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Physical, mechanical, and fire properties of oriented strandboard with fire retardant treated veneers

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Abstract This study evaluated physical, mechanical and fire properties of oriented strand boards (OSB) covered with fire retardant treated veneers. The beech (*Fagus orientalis* Lipsky) veneers were treated with either monoammonium phosphate, diammonium phosphate, lime water or a borax/boric acid (1 : 1 by weight) mixture. Physical and mechanical properties of the specimens were performed according to EN and DIN standards. A cone calorimeter was used to determine their combustion characteristics. The physical and mechanical properties of the specimens were adversely affected by the treatments. The specimens treated with lime water had the best physical performance while the specimens treated with borax/boric acid had the highest mechanical properties. The fire retardant treatments of the face veneers were effective in reducing the initial contribution of heat release to potential fire growth. In particular, the lime water treatment was an effective fire retardant treatment in that it reduced both the effective heat of combustion and the mass loss rate. It also delayed the times for sustained ignition.

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Physikalische, mechanische sowie Brandeigenschaften von OSB mit Feuerschutzmittel imprägnierten Deckfurnieren

Zusammenfassung In dieser Studie wurden die physikalischen und mechanischen sowie die Brandeigenschaften von OSB mit Feuerschutzmittel imprägnierten Deckfurnieren untersucht. Die Buchenfurniere (*Fagus orientalis* Lipsky) wurden entweder mit Monoammoniumphosphat, Diammoniumphosphat, Kalkwasser oder einer Borax/Borsäure-Mischung (im Gewichtsverhältnis 1 : 1) imprägniert. Physikalische und mechanische Eigenschaften der Proben wurden nach EN- und DIN-Normen untersucht. Das Brandverhalten wurde mittels einer Cone-Calorimeter-Prüfung bestimmt. Die Imprägnierung wirkte sich auf die physikalischen und mechanischen Eigenschaften der Proben nachteilig aus. Die mit Kalkwasser imprägnierten Proben wiesen die besten physikalischen Eigenschaften auf, wohingegen die mit Borax/Borsäure imprägnierten Proben die besten mechanischen Eigenschaften hatten. Durch die Feuer hemmende Behandlung der Deckfurniere wurde die Wärmefreisetzung verzögert. Dabei erwies sich die Imprägnierung mit Kalkwasser als besonders wirksam, da sie sowohl die Gesamtwärmefreisetzung als auch die Masseverlustrate reduzierte. Daneben verzögerte sie auch den Entzündungszeitpunkt.

1 Introduction

Since its debut in 1978, oriented strand board (OSB) has gained rapid acceptance as a structural panel. OSB has virtually replaced plywood in new residential construction in many areas of North America. Today, the model building codes in the U.S. and Canada recognize OSB panels for

the same uses as plywood on a thickness-by-thickness basis (SBA 2006). OSB is equivalent to other structural panels in its strength and rigidity, panel size and thickness, fastener performance and paintability.

Wood products are important materials in both residential and non-residential building construction. They do not need to be made flame retardant for most applications. It is well known that one can significantly improve the fire performance of wood-based composites by chemical treatment and thereby widen the options for their utilization (Kartal and Ayrilmis 2005). The fire-retardant chemicals most used for wood products contain phosphorus, especially monoammonium phosphate (MAP) and diammonium phosphate (DAP). These phosphates are among the oldest known fire-retardant systems. They are usually included in proprietary systems used for wood. Boron compounds are considered to be effective flame retardants that exert less impact on mechanical properties compared with some other flame retardant chemicals (Tran and LeVan 1990). Laufenberg et al. (2006) evaluated fire and bending properties of blockboards with various fire-retardant-treated (FRT) veneers. They reported that the treatments resulted in significant reductions in predicted flame spread rates.

The overall objective of the project was to investigate OSB with FRT rotary-cut face veneers as an high-quality alternative to structural and decorative plywood. The objective of this specific study was to determine the influence of various fire-retardants on physical, mechanical, and fire properties of the veneer faced OSB. To our knowledge, there is no information about the application of FRT veneers on OSB. For this aim, physical and mechanical properties of the untreated and treated specimens were determined at the Forest Products Laboratory, Istanbul Univ., Turkey. To evaluate the effectiveness of the fire-retardant treatment of the veneers, heat release rate tests of the untreated and treated specimens were conducted at the U.S. Forest Service Forest Products Laboratory at Madison, WI, USA.

2 Materials and methods

2.1 Materials

Rotary-cut beech (*Fagus orientalis* Lipsky) veneer sheets were applied to commercial manufactured OSB under laboratory conditions. The sheets were 1.5 mm thick and nearly defect-free. Beech is naturally grown in Northeast Turkey and has an average air-dry density of $630\,kg \cdot m^{-3}$ (Berkel 1970). It is a convenient wood for veneer, plywood, and laminated veneer lumber (LVL) manufacturing. The sheets were cut at the laboratory to obtain test panels of 500 by $500\,mm^2$. Specimens for the different tests were cut from these test panels.

Three 1220 by $2440\,mm^2$ sheets of commercial OSB/2 (structural use (dry)) were supplied by Kronospan Incorp., Bulgaria. The OSB product was made from a mixture of pine and aspen strands. Both the upper and undersides of the 15-mm thick OSB panels were initially sanded with 60 grit sand paper in a sanding machine to achieve smooth surface so that the veneers could be uniformly applied to the OSB panels. The OSB thickness was approximately 14 mm after sanding. The sanded sheets were then cut into smaller test panels with dimensions of 500 by $500\,mm^2$. A total of twenty test panels (five groups: four treatments and one control, four replicates) were obtained from the three OSB sheets. The OSB test panels and the veneer sheets were placed in a conditioning room ($20\,°C \pm 2\,°C$ and $65 \pm 2\%$ relative humidity).

Four chemicals were used in the treatments of the veneer: (1) a mixture (1 : 1 by weight) of borax-$Na_2B_4O_7.10H_2O$ and boric acid-H_3BO_3(BX/BA); (2) monoammonium phosphate-$NH_4H_2PO_4$(MAP); (3) diammonium phosphate-$(NH_4)_2HPO_4$(DAP), and (4) lime water ($Ca(OH)_2$(aq)) (LW). Lime water is a colorless and odorless alkaline aqueous solution of calcium hydroxide. Lime water can be made by dissolving either calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$) in water.

2.1.1 Chemical treatment

The veneers were pressure impregnated with the fire retardant chemicals using a full-cell pressure process. A vacuum of 650 mmHg of mercury was applied for 30 min, chemicals were added, and pressure of $1.1\,N \cdot mm^{-2}$ was then applied for 60 min. The average chemical retention was $57.7\,kg \cdot m^{-3}$ for the four treatments (Table 1).

2.1.2 Manufacturing of OSB with FRT beech veneers

Two pieces of the veneer were glued onto one piece of OSB. The face veneers were aligned to the OSB substrate so their longitudinal grain direction was perpendicular to the major axis of the original OSB panel. A commercial liquid phenol-formaldehyde (PF) adhesive was used to bond the veneers to the OSB. The PF adhesive (solids content $47 \pm 1\%$) was uniformly applied on one side of the face veneers at approximately $180\,g \cdot m^{-2}$. The OSB was then sandwiched with the sheet veneers and pressed at 65 bar and 140 °C for 7 min in a laboratory type hot press.

2.2 Methods

2.2.1 Determination of physical and mechanical properties

Prior to physical and mechanical property tests, specimens were conditioned for at least 3 weeks at $20\,°C \pm 2\,°C$ and $65 \pm$

Table 1 Retention values and average physical and mechanical test values obtained from the OSB specimens
Tabelle 1 Einbringmenge und durchschnittliche physikalische und mechanische Versuchswerte der OSB-Proben

			Mechanical properties						Physical properties	
Fire retardants	Retention ($kg \cdot m^{-3}$)	Air-dry density ($kg \cdot m^{-3}$)	Modulus of rupture ($N \cdot mm^{-2}$) ∥	Modulus of rupture ($N \cdot mm^{-2}$) ⊥	Modulus of elasticity ($N \cdot mm^{-2}$) ∥	Modulus of elasticity ($N \cdot mm^{-2}$) ⊥	Bond strength between veneer and panel surface ($N \cdot mm^{-2}$)	Screw withdrawal resistance (Face) (N)	Thickness swelling (%)	Water absorption (%)
Untreated control	–	652 (0.015)	73.2 (3.0) A	17.8 (1.5) A	10860 (851) A	2394 (392) A	20.4 (0.8) A	1884 (161) A	13.1 (1.5) A	43.0 (6.1) A
BX/BA	57.3	661 (0.019)	71.5 (2.4) AB	16.8 (0.9) B	10254 (504) B	2290 (77) A	19.4 (0.9) B	1764 (91) B	16.3 (2.1) B	48.3 (3.2) B
DAP	57.9	651 (0.017)	69.9 (2.2) BC	16.2 (0.8) BC	9888 (514) B	2079 (171) B	18.9 (1.2) B	1693 (181) B	13.8 (2.1) C	43.5 (3.5) A
MAP	57.6	649 (0.022)	68.1 (6.6) C	15.4 (1.3) C	9057 (356) C	1964 (140) BC	18.1 (0.8) C	1609 (170) C	14.2 (3.6) C	46.8 (5.1) B
Lime water	58.1	653 (0.023)	66.8 (1.6) C	14.8 (0.7) D	8289 (225) D	1861 (119) C	17.4 (0.9) D	1514 (96) D	12.4 (2.2) A	38.4 (2.6) D

Homogeneity groups: same letters in each columns indicate that there is no significant difference between the samples according to the Duncan's multiple range test. $p = 0.001$. ∥ – parallel to major axis of panel; ⊥ – Perpendicular to major axis of panel. Values in parentheses are standard deviation.

2% relative humidity. Air-dry density, thickness swelling, water absorption, three-point static modulus of rupture (MOR), modulus of elasticity (MOE), and screw withdrawal resistance, and bond strength between veneer and OSB surface were evaluated according to EN and DIN standards.

Tests of panel flexural properties (modulus of rupture (MOR) and modulus of elasticity (MOE)) were conducted according to EN 310 (1993). Twenty-four specimens with dimensions of 370 by 50 by 16 mm^3 from each test panel were tested on a Losenhausen Universal testing system equipped with a load cell with a capacity of 10000 N. Twelve specimens were cut with their long dimension parallel to the outer veneer layer and 12 specimens with their long dimension perpendicular to the outer veneer layer. Load-deflection data for the calculation of the specimen's MOE were recorded at the 10% and 40% values of failure load (*Pmax*). The crosshead speed was adjusted so that failure would occur within an average of 60 s ± 10 s.

Twenty five thickness swelling and water absorption specimens with dimensions of 50 by 50 by 16 mm^3 were taken from each of the five groups (four treatments plus control). The specimens were immediately weighed. Average thickness was determined by taking several measurements at specific locations. After 24 hours of submersion, specimens were drip-dried for 10 min, wiped clean of any surface water, and weighed. Thickness was determined as described in EN 317 (1993). Densities of the specimens were measured according to EN 323 (1993). For screw withdrawal resistance perpendicular to the plane of the board, twenty-five specimens with dimensions of 75 by 75 by 16 mm^3 were tested according to EN 320 (1993). Each screw was inserted into a prebored hole (2.7 mm in diameter and 19 mm length) and screwed into the board to a depth of 15 mm. Care was taken that the screw was kept perpendicular to the appropriate surface of the test specimen. Using a stirrup with a parallel-sided slot of such width as to fit easily to the shank of the screw, an increasing axial force was applied to the underside of the head of each screw. The force was applied at an even rate and the rate of application was adjusted so the time from the initial application of the force until failure of the test specimen was not less than 30 s and not more than 120 s. The force required to withdraw each screw was recorded.

Bond strength between veneer and OSB surface (delamination test) was evaluated on twenty-five specimens with dimensions of 50 by 50 by 16 mm^3 according to DIN 68765 B1 (1987). On the surface of the specimens, a circle with a 35.7 mm diameter was drilled through the veneer thickness. This veneer circle on the OSB surface was separated from the surrounding veneer. A metal tension seal (pull-up seal) was glued with polyurethane adhesive and placed in the movable cross-head of the universal test machine to remove the veneer circle from the OSB panel surface.

For physical and mechanical properties, all multiple comparisons were first subjected to an analysis of variance (ANOVA). Significant ($\alpha \leq 0.001$) differences between mean values of the untreated and treated specimens were determined using Duncan's multiple range test.

2.2.2 Fire performance

The cone calorimeter test method is described in ASTM E-1354-04a (ASTM International 2004) and ISO 5660-1 (International Organization for Standardization 1993). Specimens were tested in the horizontal orientation with the conical radiant electric heater located above the specimen. The unexposed surfaces of the test specimen were wrapped

Fig. 1 Lime water treated specimen for the cone calorimeter test
Abb. 1 Eine mit Kalkwasser imprägnierte Probe für die Cone-Calorimeter-Prüfung

in aluminum foil and the specimen placed on a piece of low density refractory fiber blanket within the holder. The external heat flux was $50\,kW \cdot m^{-2}$ and the retainer frame for the test specimen was used without the wire grid. The electric spark igniter was inserted above the test specimen until the time for sustained ignition of the test specimen was observed and recorded. The criterion for sustained ignition was 10 s. For the duration of the test, the heat release rate (HRR) due to combustion was determined using the oxygen consumption methodology. In addition, the mass loss of the specimen was recorded during the test. The effective heat of combustion (heat release per unit mass loss) was calculated from the heat release and the mass loss data. The amount of visible smoke produced by the burning specimen was evaluated by measuring the obscuration of a laser beam in the exhaust duct. The 57 mm orifice plate was used and the measured exhaust flow was $0.024\,m^3 \cdot s^{-1}$. The scan rate for recording of the data was one reading per second.

Fourteen cone calorimeter tests were conducted on the six types of specimens. Specimens included OSB with the four types of FRT veneers (Fig. 1), the untreated control specimen, and the OSB core without any face veneers. Specimens were conditioned at 23 °C, 50% R.H. prior to testing. The dimensions of the specimens were 100 by $100\,mm^2$. Two replicates of the veneer covered specimens and four replicates of the plain OSB specimens were tested.

3 Results and discussion

3.1 Physical and mechanical properties

Air-dry density values of the specimens ranged between 649 and $661\,kg \cdot m^{-3}$ (Table 1). Specimens treated with BX/BA, MAP, DAP, and LW showed no differences in density when compared to control specimens. Water absorption (WA) and thickness swelling (TS) values of all treated specimens except for specimens treated with LW were significantly increased as compared to those of control boards (Table 1). Specimens treated with LW had the lowest TS value with 12.4% while the highest TS was found for the specimens with BX/BA treated veneers having a value of 16.3%. Specimens with DAP and MAP treated veneers showed better performance than specimens with BX/BA treated veneers, respectively. Based on thickness swelling investigations, it was concluded that boron compounds, BX and BA, increased thickness swelling of the panels more than phosphorous compounds, MAP and DAP. No statistically significant difference in TS was found between the MAP and DAP treated specimens. Thickness swelling values of all treated specimens did not exceed the OSB minimum property requirement of 20 percent according to EN 300 OSB/2 (1997) standard. WA values demonstrated similar trends and results to those for TS.

OSB specimens with DAP, MAP and LW treated veneers showed statistically differences in MOR when compared to control specimens. The MOR values of all treated specimens were significantly decreased as compared to control values (Table 1). Specimens treated with BX/BA had the greatest MOR values of $71.5\,N \cdot mm^{-2}$ while the lowest MOR values of $66.8\,N \cdot mm^{-2}$ were found for the specimens treated with LW. The MOR values of the treated specimens, parallel to major axis of panel, varied from 66.8 to $71.5\,N \cdot mm^{-2}$. A similar test result was reported in literature as approximately $30\,N \cdot mm^{-2}$ for commercial OSB without face veneers. The MOR values of the OSB panels with face veneers were twice as much than those of OSB panels without face veneers. In addition, parallel and perpendicular-to-plane MOR values of the OSB panels with treated veneers met plywood minimum requirements F40 ($60\,N \cdot mm^{-2}$) and F10 ($15\,N \cdot mm^{-2}$) of EN 636 (1996), respectively.

Contrary to TS and WA values, specimens treated with BX/BA showed highest MOR and MOE values among treatment groups. These results were in agreement with a study performed by Myers and Holmes (1975) on fire-retardant treatments for dry-formed hardboard. They found that boron compounds did not exert a significant negative effect on MOR and MOE of the panels. Ayrilmis et al. (2005) reported bending strength and stiffness values of OSB panels treated with boron compounds and phosphates that were significantly reduced for all treatments and all loading levels when compared to control board values. Goker (1978) found an average $69\,N \cdot mm^{-2}$ MOR value for untreated beech plywood parallel to axis. The MOR parallel to major axis values of the OSB panels with treated veneers ranged from 66.8 to $71.5\,N \cdot mm^{-2}$. Bending properties of all treated pan-

Table 2 Percent change in physical and mechanical values of treatment groups as a function of chemical retention
Tabelle 2 Prozentuale Änderung der physikalischen und mechanischen Werte als Folge der unterschiedlichen Imprägnierung und der Einbringmenge

		Decreases (−) and increases (+) of physical and mechanical properties of treatment groups							
		Modulus of rupture (%)		Modulus of elasticity (%)		Bond strength			
Fire retardants	Retention ($kg \cdot m^{-3}$)	∥	⊥	∥	⊥	between veneer and panel surface (%)	Screw withdrawal resistance (Face) (%)	Thickness swelling (%)	Water absorption (%)
Untreated control	–	–	–	–	–	–	–	–	–
BX/BA	57.3	−2.32	−5.6	−5.5	−4.4	−4.9	−6.4	−24.4	−12.3
DAP	57.9	−4.51	−9.0	−8.9	−13.2	−11.3	−10.2	−5.3	−1.2
MAP	57.6	−6.97	−13.5	−16.6	−18.0	−7.4	−14.6	−8.4	−8.8
Lime water	58.1	−8.74	−16.9	−23.7	−22.3	−14.7	−20.0	+5.3	+10.7

∥ – parallel to major axis of panel; ⊥ – Perpendicular to major axis of panel

els were consistent with those reported by Goker for plywood. Based on the findings in the MOR values, it could be concluded that OSB with treated veneers can be used for concrete formwork in building construction as an alternative to commercial plywood.

Tran and LeVan (1990) reported that boron compounds were often considered a good flame retardant and these beneficial effects included preservative effectiveness, neutral pH, and less impact on mechanical properties compared to some other flame retardant chemicals. However, Bozkurt et al. (1993) expressed that boron compounds increased hygroscopicity of wood and wood products. For this reason, boron compounds, such as borax and boric acid, could negatively affect dimensional stability of the wood based panels. Middleton et al. (1965) stated that fire-retardant treatments containing phosphate such as DAP and MAP had more of an effect on the strength properties of wood than that of borate. Schaeffer et al. (1966) determined that acidic ammonium salts in both phosphate and sulfate form decrease the pH of the resin to a level much lower than that noted with the alkaline sodium salts.

The MOE values showed parallel trends and results to those for MOR. The MOE parallel to major axis of all treated specimens was between 5.5% to 23.7% lower than the average of the untreated control specimen (Table 2). The specimens with BX/BA treated veneers had the best MOE value with $10\,254\,N \cdot mm^{-2}$, followed by DAP-, MAP-, and LW-treated specimens, respectively. Parallel and perpendicular-to-plane MOE values of the OSB panels with treated veneers met the plywood minimum requirements E80 ($8000\,N \cdot mm^{-2}$) and E15 ($1500\,N \cdot mm^{-2}$) of EN 636 (1996), respectively. MOE of specimens with LW was considerably below that of the untreated control and other treated specimens. Similar results were found in a previous study carried out by Ayrilmis (2007). He found that BA, BX, MAP, and DAP treatments significantly reduced the internal bond strength of structural fiberboards made from PF resin.

As for face screw withdrawal resistance (SW), there was a significant difference between untreated and treated veneer faced OSB panels. Compared to untreated controls, significant reductions in SW (6% to 20% of untreated controls) were obtained for all of the treated specimens. BX/BA-treated specimens had the highest SW value, followed by DAP, MAP, and LW-treated specimens, respectively (Table 1). The SW values of all treated panels were higher than that (1468 N) of untreated 15 mm thick commercial plywood tested by Akbulut et al. (2002). Bond strength between veneer and panel surface was adversely affected by the fire retardants. The bond strength values showed similar trends to the results of MOR, MOE and SW tests. The test values of all treated specimens were between 5% to 15% lower than the average of the untreated control specimens. The specimens with BX/BA treated veneers had the highest bond-durability performance while the lowest bond-durability was found for the specimens with LW treated veneers.

3.2 Fire performance

The primary result from the cone calorimeter test is a HRR curve over the duration of the test (Figs. 2 to 4). A typical curve for wood is an initial increase to a peak heat release rate, then a drop to a steady-state heat release rate, which is followed by a second peak as the final portion of the specimen is consumed. For the two untreated products, the typical curve for wood products was observed in these tests (Fig. 2). For the four products with treated veneers, three peak heat release rates (PHRR) were observed (Table 3). The first PHRR was due to the ignition and combustion of the treated veneer. Compared with the untreated control specimens, the specimens of the four different treatments had dramatically reduced initial PHRR (Table 3). The MAP treatment was most effective in reducing this initial peak heat release rate. The BX/BA treatment had the least impact on this initial PHRR (Fig. 3). A second PHRR was observed when the untreated OSB core became involved in the combustion. The DAP treatment reduced this second peak slightly more than the MAP treatment but the differ-

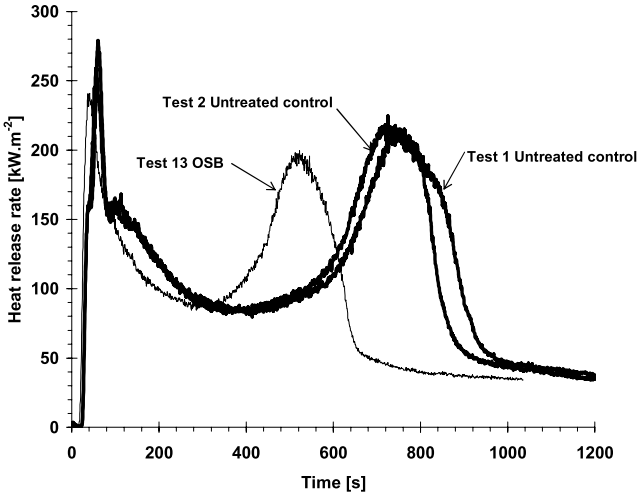

Fig. 2 Heat release rate curves for the two untreated control specimens (Test nos. 1 and 2) and for one of the OSB specimens (Test 13) without any veneer for duration of tests
Abb. 2 Wärmeentwicklungskurven über die gesamte Versuchsdauer für die zwei unbehandelten Kontrollproben (Versuchsnr. 1 und 2) sowie für eine der OSB Proben (Versuch 13) ohne Deckfurnier

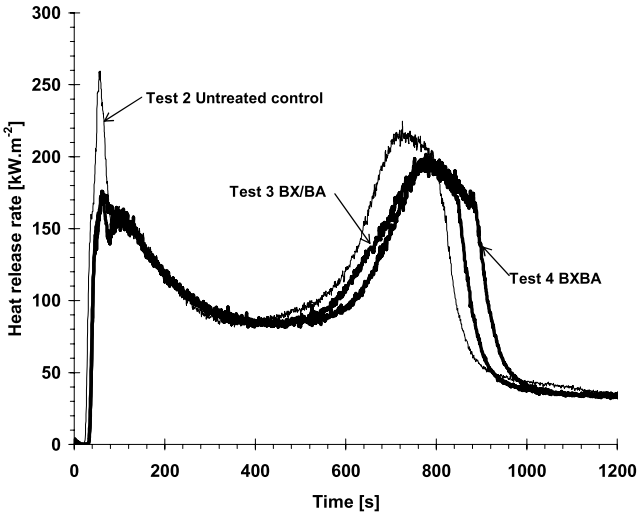

Fig. 3 Heat release rate curves for the two Borax/Boric acid (BX/BA) specimens (Test nos. 3 and 4) and for one of the untreated control specimens (Test no. 2) for duration of tests
Abb. 3 Wärmeentwicklungskurven über die gesamte Versuchsdauer für die zwei mit Borax/Borsäure imprägnierten Proben (BX/BA) (Versuchsnr. 3 und 4) sowie für eine der unbehandelten Kontrollproben (Versuchsnr. 2)

ences between the four treatments were relatively small. This was not surprising since the second peak was largely due to the untreated OSB core. For the BX/BA treated specimens, the initial PHRR was greater than the values for the second PHRR values. For the other three treatments, the second PHRR was an increase in the HRR over that observed for the initial PHRR.

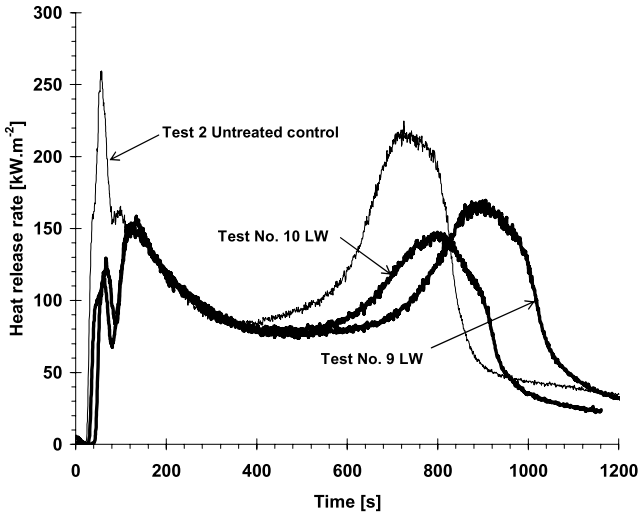

Fig. 4 Heat release rate curves for the two lime water (LW) specimens (Test nos. 9 and 10) and for one of the untreated control specimens (Test no. 2) for duration of tests
Abb. 4 Wärmeentwicklungskurven über die gesamte Versuchsdauer für die zwei mit Kalkwasser imprägnierten Proben (LW) (Versuchsnr. 9 und 10) und für eine der unbehandelten Kontrollproben (Versuchsnr. 2)

A third PHRR occurs near the end of the tests. This PHRR is normally associated with the more rapid heating of the back portion of the insulated test specimen and includes heat due to the combustion or glowing of the char layer. For the specimens with treated veneers, this portion of the tests involved the combustion of the treated veneer on the back surface of the specimen. The LW treatment had the lowest values for this third PHRR (Table 3). All the specimens with treated veneers had values for this third PHRR that were less than that observed for the two untreated control specimens.

The fire-retardant treatments reduced the average heat release rate and the total heat release values from that observed for the untreated control (Table 4). For the treated specimens, the ignition times ranged from 18 to 46 s (Table 4). The untreated control specimens ignited at 27 s. The BX/BA and LW treatments increased the ignition times to values greater than those for the untreated control specimens or the untreated OSB specimens. The average effective heat of combustion was computed from the total heat release divided by the total mass loss for the duration of the test. For all four treatments, the results for average effective heat of combustion of the treated specimens were less than the values for the untreated specimens (Table 4). The effect of the fire retardants on the effective heat of combustion was more obvious when effective heat of combustion was plotted against time. In addition to reducing the effective heat of combustion (Fig. 5), the LW treatment also caused a reduction in the mass loss rate at the start of the test (Fig. 6). The average mass loss rates for the different types of specimens (Table 4) showed that the lime water effect on mass loss rate was greater than

Table 3 Three peaks within the heat release rate curves
Tabelle 3 Drei Spitzen entlang der Wärmeentwicklungskurven

Test number	Specimen type	First peak		Second peak		Third peak	
		PHRR	Time of PHRR	PHRR	Time of PHRR	PHRR	Time of PHRR
		$kW \cdot m^{-2}$	s	$kW \cdot m^{-2}$	s	$kW \cdot m^{-2}$	s
1	Control	279	60	–	–	216	739
2	Control	260	57	–	–	224	725
3	B/BA	174	63	164	109	200	780
4	B/BA	176	61	159	99	202	777
5	MP	87	30	156	100	204	740
6	MP	66	54	149	118	183	877
7	DP	141	50	144	110	175	695
8	DP	111	31	149	107	194	800
9	LW	115	64	158	134	170	906
10	LW	129	67	154	130	148	799
11	OSB	215	44	–	–	211	562
12	OSB	225	38	–	–	228	536
13	OSB	241	41	–	–	199	522
14	OSB	215	37	–	–	198	543

Table 4 Test results from cone calorimeter tests
Tabelle 4 Versuchsergebnisse der Cone-Calorimeter-Prüfungen

Test number	Specimen type	Time for sustained ignition[1]	Average heat release rate[2] 60 s	180 s	300 s	Test duration[3]	Total heat release	Average effective heat of combustion[4]	Average specific extinction area[4]	Average mass loss rate[5]	Residual mass fraction[6]
–	–	s	$kW \cdot m^{-2}$	$kW \cdot m^{-2}$	$kW \cdot m^{-2}$	$kW \cdot m^{-2}$	$MJ \cdot m^{-2}$	$MJ \cdot kg^{-1}$	$m^2 \cdot kg^{-1}$	$g \cdot s^{-1} - m^2$	–
1	Control	27.2	183	155	132	110	129	12.8	118	10.6	0.22
2	Control	27.3	182	155	132	110	124	12.9	104	10.6	0.23
3	B/BA	36.3	149	142	125	106	117	11.8	88.3	10.7	0.22
4	B/BA	36.1	143	138	122	108	118	11.6	65.5	10.7	0.22
5	MP	18.3	70	110	104	102	104	11.7	85.1	10.1	0.28
6	MP	42.0	80	116	110	100	120	12.0	97.2	9.8	0.28
7	DP	23.0	114	122	109	95	102	11.9	85.6	9.7	0.27
8	DP	20.7	95	119	110	96	115	12.0	92.1	10.0	0.26
9	LW	32.4	86	118	110	94	116	11.4	65.3	9.6	0.26
10	LW	46.2	100	122	112	95	98.7	11.1	58.1	9.4	0.27
11	OSB	22.7	183	143	124	108	97.3	12.5	92.0	11.2	0.18
12	OSB	19.9	180	143	123	112	89.5	12.6	88.5	11.0	0.20
13	OSB	24.2	192	145	123	101	94.4	12.9	70.0	10.7	0.18
14	OSB	21.5	178	138	118	112	88.0	12.1	88.9	10.9	0.20

[1] Observation of flaming ignition that was sustained for 10 s. [2] Averaged for 60, 180, or 300 s after the time for sustained ignition. [3] Averaged from the time for sustained ignition until the end of the test. [4] Averaged over the entire duration of the test. [5] Averaged over the time period from 10% of ultimate specimen mass loss to 90% of ultimate specimen mass loss. [6] Calculated as (initial specimen mass – final mass)/initial mass

that for the other three treatments. The BX/BA treatment had the least impact on the mass loss rate.

One screening method for fire-retardant treatments is to measure the mass loss rate and the residual mass fraction. The method described in ASTM E 2102 (2004a) is the cone calorimeter without the oxygen consumption measurement of heat release. For the MAP, DAP, and LW treated specimens, the residual mass fractions of the test specimen at the end of the test were greater than the results for the untreated control specimens or the untreated OSB (Table 4). The residual mass fractions for the BX/BA treated specimens were slightly less than the untreated control specimens. The average specific extinction area was computed from the smoke obscuration data. All four of the treatments caused a reduction in the visual smoke measurements (Table 4). The LW treatment caused the greatest reduction in the average specific extinction area compared with the results for the untreated control specimens.

In the United States, the regulatory test for surface flammability of building products is the 7.32 m (25-ft) tunnel test (ASTM E 84 2004b). FPL uses the cone calorimeter to predict the flame spread index (FSI) obtained in the tunnel test (White and Dietenberger 2004). The development of the predictive model is discussed by Dietenberger and White (2001). Based on the model, a graph of the fire growth propensity can be plotted (Fig. 7). In this model, the surface fire growth propensity is represented by the initial peak heat release rate (horizontal axis in Fig. 7). For the pur-

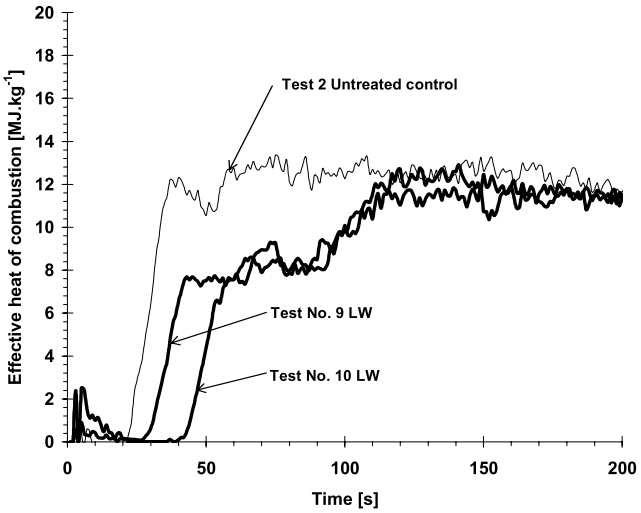

Fig. 5 Effective heat of combustion curves for lime water (LW) specimens (Test nos. 9 and 10) and for one of the untreated control specimens (Test no. 2) for the initial 200 seconds
Abb. 5 Verlauf der Gesamtwärmefreisetzung während der ersten 200 Sekunden für die mit Kalkwasser imprägnierten Proben (LW) (Versuchsnr. 9 und 10) und für eine der unbehandelten Kontrollproben (Versuchsnr. 2)

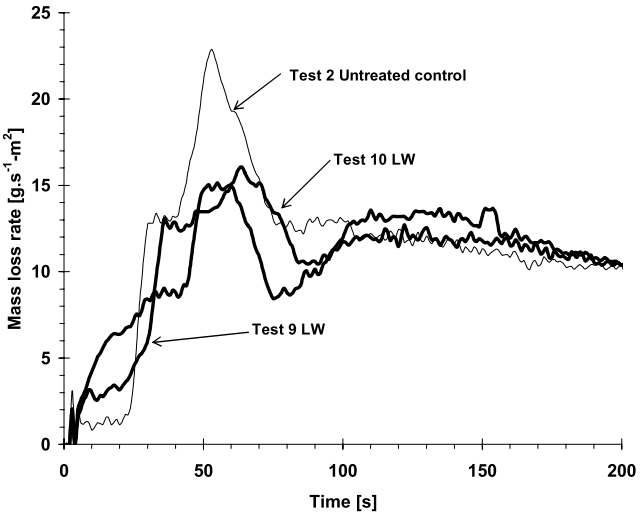

Fig. 6 Mass loss rate curves for lime water (LW) specimens (Test nos. 9 and 10) and for one of the untreated control specimens (Test no. 2) for the initial 200 seconds
Abb. 6 Verlauf der Masseverlustraten während der ersten 200 Sekunden für die mit Kalkwasser imprägnierten Proben (Versuchsnr. 9 und 10) und für eine der unbehandelten Kontrollproben (Versuchsnr. 2)

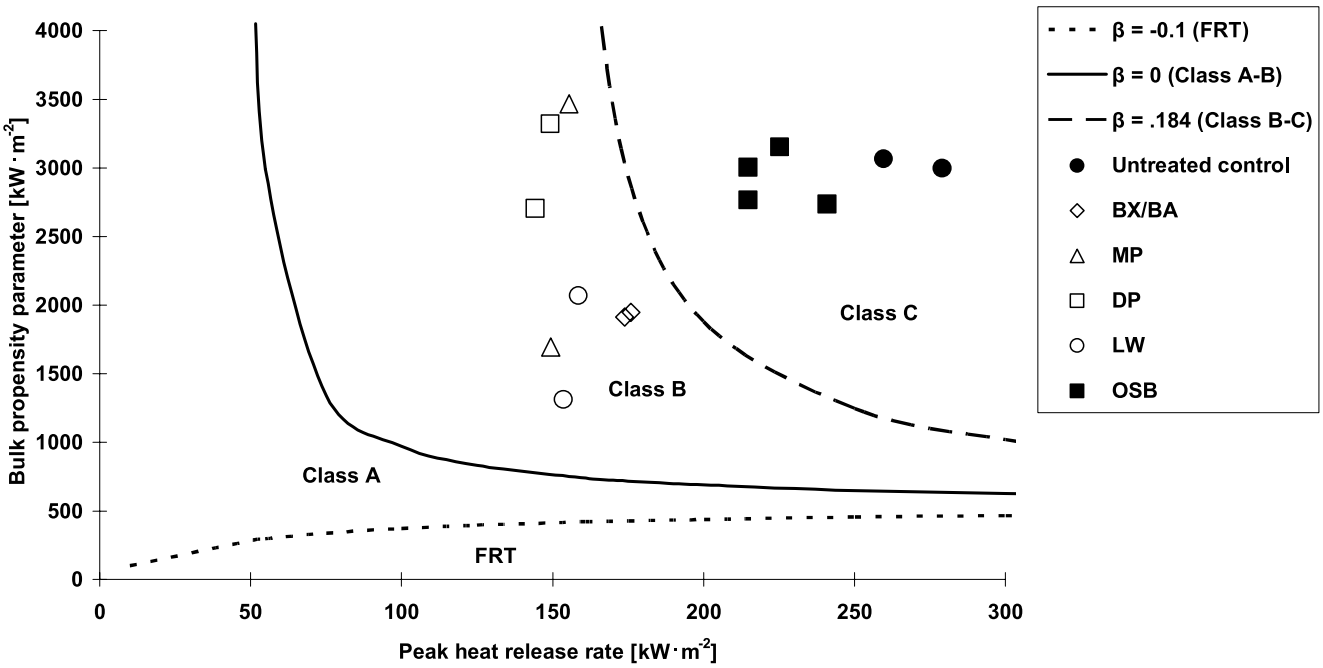

Fig. 7 Fire growth propensity of the test specimens based on a fire growth model discussed in Dietenberger and White (2004). Classes are for the surface flame spread classification in the U.S. building codes which are for ranges of the ASTM E 84 flame spread index. FRT is fire-retardant-treated wood that likely satisfies the fire performance requirements in the U.S. building codes
Abb. 7 Brandverhalten der Versuchsproben unter Verwendung eines Brandverhaltensmodells nach Dietenberger und White (2004). Die Klassifizierung der Oberflächenflammenausbreitung entspricht den US-Bauvorschriften, die sich auf den ASTM E 84 beziehen. FRT ist ein mit einem Feuerschutzmittel behandeltes Holz, das den Anforderungen an das Brandverhalten in den US-Bauvorschriften entspricht

pose of making the predictions, the greater of the first or second PHRR (Table 3) was used as input to the model (Table 5). The corresponding values for a bulk propensity parameter (y-axis in Fig. 7 and Table 5) were calculated from the total heat release (Table 4), thickness and the inverse of the time for sustained ignition (Table 4). In the

Table 5 Model predictions derived from cone calorimeter test results
Tabelle 5 Modellvorhersagen anhand der Cone-Calorimeter-Prüfergebnisse

Test number –	Specimen labels –	Peak heat release rate[1] $kW \cdot m^{-2}$	Y-axis[2] Fig. 7 $kW \cdot m^{-2}$	Beta[2] –	Estimated FSI[2] –
1	Control	279	2998	0.346	EUL[3]
2	Control	260	3064	0.318	EUL
3	B/BA	174	1914	0.151	60
4	B/BA	176	1948	0.156	61
5	MP	156	3467	0.162	64
6	MP	149	1696	0.108	47
7	DP	144	2705	0.133	54
8	DP	149	3320	0.151	60
9	LW	158	2069	0.136	55
10	LW	154	1311	0.087	43
11	OSB	215	3002	0.247	EUL
12	OSB	225	3153	0.267	EUL
13	OSB	241	2734	0.280	EUL
14	OSB	215	2766	0.241	EUL

[1] Peak heat release rate used for model prediction. Value is the greater of the first or second peak heat release rates (Table 3). [2] Calculated using methodology described in Dietenberger and White (2001) and White and Dietenberger (2004). [3] EUL – Exceed upper limits of the logarithmic correlation between the ASTM E 84 flame spread index (FSI) and β that is used to obtain the estimate of the flame spread index.

model, a variable called β is also calculated (Table 5). The lines for β in Fig. 7 are used to divide the plots into areas where the model estimates that the ASTM E84 FSI will be in one of the three classes used in the U.S. building codes to classify materials. A β of 0.184 is used to differentiate between Class C (FSI of 76 to 200) and Class B (FSI of 26 to 75) materials. Most untreated U.S domestic wood products, including OSB, are Class C. All the predictions for the untreated specimens were for Class C or higher. Treatment of the face veneers produced values for β within the boundaries for Class B (Table 5, Fig. 7). The most restrictive class is Class A (FSI of 25 or less) which requires fire-retardant treatment for U.S. domestic wood products. The model uses a β of zero to differentiate between Class B and Class A materials. In the U.S. building codes, the requirements for "fire-retardant-treated" (FRT) requires the ASTM E84 test to be conducted for a longer time period than specified in ASTM E 84. The model uses a β of -0.1 to identify materials that might qualify for such classification (White and Dietenberger 2004). Predictions for the ASTM E 84 FSI were calculated from a logarithmic correlation between β and the ASTM E84 FSI (Dietenberger and White 2001) (Table 5). Because of the logarithmic relationship between the β and the FSI, the equation used to estimate the FSI is not sensitive to variations in FSI greater than about 75 and does not produce a numerical estimate of the FSI for higher values of β (Table 5).

The layered nature of the treated products caused a difficulty for the model since it assumes an exponentially decaying HRR curve after the initial PHRR and that the initial PHRR occurred shortly after the time for sustained ignition. Due to the treatment of the outer veneer layer, the PHRR associated with the declining exponential heat release rate was the second PHRR for three of the treatments (MAP, DAP, and LW). The observed times for ignition (Table 4) occurred much earlier than the occurrence of the second PHRR (Table 3). For the predicted results in Table 5 for these three treatments, the second PHRR was used with the observed times for sustained ignition. If the time for the second PHRR was used as the input for the observed time for ignition for these three treatments, the model predicts FSI that ranged from 15 to 24, which would be for Class A. If the initial PHRR values are used with the observed times for sustained ignition, the predicted FSI for these three treatments ranged from 38 to 52.

4 Conclusions

Physical and mechanical properties of OSB panels with fire-retardant treated veneers were significantly affected by fire-retardant treatment. Mechanical properties of all treated panels were less than those for the untreated control. The panels with LW had the lowest mechanical properties while the highest mechanical properties were found for the panels with BX/BA treated veneers. Generally, the panels with BX/BA did not show a significant difference to the panels with DAP on the mechanical properties. As for physical properties, OSB panels with LW showed better performance than OSB panels with untreated veneers. However, other fire retardants decreased physical properties of the panels. The mechanical properties tested in this study were in agreement with other results for FRT plywood. The fire-retardant treatments of the face veneers were effective in reducing their initial contribution of heat release to potential fire growth. In particular, the LW treatment was an effect-

ive fire-retardant treatment in that it reduced the effective heat of combustion, reduced the mass loss rate, and delayed the times for sustained ignition. It also reduced the amount of visual smoke produced. Of the four treatments evaluated, the BX/BA treatment was the least effective. After 90 to 120 s of exposure to the 50 $kW \cdot m^{-2}$ heat flux, the untreated OSB core contributed to the heat release in a manner consistent with OSB without face veneers.

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