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Inclusion Complexes of Poly(neopentyl glycol sebacate) with Cyclodextrins

Hua Jiao, S. H. Goh,* and S. Valiyaveettil

Department of Chemistry, National University of Singapore, 3 Science Drive 3, Singapore 117543, Singapore

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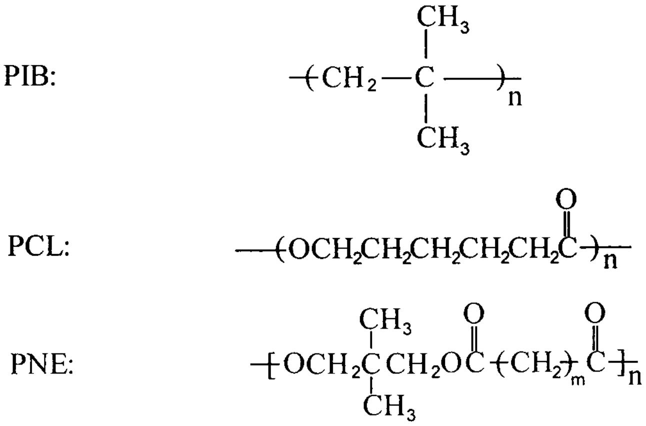
ABSTRACT: Poly(neopentyl glycol sebacate) (PNGS) is able to form inclusion complexes with three cyclodextrins (α-CD, β-CD, and γ-CD). The complexes are characterized by XRD, ^{13}C CP/MAS NMR, FTIR, ^{1}H NMR, and TGA. The complexes possess a column structure wherein some structural change occurs when the "raw" γ-CD/PNGS complex is washed and dried. It is suggested that α-CD can "squeeze" over the bulky dimethyl groups and settle on and complex the thinner part of the polymer chain.

Introduction

Cyclodextrins (CDs) are cyclic oligosaccharides of six to eight glucose units linked by α-1,4 linkage, which are called α-, β-, and γ-CD, respectively. They form inclusion complexes with a wide range of low molecular weight compounds.[1,2] Recently, with an increasing interest in macromolecular recognition, inclusion complexes (ICs) of polymers with CDs have been investigated extensively.[3−29] Harada et al.[3−12] have studied various kinds of ICs formed between polymers and CDs. They found a good correlation between the cross-sectional areas of the polymers and the cavity size of the CDs.[9] For example, poly(ethylene glycol) (PEG) can form inclusion complexes with α-CD[3,5] and γ-CD[6,21] while poly(propylene glycol) (PPG) can only form inclusion complexes with β-CD.[4,7]

Except for a few cases where block polymers were used, most studies dealt with polymers having "homogeneous" cross-sectional areas along the polymer chains. In view of the correlation between the cross-sectional areas of polymers and the cavity size of the CDs, it is of interest to investigate the behavior of polymer IC formation for a polymer with "heterogeneous" cross-sectional area. Polyisobutylene (PIB) does not form complexes with α-CD at any molecular weight because of the steric hindrance exerted by dimethyl groups on the main chain.[10] Poly(ϵ-caprolactone) (PCL) forms inclusion complexes with all three CDs wherein the γ-CD/PCL complex contains two side-by-side PCL chains in each γ-CD channel when the molecular weight of PCL is low.[14] Poly(neopentyl glycol diacid ester)s (PNEs) have intermediate structures between those of PIB and PCL. Various structures can be obtained by changing the length of the diacid monomer, and such a structural change could change the polymer IC formation behavior. Here we report our study on the inclusion complexes of poly(neopentyl glycol sebacate) (m = 8, in Scheme 1) (PNGS) with CDs. PNGS is able to form inclusion complexes with all three CDs in moderate yields. For the α-CD/PNGS complex, it is suggested that the conformational flexibility of both α-CD and PNGS enables α-CD to squeeze over the bulky dimethyl groups and settle on and complex the thinner part of the polymer chains.

Scheme 1. Strucures of PIB, PCL, and PNE



PIB: $-\!\left(CH_2-\underset{CH_3}{\overset{CH_3}{C}}\right)_n$

PCL: $-\!\left(OCH_2CH_2CH_2CH_2CH_2\overset{O}{\overset{\|}{C}}\right)_n\!-$

PNE: $-\!\left[OCH_2\underset{CH_3}{\overset{CH_3}{C}}CH_2O\overset{O}{\overset{\|}{C}}\left(CH_2\right)_m\overset{O}{\overset{\|}{C}}\right]_n$

Experimental Section

Materials. PNGS was purchased from Aldrich. The number-average molecular weight (M_n) was found by GPC to be ca. 1400. PEG (M_n = 2000) and PPG (M_n = 2000) were supplied by Aldrich. α-CD and γ-CD were obtained from Tokyo Kasei, Japan; β-CD was supplied by Acros Organics. All CDs were dried at 80 °C in vacuo for at least 12 h before use. DMSO-d_6, the solvent for NMR measurements, was supplied by Aldrich.

Preparation of Inclusion Complexes. PNGS was mixed with a saturated aqueous solution of CD at room temperature, and the mixture was stirred at 70 °C for 8 h, followed by standing overnight at room temperature. The product that precipitated was collected by centrifugation and dried in vacuo at 100 °C. The complex was then washed with water and dried in vacuo at 100 °C. Finally, it was washed with THF and dried in vacuo at 100 °C. For α-CD/PNGS, 31 mg of PNGS and 1.9 mL of α-CD solution afforded 0.05 g of complex. For β-CD/PNGS, 26 mg of PNGS and 14.6 mL of β-CD solution afforded 0.04 g of complex. For γ-CD/PNGS, 29 mg of PNGS and 1.6 mL of γ-CD solution afforded 0.07 g of complex. On the basis of the actual stoichiometry described in a latter section, the yields for α-CD/PNGS, β-CD/PNGS, and γ-CD/PNGS are 28%, 18%, and 26%, respectively. α-CD/PEG, β-CD/PPG, and γ-CD/PEG complexes were prepared following the procedures reported in the literature.[5−7,21]

Measurements. XRD patterns of the complexes were recorded on a Siemens D5005 X-ray powder diffractometer with Cu Kα (1.540 51 Å) radiation (40 kV, 40 mA). Powder samples were mounted on a sample holder and scanned with a step size of $2\theta = 0.01°$ between $2\theta = 3°$ and 50°.

FTIR spectra were recorded on a Bio-Rad 165 FTIR spectrophotometer; 32 scans were signal-averaged at a resolution

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* To whom correspondence should be addressed.

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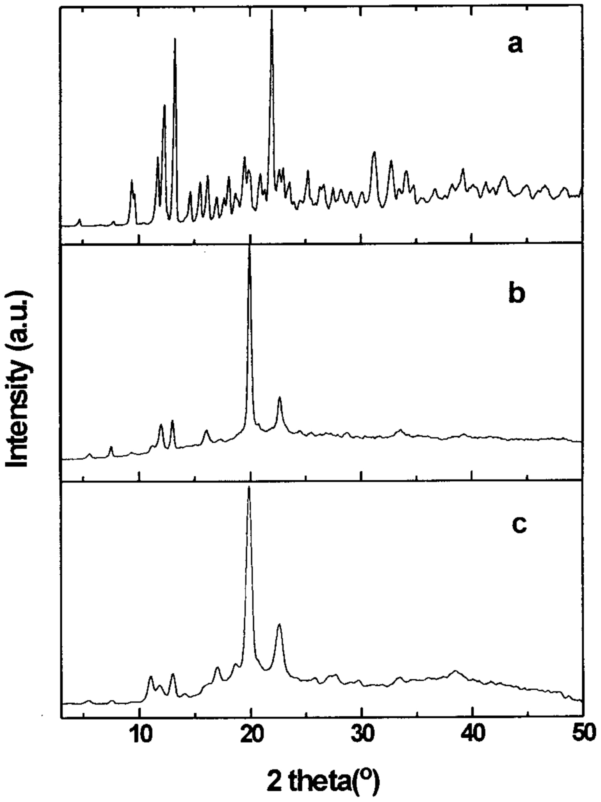

Figure 1. X-ray diffraction patterns for α-CD (a), α-CD/PEG inclusion complex (b), and α-CD/PNGS complex (c).

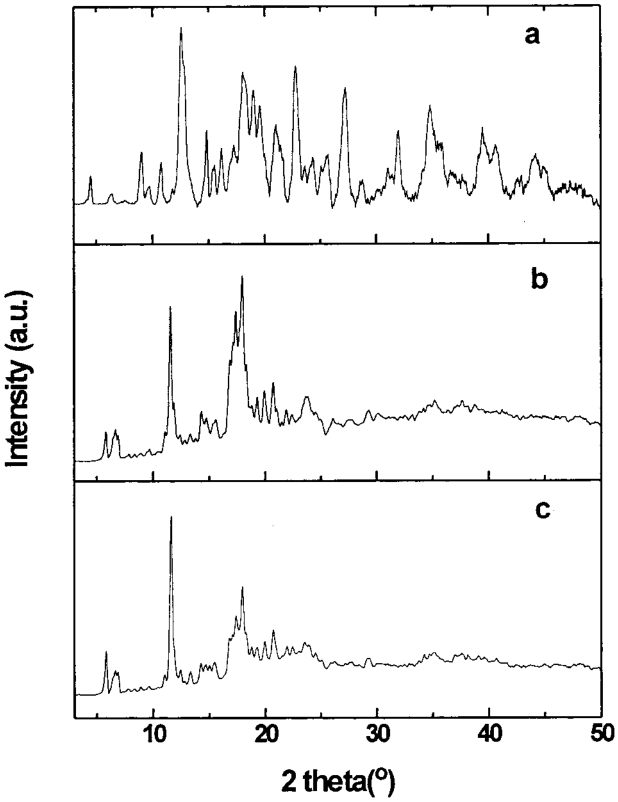

Figure 2. X-ray diffraction patterns for β-CD (a), β-CD/PPG inclusion complex (b), and β-CD/PNGS complex (c).

of 2 cm^{-1}. For measurements at elevated temperatures, a SPECAC high-temperature cell, equipped with an automatic temperature controller, was used. The complex was ground with KBr and compressed to form a disk.

Thermogravimetric analyses (TGA) were made with a TA Instruments SDT 2960 simultaneous DTA-TGA. Samples were heated at 20 °C/min from room temperature to 800 °C in a dynamic nitrogen atmosphere (flow rate = 70 mL/min).

^{1}H NMR spectra of the complexes were recorded at 300 MHz on a DPX-300 NMR spectrometer. Chemical shifts of the complexes were referenced to $\delta = 2.50$ for DMSO. ^{13}C CP/MAS NMR spectra were measured on a DRX-400 NMR spectrometer with a sample spinning rate of 8.0 kHz at room temperature. The spectra were acquired with a 2.75 μs proton 90° pulse, a 3 ms contact time, and a 3 s repetition time.

Results and Discussion

PNGS used in this study is a gummy solid. Inclusion complexes of PNGS with CDs were accomplished by mixing PNGS with three CD solutions followed by stirring at 70 °C for 8 h. All mixtures became gradually turbid, an indication of the formation of crystalline inclusion complexes between polymers and CDs.[3,5] The complexes were then isolated by centrifugation and washed with water to remove uncomplexed CD and then with tetrahydrofuran (THF) to remove free PNGS.

Figure 1 shows the XRD patterns of α-CD, α-CD/PEG, and α-CD/PNGS. Although the relative intensity of each peak is different, the diffraction patterns of the two complexes are similar. They are also similar to the inclusion complexes of α-CD and poly(oxytrimethylene)[8] and PCL.[11,15] Therefore, the α-CD/PNGS inclusion complex possesses a column structure. Figure 2 shows the XRD patterns of β-CD, β-CD/PPG, and β-CD/PNGS. It can be seen that the XRD pattern of β-CD/PNGS is very similar to that of β-CD/PPG. The latter complex has been well studied and shown to have a column structure.[4,7] Therefore, a column structure is also apparent for the β-CD/PNGS complex.

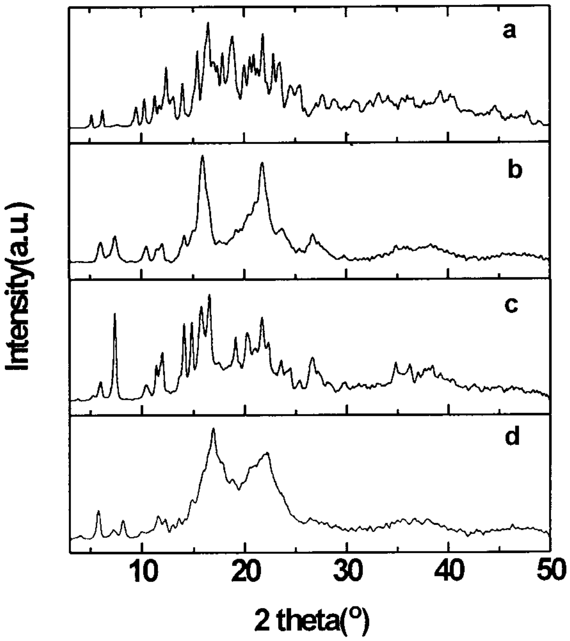

Figure 3. X-ray diffraction patterns (3°−50°) for γ-CD (a), γ-CD/PEG inclusion complex (b), and γ-CD/PNGS complexes before (c) and after (d) washed with water and THF.

Figure 3 shows the XRD patterns of γ-CD, γ-CD/PEG, and γ-CD/PNGS. Figure 3c shows the pattern of "raw" γ-CD/PNGS complex (not washed with water and THF). The XRD pattern is very similar to that of γ-CD/1-propanol complex[10] and also similar to those of the γ-CD/PEG complex (Figure 3b) and other polymer/γ-CD complexes.[10,12] The column structures of the γ-CD/1-

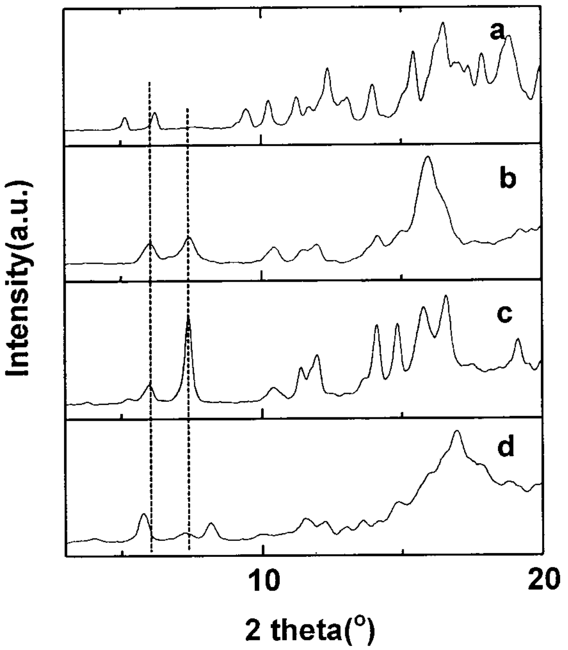

Figure 4. X-ray diffraction patterns (3°−20°) for γ-CD (a), γ-CD/PEG inclusion complex (b), and γ-CD/PNGS complexes before (c) and after (d) washed with water and THF.

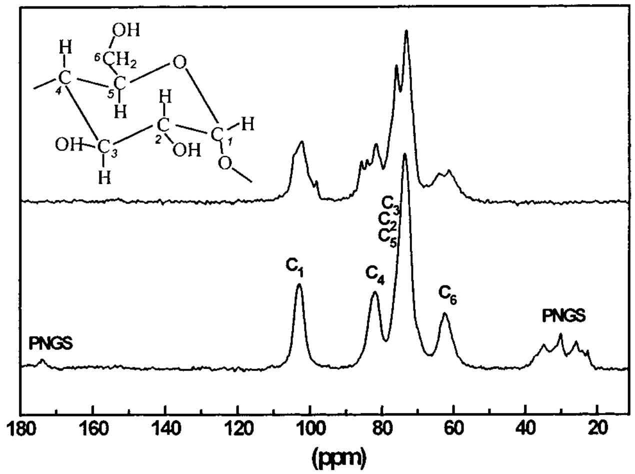

Figure 5. ^{13}C CP/MAS NMR spectra of α-CD (upper curve) and α-CD/PNGS complex (lower curve).

propanol complex[27] and γ-CD/polymer complexes have been established.[10,12] Thus, a column structure is also present in this "raw" complex. After this complex was washed with water and THF and dried, the XRD pattern (Figure 3d) is changed. The expanded spectra are shown in Figure 4 to give a clearer view. The result indicates that the crystalline structure is changed after the "raw" product is washed and dried. The phenomenon was not observed for the α-CD/PNGS and β-CD/PNGS complexes.

Figure 5 shows the ^{13}C CP/MAS NMR spectra of α-CD (upper curve) and the α-CD/PNGS complex (lower curve). The spectrum of α-CD shows resolved carbon resonances from each of the glucose units while the spectrum of α-CD/PNGS complex shows unresolved carbon resonances. A similar result was reported by Harada et al., and this was taken as an evidence of the inclusion of polymer chain in the CD cavity.[10] Thus, the formation of the inclusion complexes in the present study is further supported by the ^{13}C CP/MAS NMR measurements.

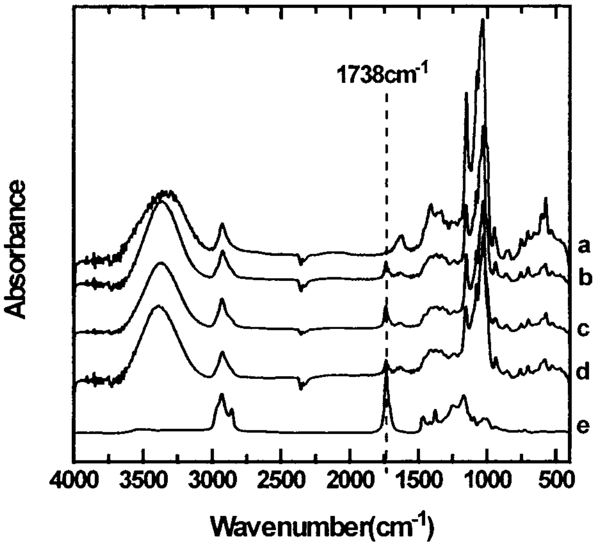

Figure 6. FTIR spectra of α-CD (a), α-CD/PNGS complex (b), β-CD/PNGS complex (c), γ-CD/PNGS complex (d), and PNGS (e).

It has been demonstrated that FTIR is a very useful tool to prove the presence of both guest and host components in ICs.[17] Figure 6 shows the FTIR spectra of pure α-CD, α-CD/PNGS, β-CD/PNGS, γ-CD/PNGS, and PNGS. The spectra of α-CD and ICs were recorded at 120 °C to exclude moisture. The spectra of ICs are similar to those of pure CDs. The broad hydroxyl band of α-CD at ca. 3360 cm^{-1} is shifted to a higher frequency at ca. 3390 cm^{-1} in the spectra of ICs. A similar shift of the hydroxyl band was also reported by Rusa et al.[17] The most distinct bands in the IC spectra are those at 1738 cm^{-1}, which are due to the stretching mode of the carbonyl groups of PNGS.

The stoichiometry of the complexes was studied by ^{1}H NMR. The spectra of the three complexes are similar. Figure 7 shows the ^{1}H NMR spectrum of the inclusion complex between γ-CD and PNGS in DMSO. Proton signals belonging to both CD and PNGS can be found in the spectrum. The small peaks at the higher fields of $C_1'H$, $C_2'H$, and $C_3'H$ are believed to be due to the end group effect. From the peak areas of γ-CD and PNGS, the ratio of γ-CD molecule to PNGS repeat unit is calculated to be 1.7. The ratios for the α-CD/PNGS and β-CD/PNGS complexes are 1.3 and 1.8, respectively. It is estimated that the length of PNGS repeat unit roughly equals that of 2.5 CD molecules. The ratios in the complexes are much smaller than 2.5, implying that the inclusion complexes are not perfect in stoichiometry.

The thermal properties of the CD/PNGS complexes were investigated by TGA. As shown in Figure 8, the initial decomposition temperatures of α-CD/PNGS (310 °C), β-CD/PNGS (311 °C), and γ-CD/PNGS (316 °C) are higher than those of CDs (about 298 °C). Huh et al.[24] reported that α-CD/poly(ϵ-lysine) (PL) IC decomposes at a higher temperature than those of α-CD and PL. They proposed that complexation has contributed to the better stability of α-CD and PL.

In some cases, a polymer is able to form inclusion complexes with all three CDs, such as PCL[14] and some aliphatic polyesters,[12] wherein these γ-CD/polymer ICs are believed to contain two side-by-side chains per channel. Li et al. reported inclusion complex formation between CDs and poly(1,3-dioxolane).[29] They found that all three CDs are able to form inclusion complexes with

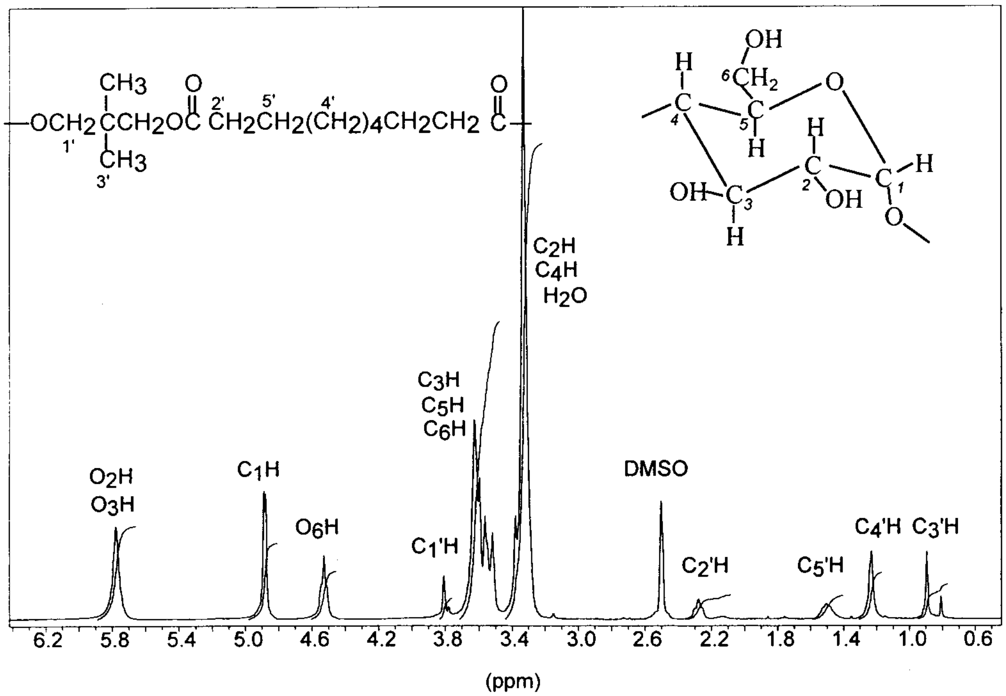

Figure 7. The 300 MHz ^{1}H NMR spectrum of the γ-CD/PNGS complex in DMSO-d_6.

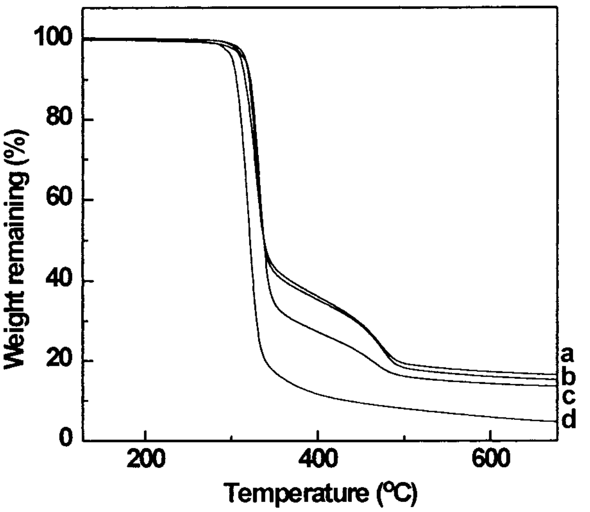

Figure 8. TGA curves of α-CD/PNGS complex (a), β-CD/PNGS complex (b), γ-CD/PNGS complex (c), and γ-CD (d).

the polymer. Complexation was believed to arise from favorable intermolecular interactions between CDs and this high oxygen atom density polymer. In the present study, PNGS forms crystalline inclusion complexes with all three CDs. α-CD does not form complexes with PIB of any molecular weight which is due to the steric hindrance by dimethyl groups on the main chain.[10] Thus, it is somewhat surprising that PNGS can form inclusion complexes with α-CD in view of the presence of dimethyl groups on the main chain of PNGS. Although the structure of CDs is stable in the solid state, constrained rotation about the glucosidic 1−4 link is permitted,[30] making the CDs have a certain degree of conformational flexibility. On the other hand, in the formation of ICs between CDs and linear chain polymers, the steric hindrance is related not only to the volume of a "single group" (the dimethyl group in PIB or PNGS) but also to the "density" of these groups. In PIB, the density of dimethyl groups is so high that every CD molecule would have to accommodate three dimethyl groups. In PNGS, however, the length between the neighboring dimethyl groups is about that of two CDs, which means that two CD molecules will accommodate one dimethyl group. Thus, the steric hindrance is highly reduced in the α-CD/PNGS complex. It is envisaged that in α-CD/PNGS complex formation, α-CD can "squeeze" over the dimethyl groups and settle on and complex the thinner part of the polymer chain. For the γ-CD/PNGS complex, the ^{1}H NMR result indicates that one PNGS chain is included in γ-CD, a different case from those in γ-CD/PCL and γ-CD/poly(1,3-dioxolane) complexes.[14,29] This is reasonable as the steric hindrance caused by dimethyl groups prevents two PNGS chains from threading through γ-CD molecules. It can be imagined that there is more "free" space in the γ-CD/PNGS complex, which may be related to the unusual structure change of the complex during purification.

Conclusion

PNGS is able to form complexes with all three CDs. XRD studies demonstrated that crystalline inclusion complexes with the column structure form in all three cases wherein some structural change occurs when the "raw" γ-CD/PNGS complex is washed and dried. For α-CD, it is envisaged that α-CD can "squeeze" over the bulky dimethyl groups and settle on and complex the thinner part of the polymer chain.

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