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Formation of Inclusion Complexes of Poly(3-hydroxybutyrate)s with Cyclodextrins. 1. Immobilization of Atactic Poly(*R*,*S*-3-hydroxybutyrate) and Miscibility Enhancement between Poly(*R*,*S*-3-hydroxybutyrate) and Poly(ϵ-caprolactone)

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ABSTRACT: Atactic poly(*R*,*S*-3-hydroxybutyrate) (a-PHB) was synthesized by anionic polymerization of β-butyrolactone with potassium methoxide as an initiator. This completely amorphous polyester is capable of forming a crystalline inclusion complex (IC) with γ-cyclodextrin (γ-CD) adopting a channel structure. There is no evidence showing that a-PHB may form IC with either α-CD or β-CD. On the basis of these discoveries, a common IC was formed with two polymer chains, a-PHB and poly(ϵ-caprolactone) (PCL), randomly distributed into the channels of γ-CD-PCL/a-PHB IC crystals. Nevertheless, in the formation of the common IC, PCL inclusion appears superior to a-PHB inclusion. Therefore, the molar ratio of a-PHB and PCL in the coalesced sample has been detected to be lower than that used in the formation of the common IC. Washing the common IC with hot water removed the γ-CD, and the molecular chains of the two polymers were coalesced. Very interestingly, only a single glass transition temperature (T_g), dependent on the composition, was observed between the T_g's of a-PHB (∼5 °C) and PCL (∼−60 °C) in the differential scanning calorimetry (DSC) measurements of the coalesced samples. To the contrary, T_g of a-PHB (∼5 °C) was found to remain unchanged in the physical blend with PCL. T_m's of coalesced blend samples are lower than that of pure PCL, while the T_m of the physical blend is almost the same as that of pure PCL. These results strongly demonstrate that the miscibility of the inherently immiscible a-PHB/PCL pair has been improved in the coalesced blends. Fourier transform infrared (FTIR), thermogravimetric analysis (TGA), ^{13}C solid-state NMR, DSC, and wide-angle X-ray diffraction (WAXD) measurements were employed to demonstrate IC formation.

Introduction

Biodegradable polyesters have been intensively investigated due to their potential pharmaceutical, biomedical, and environmental applications.[1,2] Among these polyesters, poly(3-hydroxybutyrate) (PHB) and poly(ϵ-caprolactone) (PCL) are two well-known representatives. So far, two different kinds of PHB have attracted much attention. The optically active poly(*R*-3-hydroxybutyrate) (i-PHB), which has the isotactic structure, is synthesized and accumulated by a variety of bacteria as a reserve energy source.[3,4] A remarkable characteristic of i-PHB is its excellent biodegradability in various environments. In addition, its high melting temperature (ca. 180 °C) and glass transition temperature (ca. 5 °C) are suitable for many applications, e.g., as an environmentally biodegradable thermoplastic. However, practical application of i-PHB has been greatly limited due to its narrow processability window (i.e., its melting temperature is very close to its thermal decomposition temperature) and its brittleness, resulting from its very high crystallinity.

Chemosynthesis, through anionic ring-opening polymerization of β-butyrolactone, is an alternative to the production of PHB by bacterial fermentation.[5] However, the product is usually atactic poly(*R*,*S*-3-hydroxybutyrate) (a-PHB), which is a completely amorphous polyester. Very interestingly, it has been found that pure a-PHB cannot be hydrolyzed by the depolymerases which degrade naturally occurring i-PHB, because a-PHB is “rubbery” at room temperature and thus by itself cannot offer stable enzyme binding sites.[6] Therefore, the enhancement of a-PHB biodegradation has attracted much research interest recently. It has been reported that blending a-PHB with either crystalline polymers[7] or amorphous polymers of high glass transition temperature[8] may offer enzyme binding sites and thus turn a-PHB into a biodegradable polymer. Scandola et al.[7] reported that a-PHB underwent enzymatic hydrolysis when it was blended with crystalline PCL or poly(L-lactic acid) (PLLA). However, the dependence of biodegradaton rate on blend composition in immiscible a-PHB/PCL blends is very different from that in miscible a-PHB/PLLA blends. Because of the efficient phase distribution, a-PHB biodegraded much faster in the miscible a-PHB/PLLA blends. Also, the accessibility of a-PHB to the enzymes was less affected by the blend composition in the miscible a-PHB/PLLA blends.[9]

According to this report, a-PHB biodegradation in the miscible blends is obviously more desirable for practical applications of a-PHB. On the other hand, a-PHB is completely amorphous and has no film-forming properties even at very high molecular weights. Blending a-PHB with biodegradable polymers, such as PCL, could be a good way to gain useful biomaterials with improved mechanical properties compared to a-PHB, if a-PHB and PCL were not immiscible. Therefore, from the viewpoint of either enhancing the biodegradability of a-PHB or improving the mechanical properties of a-PHB/PCL blends, it is of great importance to improve the miscibil-

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ity between a-PHB and PCL, which may be achieved by adding a so-called *compatibilizer* to the blends.[10]

In this paper, we present a novel way to immobilize a-PHB by forming an inclusion complex between amorphous a-PHB and γ-CD, which, to our knowledge, has not been reported so far. Cyclodextrins (CDs) are cyclic oligomers of amylose, consisting of 6, 7, or 8 glucose units, and are named α-, β-, and γ-cyclodextrin.[11] On the basis of the fact, discovered by Harada and many other researchers, that CDs may form crystalline inclusion complexes (ICs) with various kinds of linear polymeric guests of either hydrophilic or hydrophobic natures,[12−15] we reported very recently an attempt to suppress the phase separation in immiscible polymer blends or microphase separated block copolymer systems by first forming their common ICs with CDs and then coalescing the guest polymers from the IC crystals by washing the IC with hot water or with cold water in the presence of CD-degrading enzymes. In this manner, we obtained two intimately mixed blends from poly(methyl methacrylate)/polycarbonate (PMMA/PC)[16] and PCL/PLLA[17] pairs. Furthermore, we obtained PCL-*b*-PLLA of very low crystallinity.[18]

Here we report our successful initial attempts to form intimate a-PHB/PCL blends with improved miscibility between the two inherently incompatible components by first forming the common a-PHB/PCL-γ-CD-IC and then coalescing the common a-PHB and PCL guests into a a-PHB/PCL blend.

Experimental Section

Materials. β-Butyrolactone and 18-crown-6 ether (both from Aldrich) were purified as described in the literature.[19] ϵ-Caprolactone was dried over CaH_2 and distilled at reduced pressure under the protection of dry argon. Toluene (from Fisher) was dried over CaH_2 and distilled under dry argon. Potassium methoxide (from Aldrich), stannous(II) octoate (SnOct, from Aldrich), CDs (from Cerestar Co.), acetone, hexane, dichloromethane, and methanol (from Fisher) were used as received. All solvents were of analytic grade. 1-Dodecanol (from Aldrich) was dried by azeotropic distillation in dry toluene.

Polymer Synthesis. Monohydroxyl PCL was synthesized using 1-dodecanol and SnOct as an initiator and a catalyst, respectively. Typically, ϵ-CL, SnOct (ca. 0.1% of ϵ-CL in molar amount) and 1-dodecanol were weighed into a round-bottomed flask equipped with a magnetic stirring bar. The flask was sealed under argon and was immersed in an oil bath at 115 °C for 24 h. The product was purified, by twice precipitating into cold methanol from dichloromethane solution, and was then vacuum-dried at 40 °C. The molecular weight of PCL (1.01×10^4) was calculated from integration of characteristic peaks[20] in its ^1H NMR solution spectrum.

Atactic PHB (isotactic diad fraction $[I] = 0.50$) was synthesized through anionic ring-opening polymerization of β-butyrolactone in bulk with a potassium methoxide/18-crown-6 ether complex (molar ratio = 1:1) as an initiator, according to previous reports.[5] Polymerization was conducted for 2 weeks at room temperature under dry argon. The product was purified by twice precipitating into hexane from dichloromethane solution and then dried to constant weight in a vacuum oven at 40 °C. The structure of the synthesized a-PHB was proven by ^1H NMR measurement in solution. Its molecular weight (M_n) and molecular weight distribution (M_w/M_n) were estimated by GPC measurement to be 1.59×10^4 and 1.08, respectively.

Preparation of Samples. To prepare the inclusion complex, γ-CD (16 g as received) was dissolved in distilled water (60 mL) and heated to 60 °C in a flask equipped with a condenser. a-PHB or a-PHB/PCL blend (0.8 g) was dissolved in acetone (150 mL) and heated to 50 °C. Then the polymer solution was added dropwise to the γ-CD solution. After stirring for 3 h at 60 °C, the solution was allowed to cool to room temperature while continuously stirring overnight. A white powder was collected by filtration and then washed repeatedly with acetone and water to remove free polymer and uncomplexed γ-CD, respectively. Finally, the IC was dried in a vacuum oven at 40 °C for 48 h. A similar method was used for attempting to make ICs with α- or β- CD. The coalesced a-PBH/PCL sample was prepared by the same method we reported previously.[17,21] The physical blends of PCL and a-PHB were prepared by solution casting from chloroform as a common solvent.

Sample Characterization. Gel permeation chromatography (GPC) analysis was carried out using a Waters Styragel HR4 10^4 Å WAT044225 column with THF as an eluent and PMMA standards (Waters and American Polymer Standards) for column calibration. The eluent was analyzed with a differential refractometer R401 (Waters) together with a model 730 data module (Waters).

Solution ^1H NMR spectra were recorded on a Bruker 300 MHz DPX spectrometer in $CDCl_3$ at room temperature. Solid-state ^{13}C NMR data were collected using a Bruker DSX wide-bore system with field strength equal to a ^1H Larmor frequency of 300.13 MHz. Radio-frequency power levels were 71 kHz for spin-locking and decoupling, corresponding to $\pi/2$ pulse widths of 3.5 μs. Data were obtained using MAS speeds of 4−5 kHz on a commercial 7 mm probe. Cross-polarization (CP) contact time was 1 ms.

DSC measurements were performed at a heating rate of 10 °C/min on a Perkin-Elmer differential scanning calorimeter (DSC-7) calibrated with indium.

The thermal stabilities of γ-CD, polymers and γ-CD-polymer ICs were measured with a Perkin-Elmer Pyris 1 thermogravimetric analyzer (TGA) at a heating rate of 20 °C/min.

X-ray diffraction analysis was conducted with a Seimens type-F X-ray diffractometer (30 kV, 20 mA) using Ni-filtered Cu Kα radiation. The specimens were mounted on aluminum frames and scanned from 5 to 40° (2θ) at a speed of 1.2°/min.

The FTIR spectral studies were carried out in a Nicolet 510P FTIR spectrometer in the range between 4000 and 750 cm^{-1}, with a resolution of 2 cm^{-1}. All powder samples were pressed into KBr pellets for the FTIR measurements.

Results and Discussion

Demonstration of IC Formation. It has been found[22] that the cross-sectional areas of polymers correlate with the cavity sizes of the CDs with which they form inclusion complexes. Oligoethylene forms an IC with α-CD, although it cannot form ICs with β- and γ-CDs. To the contrary, poly(propylene glycol) (PPG) of any molecular weight does not form an IC with α-CD due to the steric hindrance of the side methyl groups, while it forms ICs with β- and γ- CDs in high yield.

To understand the influence of the side methyl groups of a-PHB on CD-IC formation, we attempted to make ICs not only with γ-CD, but also with α- and β- CDs. When α-CD or β-CD was used, all precipitates (see Experimental Section) were readily dissolved by acetone and cold water, and no IC product could be obtained. This result may indicate that a-PHB is not able to form ICs with α- or β- CD. Because of the side methyl groups and their atactic placements, the cross-sectional area of a-PHB is larger than PCL and poly(L-lactide), for example, which have been demonstrated to form ICs with α-CD.[17] Therefore, the α- or β-CD cavities might be too small to accommodate the a-PHB chain. More detailed results on the relationship between PHB tacticity and CD cavity size on their IC formation will be reported in another paper.[23]

Washing the precipitate with acetone and cold water to remove free CD and free polymer (see Experimental

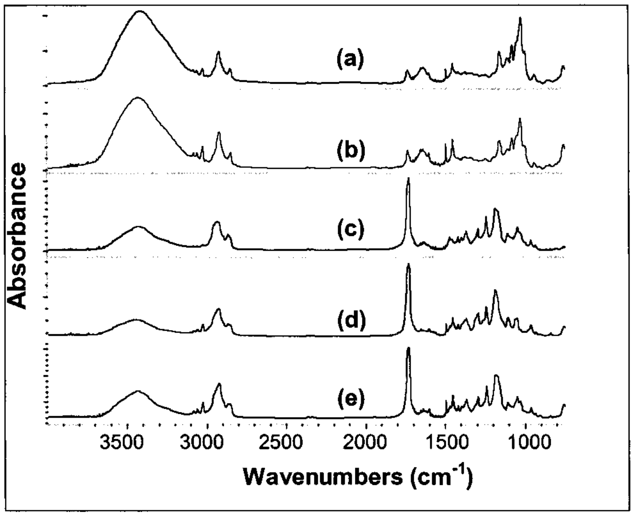

Figure 1. FTIR spectra of γ-CD-a-PHB IC (a), γ-CD-PCL/a-PHB common IC (b), coalesced a-PHB/PCL blend (repeat unit ratio $r_{a-PHB/PCL}$ = 1:3.24) (c), physical a-PHB/PCL blend ($r_{a-PHB/PCL}$ = 1:1.76) (d), and coalesced a-PHB/PCL blend ($r_{a-PHB/PCL}$ = 1:1.76) (e).

Section) produced a white powder in high yield when γ-CD was used. The FTIR spectrum of this powder shows absorptions ascribed to both a-PHB and γ-CD, as shown in Figure 1. a-PHB is characterized by a strong and distinct peak at ~1736 cm^{-1} (s, $\nu_{C=O}$), and γ-CD is characterized by the three intense bands at 1158 (antisymmetric ν_s of the C$-$O$-$C glycosidic bridge), 1079, and 1026 cm^{-1} (coupled $\nu_{s(C-C/C-O)}$).[24] This result indicates that at least both γ-CD and a-PHB exist in the powder product obtained. We cannot be sure whether a-PHB has been included by γ-CD based on this information alone. However, we may reasonably deduce that a-PHB remaining in the powder has been bound to γ-CD in some manner, because this powder has been sufficiently washed with acetone to remove any free a-PHB.

The FTIR spectrum of the common IC of γ-CD with PCL and a-PHB appears nearly identical with that of the IC of γ-CD with a-PHB. It is known[25] that the carbonyl absorption band of pure PCL in the FTIR measurement may be well resolved into two bands corresponding to crystalline (~1726 cm^{-1}) and noncrystalline (~1736 cm^{-1}) absorptions, respectively. Accordingly, we have found[18] that the expanded portion of the FTIR spectrum containing the band of the PCL carbonyl absorption is very indicative of the IC formation between α-CD and the PCL blocks of PCL-*b*-PLLA. When this α-CD IC was formed successfully, the PCL block chains were located individually in IC channels and thus were not able to aggregate to form PCL crystals. Consequently, the crystalline carbonyl absorption (~1726 cm^{-1}) of PCL blocks disappeared completely in the FTIR spectrum of the α-CD$-$PCL-*b*-PLLA IC. Figure 2 shows the expanded carbonyl bands of various samples. It is clear that the carbonyl absorption band of common γ-CD-PCL/a-PHB IC is almost identical with that of γ-CD-a-PHB IC. Namely, only the carbonyl absorption at 1736 cm^{-1} is easily identified for both ICs. This result, however, does not indicate that PCL is absent from the common γ-CD-PCL/a-PHB IC, because PCL in the IC should not show a crystalline absorption according to our previous report,[18] and carbonyl absorptions of noncrystalline PCL and a-PHB occur virtually at the same frequency (1736 cm^{-1}). The presence of PCL in the common IC is proved by the appearance of carbonyl absorption of crystalline PCL in FTIR spectra of the coalesced samples (Figure 2a,c) and will be verified further by the results of TGA, DSC, and ^{1}H NMR measurements.

TGA measurements have proven to be an effective way to demonstrate polymer$-$CD IC formation.[13,16,26] If polymer chains are included inside the CD channel, an unimodal thermal decomposition behavior should be observed. On the contrary, a physical blend of CD and polymer in the TGA scan usually exhibits two distinct weight-loss transitions corresponding to independent

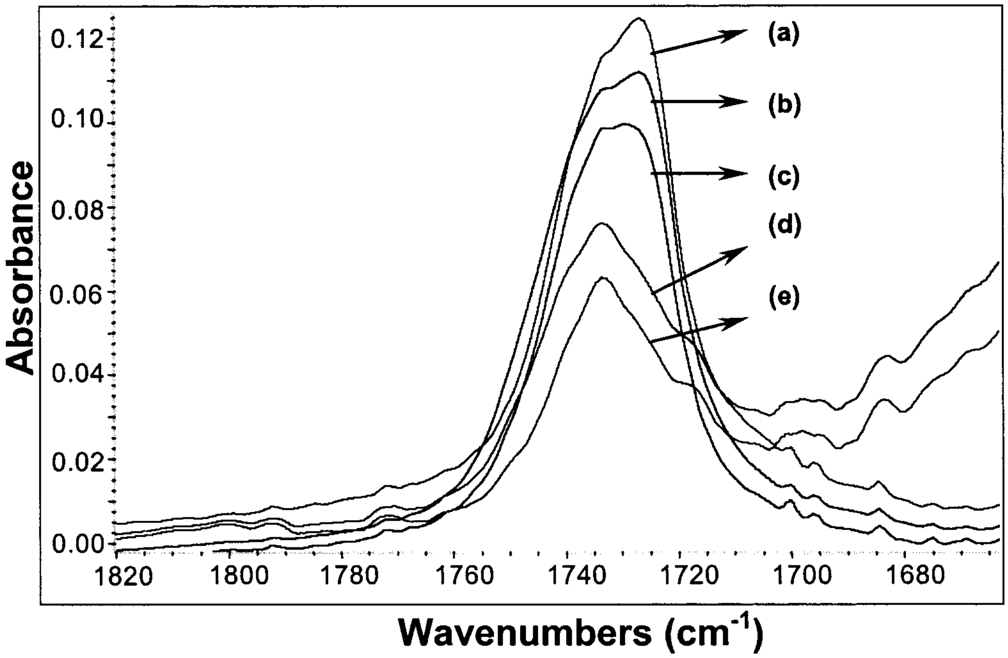

Figure 2. FTIR in the carbonyl region (s, $\nu_{C=O}$) for coalesced a-PHB/PCL blend ($r_{a-PHB/PCL}$ = 1:3.24) (a), physical a-PHB/PCL blend ($r_{a-PHB/PCL}$ = 1:1.76) (b), coalesced a-PHB/PCL blend ($r_{a-PHB/PCL}$ = 1:1.76) (c), γ-CD-a-PHB IC (d), and γ-CD-PCL/a-PHB common IC (e).

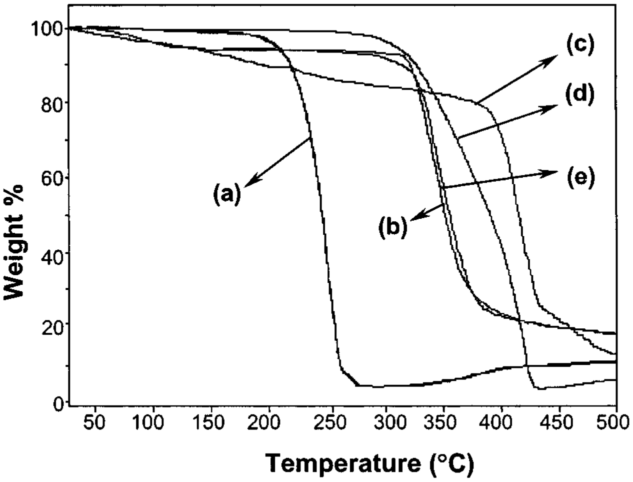

Figure 3. TGA scans of a-PHB (a), γ-CD (b), γ-CD-PCL/a-PHB common IC (c), PCL (d), and γ-CD-a-PHB IC (e).

thermal decompositions of CD and polymer. In Figure 3 are shown the thermal decomposition behaviors of γ-CD, the two polymers and their γ-CD ICs, as revealed by TGA measurements. Both ICs exhibit the unimodal thermal decomposition behavior, indicating successful IC formation. No or negligible amounts of free γ-CD or free polymer exist in the two ICs. Interestingly, the thermal decomposition behavior of γ-CD-PCL/a-PHB common IC was very different from that of γ-CD-a-PHB IC. The thermal decomposition temperature (T_d) of γ-CD-a-PHB IC is much higher than the T_d of a-PHB and is very close to the T_d of γ-CD. In contrast, the T_d of γ-CD-PCL/a-PHB IC is much higher than T_d's of a-PHB, PCL, and γ-CD. Therefore, inclusion of PCL chains apparently contributes to the higher thermal stability observed for the γ-CD-PCL/a-PHB common IC. [Note that T_d's are assumed to reflect the abrupt loss in sample weights observed at high temperatures and not the gradual weight losses observed in the γ-CD, γ-CD-a-PHB IC, and γ-CD-PCL/a-PHB common IC samples at lower temperatures, which may possibly result from the lower temperature removal of water and/or uncomplexed a-PHB.]

The solid-state CP/MAS ^{13}C NMR spectra of γ-CD, γ-CD-a-PHB IC, and γ-CD-PCL/a-PHB IC are shown in Figure 4. The spectrum of γ-CD in the uncomplexed state shows strong splitting for all C_{1-6} resonances, indicating that γ-CD molecules are in a rigid, less symmetric cyclic conformation. On the contrary, for the two ICs prepared in this paper, all C resonances of γ-CD show reduced splitting. This indicates that γ-CD in the ICs has adopted a more symmetric cyclic conformation. Similar observations, which are believed to support the formation of ICs between CDs and polymers, have been made in the solid-state CP/MAS ^{13}C NMR spectra of ICs of various polymers formed with different CDs.[13,22,26] [Note in Figure 4b,c that only weak resonances are observed for the aliphatic a-PHB and PCL carbons in the spectra of γ-CD-a-PHB and γ-CD-PCL/a-PHB common IC. This is often the case in the CP/MAS ^{13}C NMR spectra observed[13,22,26] for polymer-CD-ICs, because the high mobility of the polymer chains included in the CD-IC channels prevents their ^{13}C nuclei from being efficiently cross-polarized (CP) by their ^{1}H nuclei.]

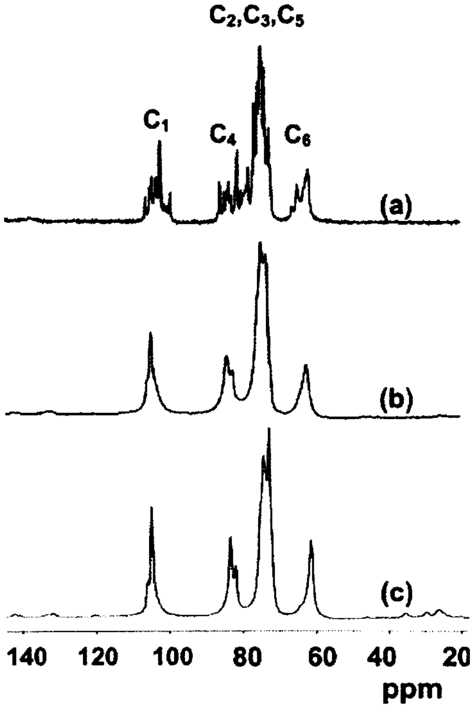

Figure 4. ^{13}C CP MAS NMR spectra of γ-CD (a), γ-CD-a-PHB IC (b), and γ-CD-PCL/a-PHB common IC (c).

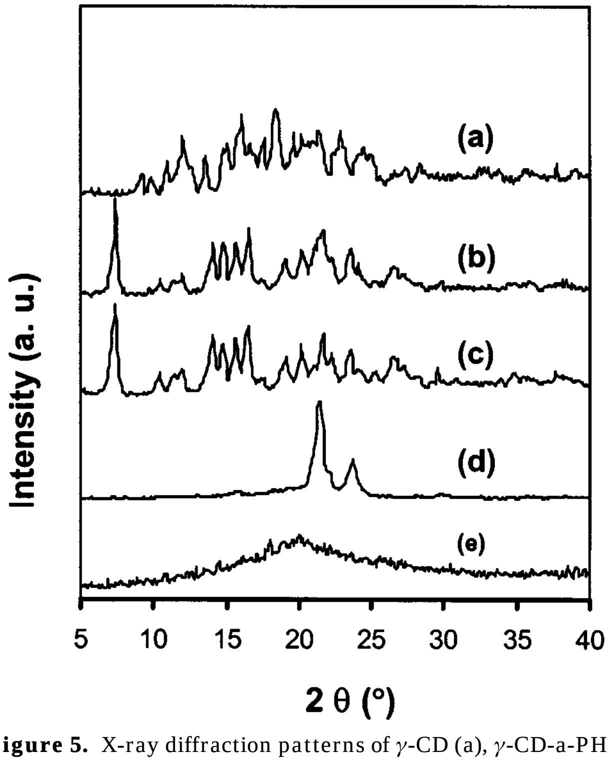

Figure 5. X-ray diffraction patterns of γ-CD (a), γ-CD-a-PHB IC (b), γ-CD-PCL/a-PHB common IC (c), PCL (d), and a-PHB (e).

More convincing evidence indicating IC formation comes from the wide-angle X-ray diffraction (WAXD) patterns shown in Figure 5. The diffraction pattern of a-PHB only shows a broad diffuse halo, and no diffraction peak from a crystalline phase was observed. This indicates that a-PHB is completely amorphous. PCL shows very strong crystalline diffraction peaks at 22° and 23.8°. The diffraction patterns of the two ICs exhibit a strong resemblance, and they are very different from those of the IC components in the uncomplexed state. Obviously, the diffraction patterns of the ICs are not simple superpositions of those of γ-CD and the polymers involved in the IC formation. A new strong diffraction peak was observed at 7.6°, which is well-known to be characteristic of γ-CD-based IC crystals adopting a channel structure.[22,26,27] This 7.6° peak characteristic of channel structure ICs is not present in the diffraction pattern of pure γ-CD which adopts a cage structure.[22,27]

We have mentioned that both PCL and a-PHB are present in the γ-CD-PCL/α-PHB common IC, according to the FTIR spectrum of the coalesced sample. The coexistence of PCL and a-PHB in the common IC is nevertheless further demonstrated by the DSC and ^{1}H NMR measurements, in which both PCL and a-PHB were found to be present in the coalesced sample.

On the basis of the above-mentioned results, we believe that γ-CD-α-PHB IC and γ-CD-PCL/α-PHB common IC of the channel structure have been successfully formed. Since it has been proven that a-PHB can undergo enzymatic attack by i-PHB depolymerases only when it has been immobilized by blending with certain crystalline polymers (e.g., PLLA) or certain amorphous polymers of high T_g (e.g., PMMA), the crystalline IC formation of a-PHB with CD is of great importance. It is logical to deduce that the enzyme binding sites[6−8] needed for a-PHB biodegradation could be produced, by forming the crystalline IC between CD and a-PHB. Since CD is not biodegraded by the i-PHB depolymerase, theoretically feasible approaches to enhance the biodegradation of a-PHB through forming ICs of a-PHB with γ-CD include (1) using both CD and i-PHB depolymerases for biodegradation, (2) forming partially included ICs, and/or (3) adding partially included ICs to a-PHB. Ongoing research in our group is being focused on these issues.

Phase Transitions from Physical Blend to Common IC to Coalesced Blend. It has been proven[9] that PCL and a-PHB are immiscible, and strong phase separation exists in their physical blend as indicated in the DSC measurements by the observation of two distinct T_g's for a-PHB and PCL, as well as a constant T_m of PCL, independent of the blend composition. In the γ-CD-PCL/α-PHB common IC, it is believed that the molecular chains of both polymers have been included inside the IC channels constructed by CD molecules. Therefore, the polymer chains are segregated, and neither PCL nor a-PHB is able to form a continuous phase in the common IC. This conclusion is demonstrated not only by the FTIR, WAXD, and TGA measurements already discussed, but also by the DSC thermograms of ICs, which do not show any fusion or glass transition peaks in the heating runs presented in Figure 6.

The phase structure of coalesced samples was also studied by FTIR and DSC measurements, and the compositions of these samples were obtained by solution ^{1}H NMR.[28] It is noteworthy that the molar ratio of a-PHB/PCL repeat units in the coalesced blend has been found to be much lower than that used in the IC preparation. For instance, when a-PHB and PCL were fed at a 1:1 molar ratio of repeat units, the a-PHB/PCL molar ratio of the coalesced sample was found to be 1:1.76. To get coalesced samples with higher a-PHB/PCL ratios, we were obliged to feed these two polymers at higher a-PHB/PCL ratios in the IC preparation. This indicates that the inclusion of PCL and a-PHB chains is competitive during their common IC formation. Obviously, inclusion of PCL chains prevails over the inclusion of a-PHB. This result is reasonable, because it has been demonstrated that each channel of γ-CD-PCL IC is occupied by two parallel, side-by-side PCL chains.[27,29] In contrast, it is believed that each of the γ-CD-a-PHB IC channels is occupied by a single a-PHB chain, because a-PHB possesses a much larger cross-sectional area than PCL, when both are extended, due to the atactic attachment of methyl side groups. This is supported by the solution ^{1}H NMR measurement of γ-CD-a-PHB IC stoichiometry.[23]

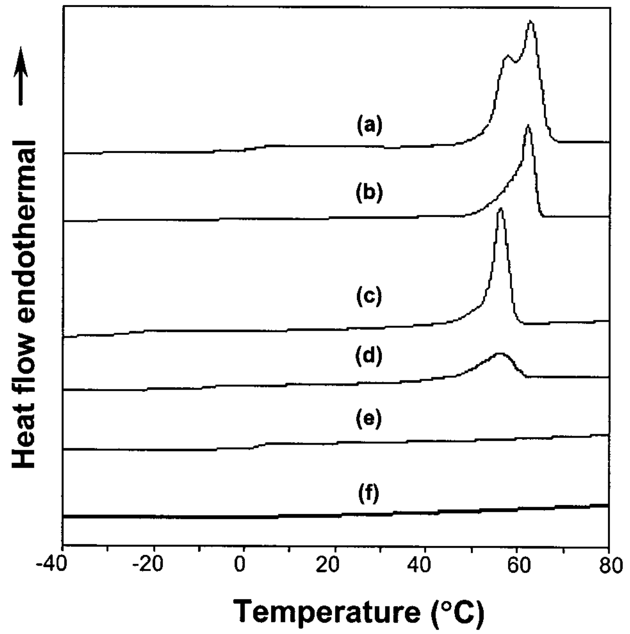

Figure 6. First heating run DSC thermograms of physical a-PHB/PCL blend ($r_{\text{a-PHB/PCL}} = 1{:}1.76$) (a), PCL (b), coalesced a-PHB/PCL blend ($r_{\text{a-PHB/PCL}} = 1{:}1.76$) (c), coalesced a-PHB/PCL blend ($r_{\text{a-PHB/PCL}} = 1.48{:}1$) (d), a-PHB (e), and γ-CD-PCL/a-PHB common IC (f).

FTIR measurement is known to be a particularly suitable technique to investigate the intermolecular hydrogen bonding between hydroxyl-bearing polymers and polyesters.[30] Moreover, it has been reported that the expanded $\nu_{C=O}$ absorption band of the semicrystalline PCL is very indicative for the PCL phase structure, in the FTIR measurements.[18,25] In the present research, expansion of carbonyl absorption bands in the FTIR spectra, as shown in Figure 2, also offers some helpful information on the phase structures of physical and coalesced blends. All blend samples show absorption ascribed to $\nu_{C=O}$ of crystalline PCL, at 1726 cm^{-1}. This indicates that a PCL crystalline phase has not disappeared completely in the coalesced blend samples. However, in comparison with the physical blend of the same composition, e.g., (b) and (c) in Figure 2, the coalesced sample shows weaker $\nu_{C=O}$ absorption of crystalline PCL at 1726 cm^{-1} but stronger $\delta\nu_{C=O}$ absorption of a-PHB and noncrystalline PCL at 1736 cm^{-1}. This indicates that the crystallization of PCL in the coalesced samples has been suppressed to some extent.

Consistent with the FTIR results, DSC measurements, as presented in Figure 6, Figure 7, and Table 1, show even clearer evidence that PCL and a-PHB chains have been more intimately mixed in the coalesced samples. The melting point (T_m) of PCL in the coalesced samples is found to decrease by ~6 °C compared to that of pure PCL, while the T_m's of pure PCL and PCL in the physical blend with a-PHB are almost the same. It

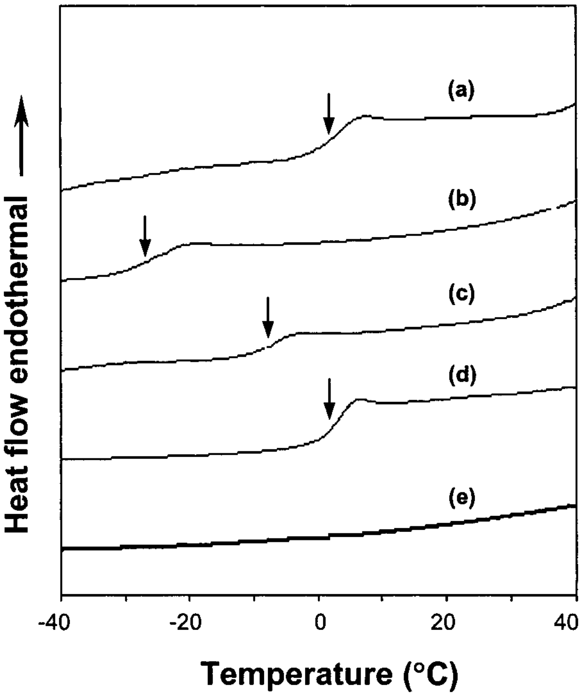

Figure 7. Expanded glass transition of physical a-PHB/PCL blend ($r_{\text{a-PHB/PCL}}$ = 1:1.76) (a), coalesced a-PHB/PCL blend ($r_{\text{a-PHB/PCL}}$ = 1:1.76) (b), coalesced a-PHB/PCL blend ($r_{\text{a-PHB/PCL}}$ = 1.48:1) (c), a-PHB (d), and γ-CD-PCL/a-PHB common IC (e), detected in first heating DSC scans.

Table 1. Thermal Properties of As−Synthesized Polymers and Their Physical and Coalesced Blends, as Revealed in Their First Heating DSC Scans

identity	composition[a] ($r_{\text{a-PHB/PCL}}$)	T_m (°C)	T_g[b] (°C)	ΔH_a (J/g)	$\chi_{\text{c-PCL}}$ (%)
PCL		62.21	−60	95.63	68.8
physical blend	1:1.76	62.33	−60, 4.95	65.50	67.3
coalesced blend A	1:1.76	56.26	−26.11	36.28	37.3
coalesced blend B	1.48:1	56.34	−7.18	14.88	22.7
a-PHB			5.03		

[a] The molar ratio of repeat units of a-PHB and PCL.[28] [b] T_g of PCL is obtained from the literature.[32,33]

is known that T_m depression is a normal behavior, in miscible crystalline/amorphous blends, due to morphological effects and for thermodynamic reasons.[31] Therefore, this result indicates that PCL and a-PHB chains are intimately mixed in the coalesced samples. However, it is noteworthy that T_m depression is not always the case for the coalesced intimate blends we have reported before. For instance, although the crystallization of PCL was demonstrated to be much suppressed, increased T_m's were observed in the coalesced PCL-*b*-PLLA samples, and the reason given was that more extended crystals with less chain folding existed in the coalesced samples.[18] In the present research, we believe that, in the coalesced a-PHB/PCL blends, the effect of miscibility enhancement on the T_m shift has prevailed over that of extended chain crystallization during the IC formation and coalescence processes. Consequently, the coalesced a-PHB/PCL blends show a T_m decrease, which is characteristic of miscible crystalline/amorphous blends prepared by conventional methods, such as solution casting.

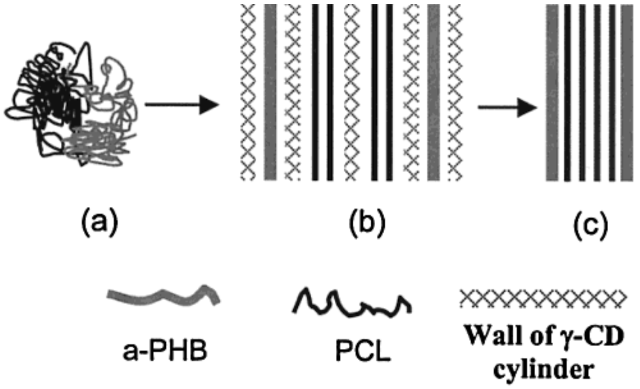

Figure 8. Proposed phase transitions of physical blend (a) to IC (b) to coalesced copolymer sample (c), during the processes of common IC formation and subsequent polymer coalescence.

Suppression of PCL crystallization in the coalesced samples is also demonstrated by DSC measurements, as shown in Table 1. The crystallinity of the PCL phase is calculated according to the following equation:

$$\chi_c = \Delta H_a/\Delta H^\circ W$$

where ΔH_a is the apparent melting enthalpy per gram of coalesced blend sample, ΔH° is the melting enthalpy of pure PCL in the completely crystalline state (139 J/g[32]), and W is the weight percentage of PCL in the sample. PCL crystallinity in the physical blend is very close to that of pure PCL. On the contrary, a significant decrease of PCL crystallinity was found for the coalesced samples.

It is well-known that the glass transition temperature (T_g) of polymer blends is a criterion in evaluating their miscibility. If two polymers are miscible in the amorphous regions of their blends, a single T_g dependent on the blend composition should be found, which is between the T_g's of the two pure blend components. In addition, the relationship between blend T_g and component T_g's usually agrees with Wood's equation.[9,33] The DSC thermograms of the coalesced samples prepared in the present research are characterized by a single T_g intermediate to those of pure PCL (−60 °C)[9,10] and pure a-PHB (5 °C). This result strongly demonstrates that PCL and a-PHB are miscible in the amorphous regions of the studied coalesced blends. Since we have not studied coalesced samples of other compositions, it remains to extend this miscibility to the full composition range. However, we are confident that the PCL/a-PHB miscibility of our coalesced samples is much enhanced compared to that of their physical blends.

To sum up, PCL and a-PHB chains were randomly distributed into the common IC channels, where two PCL or single a-PHB chains are included, and coalescing the polymers chains together by washing the CD molecules away with hot water resulted in an intimate mixture of the two. Therefore, the crystallinity of PCL and the phase separation in the amorphous regions of the coalesced blends were suppressed. It is nevertheless noteworthy that PCL chains are still able to aggregate to some extent and crystallize. Theoretically, polymer chains could be included randomly by chance, but each IC channel will include either two PCL chains or a single a-PHB chain. This means that four PCL chains will aggregate after coalescence in the case that two neighboring IC channels are each filled with two PCL chains. Therefore, PCL crystallization is expected to be suppressed but not totally eliminated for the coalesced samples. On the basis of these observations and discussion, the phase transitions from physical blend to common IC to the coalesced sample may be roughly illustrated as in Figure 8.

Conclusions

A novel method of immobilizing a-PHB was reported for the first time by forming the IC between a-PHB and γ-CD. This method potentially offers us a means to enhance the biodegradation of a-PHB. Furthermore, PCL/a-PHB blends with enhanced miscibility were obtained by forming a γ-CD-PCL/a-PHB common IC and then coalescing the polymer chains together. It is anticipated that, in comparison with the physical blend, both the mechanical properties and the biodegradability of the coalesced PCL/a-PHB blends will be improved. Therefore, enhanced biomaterials may be obtained from a-PHB through use of the CD-IC formation and coalescence method reported in this paper.

Research on the biodegradation behaviors of partially included γ-CD-a-PHB ICs, as well as a-PHB filled with partially included γ-CD-a-PHB IC, is now under way in our group. We also are studying the biodegradability, permeability, mechanical properties, etc., of the coalesced PCL/a-PHB blends of various molecular weights and compositions.

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