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Preparation and Properties of Insoluble Films of Cyclodextrin Condensation Polymers

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Abstract. The preparation and properties of smooth and stable films of cyclodextrin polymers are described. The commercially available water soluble prepolymers of α-, β-, and γ-cyclodextrin of low molecular masses were crosslinked with glutaric dialdehyde. Side-chain unreacted aldehyde groups were reduced with sodium borohydride. For the α-cyclodextrin polymer, optimum film performance was found for a 1 : 10 mass ratio of glutaric dialdehyde to prepolymer, which corresponds to a molar ratio of glutaric dialdehyde to cyclodextrin units of about 1.75 : 1. Such films, of thickness 2.4 μm, were prepared on metallic or glassy-carbon substrates for characterization by scanning-electron microscopy, and for studies with the electrochemical quartz-crystal microbalance.

Key words. Cyclodextrin polymer film, polymer modified electrode, membrane, polycondensation, electrochemical quartz-crystal microbalance.

1. Introduction

Cyclodextrins (CDs) are nonreducing cyclic oligosaccharides composed of six (α-CD), seven (β-CD) or eight (γ-CD) α-*D*-glucose units. They are known to form noncovalent inclusion complexes with organic and inorganic guest molecules [1–3]. There is an increasing interest in solid CD matrices, mainly polymeric, because of their possible applications, e.g., in analytical chemistry for developing selective sensors [4] or for chromatography [5]. Polymers of CDs are known to retain [6–12], or even enhance [13, 14] the inclusion properties of monomeric CDs.

Insoluble CD polymers have been prepared previously, e.g.: methacrylate copolymers having pendant CD groups [15]. An amphiphilic β-CD derivative containing the diacetylene group in the hydrophobic part of the molecule has been intermolecularly photopolymerized in the Langmuir–Blodgett film [16]. α-CD has been reacted with an activated glycidyl methacrylate earlier copolymerized with glycol dimethacrylate [17]. CD membranes have been prepared by reaction of the crystalline β-CD inclusion complex of water with hexamethylene diisocyanate as the cross-linking agent [10, 18].

The present paper describes a convenient and simple method of preparation of CD-polymer films from commercially available soluble prepolymers of α-, β-, and γ-CD by polycondensation with glutaric dialdehyde (GD). The cyclodextrin polymer (CDP) films produced are stable, insoluble and nonreducing. The thin polymer films are suitable for electron-microscopic studies and for fabricating polymer

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modified electrodes, which were used in this work to characterize the film properties with the electrochemical quartz-crystal microbalance (EQCM). With the thick films, absorption and luminescence spectroscopic investigations of the host-guest inclusion phenomena are conducted, and will be the subject of forthcoming papers.

2. Experimental

2.1. MATERIALS

The soluble α-, β-, and γ-CD prepolymers were obtained from CYCLOLAB, Cyclodextrin Research & Development Laboratory, Budapest, Hungary. The α-CD content was (55 ± 5) wt. % and the average molecular mass, $M \leqslant 4000\ \mathrm{g\ mol^{-1}}$; their characterization is described elsewhere [7, 9, 19, 20]. The prepolymers were purified by the method usually employed with cyclodextrins [21], i.e., by centrifuging and decanting its 15% aqueous solution followed by boiling until the solution volume was reduced to about one third of its original volume; in this way, included volatile impurities were removed. Then it was diluted to its original concentration. All other chemicals, including the 25 wt. % aqueous solution of glutaric dialdehyde ('for electron microscopy', Fluka, Buchs, Switzerland) were used without purification.

2.2. APPARATUS AND METHODS

The mass variations of polymer films in electrolytes were measured by means of the electrochemical quartz-crystal microbalance system (EQCM) designed by R. Schumacher [22] and built in the workshop of Schering AG, Berlin. The vibrators (Phelps Electronics, Inc., Goleta, CA, U.S.A.) were 14 mm in diameter, 5 MHz AT-cut quartz crystals (not polished) with 6 mm in diameter gold deposits on both sides. The EQCM sensitivity in solution was 25 ng $\mathrm{Hz^{-1}}$ per $\mathrm{cm^2}$ of the geometrical surface of the electrode. The stability of the Δf baseline reading in solution was ± 1 Hz during an experiment, i.e. over a period of several minutes. Frequency counting was performed under potentiostatic conditions at constant solution stirring with a magnetic bar. A home made potentiostat was used which maintained the working electrode, i.e., the gold film on the quartz crystal, at a true ground. A KCl saturated calomel electrode (SCE) was used as the reference. The reproducibility of Δf readings observed when one polymer coated Au/quartz electrode was exchanged for another one was only fair. Therefore, the same coated quartz crystal was normally used to complete an experimental series. Polymer coats, cast on the Au/quartz wafers, were treated as described below, and microweighed prior to the EQCM studies with a Sartorius ultramicro balance of resolution 0.0001 mg. All experiments were conducted at room temperature (25 ± 1)°C.

Scanning electron microscopy (SEM) pictures of CDP films on glassy carbon were taken with a Hitachi Model S-4000 Scanning Electron Microscope. The glassy carbon surfaces were polished with 1 μm diamond paste before film deposition.

IR spectra (KBr pellets) of CDs and their polymers were recorded with a Perkin-Elmer Model 1420 Ratio Recording Infrared Spectrophotometer. In order to obtain a homogeneous distribution of the samples in the KBr pellets, the capsules containing the specimens, dried *in vacuo* for 30 min at 60°C, and the KBr were cooled in liquid nitrogen and then shaken in a vibration mill.

2.3. PREPARATION OF CYCLODEXTRIN POLYMER FILMS

The films were prepared from solutions containing various concentrations of α-, β-, and γ-CD prepolymers and GD [23], and also different concentration ratios of GD to prepolymer. In all cases, hydrochloric acid was added to the casting solutions to render them 10 mM in HCl. The mass ratio of 1 : 10 for GD-to-α-CD prepolymer, corresponding to a molar concentration of ratio 1.75 : 1 for GD-to-α-CD units in the prepolymer was found to yield the most satisfactory films (see below). The solution for casting such thin films was typically 1.5 wt. % in α-CD prepolymer (0.83 wt. % in CD units) and 15 mM in GD. For the thicker films the concentrations of the prepolymer and GD were 14 wt. % (7.7 wt. % CD units) and 0.148 M, respectively. For film preparation the solutions were always freshly prepared. Typically, to prepare thin films 12 μL of the solution of lower concentrations were deposited on the EQCM-gold surface forming an approximately circular spot of diameter ca. 8 mm. After polycondensation, washing, and drying at ca. 40% relative humidity, this film had a mass of 0.120 ± 0.15 mg. This corresponds to a film thickness of 2.4 μm, if a density of 1 gcm^{-3} is assumed. The thicker films were normally prepared on flat PTFE surfaces from which they could be peeled off conveniently.

The polycondensation reaction proceeded in the dark at room temperature in a nitrogen atmosphere. The reaction time was 4 hours for the thin films. For the thicker films it was up to three days, whereby on the first day nitrogen was slowly flowing over the samples. The colorless films produced were washed with water to remove the catalyst (HCl). Then they were soaked for at least 6 hours in 0.1 M $NaBH_4$ to reduce the free aldehyde groups from partially reacted GD. The boric acid intermediates produced were hydrolyzed by treating the films with 10 mM HCl for 6 to 24 hours. Eventually, the films were washed thoroughly with water and stored in water because they became brittle when they were overdried. Storing the films over a period of one month led to the loss of about half of their inclusion capacity. The CDP films are insoluble in all solvents which do not cleave acetal bonds; they are swellable in polar solvents.

3. Results and Discussion

3.1. THE POLYCONDENSATION OF CD PREPOLYMERS WITH GLUTARIC DIALDEHYDE

The commercial water-soluble cyclodextrin prepolymers used have been prepared [3, 24, 25] by treating strongly alkaline solutions of cyclodextrins with 1-chloro-2,3-epoxy-propane (epichlorohydrin). Addition of water at an early stage has kept the molecular mass of the product at values of only a few thousand.

From the given values of molecular mass and the contents of CD one concludes that, in the case of the α-CD prepolymer, the molecules are mainly α-CD dimers or trimers with each of the six glucose units carrying more than one 2,3-dihydroxypropyl-ether group. One might formulate the following dimer structure:

$$X_n(CD)—O—CH_2—CHOH—CH_2—O—(CD)X_m \qquad (1)$$

where X stands for the side chains $—O—CH_2—CHOH—CH_2OH$, and n, m are 5–11. The glucose units have typically only one sec.-OH function remaining.

Besides what was postulated earlier [26], the crosslinking reaction by acetalization with GD is expected to proceed largely via the glycolic hydroxyl groups of the side chains. This means that in the CDP produced the CD dimer units (as characterized in formula (1), are separated from one another by 11 bonds. One concludes that in the considered cross-linking reaction with GD a relatively open, permeable polymer network is formed.

The structure of the CDP produced depends, of course, on the GD-to-prepolymer ratio used in the polycondensation reaction. In selecting the optimum ratio one has to compromise between the production of rigid, brittle and fractured films at too high ratios, and the partially water soluble or excessively swelling matrix obtained as a consequence of insufficient crosslinking resulting from too low a GD-to-prepolymer ratio. In Figure 1, scanning-electron micrographs of two typical states of thin α-CDP films are presented. The film of Figure 1a was prepared with the relatively low GD-to-prepolymer mass ratio of 1:20. Pronounced surface imperfections are visible. They are probably produced during film examination in the electron microscope because of the abrupt release of entrapped water from the insufficiently crosslinked polymer film. No such effects were observed at higher GD-to-prepolymer ratios. Smooth and even films, pinhole- and crack-free, are obtained at the 1:10 mass ratio (Figure 1b), which corresponds to a molar ratio of GD to α-CD units of about 1.75:1.

β- and γ-CD prepolymers were crosslinked with GD under the same conditions and with similar results.

The IR spectra of CDPs are virtually identical to the spectra of the prepolymers and to those of CD monomers [27]. In Figure 2, typical IR spectra of the α-CD prepolymer and of α-CDPs prepared from different ratios of GD-to-(α-CD prepolymer) are summarized. Spectra were taken before and after the $NaBH_4$ and HCl treatments. Apparently, the strong band at ca. 1720 cm^{-1} corresponds to the C=O stretching vibration which is due to unreacted aldehyde groups from GD. Since the half widths as well as the ratio of heights of the peaks at ca. 1630 to that at 1460 cm^{-1} remained unchanged in the course of polycondensation and subsequent chemical treatment, these peak heights could be used as an internal standard for the normalization of the C=O peak at 1720 cm^{-1}. Clearly, this C=O peak varies with the GD-to-prepolymer ratio in the expected way. It vanishes when the aldehyde groups are reduced.

3.2. ELECTROCHEMICAL QUARTZ CRYSTAL MICROBALANCE

One of the aims of our studies with CDPs is the investigation of the inclusion processes with electrochemical methods. Therefore, it was considered important to characterize the CDP films on metallic and glassy-carbon substrates, i.e., as 'polymer modified electrodes'. Since the electrochemical quartz-crystal microbalance

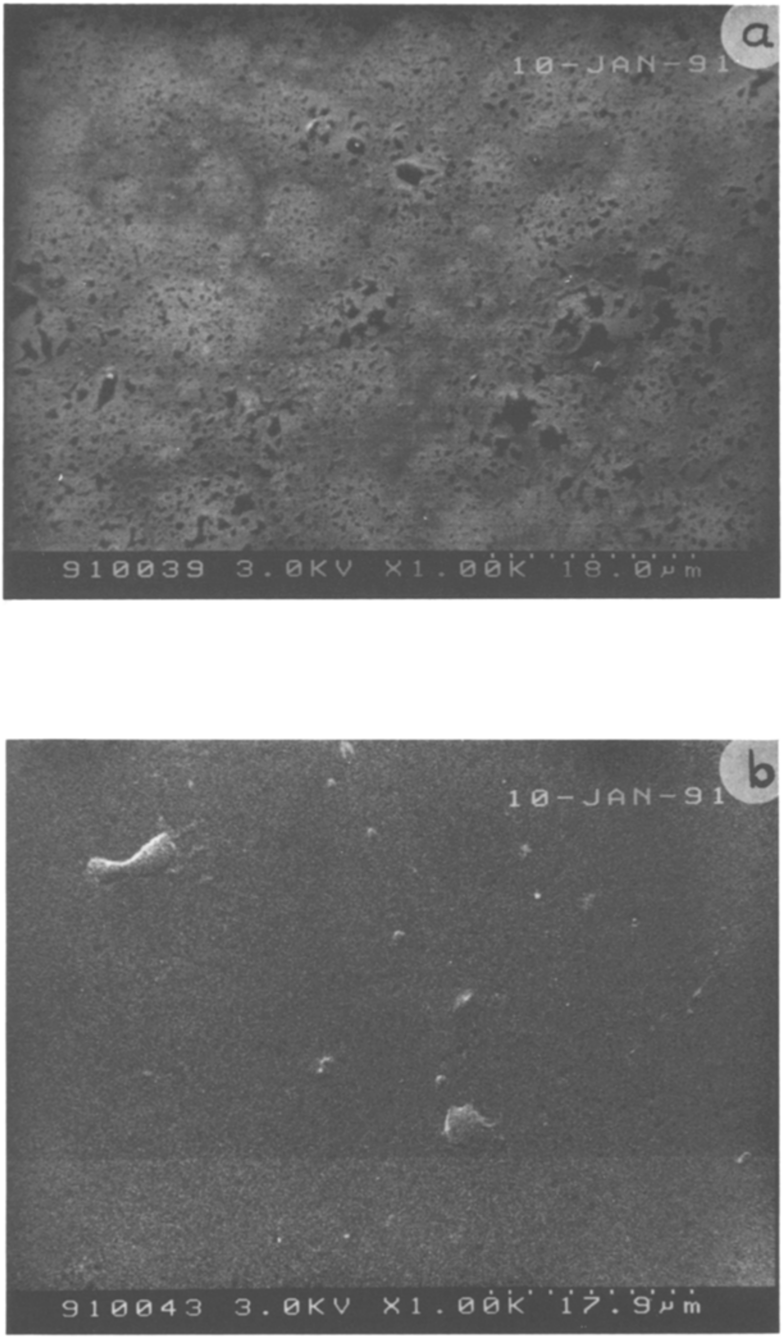

Fig. 1. SEM micrographs of glassy carbon surfaces coated with α-cyclodextrin polymer films of thickness 2.4 μm. The 10 dots (bottom right) mark a length of 18 μm. The mass ratio of glutaric dialdehyde to the α-cyclodextrin prepolymer used in the polycondensation reaction equals: (a) 1 : 20, (b) 1 : 10.

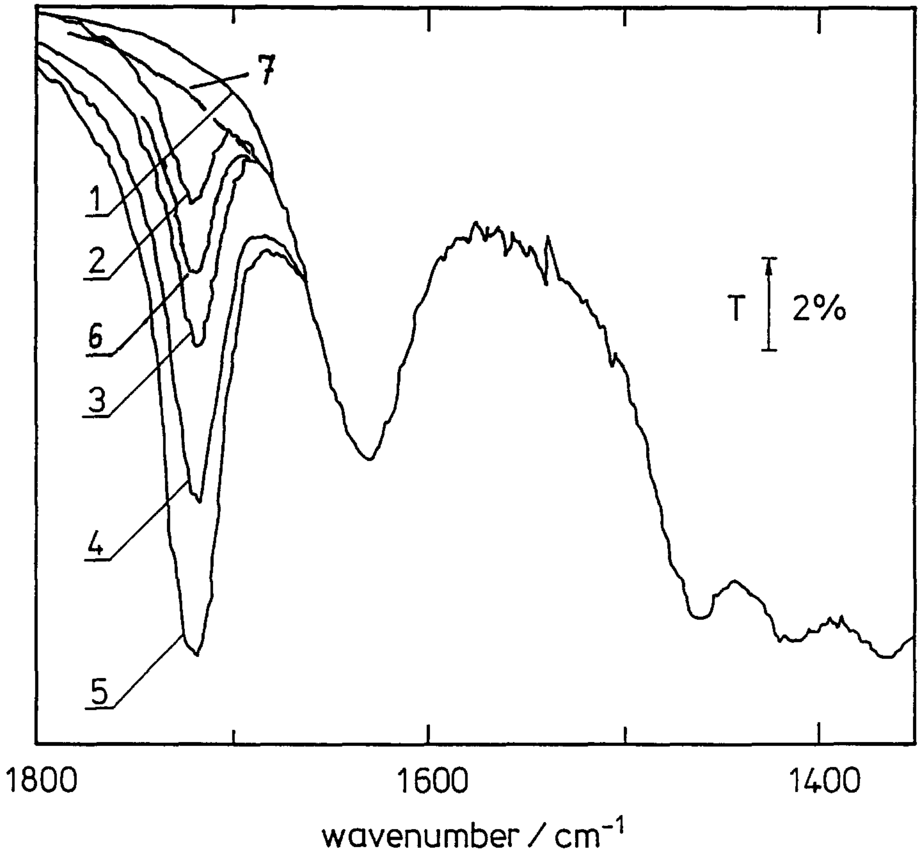

Fig. 2. IR spectra (KBr pellet): the soluble α-cyclodextrin prepolymer (curve 1); α-cyclodextrin polymer films after polycondensation with different mass ratios of glutaric dialdehyde (crosslinking agent) to α-cyclodextrin prepolymer: 1 : 20 (curve 2), 1 : 10 (curve 3), 1 : 5 (curve 4), 1 : 3.3 (curve 5); the 1 : 10 polymer after extensive rinsing with water (curve 6); and the 1 : 10 polymer after reducing unreacted aledhyde groups with $NaBH_4$ and acid hydrolysis (curve 7).

(EQCM) is an excellent tool for studying mass changes occurring with polymer modified electrodes [22, 28], we deposited the thin α-CDP films (thickness 2.4 μm) onto one side of the Au/quartz of the EQCM and conducted the following experiments.

The first observation was that the resonant frequency, f, decreased by 3 to 7 kHz when the CDP-coated Au/quartz was immersed into pure water. This compares with a $-\Delta f$ value of 1 to 2 kHz observed upon immersion of the uncoated gold surface. Owing to the sensitivity of f to differences in the mounting stress of the quartz, it is difficult to analyze this result quantitatively. However, it is clear that the CDP film adds considerably to the vibrating mass, i.e., the film adheres well to the gold substrate in contact with the aqueous phase.

Secondly, we observed the variation of f caused by changing the nature and concentration of salts dissolved in the bathing solution. The alkali chlorides were chosen because neither the cations nor chloride ions are included to a significant extent into α-CD [29]. Any variation of f observed with the α-CDP-coated Au/quartz is therefore caused by a change of the mass of the vibrating solution-like phase in the crosslinking structure. Typical results of such measurements with coated and uncoated Au/quartz are summarized in Figure 3. The values of $|\Delta f|$ observed with the polymer modified Au/quartz is larger by a factor of about 4 than $|\Delta f|$ of the clean gold surface. Since the effective thickness of the layer of aqueous solution coupled to the (i.e. vibrating with the) unmodified metal surface is known to be about 0.25 μm [22], the amount of solution present in the CDP matrix corresponds at least to an electrolyte layer of thickness 0.75 μm. This value may, in fact, be too low because shear wave attenuation may take place already in the polymer film instead of in the adjacent solution [22]. One concludes that this polymer matrix is well solvated by the aqueous solutions.

One may finally note (Fig. 3) that at any given electrolyte concentration the $-\Delta f$ variation increases with the molecular mass of the dissolved salt in the same order with the coated as with the uncoated electrode. This means, no preferential partitioning of one of the salts takes place. One could probably assume that the composition of the electrolyte phase in the free (on the molecular scale) spaces of the polymer, which is the space between alkyl main chains, i.e., outside of CD-inclusion sites, is the same as in the solution. Thus, the prepared CDP films constitute good matrices into which solutions enter freely, and from which the

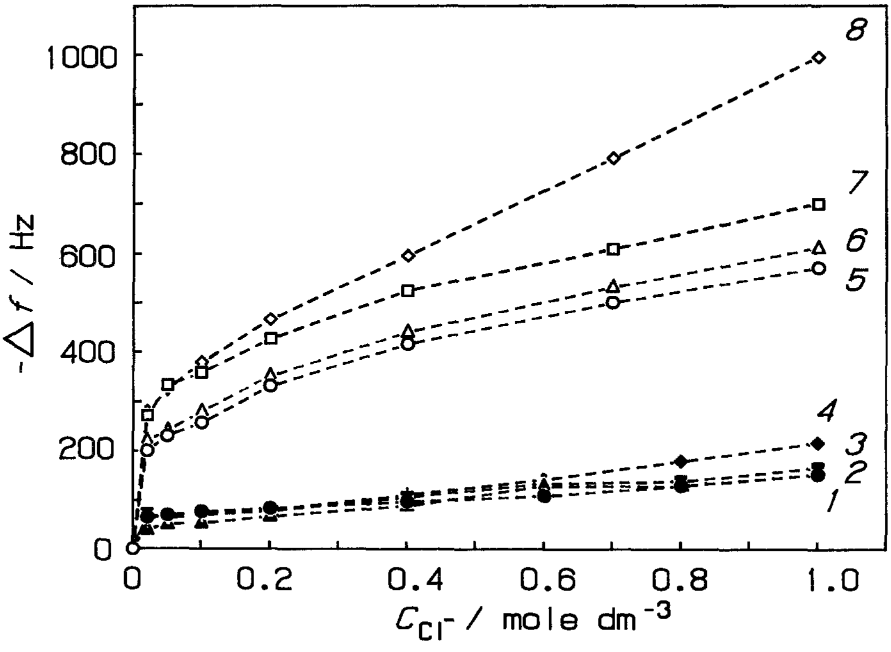

Fig. 3. Dependence of the change of the vibration frequency of the microbalance Au/quartz crystal on concentrations in solution of LiCl (curves 1 and 5), NaCl (curves 2 and 6), KCl (curves 3 and 7), and CsCl (curves 4 and 8). Bare Au surface: full symbols; Au coated with the α-cyclodextrin polymer film: empty symbols (the mass ratio of glutaric dialdehyde to the α-cyclodextrin prepolymer in the polycondensation reaction equals 1 : 10). The Au/quartz electrode was potentiostated at 0.0 V/SCE.

inclusion reactions with the CD units may take place. This feature was exploited, for example in the study of the performance of included free radicals [26] and of the selective inclusion of some guest systems governed by the charge of the guests [19, 20].

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