Preparation and characterization of the crystalline inclusion complexes between cyclodextrins and poly(1,3-dioxolane)

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Abstract The preparation and characterization of the crystalline inclusion complexes between a polymeric guest, poly(1,3-dioxolane) (PDXL), and small-molecular hosts, cyclodextrins (CDs) are reported. It is observed that the polymer guest can form crystalline inclusion complexes with three kinds of cyclodextrins, which may be attributed to the high oxygen atom density in PDXL chain. The crystalline inclusion complexes were characterized with FTIR, TGA, X-ray diffraction, SEM, ¹H NMR and ¹³C CP/MAS NMR spectrosopes. It was found that the crystalline inclusion complexes have higher temperature stability than the pure CDs. The X-ray powder diffraction patterns of the crystalline inclusion complexes proved that they have columnar structures. ¹³C CP/MAS NMR spectra of the crystalline inclusion complexes indicate that CDs adopt a more symmetrical conformation in the complexes, while pure CDs assume a less symmetrical conformation in the crystal without a guest inside their cavities. The morphology of the crystal was observed by means of SEM.

Keywords: cyclodextrin, crystalline inclusion complexes, columnar structure.

Cyclodextrins (CDs) are a series of cyclic oligosaccharides consisting of 6, 7 and 8 glucose units called α-, β- and γ-CD respectively. CDs were reported to form inclusion complexes with a wide variety of low molecular weight compounds ranging from nonpolar organic molecules to rare gases¹¹. The geometric compatibility or fit and intermolecular interaction between hosts and guests were taken as the driving forces of complex formation.

Several researchers have reported that many linear polymeric guests could form inclusion complexes with CDs resulting in either crystalline⁰²⁻⁰⁵ or soluble⁰⁶⁻⁰⁸ main-chain pseudopolyrotaxanes. For many crystalline inclusion complexes, the complexes precipitated when the polymers were added into the CDs solutions and then ultrasonicated. All crystalline inclusion complexes between CDs and polymeric guests are columnar in structure as the result of X-ray diffraction study. For examples, poly(ethylene glycol) (PEG) can form inclusion complexes with α-CD⁰²⁻⁰³ and γ-CD⁰⁹⁻¹⁰ while poly(oxytrimethylene) (POx) can only form inclusion complex with α-CD and β-CD¹¹. The study of crystalline inclusion complexes was hoped to provide an approach to investigate the behavior of single polymer chains in isolated and well-defined environments¹²⁻¹⁴. Furthermore, it is helpful in understanding the mechanism of molecular recognition between hosts.
and polymeric guests. We have reported briefly in a note that α-, β- and γ-CDs are all able to form crystalline inclusion complexes with poly(1,3-dioxolane) (PDXL)\textsuperscript{[15]}. This phenomenon is observed for the first time, and this paper will deal it in detail.

1 Experimental

1.1 Materials

1,3-dioxolane (Shanghai Solvent Co.) was refluxed with CaH\textsubscript{2} for 2 h, and then distilled. β-CD (Yunnan Cyclodextrins Co., Guangdong) was recrystallized in water. α-CD and γ-CD (Cavamax W6 and W8) were kindly supplied by Rohm & Haas Co., and used without further purification. BF\textsubscript{3} • Et\textsubscript{2}O and ethylene glycol were purified under standard method.

1.2 Measurements

FT-IR spectra were measured with a Perkin Elmer Paragon 1000 spectrometer. Samples were pressed into KBr pellets and recorded at the frequencies from 4000 to 450 cm\textsuperscript{−1} with resolution of 4 cm\textsuperscript{−1}. Number-average molecular weight measurement was performed with a K-7000 (Knauer Co., German) vapor pressure osmometer (VPO). X-ray powder diffraction patterns were taken by a Rigaku III Dmax 2500 using Cu-Kα radiation. The voltage was set to 25 kV and the current was 25 mA. Data were collected at a rate of 4 degree per minute with a step of 0.02 degree over the range 2θ = 5° − 50°. Thermogravimetry analysis (TGA) was determined with a Perkin-Elmer Model 7 thermogravimetric analyzer. The samples were put inside the platinum pans, which were hanging in the heating furnace. The weight percentage of remaining material was recorded while the furnace was heating from 50 to 450°C. Nitrogen was used as the purge gas and a heating rate of 20°C • min\textsuperscript{−1} was employed. \textsuperscript{1}H NMR spectra were recorded with a Brucker AVANCE 500 spectrometer operated at 500 MHz. Solid state \textsuperscript{13}C cross-polarization (CP)/magic-angle spinning (MAS) NMR spectrum was recorded with a Brucker DSX-300 spectrometer operated at 75.47 MHz with a sample spinning rate of 4—6 kHz at room temperature. CP spectra were acquired with a 3.6-μs proton 90° pulse. Scanning electron microscope (SEM) image was taken with a Hitachi S-2150. The accelerating voltage was set as 20 kV.

1.3 Synthesis of the polymer

PDXL was prepared by bulk polymerization under nitrogen atmosphere using ethylene glycol as the initiator and BF\textsubscript{3} • Et\textsubscript{2}O as the catalyst\textsuperscript{[16]} (scheme 1). The reaction was terminated by ammonium solution. The products were precipitated in methanol at −5°C, then washed with cold methanol, and dried under vacuum at 40°C for 24 h.

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\text{Scheme 1. Synthesis of poly(1,3-dioxolane).}
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PDXL1: FT-IR (KBr): 3501.4 (OH), 2939.9 (v as CH₂), 2881.9 (v s CH₂), 1459.6 (δ CH₂), 1411.7 (m, δ-CH₂C-), 1122.2 (s, v as C-O-C), and 1040.3 cm⁻¹ (s, v s C-O-C); PDXL2: FT-IR (KBr): 3501.7 (OH), 2940.7 (v as CH₂), 2882.1 (v s CH₂), 1459.3 (δ CH₂), 1412.3 (m, δ-CH₂C-), 1123.3 (s, v as C-O-C), and 1036.2 cm⁻¹ (s, v s C-O-C); Mn (VPO, in ethanol): 1555 (PDXL1), 1932 (PDXL2).

1.4 Preparation of inclusion complexes

(i) Normal method. Weighed α-CD was dissolved in water, and then aqueous PDXL solution was added. The mixture was stirred at 30°C for 2 h, and allowed to stand overnight. The precipitate was filtered, and washed with water several times to remove those non-included materials. The inclusion complexes between β- or γ-CD and PDXL were obtained under the same condition.

(ii) Ultrasonic method. Ultrasonifications were performed in a Brason B-52 ultrasonic cleaner with power of 248 W. Aqueous PDXL solution was added into the saturated α-CD solution, then the mixture was ultrasonicated for 10 min at room temperature, and allowed to stand overnight. The precipitate was filtered and washed with water several times to remove those non-included materials. The inclusion complexes between β- or γ-CD and PDXL were obtained under the same condition.

(iii) α-CD-PDXL1 (normal method). FT-IR (KBr): 3430.4(OH), 2931.3(v as CH₂), 1635.5, 1419.1, 1155.4, 1108.4, 1080.5(v s C-O/C-C), 1030.8(v s C-O-C), 947.1, 703.4, 573.9, yield: 92%.

(iv) α-CD-PDXL2 (normal method). FT-IR (KBr): 3434.1(OH), 2930.6(v as CH₂), 1636.2, 1420.1, 1155.5, 1107.9, 1080.7(v s C-O/C-C), 1031.1(v s C-O-C), 949.7, 703.4, 573.2, yield: 93%.

(v) β-CD-PDXL1 (normal method). FT-IR (KBr): 3431.8(OH), 2931.5(v as CH₂), 1637.4, 1419.1, 1158.6, 1108.2, 1079.8(v s C-O/C-C), 1028.3(v s C-O-C), 943.6, 705.8, 575.0, yield: 75%.

(vi) β-CD-PDXL2 (normal method). FT-IR (KBr): 3430.9(OH), 2930.8(v as CH₂), 1636.9, 1418.7, 1158.5, 1108.3, 1080.4(v s C-O/C-C), 1028.5(v s C-O-C), 942.9, 705.5, 575.3, yield: 73%.

(vii) γ-CD-PDXL1 (normal method). FT-IR (KBr): 3430.8(OH), 2930.5(v as CH₂), 1636.4, 1418.1, 1159.8, 1108.4, 1079.4(v s C-O/C-C), 1027.3(v s C-O-C), 939.9, 706.5, 580.3, yield: 85%.

(viii) γ-CD-PDXL2 (normal method). FT-IR (KBr): 3435.5(OH), 2930.3(v as CH₂), 1635.5, 1418.2, 1160.0, 1107.7, 1079.6(v s C-O/C-C), 1027.0(v s C-O-C), 941.5, 706.0, 581.2, yield: 84%.
2 Results and discussion

2.1 Formation of the crystalline inclusion complexes

Under the normal method, at 30℃, after the aqueous solutions of PDXL being added to CD solutions, the mixed solutions gradually become turbid. The appearance of precipitate is considered as the evidence of the formation of crystalline inclusion complexes between CDs and polymer chains\(^2,3\). It is interesting that all of α-, β- and γ-CDs can form crystalline inclusion complexes with PDXL, which is observed for the first time. We believe that the PDXL chains can change their conformation to fit the various sizes of the CDs’ cavities due to the high oxygen atom density on the polymer chains. Thus PDXL can form inclusion complexes with three kinds of CDs.

The solution of PDXL with α-CD became turbid in just one minute after being mixed, and that of PDXL with γ-CD in about 5 min. The product of β-CD with PDXL appeared after half an hour. Under the ultrasonic method, the appearances of the precipitations were much faster than that under normal method. When the precipitates of β-CD or γ-CD with PDXL were added into a large amount of water, they dissolved gradually. Contrarily, the precipitation of α-CD with PDXL is more stable since it does not dissolve in cold water. All the products can be dissolved in hot water.

2.2 Thermogravimetry analysis

Fig. 1 shows the TGA thermograms of pure α-CD and the crystalline inclusion complex between α-CD and PDXL. From the figure, we can see that α-CD starts to decompose at 302℃. However, the crystalline inclusion complex starts to decompose at 312℃, which is higher than that of the pure α-CD. This indicates that the polymeric guest can improve the thermal stability of the α-CD. Fig. 2 shows the TGA thermograms for pure β-CD and the crystalline inclusion complex between β-CD and PDXL made by ultrasonic method. We can see in the figure that pure β-CD starts to decompose at 320℃. However, the crystalline inclusion complex starts to decompose at 337℃, which is higher than that of the pure β-CD. This indicates that the PDXL can improve the thermal stability of the β-CD. The TGA thermograms for pure γ-CD and the crystalline inclusion complex between γ-CD and PDXL made by ultrasonic method are presented in fig. 3. We can find that γ-CD starts to decompose at 299℃. However, the crystal-
line inclusion complex starts to decompose at 320 °C, which is also higher than that of the pure γ-CD. The results indicate that the aggregations of CDs by forming inclusion complexes with polymers thus packed together can improve the stabilities of the CD molecules obviously.

2.3 Crystal structure

Fig. 4 shows the X-ray powder diffraction patterns of α-CD and the inclusion complex between α-CD and PDXL. The diffractogram of α-CD-PDXL complex is similar to those of the inclusion complexes between α-CD and PEG\(^\text{[2,3]}\), POx\(^\text{[11]}\) and so on. The characteristic reflection at \(2\theta = 20^\circ\) means that the columnar structure has been formed in the complex between α-CD and PDXL, instead of a cage structure.

The X-ray powder patterns of β-CD and the inclusion complex between β-CD and PDXL can be seen in fig. 5. The pattern of the β-CD-PDXL complex is similar to that of the inclusion complex between β-CD and PPG\(^\text{[17,18]}\), which has been reported to have the columnar structure. Therefore, the inclusion complex of PDXL with β-CD also likely assumes a columnar structure.

The X-ray powder patterns of γ-CD and the inclusion complex between γ-CD and PDXL (\(M_n = 1932\)) are displayed in fig. 6. The pattern of the
\(\gamma\)-CD-PDXL complex is different from that of pure \(\gamma\)-CD where CDs are arranged in a cage type packing\[^{19-21}\]. However, it is similar to those of the inclusion complexes between \(\gamma\)-CD and poly(alkyl vinyl ether)\[^{22}\], polyisobutylene (PIB)\[^{23}\] and so on, which have been reported to have the columnar structure. Therefore, the inclusion complex of PDXL with \(\gamma\)-CD assumes a columnar structure rather than a cage type structure.

The diffractive peaks of the crystalline inclusion complex of PDXL with \(\gamma\)-CD are dispersive, and this was caused by the polydispersity of the guest polymer. The chain lengths of the polymer are polydisperse and thus the number of the included \(\gamma\)-CD is different chain to chain. When such inclusion molecules were packed together to form the crystal, there should be many deformities. Moreover, there are double chains included in the cavities of the \(\gamma\)-CD, which will be described in the next paragraph. The result is that much more deformities were brought into the crystal. For example, maybe some \(\gamma\)-CDs which only contain single polymer chains in their cavities were brought into the crystal. And there also should be some polymer chains which were not included into CDs at the ends of the channels of the inclusion complexes.

2.4 Stoichiometry of the complexes

Fig. 7 shows the \(^1\text{H}\) NMR spectra of PDXL and that of the inclusion complex between \(\alpha\)-CD and PDXL under ultrasonic method in DMSO-\(d_6\). Here the inclusion complex between \(\alpha\)-CD and PDXL was synthesized under the ultrasonic method. In the \(^1\text{H}\) NMR spectrum of the dissolved inclusion complex between \(\alpha\)-CD and PDXL, we find hydrogen atom signals belonging
Fig. 7. $^1$H NMR spectra of (A) PDXL and (B) the inclusion complex between $\alpha$-CD and PDXL under ultrasonic method in DMSO-$d_6$.

to both $\alpha$-CD and PDXL molecules. According to the molecular molding, if a PDXL chain takes the zigzag configuration, the length of one dioxolane unit is calculated as 0.59 nm. The depth of CD molecules is 0.7 nm. Therefore, one $\alpha$-CD molecule can contain 1.2 dioxolane monomer units theoretically. For the product under ultrasonic method, the experimental ratio of the PDXL (monomer units) to $\alpha$-CD is about 1.3, which means that the inclusion complex is near perfect in stoichiometry. In the case of the complex between $\gamma$-CD and PDXL under ultrasonic method, the ratio is about 2.7 (PDXL monomer units to $\gamma$-CD). This means that double PDXL chains were included in $\gamma$-CD. As for the complex between $\beta$-CD and PDXL under ultrasonic method, the ratio is about 1.8 (PDXL monomer units to $\beta$-CD). This means that in the complex, the PDXL chains contain some flexible conformations instead of trans conformations in the cavities of $\beta$-CD. On the other hand, for the product under normal method, the experimental ratio of the PDXL (monomer units) to $\alpha$-CD is about 2.1, meaning that the inclusion complex is not perfect in stoichiometry. The reason should be that under the normal method, the reaction time was not long enough.
2.5 CD’s conformation

Fig. 8 presents the $^{13}$C CP/MAS NMR spectra of the $\alpha$-CD and the crystalline inclusion complex between $\alpha$-CD and PDXL. $\alpha$-CD assumes a less symmetrical conformation in the crystal when it does not include a guest in the cavity. So in the spectrum of the pure $\alpha$-CD, it shows resolved C-1 and C-4 resonance from each of the $\alpha$-1,4-linked glucose residues. The peaks assigned to the conformational strained glycosidic linkage are observed in the spectrum\[24\]. On the other hand, in the spectrum of the $\alpha$-CD-PDXL complex, those peaks disappear. Each carbon of glucose can be observed in a single peak. These results indicate that in the crystalline inclusion complex, $\alpha$-CD adopts a symmetrical conformation and each glucose unit of $\alpha$-CD is in a similar environment.

Fig. 9 shows the $^{13}$C CP/MAS NMR spectra of the $\beta$-CD and the crystalline inclusion complex between $\beta$-CD and PDXL. When $\beta$-CD does not include a guest in the cavity, it assumes a less symmetrical conformation in the crystal. So in the spectrum of the pure $\beta$-CD, it shows resolved C-1 and C-4 resonance from each of the $\alpha$-1,4-linked glucose residues. There are peaks assigned to the conformational strained glycosidic linkage in the spectrum. Contrarily, in the spectrum of the $\beta$-CD-PDXL complex, those peaks disappear. Each carbon of glucose can be observed in a single peak. These results indicate that in the crystalline inclusion complex, $\beta$-CD adopts a symmetrical conformation and each glucose unit of $\beta$-CD is in a similar environment.

The X-ray study of single crystals of the inclusion complex between $\beta$-CD and $p$-nitroacetanilide shows that $\beta$-CD adopts a symmetrical conformation when it includes a guest in the cavity\[25\]. The $^{13}$C CP/MAS NMR spectra of the $\beta$-CD and the crystalline inclusion complex between $\beta$-CD and PDXL are consistent with the data of X-ray studies.
\(^{13}\)C CP/MAS NMR spectra of the \(\gamma\)-CD and the crystalline inclusion complex between \(\gamma\)-CD and PDXL are presented in fig. 10. Similar to \(\alpha\)-CD and \(\beta\)-CD, \(\gamma\)-CD assumes a less symmetrical conformation in the crystal when it does not include a guest in the cavity. The spectrum of the pure \(\gamma\)-CD shows resolved C-1 and C-4 resonance from each of the \(\alpha\)-1,4-linked glucose residues. However, in the spectrum of the crystalline inclusion complex between \(\gamma\)-CD and PDXL, each carbon of glucose is in a single peak. The result indicates that in the crystalline inclusion complex, \(\gamma\)-CD adopts a symmetrical conformation and each glucose unit of \(\gamma\)-CD is in a similar environment.

2.6 SEM investigation

To obtain information concerning the morphology of crystals formed by inclusion complex between \(\alpha\)-CD and PDXL, the complex was studied by the method of SEM. A dried as-deposit piece of the crystalline inclusion complex was taken directly as the SEM sample. The crystalline structure of pure \(\alpha\)-CD is the orthogonality\(^{[26]}\).

Fig. 11 shows the corresponding SEM micrographs. The graph (b) is a magnified part of the graph (a). In the graphs, there are many regular rod-like solids. For we did not refine the sample, there should be the packages of the crystalline inclusion complex between \(\alpha\)-CD and PDXL in the figure. The sizes of the rod-like solids are not the same but all about a few microns.

![Fig. 10. \(^{13}\)C CP/MAS NMR spectra of (1) \(\gamma\)-CD and (2) the crystalline inclusion complex between \(\gamma\)-CD and PDXL.](image)

![Fig. 11. SEM images of the crystalline inclusion complex between \(\alpha\)-CD and PDXL.](image)
3 Conclusion

Crystalline inclusion complexes between three kinds of CDs and low-molecular weight PDXL are obtained and studied. It is observed that a polymer guest can form crystalline inclusion complexes with three kinds of CDs. Thermogravimetry analysis shows that the formation of the crystalline inclusion complexes can improve the thermostability of CDs. The X-ray powder patterns of the products demonstrate that the resultant inclusion complexes are crystalline and have the columnar structure. \(^{13}\)C CP/MAS NMR spectra of crystalline inclusion complexes indicate that CDs adopt a more symmetrical conformation in the complex, while pure CD assumes a less symmetrical conformation in the crystals without a guest inside its cavity. SEM investigation shows that the crystals are shaped as regular rod-like crystals.

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References

15. Li, J. Y., Yan, D. Y., Inclusion complexes formation between cyclodextrins and poly(1,3-dioxolane), Macromolecules,


