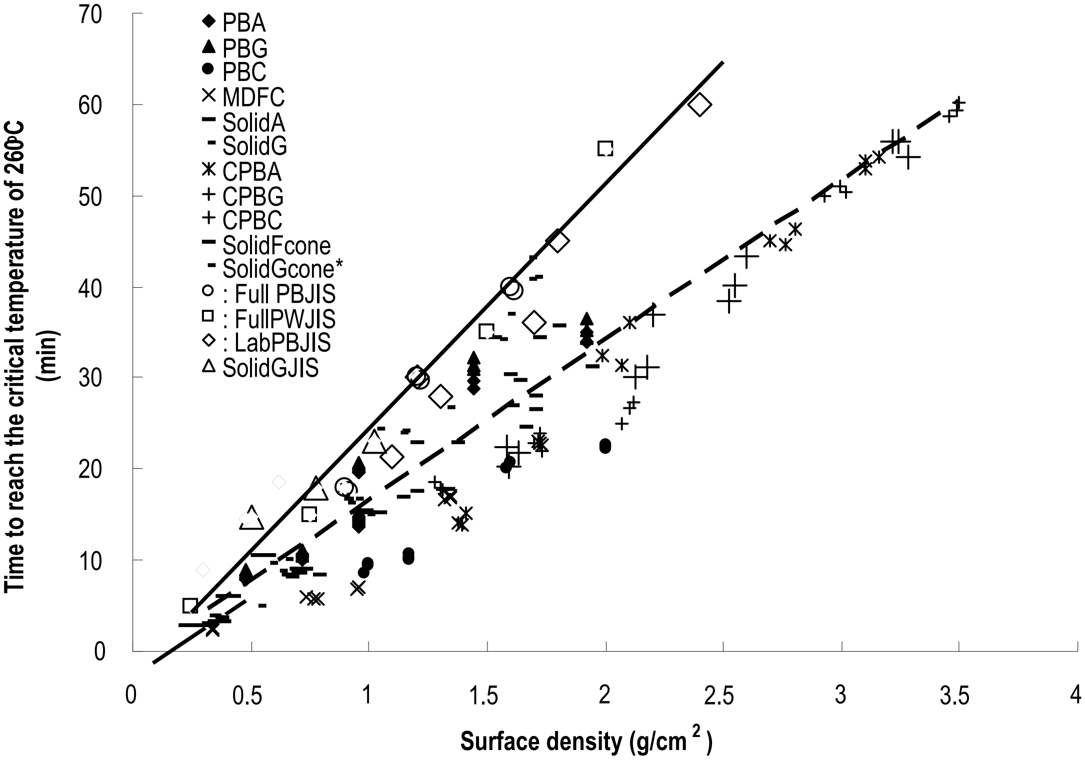

Figure 6 Relationship between surface density and time to reach the critical temperature of 260°C of boards tested under ISO 5660 and JIS A 1304. (SolidFcone, sawn timber of *P. falcataria* tested with cone calorimeter in previous study, SolidGcone*, sawn timber of *G. arborea* tested with cone calorimeter in previous study; FullPBJIS, particleboard tested in full-scale under on JISA1304; fullPWJIS, plywood tested in full-scale under JISA1304; LabPBJIS, particleboard tested in lab-scale under JISA1304; SolidGJIS, sawn timber of *G. arborea* tested under JISA1304; for other legends see Figures 1 and 5).

Conclusions

Testing on the fire performance of *A. mangium* and *G. arborea* wood and wood based materials of such species with organic and inorganic binders gave a clear figure that surface density regardless of materials type could be used as a key parameter in the fire resistant design process. The ignition time is affected by the surface density and the specific surface area of the materials. Boards reacted in different ways to the fire exposure but the time to the critical temperatures were similar of any boards regardless of materials type. Surface density also affected the time to the second peak of mass loss rate in high coefficient correlation. Particleboards and sawn timber in the same manner but cement bonded particleboards in the different one due to its different materials characteristic. Surface density could be use as a predictor for fire performance of wood and wood based panels. The prediction could be applied regardless of species as well as binder. Boards tested following ISO 5660 – cone calorimeter need for about two third of the time for those following JIS A 1304.

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