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Fire performances of foam core particleboards continuously produced in a one-step process

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Abstract For further progress of novel foam core particleboards, their fire performance was examined with cone calorimetry tests (ASTM E 1354-11a). Specimens with varying surface layer thicknesses, foam densities (polystyrene foam), and processing temperatures were tested. Using the initially recommended cone irradiance of 35 kW/m^2, different flammability parameters were measured. In comparison to particleboards, the foam core panels generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the EPS-foam component of tested panels. The time to ignition and total heat release did not vary significantly among the samples, although certain trends could be explained. The effects of variations in specimen foam densities and processing temperatures on the flammability parameters were not very significant. However, the flammability properties improved towards that of the reference particleboard as the surface layer thickness increased from 3 to 5 mm.

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Brandverhalten von in einem einstufigen Prozess hergestellten Schaumkern-Spanplatten

Zusammenfassung Im Rahmen der Weiterentwicklung neuartiger Spanplatten mit Schaumkern wurde das Abbrandverhalten mit Hilfe des Cone Calorimeter Tests (ASTM E 1354-11a).untersucht. Proben mit unterschiedlichen Decklagen-Dicken, Schaumkern-Dichten (Polystyrol-Schaum) und Presstemperaturen wurden geprüft. Bei Anwendung der empfohlenen Strahlungsintensität von 35 kW/m^2 wurden unterschiedliche Entflammbarkeiten festgestellt. Im Vergleich zu normalen Spanplatten zeigten die Schaumkernspanplatten aufgrund der EPS-Schaumanteile eine wesentlich höhere Wärmefreisetzungsrate, eine leicht erhöhte Verbrennungswärme sowie eine stark erhöhte Rauchentwicklung. Die Zeit bis zur Entzündung sowie die gesamte Wärmefreisetzung unterschieden sich nicht signifikant zwischen den Proben, wobei dennoch bestimmte Trends erklärbar waren. Die durch die Variation der Schaumkerndichten und Presstemperaturen bei der Herstellung verursachten Unterschiede waren nicht signifikant. Mit einer Zunahme der Decklagendicke von 3 mm auf 5 mm näherte sich die Entflammbarkeit der Schaumkern-Spanplatten an die Entflammbarkeit der als Referenz verwendeten normalen Spanplatten an.

1 Introduction

Sandwich panels are generally manufactured in batch processes where the layers are first separately produced and later glued together or in continuous processes by injecting a foamable liquid core material between the facings (Karlsson and Åström 1997; Zenkert 1997). The lack of a process for production of all layers in a simultaneous manner is obvious. Having this in mind, a novel technology to produce sandwich panels with wood based facings and a foam core in one single production step has been presented by Luedtke (2011). This type of lightweight foam core panels can be manufactured with some modifications of existing particleboard production machines.

Though the general benefits of the lightweight panels are obvious, the foam core implies some restrictions. The fire safety of this type of innovative panels might become a crucial aspect preventing the market acceptance of the novel panels. Their reaction to fire should meet the requirement of conventional particleboards. Cone calorimeter has gained very wide acceptance world-wide and is especially useful for the development of new products (Scudamore et al. 1991; White and Dietenberger 2004; Schartel et al. 2005). The cone calorimeter test (ASTM E 1354-11a:2011) measures the relevant reaction—to—fire parameters that have good correlation to full—scale fire behavior. The ignitability, peak of heat release rate (PHRR), total heat released **(THR),** effective heat of combustion, mass loss rate (MLR) and specific extinction area are the main parameters in cone calorimeter which were measured and analyzed in this study.

Research determining fire performances of steel sandwich panels have been extensively conducted to determine their fire performance (Collier and Baker 2004). It should be noted that the facings play an important role in the classification of panels, and core materials have no effect on this classification (Cooke 2004). Literature reviews on the resulted products of thermal decomposition and toxicity of polystyrene were done by Gurman et al. (1987). They mentioned that polystyrene has the lowest level of toxicity in comparison with other materials used in buildings. Bakhtiyari et al. (2010) studied the fire behavior of expanded polystyrene foam (EPS) with the cone calorimeter test method. They concluded that the sample thickness and density have significant effects on the fire behavior of expanded EPS foam. Essential need for a comprehensive investigation into the fire performance is indicated by a lack of studies available for foam core particleboards.

The surface layers play an important role in the fire behavior of sandwich structures. Earlier works (Shalbafan et al. 2012b) showed that different press parameters result in different foam structure and panel properties. In the current study, 19 mm foam core particleboards were produced using two different press temperatures (130 and 160 °C) and three different surface layer thicknesses of 3, 4 and 5 mm. Foam core density has an important influence on the material cost of foam core particleboard (Shalbafan et al. 2012c). Three different levels of foam density (80, 100 and 120 kg/m^3) were used as foam core while the thickness of the surface layer was kept constant (3 mm) in this set of experiment. The aim is the evaluation of flammability parameters of produced panels and comparison with conventional particleboards as reference panel.

2 Materials and methods

2.1 Experimental approach

The foam core panels with a nominal thickness of 19 mm were manufactured from a three layered mat (600 x 550 mm^2) without additional gluing between the face and core layers. Wood particles resinated with urea formaldehyde resin (Kaurit 350, BASF, Germany) were used for the face layers. Expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) was used as core material. The three-layered mat was then pressed in a lab-scale single opening hot-press (Siempelkamp, Germany). The press cycle consisted of three consecutive stages: pressing phase, foaming phase and finally the stabilization phase by internal cooling of the press plates. The temperature of the press plates was set according to the test series at 130 °C (1—EPS) and 160 °C (2—EPS). These two press temperatures were applied to generate different foam structures. At low press plate temperature (130 °C) longer pressing and accordingly longer foaming times are needed than at the higher press temperature (160 °C). This is due to the less intense heat flow from the surface layer to the thermosensitive material in the core. As a consequence of different foaming conditions the resulted foam in the 1—EPS panels looks like the glassy state. The EPS foam in the 2-EPS panels resembles packaging materials. Figure 1 shows different varieties of lightweight foam core panels produced in two different press temperature regimes.

For each press temperature three surface layer thicknesses of 3, 4 and 5 mm made of resinated wood particles

Fig. 1 Varieties of lightweight foam core panels; 1-EPS (130 °C: A, *B, C)* and 2—EPS (160 °C: *D, E, F)*

Abb. 1 Variationen der untersuchten leichten Schaumkern-Spanplatten; 1-EPS (130 °C: A, *B, C)* and 2—EPS (160 °C: *D, E, F)* were used to produce the panels. It should be mentioned that at a constant final panel thickness (19 mm) with increasing surface layer thickness from 3 to 5 mm, the core layer thickness decreases from 13 to 9 mm. The target face layer density made of resinated wood particles was calculated to be 750 kg/m^3 in all the panel variations. The foam core density of the panels was kept constant (124 kg/m^3) for the first set of experiments.

In the second set, fire performances of three different foam core densities (80, 100 and 120 kg/m^3) were also examined. The surface (3 mm) and core layer (13 mm) thicknesses were kept constant in the second set of experiments.

In each set of experiments three panels were produced as replicates and one sample from each panel was randomly selected for the fire performance tests (n = 3). Table 1 shows the experimental design of panel manufacturing. 19 mm conventional particleboard (PB) supplied from the market with a density of 650 kg/m^3 was also examined as the reference panel. According to ASTM E 1354-11a, all the samples were conditioned to constant mass at 23 °C and 50 % relative humidity for 2 weeks prior to testing. More information regarding pressing schemes and foaming conditions are explained in details in a previous publication by Shalbafan et al. (2012b).

Analysis of the data was performed using SPSS software (IBM). After checking of the data for normality, homogeneity of variances was controlled by Leven test. Thereafter, parametric ANOVA tests were performed to evaluate possible significant differences between the cone calorimeter data of panels produced using different pressing parameters. Statistical differences between variations were evaluated by multiple comparisons using either Duncan or LSD test depending on variance status. The P value level of statistical significance was set at $P < 0.05$.

2.2 Expandable polystyrene beads composition

For this study expandable polystyrene (EPS) granulate, Terrapor 4 with a granule size of 0.3-0.8 mm was supplied by Sunpor GmbH, Austria. It is well known that the EPS is a thermoplastic polymer which starts to contract and melt when exposed to temperatures above 100 °C. According to the product data sheet, Terrapor 4 contains less than 1 % cycloaliphatic as flame retardant. Babrauskas and Parker (1987) mentioned that fire retardant in foams work for very low ignition flux (<25 kW/m^2), but fire performance is essentially unchanged when larger ignition sources are used. This EPS material also contains 5.7 % pentane (by weight) as blowing agent. Depending on process parameters (e.g., press temperature) between 2 and 3 % of the initial pentane content remains in the foam cells after expansion.

2.3 Cone calorimeter test

The tests were carried out according to ASTM E1354-1 la (2011) test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, IL) at the Forest Product Laboratory in Madison, USA. Samples were

Table 1 Composition of the panel variables
Tab. 1 Herstellungsparameter der Platten

No	Face thickness (mm)	Press temperature (°C)	Target density (kg/m^3)	Foam/density (kg/m^3)	Pressing time (s)	Foaming time (s)	Stabilization time (s)
1-EPS							
A	3	130	320	124	80	45	130
B	4	130	390	124	105	45	140
C	5	130	460	124	130	45	150
2-EPS							
D	3	160	320	124	45	10	140
E	4	160	390	124	55	10	170
F	5	160	460	124	65	10	200
3-EPS							
Adl	3	130Ad1	290	80	80	45	130
Ad2	3	**130**	305	100	80	45	130
Ad3	3	**130**	320	120	80	45	130
4-EPS							
Dd1	3	160	290	80	45	10	140
Dd2	3	160	305	100	45	10	140
Dd3	3	160	320	120	45	10	140

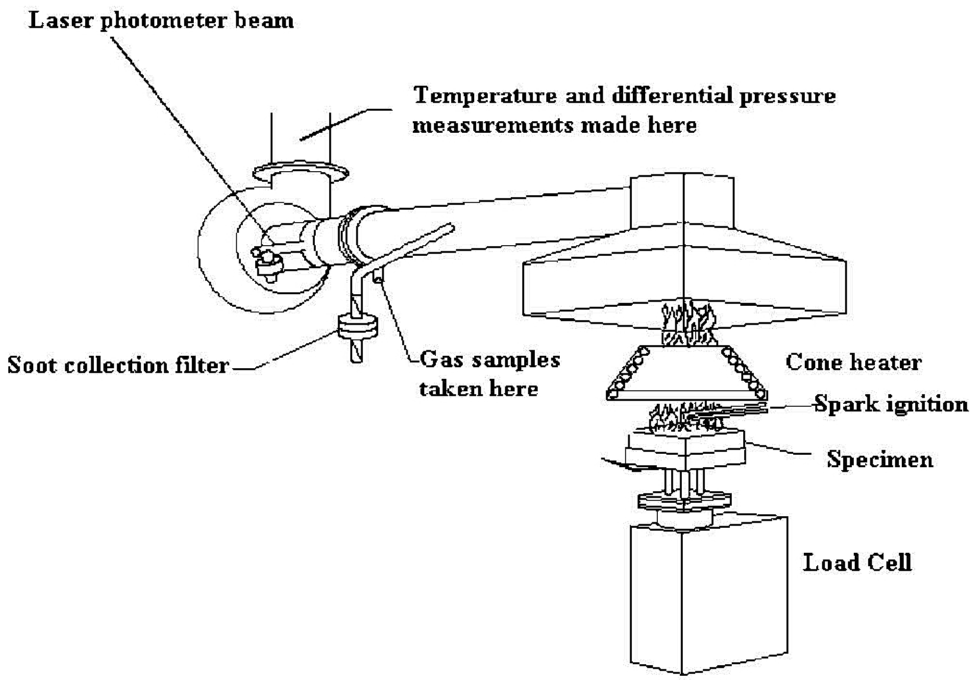

Fig. 2 Cone calorimeter test set up (http://www.pslc.ws/macroWmpm/analysis/cone.htm)
Abb. 2 Konfiguration des Cone Calorimeter Tests (http://www.pslc.ws/macorg/mpm/analysis/cone.htm)

exposed in the horizontal orientation with the conical radiant electric heater set at a heat flux level of 35 kW/m^2. In ASTM E 1354-11a (2011) a heat flux of 35 kW/m^2 is recommended for the initial tests. The sample sizes were set at 100 x 100 mm^2 with a nominal thickness of 19 mm for all the variations. The surfaces of the samples were not sanded prior to fire testing. The cone calorimeter test set up is illustrated in Fig. 2.

The specimens were tested in the optional retainer frame with the wire grid over the test specimen. As explained earlier, some amount of the pentane still remained in the specimen. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause a slight expansion of the foam during the test. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid to restrain the heated surface was used in all the cone tests. Ignitability was observed as the time for sustained ignition of the specimen and determined by using 4 s criteria for sustained ignition.

3 Results and discussion

3.1 Panel properties

Physical and mechanical properties of the panels were obtained according to the methods described in the recent literature published by the authors (Shalbafan et al. 2012a, b, c). Briefly, panels produced by lower press temperature (130 °C) have a denser surface layer, higher bending strength and internal bond values. The interface between foam cells and wood particles is well established in case of the 1—EPS panels which has a positive effect on the internal bond values. The results also indicate that the panels produced by higher press temperature (160 °C) have a better cell configuration (more numerous and smaller cell sizes) due to the faster foaming of the EPS beads. Higher values for the edge screw withdrawal resistance in the 2—EPS panels can be explained by this finding. Soaking tests revealed that the lower amount of water absorption of the 2—EPS panels resulted from better foam cell fusion and less attainment of small voids between the foam cells. Reduction of core density from 120 to 80 kg/m^3 showed that physical and mechanical properties of EPS panels with low foam densities can still meet requirements comparable to those fulfilled by conventional particleboards.

3.2 Fire performances

Fire performances of foam core particleboards were analysed by measuring important parameters with the cone calorimeters like the ignitability, PHRR, THR, effective heat of combustion, MLR and specific extinction area. These values of all characteristic fire parameters are shown in Tables 2 and 3.

3.2.1 Time to sustained ignition (TSI)

Time to sustained ignition (TSI) is defined as the period in which a combustible composite can bear heat flux radiated from an external heat source, before sustained flaming combustion starts on the heated surface. Time to sustained

Table 2 Fire performance results of the foam core particleboard with different face layer thicknesses
Tab. 2 Ergebnisse zum Abbrandverhalten von Schaumkern-Spanplatten mit unterschiedlichen Decklagendicken

Code	TSI	PHRR	tPHRR	AHRR-60	AHRR-180	AHRR-300	AEHOC	AMLR 10-90	ASEA	2nd PHRR	2nd tPHRR
A	87 (11)	275.9 (13)	158 (20)	1663 (9.9)	1502 (33)	1483 (11)	18.48 (1)	12.0 (0.5)	5178 (79)	454.3 (32)	439 (24)
B	106 (4.9)	239.0 (11)	217 (22)	1299 (10)	158A (4)	118A (6)	1523 (2)	122 (3)	347.5 (36)	4343 (32)	589 (50)
C	107 (33)	1912 (29)	228 (17)	112A (63)	1469 (62)	124.1 (7.7)	1320 (L8)	113 (03)	306.6 (46)	396.5 (36)	676 (13)
D	80 (63)	330A (38)	121 (10)	21L0 (3)	158A (7.9)	189.0 (16)	1833 (0.9)	12.6 (0.7)	554.0 (40)	4262 (29)	410 (24)
E	86 (51)	3003 (17)	156 (25)	1569 (12)	1539 (11)	143.6 (17)	17.18 (0.9)	1L6 (0.7)	4811 (55)	3523 (20)	539 (57)
F	100 (4.6)	2799 (30)	217 (5.5)	1178 (2.9)	16L8 (5.9)	130.0 (53)	15.06 (02)	11.0 (0.5)	35L5 (21)	3072 (4.8)	659 (11)
P	92 (29)	148.4 (71)	125 (0.6)	1192 (4.6)	1073 (4.6)	96.9 (5.6)	10.72 (0.4)	8.7 (0.1)	27.0 (7)	170.8 (10)	1,234 (30)

ignition of foam core particleboard is presented in Tables 2 and 3. TSI increases when the surface layer thickness increases from 3 to 5 mm what was also predicted for similar wood products by Dietenberger and Grexa (2004). Even though the TSI in the 1-EPS panels is slightly higher than those in the 2-EPS case, it is found that these differences are not statistically significant. Shalbafan et al. (2012c) showed that the density of the surface layer in the 1-EPS panels is higher than in the 2-EPS panels which could explain the longer time to reach the surface ignition temperature (Harada 2001). The similar TSI values between the foam core panels and conventional particleboard as shown in Tables 2 and 3 is indicative for the strong effect of the surface layer properties on ignition and surface ignition temperature (Dietenberger and Grexa 2004), because material density of the surface layers is similar for both types of panels.

3.2.2 Heat release rate (HRR) and total heat released (THR)

The HRR is a strong indicator for the potential of fire hazard of a combustible material. In Fig. 3, HRR graphs of foam core particleboards are depicted. A delay was observed before the panels started to release combustion heat. This delay is essentially the TSI during which the material surface temperature remains below the pyrolysis temperature at which production of significant amounts of combustible volatile gases starts, which is coincident with the surface ignition temperature for thick organic materials (Dietenberger and Grexa 2004). It can be seen that in foam core panels the whole combustion period is approximately half of that for the conventional particleboard. The foam core particleboard burned faster than conventional particleboards because of the relatively higher heat release rates (HRR) even though the THR values are very similar. Increasing the surface layer thickness from 3 to 5 mm in both the 1-EPS and 2-EPS panels resulted in a prolongation of the combustion period. It is well understood that in constant heat flux conditions (35 kW/m^2) the polymeric materials tend to burn faster than building products made of wood (Mouritz et al. 2006).

For interpreting the cone calorimeter data, the influence of the EPS foam core should be considered first. All polymer-based foams are organic materials which are combustible. The thermal conductivity of the foam strongly affects the fire performances as follows. Expanded polystyrene foam has a low thermal conductivity which acts as a protective layer underneath the wood surface layer and diminishes the conductive heat loss from the surface layer. This leads to an enhanced temperature rise of the surface layer resulting in greater production rates of combustible volatiles (Dietenberger 2012). This, in turn, results in an accordingly increased first PHRR which is significantly higher than that of conventional particleboards. After the surface ignition (and prior to the point of PHRR at about 30 kW/m^2) the char layer begins to form, and the volatile emission rate is the result of the speed at which the pyrolysis front propagates into the wood-based material. The combustion of the volatiles is what gives the flaming HRR. The drop in the heat release rate after the first peak can be explained by slowing down of the propagation of the pyrolysis front due to the gradual development of an insulating char layer in conjunction with a thermal wave propagating through the wood. Since heat of combustion remains relatively constant while the wood is pyrolysed, the HRR will reflect the decreasing MLR, which in turn is due to the slowing down of the propagation of the pyrolysis front (White and Dietenberger 2010).

During the burning of the surface layer the foam core layer starts to volatize combustible materials. The foam does not char and its volatiles with their corresponding higher heat of combustion begin to be added to the volatiles originating from the thermal decomposition of the woody matter. This is reflected in the increasing heat of combustion after a steady state phase during the test (before the 2nd PHRR). EPS foam melts and boils at temperatures much lower than those of the pyrolysis front in the wood (i.e., less than 300 °C). As the thermal wave terminates at the back of the sample, the sample gradually attains a

Table 3 Fire performance results of the foam core particleboard with different foam core density

Tab. 3 Ergebnisse zum Abbrandverhalten von Schaumkern-Spanplatten mit unterschiedlichen Schaumkerndichten

Code	TSI	PHRR	tPHRR	AHRR-60	AHRR-180	AHRR-300	AEHOC	AMLR 10–90	ASEA	2nd PHRR	2nd tPHRR
Ad1	102.2 (1.6)	262.4 (8.6)	173.3 (5.7)	165.2 (8)	153.4 (5.3)	143.0 (7.4)	17.4 (0.8)	12.7 (0.1)	395.9 (46)	464.6 (63)	466.6 (20)
Ad2	103.4 (2.3)	281.6 (26)	174.0 (5)	167.2 (15)	155.9 (4.8)	137.1 (12)	16.4 (0.8)	12.9 (0.4)	441.2 (41)	447.5 (24)	476 (6)
Ad3	87 (11)	275.9 (13)	158 (20)	166.7 (9.9)	150.2 (3.7)	148.7 (27)	18.4 (1)	12.0 (0.5)	517.8 (79)	454.3 (32)	439 (24)
Dd1	85.7 (7.8)	316.2 (35)	139.0 (18)	193.1 (15)	164 (1.7)	171.1 (16)	16.6 (0.08)	14.0 (0.7)	469.2 (15)	461 (39)	432.6 (27)
Dd2	87.1 (3.2)	335.4 (26)	144.7 (8.9)	194.2 (18)	161.4 (19.9)	157.3 (32)	17.7 (.04)	12.5 (0.6)	531.9 (31)	453.6 (2.3)	470 (1)
Dd3	80 (6.2)	330.4 (38)	121 (10)	211.0 (2.9)	158.4 (7.8)	189.0 (16)	18.3 (0.9)	12.6 (0.7)	554.0 (40)	426.2 (29)	410 (24)

Values in parentheses are standard deviations. *TSI* time to sustained ignition, *PHRR* initial peak of heat release rate, *tPHRR* time of first peak heat release rate, *AHRR-60* average of heat release rate over 60 s of sustained ignition, *AHRR-180* average of heat release rate over 180 s of sustained ignition, *AHRR-300* average of heat release rate over 300 s of sustained ignition, *AEHOC* average of effective heat of combustion, *AMLR 10–90* average mass loss rate for 10–90 % of ultimate mass loss, *ASEA* average specific extinction area, *2nd PHRR* second peak of heat release rate, *2nd tPHRR* time of 2nd peak of heat release rate

Werte in Klammern sind Standardabweichungen. *TSI* Zeit bis zu anhaltender Flammenbildung, *PHRR* erster Peak der Wärmefreisetzungsrate, *tPHRR* Zeit bis zum ersten Peak der Wärmefreisetzungsrate, *AHRR-60* mittlere Wärmeabgabe über die ersten 60 s anhaltender Flammenbildung, *AHRR-180* mittlere Wärmeabgabe über die ersten 180 s anhaltender Flammenbildung, *AHRR-300* mittlere Wärmeabgabe über die ersten 300 s anhaltender Flammenbildung, *AEHOC* mittlere effektive Verbrennungswärme, *AMLR 10- 90* mittlere Masseverlustrate über den Masseverlustbereich von 10-90%, *ASEA* mittlere spezifische Extinktion, *2nd PHRR* zweiter Peak der Wärmefreisetzungsrate, *2nd tPHRR* Zeit bis zum zweiten Peak der Wärmefreisetzungsrate

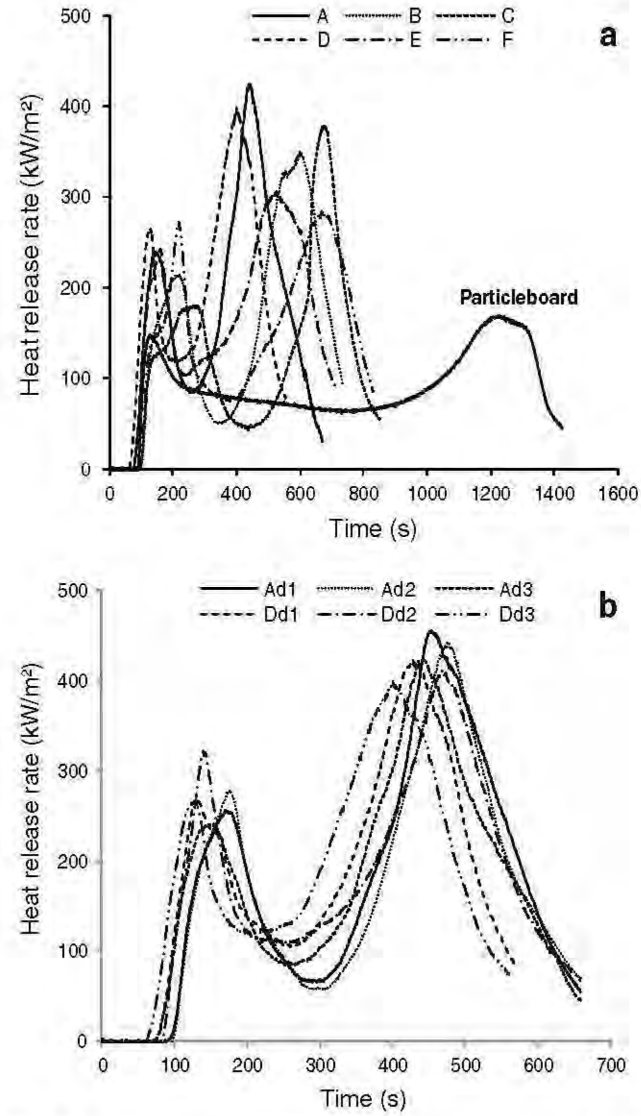

Fig. 3 Heat release rate (HRR) of foam core particleboard with different surface thicknesses: **a** with different surface thickness, **b** with different foam core densities

Abb. 3 Wärmefreisetzungsrate (HRR) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

thermally thin response that leads to the second HRR peak due to the pyrolysis front accelerating and broadening into a pyrolysis zone while transitioning to a thermally thin condition (Dietenberger 2002; Hagge et al. 2004). Finally, the pyrolysis zone reaches the back of the samples and causes the thermal feedback effect for an elevated temperature for more rapid pyrolysis (Schartel and Hull 2007). Overall, the second HRR peak is due to the foam and the volatilization of the back side of the board. A transition to glowing which is seen by heat of combustion approaching 30 kJ/g, what corresponds with pure carbon. This means that the wooden matter has been transformed into almost pure carbon, which does not combust until the air is able to penetrate into the carbonized matter until generation of volatiles has diminished. Conventional particleboards as a charring material also show a second peak at the end of the test due to a similar process as explained above.

A difference between the 1st and 2nd peak of the HRR in the foam core particleboards is shown in Fig. 4. Both peaks decrease significantly with raising surface layer thicknesses from 3 to 5 mm, which is consistent with their increased heat capacitance that lowered the temperature rise rate and the peak temperatures during pyrolysis. The differences between the 1st and 2nd peaks in the 1—EPS are higher than those in the 2—EPS panels. A corresponding comparison shows that the 1st peak of HRR in the 1—EPS panels is lower than those in the 2—EPS panels. Conversely, the 2nd peak of HRR in the 2—EPS is lower than the corresponding values of the 1—EPS panels. With respect to the similarly available combustible mass and according to insignificantly changes of MLR, this difference can be explained by the different foam structure which resulted from different foaming conditions. Presumably more volatiles are emitted from the 2—EPS foam after the surface ignites. Another possible explanation can be the lower temperature resistance of the 2—EPS panels and having a premature melting of that from the sides which result in higher combustible volatiles. The graph shows that the reference panels have lower 1st and 2nd peak of HRR rate when compared with the foam core particleboards.

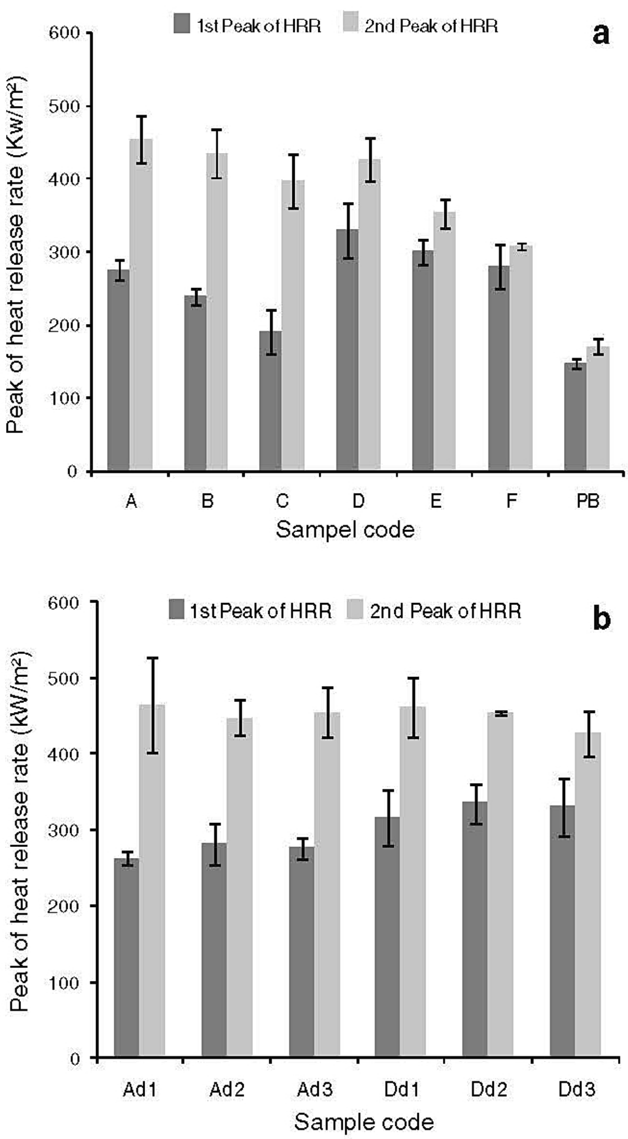

Fig. 4 First and second peak of heat release rate (PURR) of foam core particleboard: **a** with different surface thicknesses, **b** with different foam core densities

Abb. 4 EWärmefreisetzungsrate tzenwert der Wkinefreisetzungsrate (HRR) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

In Fig. 4b, the difference of the peaks in foam core panels with different foam core densities is illustrated. Changing of foam core density has no significant effect on both the 1st and 2nd peaks of HRR in 3—EPS and 4—EPS panels. The same trend as for 1—EPS and 2—EPS was also observed for the 3—EPS and 4—EPS panels.

The THR of foam core particleboards is compared with conventional particleboards and illustrated in Fig. 5. The THR in the 2—EPS panels seems somewhat higher than that in the 1—EPS panels. In respect of the similar combustible materials in the corresponding samples, this difference can be explained by the different foaming processes for the 1-EPS and 2—EPS panels. Due to the longer pressing and foaming times in the 1—EPS panels, the EPS beads were transformed to a semi-viscous state and then slowly started to expand (Shalbafan et al. 2012b). Presumably more volatiles of EPS were emitted during the foaming phase of the 1—EPS panels. The THR does not significantly change in the 3—EPS and 4—EPS panels.

All the variations of foam core particleboards have about a 10-20 % lower amount of THR when compared with conventional particleboards. This is due to the substitution of a high amount of coarse wooden middle layer particles by a small amount of polymer in foam core particleboards. Since the heat of combustionMJ/kgPS foam (approximately 40-MJ/kg/kg) is higher than wood (13 Milkg), the expected decrease in total heat release rate is partly compensated by the higher heat of combustion of the EPS foam (Luedtke 2011; Troitzsch 1990).

Some of the cone calorimeter data describe material properties, while other data are strongly dependent on the particular test setup. One of the most frequently used results from the cone calorimeter test is the PHRR which is strongly dependent on the test setup. This has to be considered for data interpretation (Schartel et al. 2005). Flashover propensity is a useful parameter of full scale fire behaviour. Flashover propensity is calculated by the peak

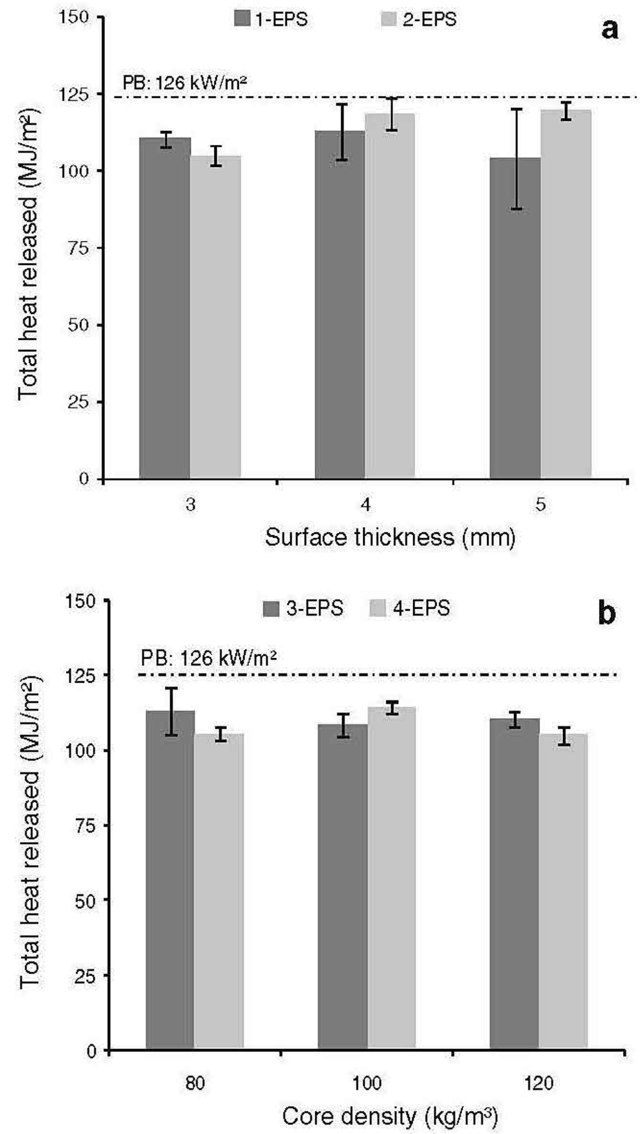

Fig. 5 Total heat released (THR) of foam core particleboard: a with different surface thicknesses, **b** with different foam core densities
Abb. 5 Gesamte Wärmefreisetzung (THR) der Schaumkern-Spanplatten: a mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

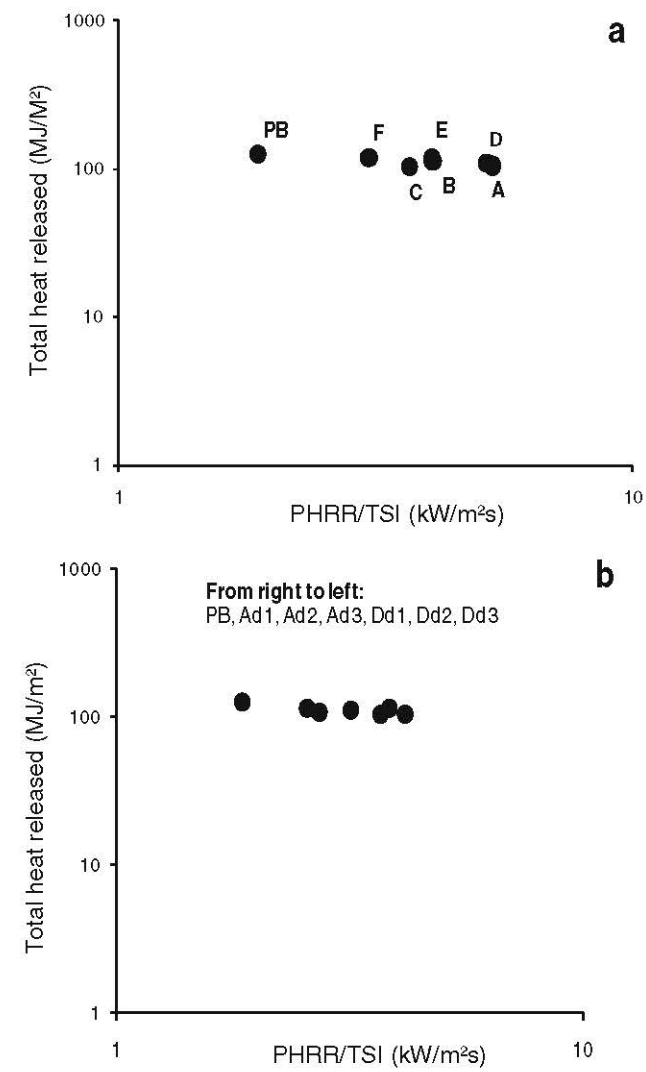

Fig. 6 Flashover propensity and total heat released for the foam core particleboard, a with different surface thicknesses, **b** with different foam core densities, and conWärmefreisetzungleboard (PB)
Abb. 6 Neigung zu schlagartiger Flammenausbreitung und gesamte Wunterschiedlichenn Schaumkern-Spanplatten, a mit unterschiedlichen Decklagendicken, **b** mit unterschieollichen Schaumkerndichten, und normalen Spanplatten (PB)

heat release rate divided by the time to sustainPHHR/TSIion (Hirschler 1992). Petrella (1994) mentioned that when the flashover propensity (PHHRJTSI) is combined with the total heat release a better understanding of full scale fire behaviour is achieved. Figure 6 shows the flashover propensity and total heat release for the foam core panels and conventional particleboard. The slope of THR—flashover propensity in Fig. 6 is almost zero. The flatness of the slope can be explained by the small range of the THR from 100 to 130 MJ/m^2. Figure 6 shows that changing surface layer thickness in foam core panels increases the flashover propensity from 3 to 5.4 while having little or no effect on the THR. Higher flashover propensity means that the panels are ignited faster or that the resulting peak heat release rate is higher. As a conclusion it can be said that the panels with thinner surface layers (panels A and D) were ignited faster than those with thicker surface layers. And accordingly, it can also be expected that the panels with higher foam core density (Ad3 and Dd3) are ignited faster than the ones with lower foam core densities.

3.2.3 Effective heat of combustion (EHOC) and mass loss rate (MLR)

The effective heat of combustion is calculated as the ratio of **HRR** to the MLR as a function of time, while the average effective heat of combustion is calculated as the ratio of THR to total mass loss (ASTM E 1354-11a). The average effective heat of combustion of foam core particleboard is illustrated in Fig. 7. The EHOC is decreased while the surface thickness is raised from 3 to 5 mm. Enhancing surface layer thickness causes a reduction in the foam core layer thickness which has an important effect on the lowering of EHOC. Due to the higher THR in the 2—EPS panels, as a result of different foaming condition, a higher average EHOC is also obtained for the 2—EPS panels compared with the 1—EPS.

The amount of thermal decomposition and the resulting volatilization of a combustible material in fire is entitled total mass loss. The average MLRs between the time when the samples lose 10 and 90 % of their total mass and the average effective heat of combustion are tabulated in Tables 2 and 3. High HRR values generally indicate more complete pyrolysis and volatilization of the combustible materials which results in higher mass loss. Due to the dependency of HRR and MLR on the rate of decomposition reaction, a strong linear correlation can be seen between them shown in Fig. 8.

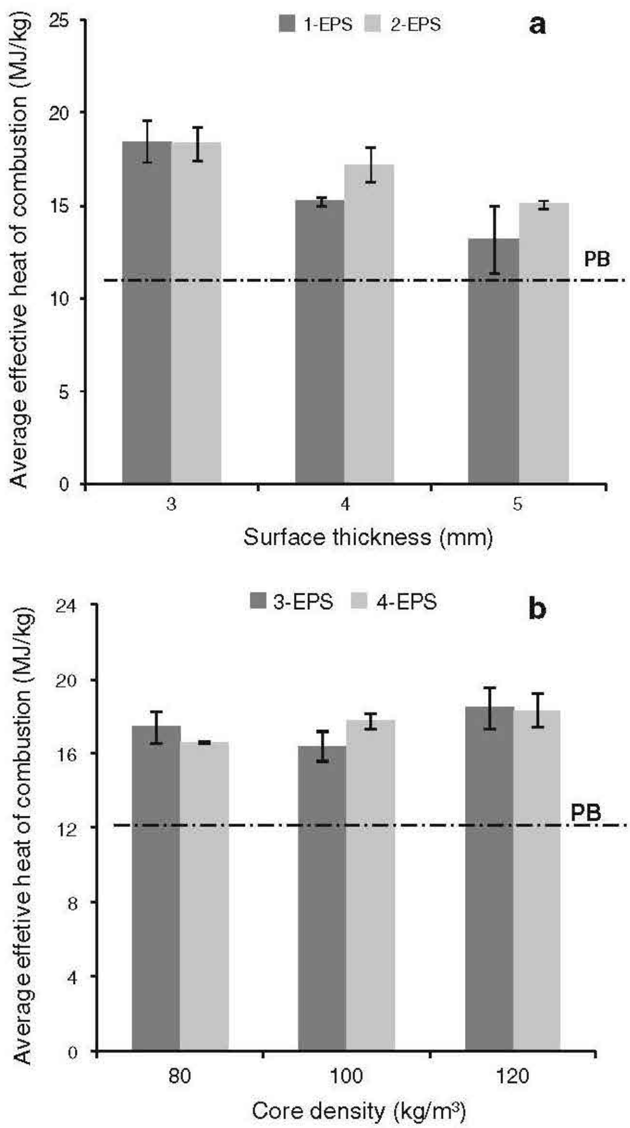

Fig. 7 Average effective heat of combustion (EHC) for the foam core particleboard and conventional particleboard (PB): a with different surface thicknesses, **b** with different foam core densities
Abb. 7 Durchschnittliche effektive Verbrennungswarme (EHC) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

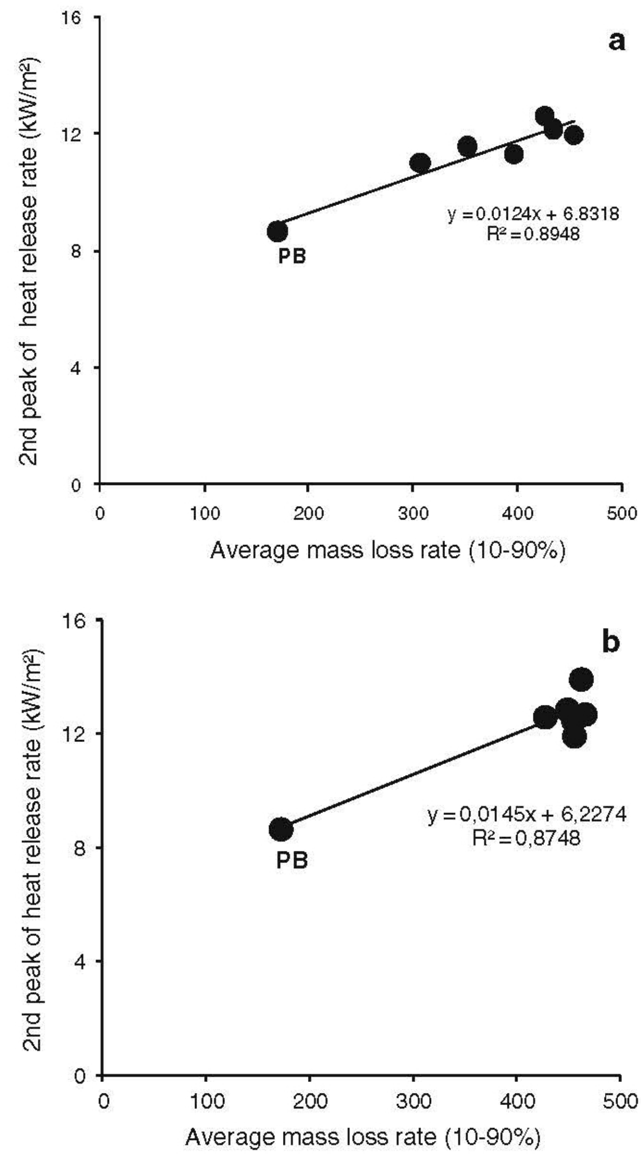

Fig. 8 Average mass loss rate (MLR) against the 2nd peak of heat release rate: **a** with different surface thicknesses, **b** with different foam core densities
Abb. 8 Durchschnittliche Masseverlustrate (MLR) aufgetragen gegen die Witmefreisetzungsrate (zweiter Spitzenwert): **a mit** unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

3.2.4 Average specific extinction area (ASEA)

The main fire hazard is the smoke which is a result of incomplete combustion. The specific extinction area is characterized by the smoke obscuration where the reduction of light transmission is measured by a laser beam through the exhaust duct. The results of ASEA are illustrated in Fig. 9. Figure 9a shows that with increasing surface layer thickness from 3 to 5 mm, the ASEA is decreased. This can be explained by the decreasing amount of EPS—foam core materials while surface layers are thickened. It is also obvious that the 2—EPS panels have significantly higher ASEA compared with the 1—EPS panels due to different foam structures.

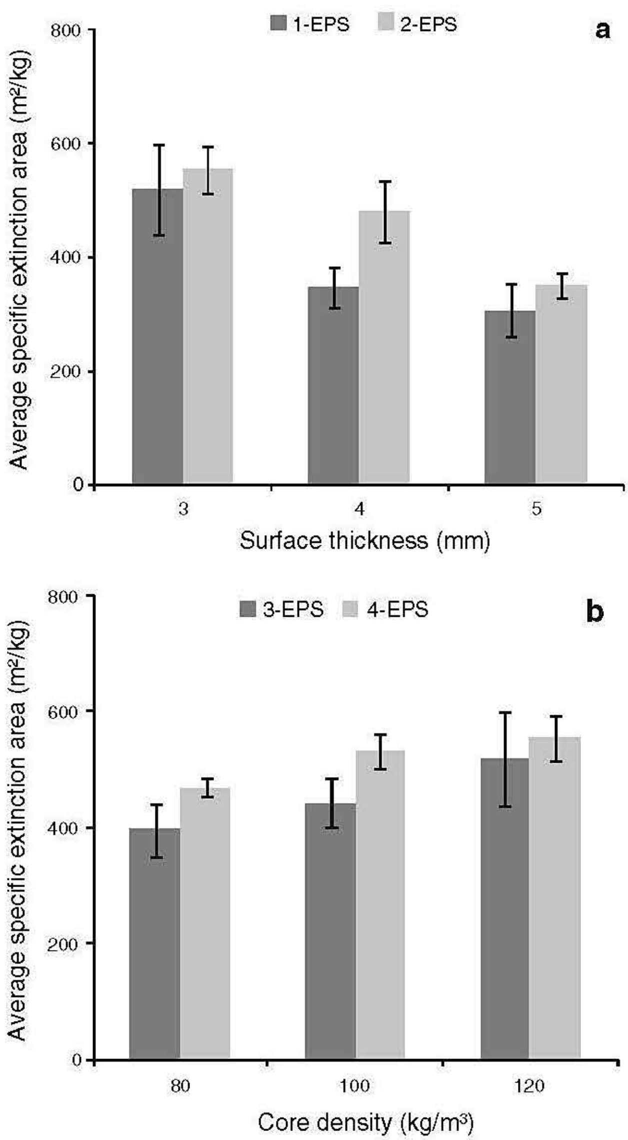

Fig. 9 Average specific extinction area (ASEA) for the foam core particleboard: **a** with different surface thicknesses, **b** with different foam core densities

Abb. 9 Durchschnittliche effektive Extinktionsfläche (ASEA) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

Trends like this can also be found for Fig. 9b. With decreasing foam density from 120 to 80 kg/m^3 the ASEA is decreased for both the 3—EPS and 4—EPS panels. Additionally, the 4—EPS panels which were produced at higher press temperature (like the 2—EPS panels) show significantly higher ASEA in comparison with the 3—EPS panels. In comparison to conventional particleboards the foam core panels generally had much higher ASEA due to the EPS-foam component of the tested panels. Ostmann and Tsantaridis (1993) mentioned that the polystyrene foam has lower smoke production in the room fire test than that of the cone calorimeter test. This is due to the falling down of the droplets in the room fire test which stops the smoke production, but it may result in other hazards.

4 Conclusion

To confirm and support general advantages of lightweight foam core particleboards, the possible restriction due to fire performance was examined with cone calorimetry tests (ASTM E 1354-11a) of specimens with variations of surface layer thicknesses, foam densities, and processing temperatures. Using the initially recommended cone irradiance of 35 kW/m^2 ignitability, PHRR, THR, effective heat of combustion, MLR and specific extinction area were measured and analyzed with the following results. In comparison to the reference particleboard the foam core panels generally had much higher heat release what reduced their burning times approximately by half. They also show higher heat of combustion and smoke production due to the EPS component of lightweight panels. Other measured parameters like time to ignition and total heat release did not vary significantly among the samples. The variation of foam densities and processing temperatures were likewise not very significant, although some trends could be identified. However, as the surface layer thickness was increased from 3 to 5 mm, the flammability properties began to improve and approached, as expected, those of the reference particleboard.

Some wood products used in paneling application have similar flammability properties as measured here for the lightweight foam core panels. Therefore, the lightweight sandwich panels without any treatment may find niche markets. If it is desired on the basis of fire performance to achieve better flammability results, then some means of fire retardant treatment (FRT) is recommended and tested in the cone calorimeter under appropriate conditions, such as the irradiance set to 50 kW/m^2. The option of applying a veneer treated with an intumescent FRT coating to the surface layer is subject of a follow—up investigation. It should be pointed out that if the edge properties of the product are taken into account, the fire behavior may be worse. This has to be further studied if the product is being used with exposed edges.

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References

ASTM E 1354-11a (2011) Standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter. ASTM International, West Conshohocken, PA

Babrauskas V, Parker WJ (1987) Ignitability measurements with the cone calorimeter. Fire Mater 11:31-43

Bakhtiyari 5, Taghi–Akbari L, Barikani M (2010) The effective parameters for reaction–to–fire properties of expanded polystyrene foams in bench scale. Iran Polym J 19:27-37

Collier PCR, Baker GB (2004) Improving the fire performance of polystyrene insulated panel in New Zealand. New Zealand Fire Service Commission research report number 45. ISBN number 1-877349-08-9

Cooke GME (2004) Stability of lightweight structural sandwich panels exposed to fire. Fire Mater 28:299-308

Dietenberger MA (2002) Update for combustion properties of wood components. Fire Mater 26:255-267

Dietenberger MA (2012) Pyrolysis kinetics and combustion of thin wood using an advanced cone calorimetry test method. J Therm Anal Calorim 109:1215-1228

Dietenberger MA, Grexa **O** (2004) Ignitability of materials in transitional heating regimes. In: Proceedings of 5th international scientific conference of wood & fire safety. Slovak Republic, pp 31-41

Gurman JL, Baier L, Levin BC (1987) Polystyrenes: A review of the literature on the products of thermal decomposition and toxicity. Fire Mater 11:109-130

Hagge MJ, Bryden KM, Dietenberger MA (2004) Effect of backing board materials on wood combustion performance. In: Proceedings of 5th international scientific conference of wood & fire safety. Slovak Republic, pp 51-58

Harada T (2001) Time to ignition, heat release rate and fire endurance time of wood in cone calorimeter test. Fire Mater 25:161-167

Hirschler MM (1992) Heat release from plastics materials. In: Babrauskas V, Grayson SL (eds) Heat release in fires. Elsevier, New York, pp 418-419

Karlsson K, Åström T (1997) Manufacturing and applications of structural sandwich components. Compos Part A Appl Sci Manuf 28:97-111

Luedtke J (2011) Entwicklung und Evaluierung eines Konzepts für die kontinuierliche Herstellung von Leichtbauplatten mit polymerbasiertem Kern und Holzwerkstoffdecklagen. Dissertation. Hamburg University, Germany. http://ediss.sub.uni hamburg.de/volltexte/2011/5470/

Mouritz AP, Mathys Z, Gibson AG (2006) Heat release of polymer composites in fire. Compos Part A Appl Sci Manuf 37:1040-1054

Ostmann BA-L, Tsantaridis LD (1993) Smoke data from the cone calorimeter for comparison with the room fire test Fire Mater 17:191-200

Petrella RV (1994) The assessment of full–scale fire hazards from cone calorimeter data. J Fire Sci 12:14-43

Schartel B, Hull TR (2007) Development of fire-retarded materials-Interpretation of cone calorimeter data. Fire Mater 31:327-354

Schartel B, Bartholmai M, Knoll U (2005) Some comments on the use of cone calorimeter data. Polym Degrad Stab 88(3):540-547

Scudamore MJ, Briggs PJ, Prager FH (1991) Cone calorimetry-a review of tests carried out on plastics for the association of plastic manufacturers in Europe. Fire Mater 15:65-84

Shalbafan A, Luedtke J, Welling J, Thoemen H (2012a) Comparison of foam core materials in innovative lightweight wood-based panels. Eur J Wood Prod 70:287-292

Shalbafan A, Welling J, Luedtke J (2012b) Effect of processing parameters on mechanical properties of lightweight foam core sandwich panels. Wood Mater Sci Eng 7:69-75

Shalbafan A, Luedtke J, Welling J, Fruehwald A (2012c) Physiomechanical properties of ultra-lightweight foam core particleboard: Different core densities. Holzforschung. doi:10.1515/hf-2012-0058

Troitzsch J (1990) International plastics flammability handbook: principles—regulations—testing and approvals, 2nd edn. , Munich

White RH, Dietenberger MA (2004) Cone calorimeter evaluation of wood products. In: Proceedings of 15th annual BCC conference flame retardancy. Stamford, Connecticut, pp 331-342

White RH, Dietenberger MA (2010) Fire safety of wood construction. In: Wood handbook: wood as an engineering material. Forest Products Laboratory, Department of Agriculture Forest Service, Madison, WI, pp 18-1-18-22

Zenkert D (1997) The handbook of sandwich construction. Cradley Heath: Engineering Materials Advisory, UK