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Biodegradability and waste behavior of industrial wood-based construction materials

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Industrial wood-based construction materials: chipboard, plain and overlaid plywood, phenolic surface film, laminates and selected synthetic polymers were studied for their biodegradability under aerobic and anaerobic conditions and for the environmental quality of the degradation residue. The yields of carbon dioxide plus methane from the wood-based materials in 6 months under anaerobic conditions at 33°C ranged from $\leqslant$3% to 79% compared to that obtained from starch, and under aerobic conditions from $\leqslant$7% to 55% of that obtained from acetate, measured in 28 days at 25°C. The plywoods were more readily degraded under aerobic and anaerobic conditions. The microbes attacked mainly the S_2-layer of the plywoods and started from the S_3-layer of the wood cells of chipboard in the compost. Extensive cavities, occupied with microbes, were observed by electron microscopy in the decaying plywoods, chipboard and laminates. The contents of Cu, Cr, Pb, Ni, and Cd of the wood-based construction materials were low, $<$10 mg kg^{-1}, compared to PVC and to a typical municipal solid waste. Toxicity and the amount of leachable organic halogen from the wood-based construction materials were low, EC_{50} of 4–8 g L^{-1} to *V. fischeri* and $<$12 μg adsorbable organic halogen (AOX) of g^{-1}. The results show that the wood-based construction materials studied were aerobically biodegradable and the plywoods also anaerobically. There was no toxicity towards photobacteria or substances of environmental concern in the biodegradation and incineration residues of the materials tested. *Journal of Industrial Microbiology & Biotechnology* (2000) **24,** 210–218.

Keywords: biodegradation; compostability; construction materials; toxicity; ultrastructure

Introduction

A large fraction of wood-containing waste originates from construction and demolition of buildings. Of this waste only 26% was recycled or reused in European Union countries. Life cycle analysis is important for predicting the waste behavior of industrial products.

Biodegradability is often the least well-known quality of the industrial product. Biodegradation of natural wood has been studied widely using electron microscopy and other methods [for reviews see Refs 10, 12]. But when industrially processed wood is studied, the interest is usually focused on improving its resistance towards microbial attack. Thus far bacteria [26] and soft rot fungi [27] were shown to degrade copper-chrome-arsenate (CCA)-treated wood. Yalinkilic *et al* [31] reported weight loss of melamine and phenol formaldehyde resin boards upon exposure to white rot fungi. The bacterial degradation of lignocellulolytic substances under aerobic conditions has been studied extensively. Three types of decay caused by bacteria can be distinguished according to microscopic observations: erosion, tunneling and cavitation [10,26]. In oxygen-limiting environments erosion bacteria were the primary degraders [5]. Clausen [8] cited a report on tunneling decay of wood by anaerobic bacteria, identified as *Clostridium xylanolyticum*, a xylan degrader [23].

No quantitative data on the biodegradability of industrial wood-based construction materials appear to have been published. This paper reports on the aerobic and anaerobic biodegradability of chipboard, plain and overlaid plywood, phenolic surface film, laminates and synthetic polymers under laboratory conditions and in compost. The elemental composition, leachate quality and the toxicity towards photobacteria of the materials were also determined.

Materials and methods

Before analyses of mineralization and of toxicity, the chipboard, plywoods and laminates were ground to dust (1–2 mm), phenolic surface film and polyvinylalcohol-starch polymer were crushed to particles of $<$5 mm and other synthetic polymers were cut to $<$20-mm particles.

Analysis of biodegradation

Aerobic mineralization was measured as described in European Union Directive 92/69/EEC [13] using activated sludge from Helsinki city, Viikki sewage works as the inoculum and carbon dioxide-free air for aeration. The carbon dioxide evolved was sorbed into 0.05 M aqueous sodium hydroxide and quantified using a TOC analyzer (TOC-5000, Shimadzu, Kyoto, Japan). Construction material (100 mg dw) was added as the substrate in each reaction flask holding 1 L of the reaction mixture and 30 mg (dw) of activated sludge as the inoculum. The materials contained no significant amount of inorganic carbonate. The yield obtained with inoculum without construction material was subtracted. Sodium acetate (analytical

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grade, Merck, Darmstadt, Germany) was used as a ready biodegradable reference substance.

Anaerobic mineralization was measured according to ASTM standard method D-5210–92 [2] using Helsinki city, Viikki, sewage-digested sludge as the inoculum. The methane and carbon dioxide evolved were measured from the headspace of reaction flasks by gas chromatography (Model 3700, Varian, Palo Alto, CA, USA) with a Hayesep Q 80/100 column (Hewlett Packard, Palo Alto, CA, USA), TC-detector (Varian), integrator (Model D-2000, Hitachi, Tokyo, Japan) and He as the carrier gas. Soluble starch (analytical grade, Merck, Germany) and carboxymethyl cellulose (CMC), DS = 0.5 (Finnfix, Metsäserla Chemical Division, Äänekoski, Finland) were used as reference substances. Construction material (500 mg dw) was added as the substrate in each reaction flask holding 75 ml of the reaction mixture and 200–230 mg (dw) digested anaerobic sludge as the inoculumn. The materials contained no significant amount of inorganic carbonate. The yield obtained with the inoculum in the absence of construction material was subtracted. In both aerobic and anaerobic testing systems the mineralization yield of the reference substance (sodium acetate and soluble starch, respectively) was $\geqslant$70% of the TOC and the deviation parallels was $\leqslant$20%, as required for validity of the standard protocols.

Compostability was tested in outdoor piles (1 m^3) using weight loss as the criterion. The materials were cut to 30–200 mm × 90–200 mm and enclosed in nylon nets (exclusion size 5 mm × 10 mm) or tied to wooden sticks as described by Gilmore *et al* [15]. The bags and sticks were sandwiched between catering waste from the University lunchroom and chipped bark so that there was no contact between the bags or the sticks. Moisture and aerobiosis were maintained by irrigating and agitating the piles twice a month. Temperature was measured twice a week at 0.2 m depth.

Analytical protocols

Toxicity was tested as described by Brouwer *et al* [7] using *Vibrio fischeri* (NRRLB–11177). The materials were blended in 18 ml of 2% sodium chloride with 2 ml of an 18–24 h culture of *V. fischeri* added in screw-capped tubes and incubated in a water bath at 15°C for 15 min and then centrifuged at 15°C for 5 min at 300 × *g* (Sorvall Instruments RC5C, rotor GS5, Du Pont, Wilmington, DE, USA). The luminescence of the supernatant was measured (Luminometer 1253, Bio-Orbit, Turku, Finland) and compared to that of the blank with *V. fischeri* in aqueous 2% sodium chloride.

The chlorine content, the carbon content and the heavy metals from ash (4 h at 550°C ± 25°C) were measured as described elsewhere [21]. Leachable organic carbon and halogen were assayed from extracts prepared from 50 g of material L^{-1} in 0.2 M acetic acid, pH 4.85 as described in standard D-5233-92 of ASTM [3] or in distilled water as prescribed in DIN standard 38414 S4 (published by CEN [14]) except that glass microfiber filter (GF/C, Whatmann, Maidstone, UK) was used for filtration. Activated-carbon adsorbable organic halogen (AOX) in the leachates was determined according to the International Standardization Organisation (ISO) standard 9562 [19], the total (TOC) and dissolved (DOC) organic carbon according to the standard ISO 8245 [18].

The samples were prepared for transmission electron microscopy, stained, thin sectioned and analyzed as described by Väisänen *et al* [30]. For scanning electron microscopy, 1-mm^3 sized samples were cut from composted construction materials and fixed in 2.5% (w/v) glutaraldehyde in 0.1 M phosphate buffer (pH 7) for 2 h. The samples were then rinsed three times with the buffer, dehydrated in a graded series of ethanol and critical point dried. The samples were coated with gold and observed with SEM Zeiss DSM 962 microscope.

Results

Biomineralization under aerobic conditions

Seven wood-based construction materials (Table 1) were tested for biomineralisation under standardized aerobic conditions with activated sewage sludge as the seed (Figure 1). The carbon dioxide yields obtained in 28 days (25°C) were 37%, 21% and 17% of the TOC of the plain plywood, of phenolic surface film overlaid plywood and of phenolic surface film, respectively. These were equivalent to 55%, 31% and 25% of that obtained from acetate (readily biodegradable model substrate, *ca* 70% mineralized) under identical conditions. The yield from chipboard was <7% of TOC (Figure 1) and those from the laminates were below the detection limit ($\ll$5%, not shown in Figure 1). The synthetic materials polyvinylalcohol-starch polymer, PVC and HD-PE, emitted 12%, <5% and <5% (detection limit) of TOC, respectively, as CO_2 within 28 days. Carbon dioxide evolution from the wood-based materials started after a lag of 10 days, when that from acetate was almost complete (=70% of TOC, Figure 1). The lag period may reflect the time required for hydrolysis of the polymer molecules, preceding mineralization.

We conclude from Figure 1 that the plain plywood, phenolic surface-film overlaid plywood and phenolic surface film were moderately biodegradable aerobically whereas chipboard, the laminates, polyvinylalcohol-starch polymer, PVC and HD-PE biodegraded slowly or poorly.

Biomineralization under anaerobic conditions

The seven wood-based construction materials were analyzed under standardized conditions with municipal digested sludge as the seed. The yields of carbon dioxide plus methane are shown in Figure 2. Soluble starch and carboxymethyl cellulose (CMC, DS = 0.5) were used as reference substrates. The mineralization yield from plain plywood in 6 months at 33°C was 55% of the TOC. Seventy percent of the TOC content of starch and 46% of CMC were mineralized during the same period. A lower yield, 33%, was obtained from plywood overlaid with phenolic surface film. The carbon dioxide plus methane generated from the flasks with no added substrate (blanks) was subtracted from that generated from the flasks containing wood-based construction materials as substrates. The total carbon content of these blanks was 80–90 mg. The yield of methane plus carbon dioxide measured from them was $\leqslant$1.5 mg, ie <2% of the carbon content of the digested sludge inoculum. The low yield is explained by the fact

Table 1 Specifications of the materials studied. All were normal tradeware obtained from local commercial sources in 1994

Material	Description	Principal use	Contents of Moisture % w/w	Contents of C % w/w	Weight (g m^{-2})
Chipboard	Wood chips, ureaformaldehyde as adhesive	Building	6.5	46	10600
Plain plywood	Veneer of birch and spruce with formaldehyde adhesive	Building	5.9	43	5500
Phenolic surface film overlaid plywood	Plain plywood overlaid with phenolic film (2% w/w)	Concrete shuttering, traffic signs, vehicles	5.1	51	5800
Decorative outdoor laminate (compact)	Phenol formaldehyde impregnated paper lined with melamine-impregnated paper	Building, facades	4.1	48	2000
Decorative high pressure laminate	Laminate with melamine-impregnated paper on one side only	Kitchen table top	4.6	52	1200
Phenolic surface film	Phenol formaldehyde resin (65%), paper from kraft pulp (35%)	Wooden panel overlaying	–[a]	52	120
Saw dust	Saw dust of birch	Reference material	–[a]	–[a]	–[a]
Saw dust	Saw dust of spruce	Reference material	–[a]	–[a]	–[a]
PVC	Polyvinyl chloride, containing 36% (w/w) of plasticizer	Floor coating	–[a]	39	1900
HD-PE	Food grade high density polyethylene	Packaging	–[a]	85	8010
PVA-starch polymer	Polyvinyl alcohol with starch (1:1)	Disposable shopping bags	–[a]	60	42

[a] Not determined.

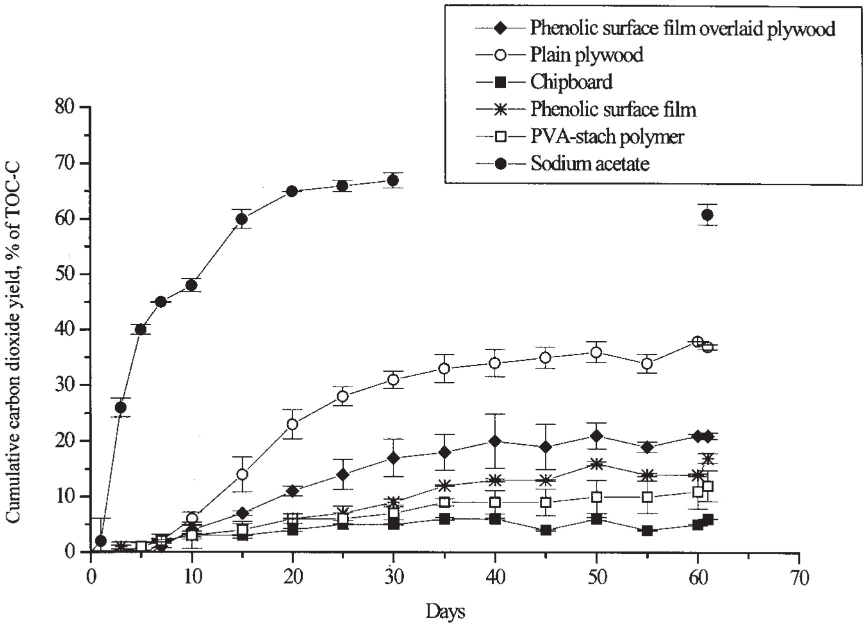

Figure 1 Aerobic biomineralization of construction materials at 25°C (European Union Directive, EU 92/69). The net yields of CO_2-C (blank of activated sludge is subtracted) are given as per cent of the total carbon contents of the materials. Sodium acetate was used as a readily degradable reference compound. Vertical bars indicate deviations of parallel experiments ($n = 2$) and of sodium acetate ($n = 4$).

that sludge was digested anaerobically for 30 days at 37°C before use as inoculum. Had the digested sludge mineralized equally to starch (70%) 50–60 mg of $CO_2 + CH_4$–carbon could have emanated from it. From the flasks containing plain plywood $\geqslant$120 mg and phenolic surface film overlaid plywood $\geqslant$80 mg of mineralized carbon (ie $CO_2 + CH_4$) evolved. These amounts could not have been from the digested sludge inoculum.

Methane was generated in high yield from plain plywood and from phenolic surface film overlaid plywood, 27% and 16% of the carbon content at the end of incubation, respectively. The methane yields indicate that degradation of plywoods was by the anaerobic microbial community. These results show that moderate to good anaerobic biomineralization of plywoods had occurred.

Plain plywood was more readily biodegradable anaerobically than CMC (DS = 0.5). Chipboard and polyvinylalcohol-starch biomineralized more slowly (yield of TOC <10%). The laminate, PVC, HD-PE and phenolic surface film mineralized poorly if at all (<2%, not shown in Figure 2).

Biomineralization yields from the plywoods were higher

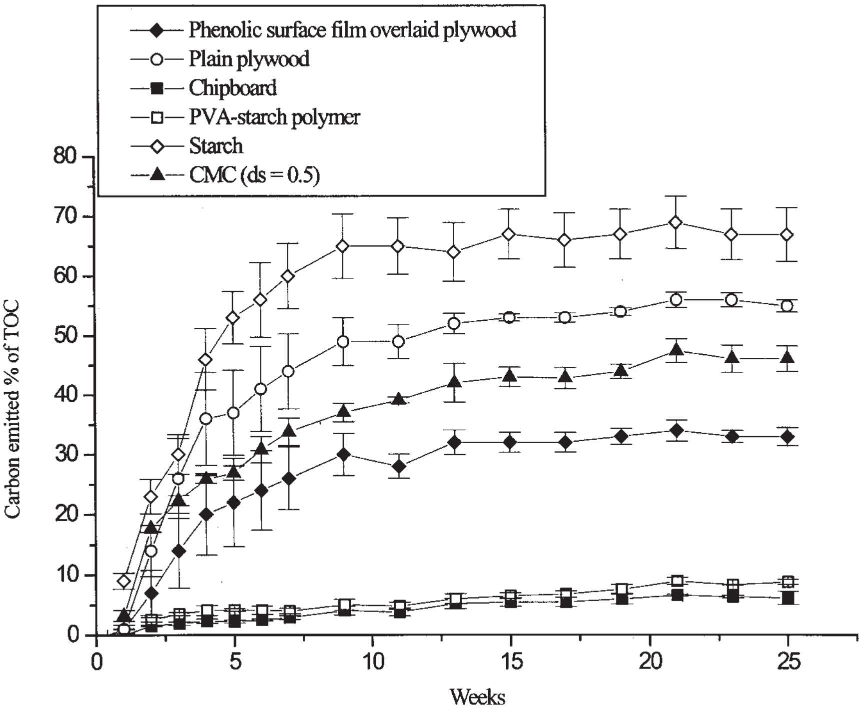

Figure 2 Anaerobic biomineralization of construction materials at 33°C (ASTM standard D 5210–92). The net yields of carbon as CO_2 plus CH_4 (blank of digested sludge is subtracted) are given as per cent of total carbon contents of the materials. Soluble starch was used as a readily degradable reference compound. Vertical bars indicate deviations between parallel experiments ($n = 3$, and for starch $n = 6$).

under anaerobic than under aerobic conditions. This may reflect the lower biomass yield of the anaerobic degradation process, and hence a higher mineralization yield than aerobic degradation similar to what is observed in biological wastewater treatment.

Aerobic as well as anaerobic biomineralization yields from plain plywood were almost twice as high as those obtained from phenolic surface film overlaid plywood, even when the weight of the phenolic surface film was excluded (Figures 1 and 2). Thus overlaying of plywood increased the resistance towards biodegradation both in aerobic and anaerobic environments (Figures 1 and 2). The plywoods and chipboard were mineralized to a degree 5–20 × higher than were the synthetic polymers, PVA-starch, PVC and HD-PE.

Weight loss of materials during composting

Table 2 displays the weight loss of five construction materials when composted in the presence of catering waste. The phenolic surface film and plain plywood were most readily compostable. Phenolic surface film lost 17% of its weight in 154 days. Chipboard lost 10% of its weight similar to plywood (12%) in 365 days. Overlaying the plywood with phenolic surface film increased its resistance to

Table 2 Weight loss (%) of construction materials composted in the presence of catering waste. Temperature in the compost piles was most of the time ≤40–60°C (measured at the depth of 0.2 m and at 0.2 m distance from the outer edge of the 1-m^3 pile). When the temperature of the compost decreased to <10°C, the test materials were removed and placed into a newly-started batch compost

Material	Weight loss % Mean ($n = 2$–4) (range)				
	14 days	28 days	56 days	154 days	365 days
Chipboard	<1.0 (<1.0–<1.0)	<1.0 (<1.0–<1.0)	2.5 (2.4–2.6)	6.3 (5.9–6.6)	10.1
Plain plywood	<1.0 (<1.0–1.9)	2.4 (1.8–3.4)	5.0 (4.0–5.7)	14.4 (10.8–16.5)	11.7 (10.4–13.0)
Phenolic surface film overlaid plywood	<1.0 (<1.0–<1.0)	1.6 (1.0–2.2)	1.4 (<1.0–2.1)	3.5 (3.0–4.3)	5.6 (3.8–7.4)
Phenolic surface film	4.7 (1.9–7.5)	7.2 (6.9–7.6)	4.0 (<1.0–8.9)	17.0 (16.7–17.4)	–[a]
PVA-starch polymer	<1.0 (<1.0–<1.0)	12.7 (<1.0–32.1)	14.5 (9.2–19.8)	21.0 (12.7–29.4)	–[a]

[a] Not determined.

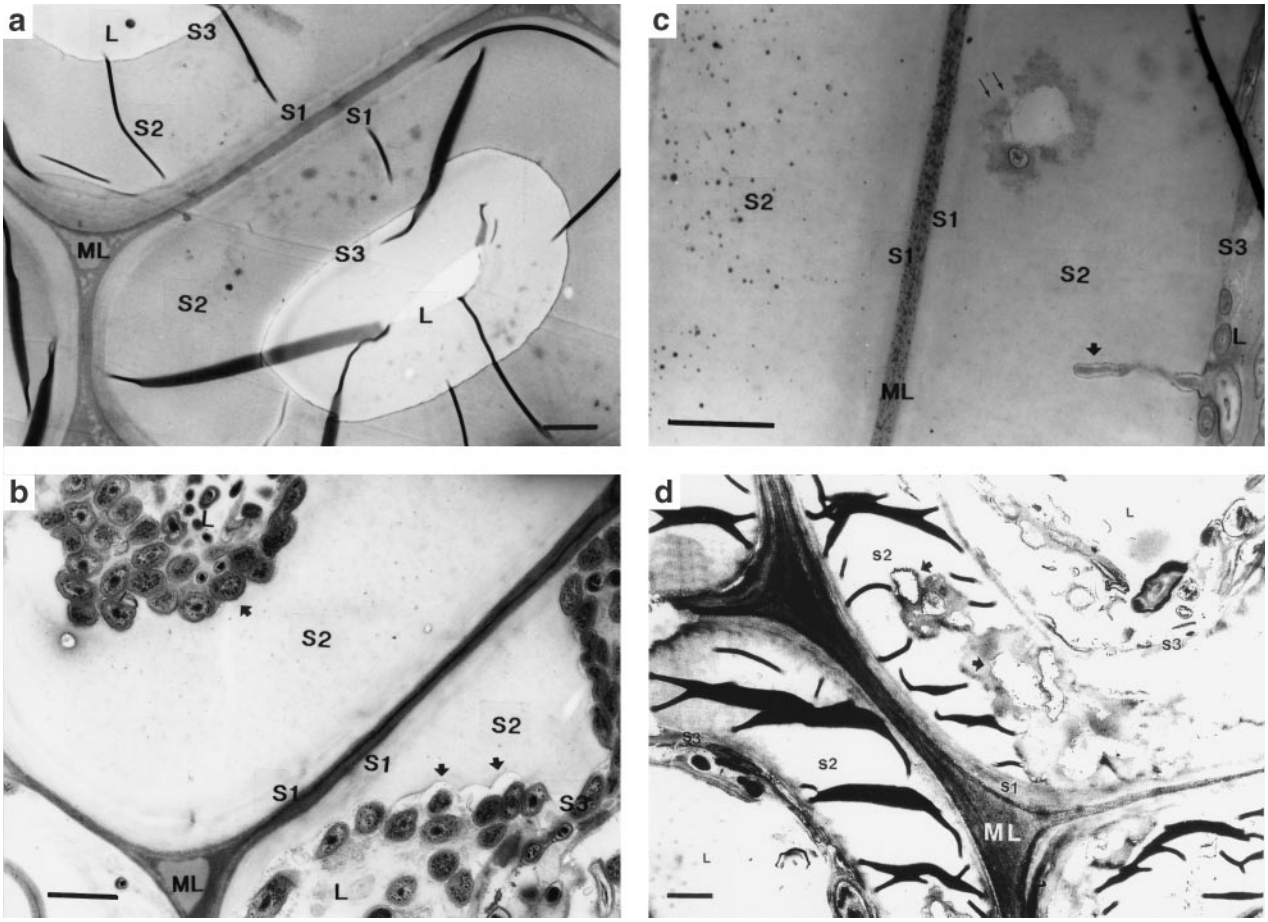

Figure 3 Transmission electron micrographs of thin sections of phenolic surface film overlaid plywood after 0 days (a), chipboard after 154 days (b), plain (c) and phenolic surface film overlaid plywood (d) after 365 days of composting. In panel (a) middle lamella (ml), S_1-, S_2-, and S_3-layers of the non-attacked wood cells are visible. In panel (b) microbes appear to have completely occupied and cavitated (arrows, b) the S_3-layer and part of the S_2-layer of the wood cell wall. Panel (c) shows cavitation (thin arrows) of the S_2-layer of a wood cell in plain plywood and thin fungal hypha (thick arrow) growing from the lumen (L) into the S_2-layer of wood cell. Panel (d) displays cavitation (arrows) of the S_2-layer in phenolic surface film overlaid plywood after composting it for 365 days. Bars = 1 μm.

decay by a factor of 2, even if the phenolic surface film lost 17% of weight in 154 days. The ureaformaldehyde adhesive used in chipboard manufacture (Table 1) may have protected the chipboard from fungal attack better than did the formaldehyde adhesive used in plywood manufacture. This could explain the slightly slower weight loss of chipboard compared to plain plywood during composting (Table 2). PVC and HD-PE or the laminates did not lose weight ($<$1%, not shown in Table 2) during 365 days of composting. PVA-starch polymer lost 32% of its weight but variation between parallel samples was high (SD 16.9%). One source of this error was the difficulty of properly removing the fragile polymer from the wood stick after composting, but it is also possible that patches with a high temperature (up to 60°C) in the compost promoted saponification of the acetyl residues and leaching of the starch plasticizer from the polymer.

Electron microscopic analysis of the composting of wood-based construction materials

Close to 700 transmission electron micrographs were prepared to analyze the events during composting of the construction materials. The essential features of the degradation events are illustrated in Figures 3 and 4. Bacteria occupied the whole S_3-layer of chipboard and also most of the S_2-layer after 154 days (Figure 3b), whereas both types of plywoods (Figure 3c, d) were invaded by microbes through the lumen of the wood cell and cavities of 1–2 μm were formed in the S_2-layer of the cell wall. In the plywoods the S_3-layer remained mainly intact even when the S_2-layer of the wood cell wall appeared hollowed and packed with microbes (Figure 3c, d). The large cavities in the secondary wall in the cells of composted wood are occupied by microbes (Figure 3b, c, d), indicating that microbial degradation of the woody components had occurred. The composted decorative outdoor laminate (Figure 4a, c) showed bacterial spores with rod- and coccus-shaped vegetative cells and dissolution of the S_2-layer of the woody cell wall during composting. Decorative high pressure laminate also showed dissolution of woody cell walls after 364 days of composting (Figure 4b, d). These results indicate that the laminates were being biodegraded even though the weight loss during 52 weeks of composting was small.

We conclude that chipboard, plain and overlaid plywood, phenolic surface film, decorative outdoor laminate and dec-

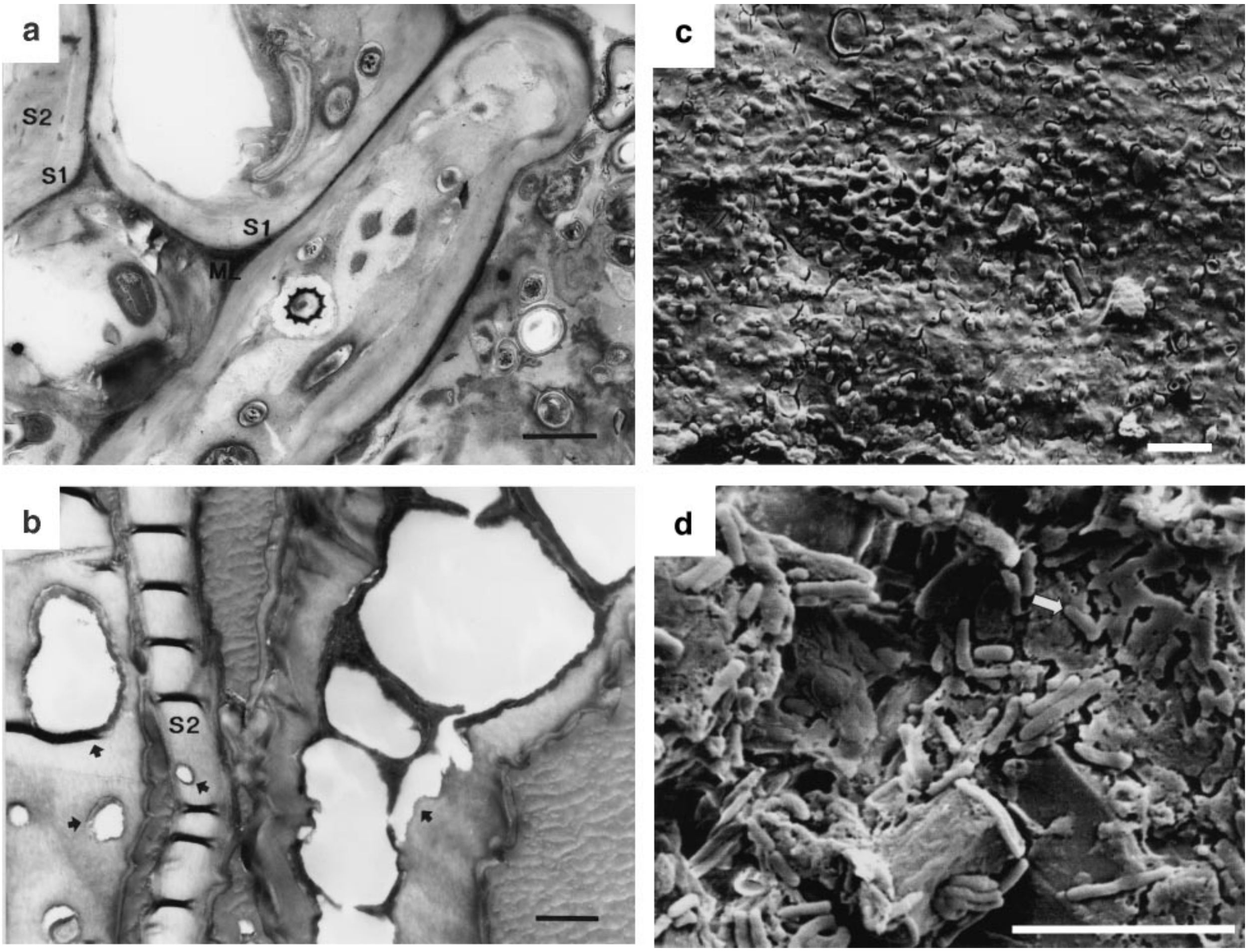

Figure 4 Transmission electron micrographs of a thin section of decorative outdoor laminate after 56 days (a) and of decorative high pressure laminate after 365 days (b) of composting. Bar = 1 μm. Scanning electron micrographs of decorative outdoor laminate (c) and of decorative high pressure laminate (d) after 365 days of composting. Bar = 10 μm. The vegetative cells and spores of bacteria have invaded interior (a) and the surface of the wood cell (c). (b) and (d) Show the dissolution of wood cell wall (arrows).

orative high pressure laminate were biodegraded in the compost.

Inhibition of bioluminescence of Vibrio fischeri

Inhibition of light emission by *V. fischeri* was observed with EC_{50} values of 35 g L^{-1} for birch wood dust and 60 g L^{-1} for spruce wood dust. EC_{50} values indicate here the concentration of the test material attenuating light emission by *V. fischeri*, NRRLB-11177, to 50% after contact of 15 min at 15°C, when light emission measured with 2% saline as suspending medium was set at 100%. The corresponding EC_{50} values of the wood-based construction materials were 4–8 g L^{-1}, which is 1000 times higher than that of the toxicity calibration substance, 3,5-dichlorophenol ($EC_{50} = 0.0082$ g L^{-1}). Thus, toxicity of the wood-based construction materials measured with *V. fischeri* was low. Ureaformaldehyde- and formaldehyde-based adhesives, components of the commercial construction materials studied (Table 1), may be responsible for the slightly higher inhibition by the construction materials as compared to the wood itself. Shading of emitted light may have caused a part of the apparent inhibitory effect of the wood dusts and construction materials.

The ash quality of materials

The ash compositions of the materials shown in Table 3 show that the total chlorine content of the wood-based construction materials was <1 g kg^{-1}, dramatically lower than that of PVC (380 g kg^{-1}). The concentrations of toxic heavy metals Pb, Ni and Cd in the wood-based construction materials were low, $\leqslant 5$ mg kg^{-1} (Table 3). PVC had a high content of cadmium, 7300 mg kg^{-1} and also contained more copper (11 mg kg^{-1}) and chromium (10 mg kg^{-1}) than the wood-based construction materials (<7 mg of Cu and <3 mg of Cr).

Leachate quality of the wood-based construction materials

The wood-based construction materials were cut (<10 mm) or milled (<2 mm) prior to leaching with distilled water or with dilute acetic acid, respectively, to simulate the worst case landfill behavior. Only small amounts of organic hal-

Table 3 The element composition of combustion residue of selected construction materials

Material	Element, mg kg^{-1}													Ash weight %
	Cl[a]	Cu	Fe	Mn	Mg	K	Cr	Zn	Pb	Ni	Na	Ca	Cd	
Chipboard	520	4.8	45	86	130	510	2.8	10.9	<0.4	0.5	92	1180	0.07	0.4
Plain plywood	7	4.4	12	79	180	1960	0.4	16.6	5.1	0.7	6190	5690	0.08	2.7
Phenolic surface film overlaid plywood	15	6.4	11	49	160	1900	<0.3	7.2	3.6	0.7	6240	5360	–[b]	2.6
Phenolic surface film	28	–[b]	200	300	3400	4200	–[b]	80.0	1.1	5.2	11700	8500	0.18	2.7
Decorative outdoor laminate	73	3.7	35	26	72	140	0.7	3.1	<0.6	0.6	576	600	0.03	2.8
Decorative high pressure laminate	790	5.4	240	44	160	59	1.7	5.6	<0.7	1.2	1660	1070	0.55	2.9
PVA-starch-polymer	170	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	0.02
PVC	380 000	10.8	42	0.5	34	31	9.7	3.1	<0.9	1.3	58	3330	7280	1.9
HD-PE	0.02	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]

[a] Chlorine was determined microcoulometrically after combustion of the material in a stream of oxygen. The other elements were determined from pre-ashed (550°C) materials. All figures are calculated per kg of dw of non-combusted material.

[b] Not determined.

Table 4 Leaching organic halogen and organic carbon from wood-based construction materials. The tests were done for 16 h with dilute acetic acid (ASTM D5233–92 standard [3]), or for 24 h with distilled water (DIN 38414 S4 [14]). In the acetic acid, particles of <2 mm and in distilled water 10 mm × 10 mm were extracted. Organic halogen (AOX) and carbon (DOC) were measured in the extracts

Construction material	pH of		Leachable into acetic acid or distilled water			
	Reagent	Leachate	AOX μg Cl g^{-1}		DOC mg C g^{-1}	
			Mean	SD ($n=4$)	Mean	SD ($n=6$)
Chipboard						
into acetic-acid	4.85	4.84	0.9	0.04	<15.0[b]	–
into distilled water	–[a]	–[a]	0.4	0.08	4.2	0.1
Phenolic surface film overlaid plywood						
into acetic acid	4.85	4.99	<0.4	–	<15.0[b]	–
Phenolic surface film						
into acetic acid	4.85	5.37	<0.4	–	49.0	6.5
Decorative high pressure laminate						
into acetic acid	4.85	4.94	11.6	1.2	20.5	7.2
Plain plywood						
into distilled water	–[a]	–[a]	<0.4	–	7.4	0.07

[a] Not determined.

[b] The detection limit for leached DOC was 15 mg of C g^{-1} for extraction with acetic acid and 0.02 mg of C g^{-1} with distilled water.

AOX = activated carbon adsorbable organic halogen (ISO 9562 [19]).

DOC = dissolved organic carbon (ISO 8245 [18]).

ogens (AOX) were leached from the tested wood-based construction materials, <12 μg of AOX-Cl g^{-1} of materials (Table 4). Moderate amounts of organic carbon leached with dilute acetic acid (pH 4.85) from the phenolic surface film, 50 mg of DOC g^{-1} (9% of TOC of solid material), and from the decorative high pressure laminate, 21 mg g^{-1} (4% of TOC of solid material) (Table 4). The leachability of organic carbon into dilute acetic acid from the phenolic surface film overlaid plywood and the chipboard was below the detection limit ($\leqslant 15$ mg g^{-1} of DOC). Distilled water leached much less than did acetic acid, 4 mg of DOC g^{-1} from chipboard and 7 mg g^{-1} from the plain plywood (Table 4).

Discussion

None of the wood-based materials was recalcitrant towards microbial attack in contrast to synthetic polymers. The results also show that a combination of the results from different methods is required for elucidating the waste behavior of these materials.

Chipboard, plain and overlaid plywood, phenolic surface film and laminates were biodegraded at least to some extent under aerobic conditions. The plywoods, studied as dust (particle size 1–2 mm), were also biodegraded under anaerobic conditions. Bacteria like clostridia are capable of anaerobic growth and have been reported to be capable of anaerobic degradation of cellulose [12] and xylan [23]. Clostridia are also involved in the hydrolysis and acidogenesis stages of anaerobic digestion [11]. Also there are reports of bacterial degradation of wood in near-anaerobic aquatic habitats [5,17,25], but isolation and identification of these bacteria has so far been unsuccessful. Degradation of industrially produced lignocellulolytic substances has not been demonstrated previously under anaerobic environments. The production of methane in this study can be regarded as an indicator of anaerobic conditions because methanogenic bacteria are strict anaerobes. The high anaerobic mineralization yields (Figure 2) from plain plywood (55%) in this study may rely on the fact that mechanical grinding perforated lignified cell walls which would otherwise have protected the interior walls against microbial attack in the intact wood. The plywoods were composed of a mixture of spruce and birch veneers. Assuming that lignin (27% in spruce and 20% in birch [12]) does not degrade anaerobically but cellulose, hemicellulose, fatty acids and resins would degrade up to 80%, the expected mineralization yield from plywood would then be 56%. The measured mineralization yield from plain plywood thus was close to this theoretical approximation. We used optimized conditions to promote biodegradation. It has been reported that for soft rot fungi a high nutrient concentration is necessary for decay [22].

Chipboard degraded in the compost slightly better (10% per year) than in the laboratory tests, but plywood degraded better in laboratory biodegradation tests than in the compost. Composting may reflect prevailing conditions in waste management better than do the mineralization tests standardized for the laboratory [29]. This may relate to the particle size, which was 1–2 mm for chipboard and plywoods, <5 mm for phenolic surface film and polyvinylalcohol-starch polymer and <20 mm for other synthetic polymers in the laboratory standard biodegradation tests. Particle sizes of 30–200 mm were used for composting. Starnecker and Menner [28] showed that aerobic biodegradation rates increased significantly with decreasing particle size. The phenolic surface film did not biomineralize in the anaerobic environment, possibly due to the phenolic resin substances [16] which require attack by oxygenases not necessarily functioning in the anaerobic environment. In the overlaying process the phenolic resin becomes polymerized [16]. This may explain the observed decrease in biodegradability of overlaid plywood.

The biodegradation of chipboard and plywoods in the compost measured by weight loss may reflect not only the dissolution of glues and resins, but also true biodegradation of wood cells was detected as shown in Figure 3 where microbial attack toward wood cell walls is visible. Transmission electron microscopic evidence showed that the cavities in the S_2-layer of the wood cell wall of plywoods (Figure 3c and d) were formed by microbes. In chipboard, degradation started from the S_3-layer and seemed to be catalyzed by bacteria (Figure 3b). The laminates were also invaded by bacteria (Figure 4). Changes observed by transmission electron microscopy in the S_2- and S_3-layers during composting of chipboard (Figure 3b) resemble those described for erosion bacteria [24–26] whereas the cavities observed in composted plywoods (Figure 3c, d) resembled those typical of soft rot fungi [6,10,12,22]. Melamine and phenol formaldehyde resin boards lost weight upon 12 weeks of exposure to white rot fungi [31]. Bacteria degrade wood more slowly than fungi [26] and thus in the case of laminates, where the bacterial attack was visible, weight loss might have occurred later.

Toxicities to photobacteria of wood-based construction materials were low and similar to that of wood dust, never industrially processed, and 1/1000 of that of the toxicity calibration substance, 3,5-dichlorophenol or phenol (0.019 g^{-1}, 15 min [20]). The mild inhibition caused by wood dust may relate to polyphenols, tannins, tropolones, terpenoids or other extractives contributing to the natural durability of wood [32] in addition to ureaformaldehyde- and formaldehyde-based adhesives.

The presence of harmful inorganic elements is of importance when wood waste (20 kJ g^{-1}) or plastic waste (PE, 40 kJ g^{-1}) are intended to be used as fuel [4]. The contents of toxic heavy metals (Cr, Pb, Ni, and Cd) and of chlorine in the wood-based construction materials used in this study were lower than that reported for mixed municipal refuse which contains 100–200 mg kg^{-1} of toxic heavy metals [1,9] and 5–10 g of chlorine kg^{-1} [4]. The high content of sodium in phenolic surface film originates from the alkaline catalyst in the process (Vauhkonen L, Enso Group, Kotka, Finland, personal communication).

The low leaching of organic halogens from wood-based construction materials and organic carbon into dilute acetic acid indicate that landfilling of the wood-based construction materials or their ashes is of low environmental risk.

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