Inclusion Complexes of Single-C_{60}-End-Capped Poly(ethylene oxide) with Cyclodextrins

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ABSTRACT: Single-C_{60}-end-capped poly(ethylene oxide) (FPEO) forms a stoichiometric inclusion complex with α-cyclodextrin in high yield. The complex was characterized by XRD, ^{13}C CP/MAS NMR, ^{1}H NMR, DSC, and TGA. The incorporation of C_{60} results in no apparent change in the crystal structure. No complex forms between FPEO and *β*-cyclodextrin. *γ*-Cyclodextrin (*γ*-CD) and FPEO form a thermoreversible gel in aqueous solution instead of a stoichiometric crystalline complex, whereas uncapped polymers form crystalline inclusion complexes with *γ*-CD in high yields. Interestingly, in a *γ*-CD/FPEO/PEO aqueous solution, two PEO chains are able to "recognize" each other and thread through the *γ*-CD cavity to form a *γ*-CD/PEO inclusion complex.

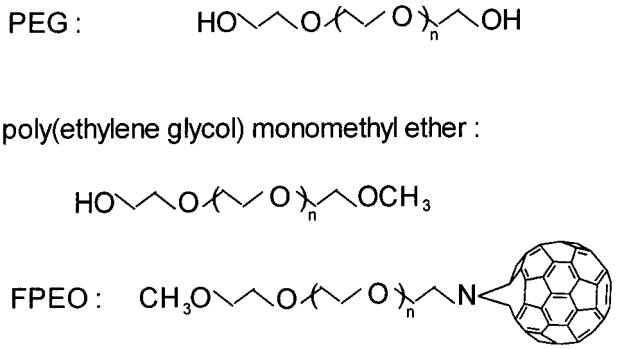
Introduction

Cyclodextrins (CDs) are cyclic oligosaccharides of six to eight glucose units linked by an α-1,4 linkage which are called α-, *β*-, and *γ*-CD, respectively. They form inclusion complexes (ICs) with a wide range of low molecular weight compounds[1,2] and are also used as hosts for various monomers in polymer synthesis.[3] In recent years, with an increasing interest in macromolecular recognition, inclusion complexes (ICs) of polymers with CDs have been investigated extensively.[4−35] Harada et al.[5−13] have studied various kinds of ICs formed between polymers and CDs. The inclusion complex between poly(ethylene glycol) (PEG) and α-CD is the first example of stoichiometric inclusion complexes between CD and polymers.[5] Harada et al. also reported double-stranded inclusion complexes of *γ*-CD threaded on end-modified PEGs.[7]

Fullerene (C_{60}) is a big and symmetrical molecule which possesses a variety of interesting conducting, magnetic, photochemical, and electrical properties.[36] Recently, supramolecular chemistry based on C_{60} and cyclic host molecules has attracted much attention due not only to the obvious elegance of the systems but also to the application for the facile purification of C_{60}.[37] For the formation of the CD−C_{60} supramolecular complex, the cavities of α-CD and *β*-CD are too small to encapsulate C_{60} while *γ*-CD can partially encapsulate C_{60} to form a sandwiched 2:1 complex.[37,38]

We have recently studied the complexation and crystallization behavior of C_{60}-end-capped poly(ethylene oxide)s.[39−41] In view of the interesting host−guest chemistry of both C_{60} and poly(ethylene oxide) (PEO) with CDs, it is of interest to study the IC formation behavior of single-C_{60}-end-capped poly(ethylene oxide) (FPEO) with CDs. FPEO has one "open" end which allows CD molecules to thread freely over PEO chains. As a result, inclusion complexes could be formed between FPEO and CDs. On the other hand, the incorporation of C_{60} not only blocks one end of the PEO chain but also exerts steric hindrance on it, both of which may affect the IC formation between FPEO and CDs. Here we report our study on the inclusion complexes of FPEO and CDs. For comparison purposes, the precursor of FPEO, poly(ethylene glycol) monomethyl ether (PEO-2200), and two poly(ethylene glycol)s (PEG-2500 and PEG-1000) were also studied. FPEO is able to form IC with α-CD in a similar way as PEO-2200. Also similar to PEO-2200, FPEO does not form IC with *β*-CD. On the other hand, mixing of the saturated *γ*-CD solution and FPEO solution does not lead to the formation of a crystalline precipitate, but a homogeneous gel is gradually formed, whereas uncapped polymers form crystalline ICs in high yields.

Scheme 1. Structures of PEG, Poly(ethylene glycol) Monomethyl Ether, and FPEO



Experimental Section

Materials. PEO-2200 was obtained from Aldrich; its number-average molecular weight (M_n) is 2200, determined by GPC. PEG-2500 was obtained from Aldrich; its M_n is 2500. PEG-1000 (M_n = 1000) was supplied by Merck. The synthesis of FPEO was reported previously.[39] The molecular structures of PEG, poly(ethylene glycol) monomethyl ether, and FPEO are shown in Scheme 1. 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. D_2O, the solvent for NMR measurements, was supplied by Aldrich.

Preparation of Inclusion Complexes. Aqueous polymer solution (10% w/v) was mixed with a saturated aqueous solution of CD at room temperature, and the mixture was sonicated for 15 min, followed by standing overnight at room temperature. A feed ratio of 2:1 (ethylene glycol unit:CD) was used for systems involving α-CD and *β*-CD while a 4:1 ratio was used for *γ*-CD systems. In the case where precipitation occurred, the inclusion complex in the form of a precipitate

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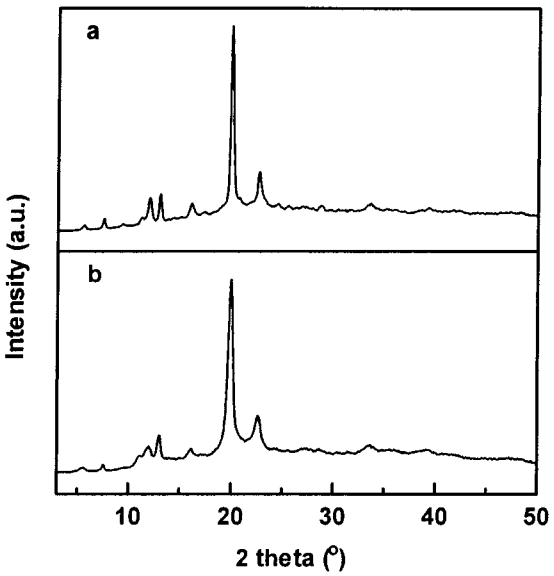


Figure 1. X-ray diffraction patterns for α-CD/PEO-2200 IC (a) and α-CD/FPEO IC (b).

was isolated by centrifugation, washed with water, and dried in vacuo at room temperature for 2 days.

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°.

The electronic absorption spectra were recorded on a Hewlett-Packard 8452A diode array spectrophotometer.

Differential scanning calorimetry (DSC) measurements were carried on a TA Instruments 2920 differential scanning calorimeter with a heating rate of 20 °C/min. 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 $\delta = 4.70$ ppm for HOD. ^{13}C CP/MAS NMR spectra were acquired 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

FPEO is able to form an inclusion complex with α-CD. For comparison purposes, PEO-2200, the "precursor" of FPEO, was studied in the same way as FPEO. For both polymers, after the aqueous solutions of polymer and α-CD were mixed, the solution became turbid within 1 min, indicating the formation of crystalline inclusion complexes.[5,6] The mixtures were then sonicated for 15 min, followed by standing overnight at room temperature. It was noted that α-CD/FPEO was more difficult to settle than α-CD/PEO-2200 during standing. The complexes were then separated by centrifugation, washed with water, and dried in vacuo at room temperature for 2 days. The yield of α-CD/FPEO is 97%, which is nearly the same as that of α-CD/PEO-2200 (96%). Both complexes dissolve in water on heating.

Figure 1 shows the XRD patterns of α-CD/PEO-2200 and α-CD/FPEO. The diffraction patterns of the two complexes are very similar. They are also similar to those of the inclusion complexes of α-CD and poly(oxytrimethylene)[9] as well as poly(ϵ-caprolactone).[11,14] Since a columnar structure has been established in those inclusion complexes, the present XRD results show that α-CD/FPEO possesses a columnar structure. The very similar XRD patterns of α-CD/FPEO and α-CD/PEO-2200 indicate that the incorporation of C_{60} produces no apparent change in unit cell dimensions and hence in crystal structure. We have observed that the crystal structure of FPEO is not different from that of PEO.[41]

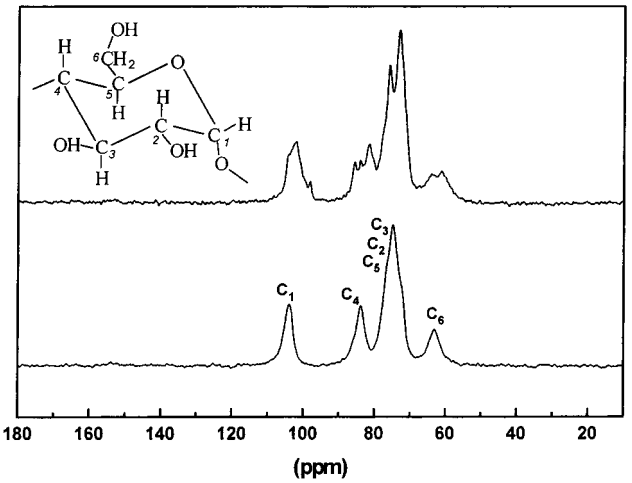


Figure 2. ^{13}C CP/MAS NMR spectra of α-CD (upper curve) and α-CD/FPEO IC (lower curve).

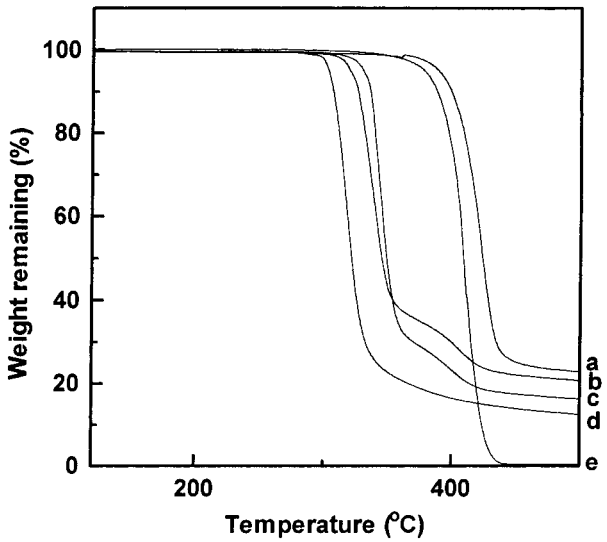


Figure 3. TGA curves of FPEO (a), α-CD/FPEO IC (b), α-CD/PEO-2200 IC (c), α-CD(d), and PEO-2200 (e).

Figure 2 shows the ^{13}C CP/MAS NMR spectra of α-CD and α-CD/FPEO. The spectrum of α-CD shows resolved carbon resonances from each of the glucose units while the spectrum of the inclusion complex shows unresolved carbon resonances. A similar result was reported by Harada et al., and this was taken as evidence of the inclusion of polymer chain in the CD cavities.[10] The PEO peak in α-CD/FPEO is difficult to observe by solid-state NMR, and the C_{60} signal is also too weak to be detected.

The α-CD/PEG inclusion complex has a stoichiometry of 2:1 (ethylene glycol unit:α-CD).[5,6] ^{1}H NMR shows that the present α-CD/PEO-2200 and α-CD/FPEO complexes also have 2:1 stoichiometry, indicating a close packing of α-CD along the polymer chains. TGA shows that the decomposition temperatures of α-CD/PEO-2200 and α-CD/FPEO are higher than that of α-CD (Figure 3). Huh et al.[26] also reported that α-CD/poly(ϵ-lysine) (PL)

IC decomposes at a higher temperature than that of α-CD and PL. They proposed that complexation has contributed to the better stability of α-CD and PL. DSC measurements show no melting peaks for both α-CD/PEO and α-CD/FPEO, indicating that the original crystalline polymer phase is absent in the complex.

It was found that PEG with both ends carrying bulky substituents, which do not fit or pass through the α-CD cavity, cannot form complexes with α-CD.[5] C_{60} is spherical and is larger than the cavity of α-CD.[42] As a result, α-CD can only thread over a FPEO chain from one end. We noted that the complex formation of α-CD/FPEO is fast and the rate is comparable to that of α-CD/PEO-2200, indicating that "blocking" one end of polymer chain does not significantly affect the rate of complex formation. The high yield and perfect stoichiometry of α-CD/FPEO are noteworthy. It is envisaged that the incorporation of C_{60} may affect the crystal size but not the crystal structure of α-CD/FPEO, and the smaller crystal size makes α-CD/FPEO more difficult to settle than α-CD/PEO-2200 during standing.

Similar to PEO-2200, FPEO cannot form a complex with β-CD. When γ-CD is involved, on the other hand, FPEO behaves very differently from PEO-2200. Harada et al.[7] reported that PEG formed only a trace amount of complex with γ-CD while some PEG derivatives formed complexes with γ-CD to give crystalline compounds in high yields. We found that three "uncapped" polymers are all able to form inclusion complexes with γ-CD in relatively high yields. Under the present experimental conditions, the yields of γ-CD/PEO-2200, γ-CD/PEG-2500, and γ-CD/PEG-1000 are 72%, 88%, and 66%, respectively. ^{1}H NMR measurements show that these three complexes have an ethylene glycol unit:γ-CD ratio of 4:1, indicating that the complexes are double-stranded.[7] However, no precipitate formed when FPEO solution was mixed with γ-CD saturated solution. Gelation gradually developed in 2 h, and a chocolate-like gel was obtained. The gel is stable under centrifugation at 5000 rpm. The melting point (the temperature at which the gel becomes a fluid under its own weight) of the gel is ca. 75 °C. Gelation occurred again when the melted gel was allowed to stand below the melting temperature, indicating that the gel is thermoreversible.

The XRD patterns of γ-CD/PEO-2200, γ-CD/PEG-2500, and γ-CD/PEG-1000 are very similar and are also similar to the γ-CD/1-propanol complex[31] and other polymer/γ-CD complexes.[10,12] The columnar structures of γ-CD/1-propanol complex[31] and polymer/γ-CD complexes[10,12] have been established. Thus, the present three complexes also have a columnar structure. For the γ-CD/FPEO gel, a sample was obtained by freeze-drying, and its XRD pattern was acquired. Figure 4 shows the XRD patterns of γ-CD/PEO-2200 and the freeze-dried γ-CD/FPEO gel. Although the diffraction pattern of the dried gel is poor, it is rather similar to that of γ-CD/PEO-2200. The key feature that serves as a fingerprint for the channel-type structure of γ-CD-ICs is the peak at ca. 8.0°.[10,20] This feature is present in both the dried gel and γ-CD/PEO-2200. The result indicates that crystalline domains with a columnar structure exist in the gel.

It has been established that γ-CD and PEG form a double-stranded inclusion complex.[7,23] For the γ-CD/FPEO gel, the same structure is expected for the crystalline domains of the gel. We found that the γ-CD/FPEO gel can be dispersed in a small amount of water

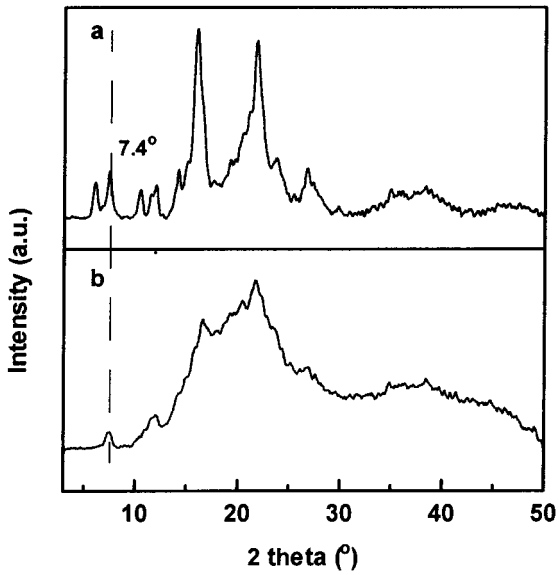
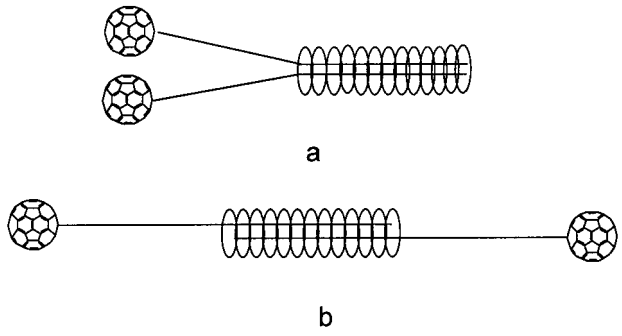


Figure 4. X-ray diffraction patterns for γ-CD/PEO-2200 IC (a) and the freeze-dried γ-CD/FPEO gel (b).

Scheme 2. Two Possible Structures of an Unit Strand of γ-CD/FPEO Complex Wherein Only One Stoichiometric IC Domain Exists; IC Domains of Different Unit Strands Aggregate to Microcrystals Which Act as Physical Cross-Links



with the help of gentle stirring. The dispersed "gelated" solid can be separated by centrifugation. In this way the γ-CD/FPEO gel was washed with the same volume of water three times to remove free FPEO and γ-CD and then freeze-dried. The ^{1}H NMR result shows an ethylene glycol unit:γ-CD ratio of 6.5:1 in the washed gel. Since an ethylene glycol unit:γ-CD ratio of 4:1 is expected for a close packing of γ-CD along double polymer chains, the ^{1}H NMR result shows that part of FPEO chain is "exposed" in the gel. Two possible structures of γ-CD/FPEO are shown in Scheme 2. Li et al. reported a sol−gel transition during inclusion complex formation between α-CD and high molecular weight PEG in aqueous solution.[8] They proposed that the PEG chain penetrated α-CD from both ends so that α-CD/PEG complex domains were formed close to the chain ends of PEG, and the complex domains then aggregated to microcrystals which acted as physical cross-links giving rise to a network. A similar explanation could be applicable to the γ-CD/FPEO gel. Since gelation did not occur for γ-CD/PEO-2200, γ-CD/PEG-2500, and γ-CD/PEG-1,000, the C_{60} in FPEO must have played a role in the gelation process. FPEO is actually an amphiphilic macromolecule with a highly hydrophobic C_{60} end. We have earlier reported that in a hydrophilic solvent fullerene-containing polymers can form a micelle-like core−shell aggregate with C_{60} as the core.[43] Thus, it is envisaged

that the C_{60} ends of γ-CD/FPEO complex aggregate and act as another type of cross-link in the γ-CD/FPEO gel. The aggregation of C_{60} ends could also be facilitated by the double-strand nature of the γ-CD/FPEO complex since the α-CD/FPEO complex does not gel.

During the course of preparation of "hybrid" double-strand inclusion complexes of γ-CD/FPEO/PEO-2200 with the two polymers in 1:1 molar ratio in the feed, we found that a heterogeneous gel formed slowly. White particles deposited at the bottom part of the chocolate-like gel. The mixture was then heated at 90 °C for 4 h. The supernatant solution was carefully decanted, and the white solid obtained was washed with water and dried. The white solid has the same stoichiometry and similar XRD pattern as the γ-CD/PEO-2200 IC. Absorption features of C_{60} between 190 and 410 nm[38,39] cannot be observed in solutions of the white solid at any concentrations. These results indicate that this white solid is γ-CD/PEO-2200 IC. Gelation occurred again when the supernatant solution was allowed to stand at room temperature. The newly formed gel was homogeneous in appearance. However, white particles slowly "grew" in the gel during standing. Again the white particles were proved to be γ-CD/PEO-2200 IC. The above results suggest that two PEO-2200 chains are able to "recognize" each other and thread through the γ-CD cavity to form γ-CD/PEO-2200 IC.

Conclusion

FPEO forms a stoichiometric inclusion complex with α-CD in high yield. Incorporation of C_{60} results in no apparent change in the crystal structure. No complex forms between FPEO and β-CD. γ-CD and FPEO form a thermoreversible gel in aqueous solution instead of a stoichiometric crystalline complex. C_{60} could have played a role in the gelation. Interestingly, in a γ-CD/FPEO/PEO-2200 aqueous solution, two PEO-2200 chains are able to "recognize" each other and thread through the γ-CD cavity to form γ-CD/PEO-2200 IC.

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(42) The diameters of the cavities of α-CD, β-CD, and γ-CD are 4.9, 6.2, and 7.9 Å, respectively (ref 17). For C_{60}, the nearest-neighbor distance between two C_{60} molecules in small crystals is 10.02 Å whereas the diameter calculated for the carbon cage itself is 7.1 Å. The difference between these two values represents the effective van der Waals diameter set by the repulsion of the π electron clouds extending outward from each carbon atom (see: Kratschmer, W.; Lamb, L. D.; Fostiropoulos, K.; Huffman, D. R. *Nature (London)* **1990**, *347*, 354).
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