Biodegradation Potential of Some Barrier-Coated Boards in Different Soil Environments

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Received 1 March 2004; accepted 6 September 2005
DOI 10.1002/app.23591
Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT:: Three pilot barrier-coated boards that were recently produced at the Tampere University of Technology were tested for biodegradation potential using the soil-burial test method. The tests were conducted in the field as well as in the laboratory. We found that the baseboards degraded regardless of differences in coating; however, the degradation rate was different. The laboratory conditions as well as the addition of inoculum accelerated the degradation process. The coated layer of the boards was isolated by laminating with black polyethylene; then their biodegradation rate was compared to the biodegradation rate of the control, boards coated with low-density polyethylene. It was observed that paperboards coated with polyester-based polymers were biodegradable but at different rates. The differences in the biodegradation rates of the boards were attributed to their coating formulations. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 100: 3193–3202, 2006

Key words: biodegradable; barrier; polyesters; polyethylene (PE)

INTRODUCTION

Packaging product is a key component of modern society. Packaging products that have been coated with resin or laminated with plastic are not degradable in a reasonable time. So they contribute to the filling of landfills and to loading the environment. To halt the growth in waste, industrial countries at local or national levels have passed a wide range of legislation. Recently, about 40 states in the United States passed recycling laws or implemented voluntary goals and directives to hinder fibrous-waste growth in landfills.[1] European Union (EU) countries have been compelled to pursue waste-reduction guidelines (94/62/EU)[2] as well. The EU Landfill Directive suggests a 25% reduction in the 1995-level waste stream to landfill by 2010, a 50% reduction by 2013, and a 65% reduction by 2020. Recycling technology does not yet have the infrastructure or the capacity to deal with the rapid growth of wastepaper and -paperboard. Therefore, the waste-reduction scheme should also include a means of composting or incinerating in order to counteract this growth in waste. The materials to be composted should be biodegradable.

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Journal of Applied Polymer Science, Vol. 100, 3193–3202 (2006)

There have been many attempts to produce biodegradable barrier-coated products.[3–7] Some of these products are already on the market. It is claimed that these coated products are biodegradable; however, there is little information on their rate of biodegradability or their barrier properties in different environments.

One of the objectives of this project was to examine the biodegradability potential of some of these coated products in general. Another objective was to assess the influence of tropical conditions on the biodegradation rate of these products in particular. The literature is abundant on biodegradation of fibrous materials but has little on the biodegradation of recent barrier coating formulas.[6]

EXPERIMENTAL

Materials

The barrier-coated boards used in this experiment were supplied by Tampere University of Technology (TUT), Finland. The samples were uncoated board (A) and four types of one-side-coated boards (B, C, D, and E). The coating layer of the B, C, and D boards was formulated using polyester polymers. The polymer used in the formulation of the B and C coatings was polyester-based resin, but board D was coated with polylactic acid (PLA). These consumer-ready boards were introduced as biodegradable materials (Table I). The coating formulation of board E was developed

TABLE I
The Paperboard Samples with or without Coating

Brand names of the boards	Sample Code	Coating polymer
Ensocup210 (Uncoated board)-Baseboard	A	Uncoated
KoGreen150TM coated board	B	Polyester-Bbased Resin
KoGreen120W coated board	C	Polyester-Based Resin
EcoPLA1100D coated board	D	Polylactic Acid
Polyethylene coated board	E	Low Density Polyethylene

using low-density polyethylene polymer. Low-density polyethylene is said to generally have less crystallinity than high-density polyethylene.[3] Water vapor can pass through the amorphous region of polyethylene, but it cannot pass through the crystalline region.[3] The baseboards were bleached chemical pulp (mostly holocellulose) comprised of three layers of softwood and hardwood blended in different proportions (mostly hardwood, as was judged based on average fiber length). The baseboard of the samples was from the same raw material.

Soil preparation

The soil used in the experiments was topsoil from north of Bangkok, Thailand, referred to as AIT soil. Soil samples were air dried for 24 h and subsequently were ground, then sifted with a ⅛-inch screen to remove the large clumps and plant debris. Two sets of soil in two conditions were developed and labeled either laboratory or field soil. Laboratory soil was prepared by mixing AIT soil with compost-amended soil and then with an enriched stock. The compost-amended soil was a mixture of soil and manure. The enrichment stock comprised 60 L of water, 400 g of molasses, and 50 g of urea. It was added to the mixed soil at a rate of around 100 mL/kg soil. The soils were prepared in two forms: with inoculum and without inoculum. A mixed culture (PD1) from the Land Development Department of the government of Thailand was used as inoculum. The moisture content and pH of the soils were kept at 40% (g/g; i.e., the maximum water-holding capacity of soil) and 7.49, respectively (Table II). Two field soil samples also were prepared, one with and one without inoculum. These samples were not mixed with either compost-amended soil or with enriched stock. In addition, the moisture content and pH of the soils were not adjusted, so they varied by climate condition. On the basis of these differences with the laboratory soil, these soils were considered field soils. The characteristics of both soils are reported in Table II.

The populations of bacteria, fungi, and actinomycetes in the soil were determined by the plate count technique according to *Methods of Soil Analysis*.[8] The moisture content of the soil was determined as a percentage of its dry weight by British Standard 1377:1961 (UDC624.131). The soil pH was determined according to the same standard as well. The microbial population of the soils at different burial stages were measured and are reported in Appendix A.

Sample preparation

The samples were cut into pieces 50×150 mm^2 in size in the machine direction. These samples were used to investigate the biodegradation potential of coated boards. In these samples, the microorganisms had the option of attacking through either the coated or uncoated surfaces. Each sample was marked with an identification number and conditioned at 50°C and 50% relative humidity (RH) for 48 h. Then the weight of each sample was measured and recorded along with its corresponding strip number. There was a required number of basketfuls of soil, but covered with perforated plastic to prevent the soil from passing through while still accommodating essential air circulation. The samples were then laid on the soil and covered with another inch of soil. Each layer had about 10 sample strips. Five strips of each sample were retrieved at a time, then cleaned by washing with deionized water and dried at 60°C for 30 min in an oven. The retrieved strips were then placed overnight in a conditioned room at a constant relative humidity (RH) and temperature (50% and 23°C, respectively). The tensile strength and weight loss of the samples were subsequently measured.

Methods of evaluating biodegradation

Weight loss

It was reported that soil bacteria, actinomycetes, and fungi are all capable of producing cellulolytic en-

TABLE II
The Experimental Condition and Soil Characteristics

		Qualities of soil	
Parameters	Units	Field soil	Laboratory soil
Moisture	%	varied +	40
pH		4.03	7.49
Organic matter	%	0.8	5.5
Total nitrogen	%	0.11	0.53
Humidity*	%	75 ± 3	75 ± 3
Temperature*	C°	31 ± 3	31 ± 3

*These are the ambient temperature and humidity; +. Varied with atmospheric condition

TABLE III
Board Characteristics

Property	A		B		C		D		E	
	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD
Fiber length (mm)	0.95	0.00	0.98	0.01	0.95	0.00	0.95	0.00	0.94	0.01
Fiber coarseness (mg/m)	0.095	0.00	0.101	0.002	0.097	0.001	0.098	0.004	0.102	0.001
Coat weight (wt %)	NC	—	15	1.80	34	7.02	17	6.63	18	0.60
Coat weight (g/m^2)	NC	—	35	0.64	95	6.68	39	2.26	43	1.34
Thickness (μ)	272	3	297	4	367	23	307	14	325	13
Gm (g/m^2)	215	0.64	246	1.16	301	10.7	251	1.24	256	7.75
WVTR (g/m^2)	3493	35	132	4	82	3	175	8	29.4	0.14
TI (MD), Nm/g	85.36	2.05	61.47	1.49	75.18	1.70	72.00	2.19	70.56	1.43

Gm: grammage; SD: standard deviation; WVTR: water vapor transmission rate.

zymes,[6] of which there are three major types: endoglucanase, cellobiohydrolase, and b-glucosidase. Endoglucanase is thought to be more active on amorphous cellulose. Cellobiohydrolase can affect hydrolysis of both amorphous and crystalline cellulose by removing cellobiose from the nonreducing end of the cellulose chains. b-Glucosidase completes the hydrolytic process by catalyzing the hydrolysis of cellobiose to glucose through the removal of a glucosyl residue from the nonreducing end of soluble cellooligosaccharide.[9] The sugars that diffuse out of the paper or board substrate are washed away, and the biodegradation in soil environment is reported as weight loss of the substrate. After retrieval from the soil, the samples were wet and almost completely coated with soil debris. Washing the debris from the samples was a very tedious job, and it was a major source of error. However, it was used as one of the methods in burial experimentation because of the lack of a suitable alternative.

Tensile strength loss

Tensile strength was previously used as a method of biodegradation assessment for paper and board.[6] TAPPI standard T 404 cm-92 was used in tensile strength measurement. Tensile strength is an indicator of the strength of weak points of paper or board. Therefore, using it as a parameter could be a reliable approach for evaluating paper or board biodegradability. Its major drawback in evaluation of the retrieved samples is the sample preparation process. The samples retrieved from the soil should be washed to remove soil and debris. Washing the debris weakens the retrieved samples. It is well documented that repeated washing and drying of paper or board deteriorates its tensile strength.[10] Depending on the raw material of the board or paper, the loss could be in the range of 10%–30%. Based on this, the reported figures on tensile strength should be corrected for the recycling effect. Random distribution of degraded areas could be another source of error. The latter could be overcome by careful preparation of the test strips, which should be representative and statistically acceptable.

Water vapor transmission

The water vapor transmission rate (WVTR) of the boards was measured at 40°C and 90% relative humidity using the Cup method (JISZ0208). The WVTR measures the amount of water vapor transmitted through a sample over 24 h in a specific atmospheric condition. The mechanism of transmission involves both solution and diffusion.[11] The water molecules dissolve on the polymer surface; then the dissolved water diffuses through the surface and transmits from the opposite side.

Estimation of coated-layer degradation

For biodegradability of the coated layers, a new set of samples were developed. All the samples were laminated with black polyethylene except for one of the coated surfaces. To assess the biodegradability of the coated layers, the degraded areas of the laminated samples were measured by the grid system (the grid was 0.5×0.5 mm^2 in area); then the ratio of the degraded area to the total coated area was calculated as a percentage.

RESULTS

Board characteristics

The board properties are summarized in Table III. The coat weight percentage of barrier-coated board (C) was almost twice those of the other samples (Table III).

TABLE IV
Level of Degradation Based on Weight or Tensile loss

	Weight loss								Tensile loss							
	Field				Laboratory				Field				Laboratory			
	No inoculum		Inoculum		No inoculum		Inoculum		No inoculum		Inoculum		No inoculum		Inoculum	
SC	WL (%)	Time (days)	WL (%)	Time (days)	WL (%)	Time (days)	WL (%)	Time (days)	TL (%)	Time (days)	TL (%)	Time (days)	TL (%)	Time (days)	TL (%)	Time (days)
A	76.9	42	77.8	35	78.5	14	72.4	12	50	6[a]	66.9	7	90.0	7	91.8	7
B	79.2	84	82.0	56	75.8	22	76.5	20	56.2	7	71.9	7	88.0	7	90.4	7
C	70.5	105	76.9	105	75.4	70	78.2	70	62.6	7	75.7	7	83.2	7	84.8	7
D	79.1	84	76.6	63	79.7	56	77.8	28	61.0	7	70.0	7	90.8	7	92.3	7
E	80.0	105	77.1	63	78.6	42	78.9	42	63.0	7	69.4	7	89.8	7	92.6	7

SC: sample code.
[a] Sample could not be retrieved after 6 days; WL: weight loss; TL: tensile loss.

Its basis weight was also the highest. The fiber length and coarseness of the fibers from the board samples were the same, and they were similar to the dimensions of hardwood, indicating that hardwood should be a major component of the baseboards. The WVTR results showed that board D had a higher WVTR than did the other three coated boards (B–E); it was almost twice that of board C, 4/3 that of board B, and almost 6 times higher than that of board E. The water vapor transmission rate describes the amount of water vapor transmitted through a sample over 24 h in a specific atmospheric condition. It was assumed that the WVTR might correlate with the moisture resistance of the boards.[3] The coat weight of sample C was the highest of the coated samples. Its WVTR also was lower, which indicated that the WVTR was lower in the board with a higher coated weight. Similar observations were reported previously.[12] The WVTR of board E was the lowest (almost 29.4 g/m^2), which indicates that board E (polyethylene-coated board) was almost impermeable to moisture. This observation also was previously reported.[13] The tensile strength of board B was the lowest even though its fiber properties and paper density were the same.

Weight loss from biodegradation

The biodegradation potential of the samples in field conditions (Table IV), determined by weight reduction, shows that all the samples degraded regardless of their differences in coating; however, the rate of degradation varied from sample to sample (Appendix B). Almost 80% of sample A was degraded after 6 weeks. The rest of the samples took 12 or 15 weeks to degrade by that magnitude. In general, it was expected that the coated boards would all degrade at the same rate. This is because the coated boards were coated on only one side, so they were equally susceptible to microorganisms on all sides except one. However, the C sample was the slowest to degrade (Table IV and Appendix B). The coat weight of sample C was almost 2.5 times higher than those of the rest of the samples. Its basis weight also was the highest. It was reported that basis weight does not influence the degradation rate.[6] Thus, the higher percentage of coat weight might have influenced the degradation rate.

In the laboratory conditions, compared to in field conditions, the time required to have 80% of the samples degrade was reduced by two or four times, depending on the substrate (Table IV). After about 3 weeks, the B board has lost almost 80% of its weight. However, the influence of inoculum on the degrading potential of the laboratory soil was insignificant (Table IV). This was because the laboratory conditions and the addition of inoculum were somehow equally favorable to activation of the microorganism.

Figure 1 shows a comparison of the biodegradation rate of the boards exposed to the field soil (the soil mixed with inoculum), which indicated that the coated boards degraded at a slightly lower rate than did uncoated board A. Figure 1 also highlights that even one-sided coating resisted degradation. Similar results were reported previously.[12]

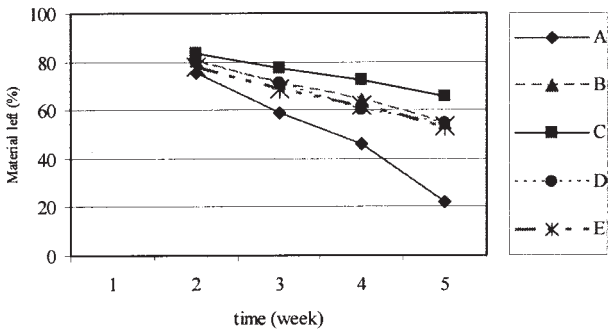

Figure 1 Biodegradability of one-side-coated boards (B, C, D, E) compared to the uncoated board (A).

Loss of tensile strength from biodegradation

The tensile strength data supported the biodegradation trend based on weight-loss approach; however, aside from sample A, they did not indicate any differences in degradation rate (Table IV). Note that sample A degraded faster than the other samples (B–E). In addition, tensile strength loss had occurred much earlier than weight loss. After almost 1 week of field exposure, tensile loss was about 60%, but it took 6 weeks of field exposure to show the same loss in weight. The addition of inoculum to the field soil accelerated tensile loss by 10%–40% depending on the board grade, but it did not add to the biodegradative potential of the laboratory soil (Table IV). Tensile strength was the measure of weak points of a test strip. Therefore, any minute decay in the sample would weaken either the fibers or the network. This weakening could cause detectable reduction in the tensile strength of the sample. On the other hand, weight loss requires fragmentation of the sample, chain scission of the polymer, and the consequent production of soluble saccharides, which might eventually diffuse out of the paper. On the basis of these factors, it is conceivable that loss of tensile strength will always occur earlier than weight loss. A faster rate of strength loss than of weight loss in biodegradation also was reported previously.[6,14] The smaller loss of tensile strength of sample C in laboratory conditions supports the trend of the weight loss experimentation, but sample C in field conditions showed the opposite trend. The latter observation could not be justified and thus was attributed to experimental error.

Influence of climate on biodegradation rate

The strength loss of the samples (B–E) in field conditions were compared with a one-side-coated polyethylene sample (paper cup used for hot beverage; see Kawamukai et al.[3] for more details), which had been tested for degradation in North Carolina. Tensile loss for the paper cup after a 3- or 6-week exposure was about 80%. A similar loss in tensile strength (90% loss) for samples B–E in the present study was observed after 2 weeks of field exposure and 1 week of laboratory exposure (Appendix B, Tables III–IV). The characteristics of the soil used by Andrady et al.[6] for field exposure were not reported; however, there were differences in ambient temperature and humidity between the two experiments. The temperature for field exposure of the paper cup was in the range of 10°C–20°C, but it was in the range of 30°C–35°C for the present study. In addition, the present experiment was conducted mainly in the rainy season, when fields are completely wet and humidity is always more than 70%. The weight loss data suggested a similar trend. Thus, the tropical conditions may have influenced the acceleration of the biodegradation process. Itavaara and Vikman[7] hypothesized that biodegradability of polymers should vary tremendously on a global scale.

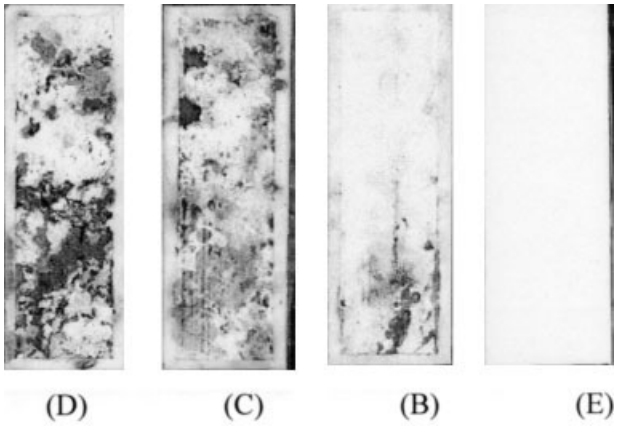

Figure 2 Biodegradation of different coating materials in laboratory soil (without inoculum) after 10 weeks.

Degradation of coated layers of the boards

Although the fibrous parts of the boards were extensively degraded, the degradation of the coated layer was unnoticed in the preceding observations. To determine the influence of microorganisms in the coated layer, the coated boards were laminated with black polyethylene on all surfaces except one, as previously illustrated. The only area left accessible to microorganism was the coated layer. Therefore, the microorganisms were guided to work on the coated layer. Figure 2 shows the changes in the color of the coated layers from biodegradation.

The ratio of the colored area to the total area of the coated layer was measured and reported as an indicator of the degradation of the coated layer. It should be noted that the photos are slightly misleading. All the colored areas do not indicate the degraded area of the coated layers. The dense dark colors are the only ones, which are, in fact, degraded. The degradation activity was transferred to the fibrous component of the boards as soon as they become accessible to the microorganism. Figure 2 highlights that the surface of sample D degraded the most (about 12%) after 10 weeks, followed by sample C (with about 3%) and then sample B (almost 0.5%). After about 10 weeks sample E [Fig. 2(d)] still showed no sign of degradation. The coating layer of sample D, which was formulated using polylactic acid, was more susceptible to biodegradation than were the other two samples, B and C. This observation indicates that the chemical structure of the polyesters that were used to coat the B, C, and D boards might be different.

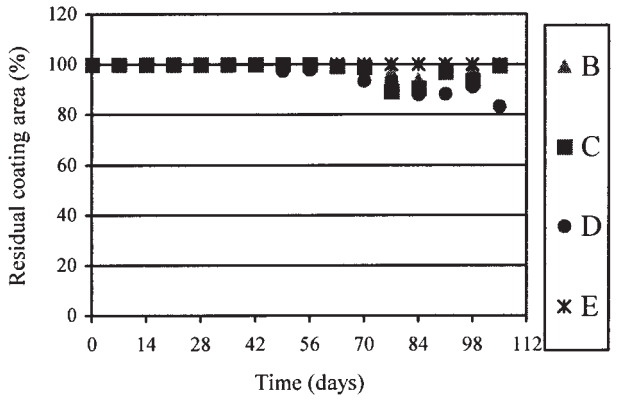

Figure 3 Degradation of the coating layer in field conditions (with inoculum).

Degradation of coated layers in field conditions

The ratio of the unimpaired area to the total area of the coated layers was plotted against the burial time of the boards (Figs. 3–4). The degradation of the coated layers with inoculum-free soil after about 4 months was almost negligible. Unlike the aforementioned soil, the soil that was enriched with inoculum had accelerated the degradation rate of the coated layers (Fig. 3). The coated layers that were buried in the enriched-soil (inoculum-added soil) began degradation at an earlier stage (about 50 days). These observations indicate that the inoculum played a significant role in enhancing the degradation rate in field conditions.

Degradation of coated layers in laboratory conditions

Figure 4 shows degradation of the coated layers of the boards tested in laboratory conditions. Degradation also was examined for two types of soil: soils with inoculum and without inoculum. Figure 4 shows that the degradation of the coated layers of D, C, and B started after 40, 50, and 60 days, respectively. This indicates that the poly(lactic acid)–coated layer degraded faster than the other two polyester-coated layers. Coating layer C, despite its thicker coating layer, showed more susceptibility to biodegradation than did B. The latter observation also highlights the importance of the coating formulation in biodegradation.

DISCUSSION

Degradation of baseboards

The results (Table IV and Appendix B) suggest that the fibrous component of the boards (baseboards) was biodegradable regardless of the type of coating used. The presence of a barrier coating combated the process but could not prevent it. Weight loss occurred only when the substrate degraded and diffuse out of the paper matrix. The degraded substrate on the paper surface was washed away when sample was retrieved from the soil. It is assumed that the flow of degraded substrate was impaired for the one-side barrier-coated boards because of capillary forces. Therefore, the differences in the biodegradation rate between the uncoated and one-side barrier-coated boards might also have been influenced by differences in the diffusion rate of the degraded substrates. The loss of tensile strength supported the observations on weight loss of the boards; however, the tensile strength of the boards deteriorated faster than the weight of the boards (Table IV and Appendix B). The magnitude of differences in degradation among the samples also was marginal. Tensile strength was sensitive to weak areas of the test strips. It is assumed that these weak areas were responsible for the strength loss.

According to the weight loss data, sample C degraded more slowly than the other samples (Fig. 1). The WVTR data also supported this observation (Table II). Probably, the higher coating thickness of sample C impeded the degradation process.

Soil conditions and microorganism population also may have influenced the biodegradation rate of the samples. The addition of inoculum significantly accelerated the degradation process for all the samples; however, acceleration was less intensive for sample C (see Appendix B). In laboratory conditions the boards degraded two or four times faster than in field conditions (Table IV). In addition, the percentage of degradation of the boards almost doubled in the microorganism-enriched laboratory soil. From these observations it is plausible to assume that both soil conditions as well as the density of the microorganism population contributed to the degradation rate of the boards. The experiments in both the field and laboratory conditions were carried out at an ambient temperature and relative humidity (RH) of 31°C ± 3°C and 75% ± 3%, respectively. The latter condition was probably what favored the degradation process. On the basis of these observations, it was reasonable to assume that

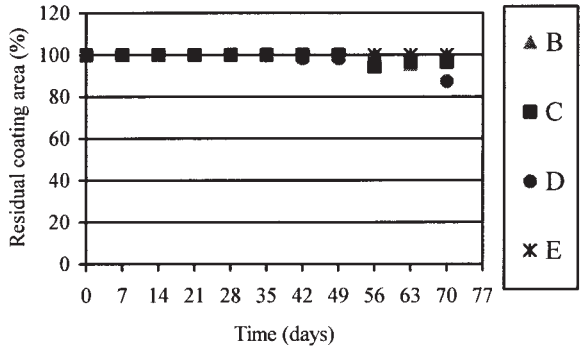

Figure 4 Degradation of the coating layer in laboratory conditions (without inoculum).

the tropical conditions should also have contributed to enhancing the biodegradation rate.

The population of different species of soil microorganisms also was monitored and compared. The bacteria population increased in both laboratory and field conditions. However, the growth in population halted after 50 days during tests in the laboratory conditions (Appendix A). This was attributed to the reduction in soil nutrients beneficial to bacteria; the other two microorganisms behaved slightly differently. The mold population in the field soil grew with inoculum but remained constant in laboratory conditions (Appendix A). The population of actinomycetes in field conditions remained constant, but it increased in laboratory conditions regardless of its inoculum component (Appendix A). The general conclusion was that microorganism growth depends on soil condition. However, on the basis of these observations, it was difficult if not impossible to suggest any correlation between growth of a specific microorganism and the degradation rate.

Degradation of coated layers

The degradation of barrier-coated layers was barely detectable after about 3 months of field exposure. The magnitude of degradation was sizable after the addition of inoculum to the field soil (Fig. 3). The laboratory soil demonstrated a substantial influence on the degradation of coated layers. The degradation of the layers started after 20 days in the laboratory soil (Fig. 4). These observations suggest that soil conditions favorable to microorganism growth is an important factor in biodegradation rate. Sample E did not show any sign of degradation for either of these conditions. In light of these facts, it was concluded that the polyester-coated layers (B, C, and D boards) were degradable in suitable conditions in a reasonable period of time, but that the polyethylene-coated layer of E board was not. Okada et al.[15] studied the biodegradability of polyesters in soil environment. He buried a thin film of several homo- and copolyesters in soil for 1–3 months. The polyesters completely disintegrated into small pieces at different rates, depending on their molecular structure.

In general, linear aliphatic polyesters are degradable. These polyesters include: poly(lactic acid), polyglycolide, poly(*p*-dioxanone), trimethylene carbonate block copolymer, and poly(e-caprolactone).[14] All these polymers degrade as a result of hydrolytic cleavage of the ester linkage.

Polyester versus polyethylene

Polyester-coated boards have applications in frozen-food packaging or baking and thus can go directly from the freezer to the oven.[13] Properly formulated polyesters provide good adhesion without primers; they offer scratch and abrasion resistance, superior hardness, outstanding flexibility, and impact resistance.[13] Because of their high versatility, they have a variety of biomedical, pharmaceutical and coating applications.[13] However, polyester is costly, and its extrusion coating is difficult. Polyester-coated boards also are poor barriers against water vapor and moisture compared to low-density polyethylene (Table III, see WVTR values).

On the other hand, low-density polyethylene is easy to process. It provides an adequate moisture barrier (Table III) and has excellent sealing properties while maintaining low cost.[13] Drawbacks of polyethylene films include poor abrasion, minimum cut resistance, poor adhesion, and lessened outdoor durability.[14] Most important, polyethylene polymer is not biodegradable within a reasonable time (Figs. 3–4), even though its baseboard is fully recyclable and biodegradable.[16] The baseboard could be stripped away in the screening process and recycled. The polyethylene portion of the board (which constitutes about 15% of the board) could be incinerated for energy use. Because of its excellent barrier properties, its lower cost, and the recyclable potential of its baseboard, polyethylene is still the largest single category of coating plastics.

However, biodegradable polyesters have gained widespread momentum because of increased environmental concerns and their highly versatile nature. Takashi et al.[3] developed a recyclable moisture barrier formula consisting of styrene–butadiene rubber (SBR) latex and platelike filler, which competes well with polyethylene-laminated paper. The formulation was developed based on the assumption that the platelike fillers reduce the solubility coefficient of SBR latex. Permeability of polyester film is almost equal to that of polyethylene film, but its permeation mechanisms are different.[3] The solubility parameter of polyester film is much larger than that of polyethylene, whereas its diffusion parameter is smaller. If a specific filler or additive could reduce its solubility, then a formula based on polyester could be found that would be comparable in quality to polyethylene but friendly to the environment. Then, the large-scale production can bring costs down and open the way for new and exciting applications.

CONCLUSIONS

The polyester-coated boards were found to be biodegradable regardless of their coating formulations. The fibrous component of the boards degraded in a very short time in a soil-burial environment. However, the soil ingredients as well as the environmental conditions were the critical factors. The laboratory soil accelerated the degradation process two or four times depending on the board grade. The addition of inoc-

ulum to field soil or laboratory soil accelerated the degradation process as well. However, the response of sample C (the sample with the highest coating thickness) to the addition of inoculum in either field or laboratory conditions was less intensified.

It was inferred that the degradation of the coated materials of the boards depended on the formulation of the coating, although the exact formulation remained undisclosed by the supplier of the boards. The coating layer of sample D, which was formulated using poly(lactic acid) (PLA), had the highest percentage of degradation (about 12%) after about 10 weeks. The other polyester-based layers (samples B and C) were slow in degradation, 3% and 0.5%, respectively. Polyethylene had not begun to degrade in the same the time (in 3 months) during which the other samples. It was concluded that the coated materials of the barrier-coated boards (i.e., B, C, and D boards) were biodegradable, although the degradation rate varied from sample to sample. In addition, to establish biodegradable polyesters as the barrier-coating material of choice will require further investigation of its barrier properties.

APPENDIX A
TABLE I.
Variation of Microbial Populations in Soil Environment

	Field soil (No-Inoculum)			Field soil (Inoculum)			Artificial soil (No-Inoculum)			Artificial soil (Inoculum)		
Time (days)	Bacteria $\times 10^6$	Mold $\times 10^2$	Ac. $\times 10^2$	Bacteria $\times 10^6$	Mold $\times 10^2$	Ac. $\times 10^2$	Bacteria $\times 10^6$	Mold $\times 10^2$	Ac. $\times 10^2$	Bacteria $\times 10^6$	Mold $\times 10^2$	Ac. $\times 10^2$
0	5.8	6.7	1.5	1.1	3.5	2.2	4.2	3.5	6.4	8.2	1.4	1.7
10	6.2	18	1.8	1.3	17	2.0	2.8	4.9	7.6	13	5.5	2.1
20	32	360	150	5.2	51	450	12	5.3	12	30	7.2	2.0
30	36	440	250	17	57	510	13	5.2	13	21	7.1	3.0
40	14	330	1.4	11	41	2.1	32	5.1	18	46	8.0	2.6
50	68	320	1.6	11	46	1.8	45	6.4	27	61	7.6	4.1
60	110	360	1.7	13	47	2.1	8.0	4.8	40	97	8.2	11
70	140	370	1.4	17	50	1.7	3.8	4.4	41	55	7.0	6.4

Ac: Actinomycetes

APPENDIX B
TABLE I.
Degradation of Boards at Field Condition (with or without Inoculum)-Weight Loss Approach

	A		B		C		D		E	
Days	NI	I	NI	I	NI	I	NI	I	NI	I
0	100	100	100	100	100	100	100	100	100	100
7	94.68	89.83	97.15	94.32	96.47	93.67	96.05	93.07	96.02	93.15
14	84.66	75.47	83.52	80.08	90.60	83.63	83.92	79.97	88.52	77.69
21	75.74	59.13	78.28	71.20	82.57	77.02	77.63	71.33	80.48	68.74
28	60.07	46.04	69.34	64.56	76.01	72.49	72.12	60.10	75.50	61.96
35	40.08	22.16	60.84	54.73	70.60	65.88	61.43	54.90	70.45	53.39
42	23.08	17.75	53.21	47.98	66.10	52.45	57.47	42.05	66.06	50.64
49	14.04	10.44	42.11	27.35	59.67	47.09	52.58	30.62	59.50	37.86
56	10.21	9.82	35.84	17.91	52.85	40.57	36.78	27.60	57.66	27.35
63	10.40		32.12	16.33	45.35	38.35	30.32	23.41	56.69	22.86
70			29.58	10.84	41.56	33.34	25.44	19.53	44.83	20.57
77			25.17	11.69	42.04	34.26	24.84	20.95	33.78	22.78
84			20.78	10.84	40.58	31.68	20.87	18.94	29.47	20.92
91			19.79	10.92	36.63	29.16	18.03	17.50	27.68	19.31
98			17.27	10.15	31.74	27.06	16.43	15.43	25.46	17.59
105			14.93	9.96	29.50	23.09	15.10	12.42	19.92	16.30

NI: No-inoculum; I: Inoculum

TABLE II.
Degradation of Boards at Laboratory Condition (with or without Inoculum)-Weight Loss Approach

	A		B		C		D		E	
Days	NI	I	NI	I	NI	I	NI	I	NI	I
0	100	100	100	100	100	100	100	100	100	100
2	95.69	93.64	96.46	95.87						
4	92.35	87.15	90.10	89.41						
6	89.44	82.15	77.84	76.13						
7	87.34	80.19		87.26	74.21	80.47	70.77	76.15	74.26	
8	85.74	72.29	74.21	73.08						
10	76.31	65.50	70.34	67.08						
12	52.26	27.55	65.37	59.82						
14	21.47		62.23	56.60	68.46	63.12	73.03	45.37	63.82	63.15
16	15.54		48.06	36.36						
18	10.43		43.05	32.77						
20			36.63	23.49						
21					61.91	50.58	62.35	36.25	56.49	55.41
22			24.18	12.88						
24			15.54	12.54						
26			12.01	10.70						
28				8.66	58.05	43.00	56.87	22.12	48.15	47.46
30				8.45						
35					49.60	34.13	43.34	17.59	41.61	31.05
42					42.19	33.11	33.67	15.62	21.39	21.08
49					35.75	30.79	26.43	14.03	18.77	18.00
56					33.72	26.28	20.27	10.21	18.63	16.29
63					29.09	26.03	16.85		18.47	17.11
70					24.57	21.76	12.31		17.17	15.45

TABLE III.
Degradation of Boards at Field Condition (with or without Inoculum)-Tensile Approach

	A		B		C		D		E	
Days	NI	I	NI	I	NI	I	NI	I	NI	I
0	85.36	85.36	75.18	75.18	61.47	61.47	72	72	70.56	70.56
3	55.89	49.46	55.65	46.75	44	36.99	51.87	45.28	50.35	44.55
6	38.61		36.13		26.53		31.75		30.14	
7		24.89	29.62	18.32	20.71	12.51	25.04	18.56	23.4	18.53
14			7.12	5.6	11.42	3.83	5.97	5.14	9.21	2.1
21			4.92	3.32	3.62	3.41	4.66	2.47	4.64	1.44
28			3.96	2.84	2.8	2.66	3.17	1.59	3.7	1.19
35			2.84	2.43	2.28	2.33	1.55	1.17	2.84	0.68
42			2.01	1.61	2.27	1.83	1.18	0.54	2.28	0.89
49			2.04	1.71	2.05	1.92	0.88	0.49	2.55	
56			1.72	1.36	1.6	1.95	0.73	0.41		
63			1.55	1.04	1.11	1.44	0.4	0.35		
70			0.41		1.25	0.92	0.26	0.21		

TABLE IV.
Degradation of Boards at Laboratory Condition (with or without Inoculum)-Tensile Approach

	A		B		C		D		E	
Days	NI	I	NI	I	NI	I	NI	I	NI	I
0	85.36	85.36	75.18	75.18	61.47	61.47	72	72	70.56	70.56
4	17.48	14.24	9.74	12.2	16.54	15.48	14.55	5.73	17.63	6.94
7	7.63	6.12	7.95	6.24	9.29	7.87	5.95	4.74	6.45	4.46
14			3.87	0.76	4.75	2.72	4.76	3.06	3.18	1.35
21			1.79	0.21	2.25	2.28	3.81	2.99	2.96	
28					2.08	1.37	3.29	1.67	2.13	
35					1.77	0.89	1.79	1.14		
42					1.37	0.76	1.22	1.42		

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