Properties of the Gamma-Cyclodextrin/CL-20 System

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Abstract: Cyclodextrin (CD) is a cyclic compound with a spatial structure in the shape of a toroid. It is characterized by specific properties. The outer portion of the structure has hydrophilic properties, while the cavity of the toroid is hydrophobic. This enables cyclodextrin to form inclusion complexes with the enclosure of lipophilic molecules in the interior. This paper presents the results of attempts to form a complex of γ-CD/CL-20. This study determined unambiguously that a γ-CD with CL-20 complex in a mole ratio 1:1 is formed as a result of mixing of solutions of γ-CD and CL-20. This conclusion was corroborated by FTIR, ^{1}H NMR, UV-Vis spectroscopic techniques and by measurement of the density of the complex obtained. The resulting complex of γ-CD/CL-20 is characterized by much lower sensitivity to friction and impact than CL-20 itself.

Keywords: CL-20/γ-CD complex preparation, properties of CL-20/γ-CD complex, cyclodextrin, 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazaiso-wurtzitane, CL-20.

1   Introduction

Highly energetic explosives are widely used both in civil applications and military operations. In this connection they are constantly being improved and developed to achieve increasingly better detonation characteristics, with retention of their safety aspects.

2,4,6,8,10,12-Hexanitro-2,4,6,8,10,12-hexaazaisowurtzitane (CL-20, HNIW) is an explosive with a caged three-dimensional structure, represented in Figure 1. The CL-20 cage consists of two five-membered rings and one six-

membered ring. This structure is responsible for considerable stress between the atoms of the cage-structure, which significantly raises the energy released in decomposition. As of today, CL-20 is an explosive with the best detonation parameters. Its major drawback, however, is its high sensitivity to mechanical shock. The problem of the sensitivity of CL-20 has been investigated in a number of studies [1, 2]. Research has shown that the crystallization process is a suitable technique for improving the quality of CL-20, particularly for decreasing its sensitivity. In the literature the results of a new method of purification to obtain ε-CL-20 with low impact sensitivity have been described. This method is based on removing the impurities from a solution of CL-20 by chemical reaction to obtain the pure ε-form [3]. Likewise, by forming the CL-20 complex with a cyclodextrin (CD), CL-20 with reduced sensitivity to mechanical stimuli may be achieved.
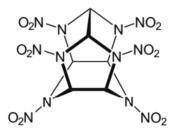

Figure 1.   3D structure of a CL-20 molecule.

Cyclodextrins (CDs), also known as cycloamyloses, are a group of oligosaccharides (carbohydrates) made by the combination of six or more α-D-glucopyranoses (glucoses) by α-1,4-glycosidic bonds. The most common cyclodextrins are the varieties composed of 6, 7, or 8 glucose molecules, denoted with Greek letters α, β and γ, respectively (*cf.* Figure 2).
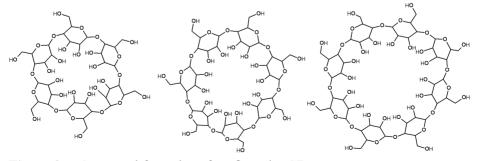

Figure 2.   Structural formulae of α-, β- and γ-CD.

CDs are readily soluble in water and, when in solution, they assume a 3-dimensional toroidal structure. The toroidal structure of the CD molecules is due to the chair conformation assumed by all of the glucose rings. Thus all of the primary hydroxyl groups form the narrower part of the toroid, whereas the secondary groupings are responsible for the wider part of the toroid. The structure under consideration here is represented in Figure 3.
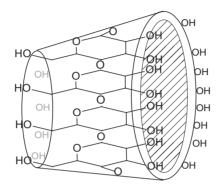

Figure 3. Shape of the γ-CD molecule in solution.

It is this structure that is responsible for the characteristic properties of cyclodextrins and their capability to form special host-guest type inclusion complexes [4-6]. A considerable number of the hydroxyl groups in the CD molecule permit its easy modification. This opens up additional opportunities for a change in properties of the complexes obtained.

In a study on the effects of CL-20 on the environment, its solubility and stability in water, and its decomposition effects in soil [7], attention was paid, among other things, to CL-20's solubility in hydroxypropyl-β-cyclodextrin (HP-β-CD) and heptakis-2,6-di-O-methyl-β-cyclodextrin (DM-β-CD) solutions in comparison with its water solubility.

CD has also found application in explosives manufacture as a substrate for novel explosive materials. An example of such an application is the US Patent [8] concerned with novel CD esters-based polymers. Methods were reported in this patent concerned with the preparation of a variety of CD polymers, and additionally methods for their nitration to impart highly energetic properties. An explosive material (RDX) was introduced into these polymers. The formation of the complex reduced the sensitivity of the material obtained in relation to pure RDX.

In other work [9] inclusion complexes of nitrobenzene (NB) with β-CD were studied. The complexes were made by adding a methanolic NB solution to an aqueous β-CD solution.

In yet another study [10] the formation and application of the CD-nitroglycerin complex was reported. Effort was directed towards the use of this complex in pharmacy, in order to make a medicine in tablet form.

The aim of the present work was to make the inclusion complex of CL-20 with γ-CD and to determine the major physicochemical properties of the complex.

2 Experimental

2.1 Materials

CL-20 (purity 99.3%, as determined by HPLC) was prepared at the High Energy Materials Laboratory, Warsaw University of Technology, Department of Chemistry, in the ε-form (≥ 95% as determined by IR). γ-Cyclodextrin (γ-CD) (purity 98.4%) was obtained from Trappsol. Other reagents and chemicals were of AR grade.

2.2 Preparation of the CL-20/γ-CD complex

2.2.1. *Reaction in acetone/water solution*

Into a three-necked (50 mL capacity) flask placed on a magnetic stirrer, were added CL-20 (0.68 g, 1.55 mmol) and acetone (2 mL), and then stirred until complete dissolution of the CL-20 had occurred. γ-CD (2.01 g, 1.55 mmol) was added to the acetone CL-20 solution. Stirring was commenced and water (6 mL) was added dropwise. The time of the addition was 10 min. As soon as half of the water had been added, the solution could be seen to become dense and a white precipitate began to form. 35 min after completing the addition of the first portion of water, a further quantity of water (10 mL) was added dropwise (15 min). 1 h after completing the addition of the second portion (10 mL) of water, the stirring was turned off and the reaction mixture was allowed to stand for 0.5 h. After that time the resultant white precipitate was filtered off, washed with water and acetone (15 and 5 mL portions, respectively) and then allowed to dry. The complex CL-20/γ-CD (2.02 g) was obtained.

2.2.2. *Reaction in water*

Into a three-necked (100 mL capacity) flask placed on a magnetic stirrer, were added γ-CD (2.01 g, 1.55 mmol) and water (60 mL), and stirring was commenced. On complete dissolution of the γ-CD, CL-20 (0.68 g, 1.55 mmol) was added to the solution. The flask contents were stirred for 6 h on a water-bath at 55-60 °C. After that time the contents were found to have become thick and an amorphous

white precipitate had formed, evidence of the formation of a new compound. On turning off the heating, the reaction, with the stirring still on, was allowed to proceed for 139 h. After that time the white precipitate that had formed was filtered off, washed with water and acetone (in portions of 15 and 5 mL, respectively) and allowed to dry on the filter funnel. The complex CL-20/γ-CD (1.81 g) was obtained.

2.3 Infrared spectroscopy (FTIR)

The infrared spectroscopic examination was carried out using a Nicolet 6700 FT-IR with a SMART ATR attachment from Thermo Scientific, employing the single ATR of the IR beam from a diamond crystal technique.

2.4 Proton nuclear magnetic resonance (^{1}H NMR) spectroscopy

The ^{1}H NMR spectroscopic study was carried out using a Varian Mercury-400BB instrument, with deuterated water (D_2O) or deuterated methanol (CD_3OD) as solvents.

2.5 UV-VIS spectroscopy

The measurements of the spectra in the visible range were recorded using a UV-Visible Spectrophotometer Evolution 60S from Thermo Scientific. The spectra were measured over the range 190-500 nm. Water was used as the solvent. The measurements were made for solutions of the complex at a concentration of 0.2 mg/mL (1.15×10^{-4} mol/L) and for γ-CD at a concentration of 92.8 mg/mL (7.15×10^{-2} mol/L).

2.6 Density measurement

The density was measured using a helium-fed Micromeritics AccuPyc II 1340 gas pycnometer. The measurements were made with an accuracy of 0.01 g/cm³.

2.7 Friction and impact sensitivity

The friction sensitivity of the samples was determined with a BAM friction apparatus until no explosion/ignition in six consecutive test samples at that weight were observed. The impact sensitivity tests of CL-20 were performed with a BAM Fallhammer apparatus with a load weight of 2 kg. The lower limit of sensitivity was defined as the highest load at which the result "explosion" was obtained from at least one out of six trials. The upper limit of sensitivity was defined as the lowest load at which the result "explosion" was obtained in six out of six trials.

3   Results and Discussion

The reason behind the choice of the cyclodextrin used was the size of the CL-20 molecule in relation to the volume of the CD cavity. γ-CD is the largest of the three systems and additionally it offers the only opportunity for the CL-20 molecule to lodge inside its cavity, in contrast to α- or β-CD. The cavity volume for the three CD homologues and the volume of the CL-20 molecule are listed in Table 1.

Table 1.   Key properties of cyclodextrins and CL-20

Property	Cyclodextrin			CL-20
	α	β	γ	
Number of glucose rings	6	7	8	
Molecular formula	$C_{36}H_{60}O_{30}$	$C_{42}H_{70}O_{35}$	$C_{48}H_{80}O_{40}$	$C_6H_6N_{12}O_{12}$
Number of hydroxyl groups	18	21	24	0
Molecular mass	972.85	1134.99	1297.14	438.19
Cavity diameter, [Å]	4.7-5.3	6.0-6.5	7.5-8.3	-
Torus height, [Å]	7.9	7.9	7.9	-
Cavity volume, [Å^3]	174	262	427	-
Molecule volume, [Å^3]	-	-	-	356 (ε)
Water solubility, 25 °C [g/100 mL]	14.5	1.85	23.2	0.36×10^{-3}
Density, [g/cm^3]	1.48	1.44	1.52	2.04 (ε)

On the basis of the cavity volume for one mole of γ-CD and the volume of one mole of CL-20, the theoretical mole ratio for the γ-CD complex formed, γ-CD/CL-20, was calculated as 1:1.19.

As a result of mixing CL-20 with γ-CD in an aqueous or water-acetone solution, the initial CL-20 suspension became increasingly thicker, while the white colour grew whiter, as the precipitate was being formed in increasing amounts. On filtering, washing off and drying, a white powder was obtained in ca. 67.5% yield. The complex γ-CD/CL-20 obtained was sparingly soluble in water, yet more readily soluble than CL-20. The solubility of the complex formed by reaction in aqueous medium at a mole ratio of 1:1 was determined to be 400 mg/L (0.23 mmol/L).

The lower limit of the sensitivity to friction for the complex γ-CD/CL-20 was 158.4 N, while the upper limit was 284.4 N. For comparison, the values for CL-20 itself were 94 and 128 N, respectively. The lower limit of sensitivity to impact for the complex γ-CD/CL-20 was 7 ± 0.2 J, while the upper limit was

9.8±0.2 J. For comparison, the values for CL-20 itself were 2±0.2 and 4±0.2 J, respectively.

An attempt to use β-CD to make an inclusion complex with CL-20 failed. The reason for this may be that the volume of the cavity in the CD structure is too small to be capable of allowing the CL-20 molecule to become lodged in the cavity.

3.1 Examination of the complex by infrared (FTIR) spectrophotometry

The γ-CD/CL-20 complexes obtained were studied by infrared spectrophotometry. The spectra of the complexes were recorded and compared with the spectra of the neat precursors (*i.e.* γ-CD and CL-20) and of a mechanical mixture of the precursors in a mole ratio of 1:1. The characteristic absorption bands were determined for the spectra. The spectrum of the starting γ-CD is shown in Figure 4.
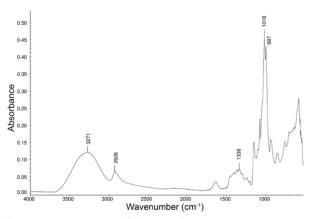

Figure 4.   The FTIR spectrum of the starting γ-CD.

A low-intensity, very broad band can be seen in the spectrum over the range of 3600-3000 cm^{-1} with a maximum at 3271 cm^{-1}. This band is due to the stretching vibrations of the OH groups in the glucose rings. A low-intensity band with a maximum at 2926 cm^{-1}, which overlaps with the former, is assigned to the stretching vibrations of the C-H bonds in the CH$_2$ and CH groups. A high-intensity doublet, with maxima at 1019 and 997 cm^{-1}, is assigned to the C-H out-of-plane bending vibrations and the C-O stretching vibration modes. The spectrum of CL-20 with its characteristic bands is shown in Figure 5.
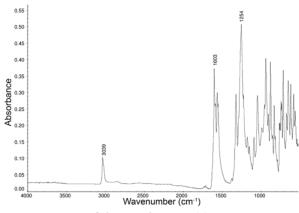
Figure 5. FTIR spectrum of the starting CL-20.

A low-intensity narrow band is visible in the spectrum with a maximum at 3039 cm^{-1}, due to the stretching vibrations of the C-H bonds in the isowurtzitane cage. Other band assignments include: a moderate-intensity band with a maximum at 1603 cm^{-1}, assignable to the asymmetric stretching mode of the N-O bond in the NO$_2$ groups; a high-intensity band at 1254 cm^{-1} due to the symmetric stretching mode of the N-O bond in the NO$_2$ groups.
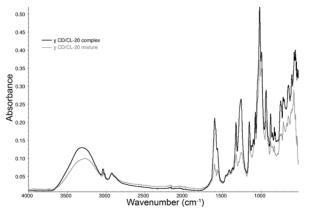

Figure 6. Superimposed spectra of the complex and that of the mechanical mixture.

The FTIR spectrum of the complex obtained, along with a spectrum of a mechanical mixture of the γ-CD and CL-20 precursors in a mole ratio of 1:1 is shown in Figure 6, while Table 2 lists the characteristic bands of the γ-CD/CL-20 complexes. The data refer to the product from reaction in aqueous acetone

and aqueous media for a 1:1 substrate ratio, and the product from reaction in an aqueous medium with γ-CD and CL-20 in a mole ratio of 1:2. Also listed are the evaluated shifts of the peaks (Δδ) in relation to the spectrum of the mechanical mixture.

Table 2.   Wavelengths of the characteristic bands in the FTIR spectra of the mechanical mixture and of the γ-CD/CL-20 complex obtained in aqueous acetone (I) and aqueous (II) medium in a 1:1 mole ratio and in an aqueous medium (III) in a 1:2 mole ratio

Characteristic wavelengths and relative wavelength shifts for:						
Mixture $[cm^{-1}]$	Complex I $[cm^{-1}]$	Δδ $[cm^{-1}]$	Complex II $[cm^{-1}]$	Δδ $[cm^{-1}]$	Complex III $[cm^{-1}]$	Δδ $[cm^{-1}]$
3271	3311.4	40.4	3319.3	48.3	3316	45
3039	3040.4	1.4	3041.7	2.7	3040	1
2928	2927.8	−0.2	2929	1	2927.5	−0.5
1603	1600	−3	1602	−1	1601.9	−1.1
1255.6	1272	16.4	1272	16.4	1271	15.4
1019.6	1020.7	1.1	1021	1.4	1021	1.4
997	996.9	−0.1	996.6	−0.4	997	0

On the basis of the FTIR spectra and from a consideration of the similarities of the spectra obtained to the spectrum of the mechanical mixture and the observed shifts of the maxima of the characteristic bands, it was deduced that the complex was produced under all of the three reaction conditions. Particular attention was paid to the characteristic bands from CL-20 and to their maxima. In the spectra of the complexes an increase in band intensity and in the value of the wavelength shift was observed. For the stretching vibrations of the C−H bonds in the isowurtzitane cage a wavelength shift from 3039 cm⁻¹ to 3041.7 cm⁻¹ (Complex II) was observed, and in particular an increase in intensity and a shift in position of the band assigned to the N−O bonds of the NO_2 group, for which the shift of the 1255.6 cm⁻¹ peak, corresponding to symmetrical vibration mode, was found to be 16.4 cm⁻¹ (Complexes I and II) and 15.4 cm⁻¹ (Complex III). The shifts of the maxima of the characteristic groups of the CL-20 molecules were assumed to be due to the interaction of the bonds and the NO_2 groups with the OH groups in γ-CD. As the CL-20 molecules become encapsulated inside the γ-CD toroid, the interactions are increased compared with the common mechanical mixture at a 1:1 mole ratio. These interaction are not unilateral; for that reason a considerable shift was observed for the 3271 cm⁻¹ peak of the band characteristic of the OH groups in γ-CD, from 40.4 cm⁻¹ (Complex I) to

48.3 cm^{-1} (Complex II) in the FTIR spectra of the complexes.

3.2 Examination of the complex by ^{1}H NMR spectroscopy

Chemical shifts were determined for the γ-CD protons on the basis of an analysis of the ^{1}H NMR spectra for the starting γ-CD and the complex obtained in the reaction in an aqueous medium. For the complex, because of its poor solubility in water, the recorded spectrum contains low-intensity signals. The arrangement of the hydrogens in a single glucose ring and in the γ-CD molecule is shown in Figure 7, together with the numbering of the ring carbons and their corresponding hydrogens. The ^{1}H NMR spectrum of the complex in the 3.50-4.00 ppm range is shown in Figure 8.
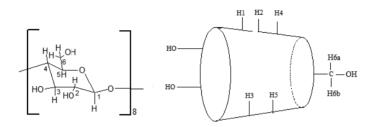

Figure 7. Structural formulae of γ-CD that represent the arrangement of hydrogen atoms in the glucose ring and in the cyclodextrin torus.
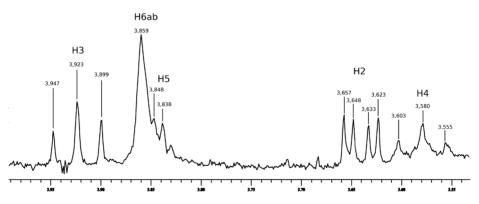

Figure 8. ^{1}H NMR spectrum of the complex obtained from the reaction in aqueous solution for a reactant mole ratio of 1:1.

Table 3 lists the proton signals present in the spectrum of the original γ-CD and of its inclusion complex with CL-20.

Table 3. Chemical shifts (δ, ppm) and their difference (Δδ, ppm) for the protons in the original γ-CD and its inclusion complex with CL-20

Compound	δ for protons, [ppm]					
	H1	H2	H3	H4	H5	H6ab
γ-CD	5.092	3.642	3.918	3.573	3.833	3.854
γ-CD/CL-20	5.097	3.648	3.923	3.580	3.848	3.859
Δδ	0.005	0.006	0.005	0.007	0.015	0.005

The increase in chemical shift noted for hydrogen H5 in γ-CD is caused by its interaction with the CL-20 closed inside the γ-CD toroid, and lends credence to the concept of inclusion complex formation. In the ^{1}H NMR spectrum of the complex, the signals derived from the protons of CL-20 are also visible. They appear at 8.188 and 8.312 ppm, and are shifted relative to pure CL-20, for which the corresponding signals appear at 8.212 and 8.344 ppm. The seconclusions are consistent with the inferences from a great many studies on other inclusion complexes of CDs [1]. It is frequently observed that the chemical shift of the H3 proton, being another proton that remains inside the toroid, is also affected, although this effect is not found for all complexed compounds [1]. The remaining hydrogens, being outside the toroid, are affected to a lesser extent by the encapsulation effect. Therefore, the increase in the chemical shift in their cases is less pronounced than that for H5.

3.3 Examination of the complexes by UV-VIS spectroscopy

The absorption of ultraviolet and visible light by aqueous solutions of the starting γ-CD and of the γ-CD/CL-20 complex was also measured. Based on the spectrum recorded, the characteristic absorption maxima for γ-CD were at 193 and 196 nm. The characteristic absorption maxima for the complex appeared at 192 and 196 nm, which are due to the γ-CD, with a broad band at 226 nm characteristic of the N=O bonds in the NO_2 groups of CL-20. The appearance of an absorption maximum at 226 nm is evidence for the formation of a γ-CD/CL-20 inclusion complex.

3.4 Determination of the density of the complexes

Density measurements were made for the complexes produced, the precursors CL-20 and γ-CD, and the mechanical mixture of CL-20 with γ-CD in a mole ratio of 1:1. The results of these determinations are listed in Table 4.

Table 4.   Values of the density measurements for the precursors CL-20 and
γ-CD and their reaction products

Substance	Density, [g/cm^3]
γ-CD	1.52
CL-20	2.00
Mechanical mixture 1:1 γ-CD/CL-20	1.63
γ-CD/CL-20 Complex (from acetone-water at a 1:1 mole ratio)	1.61
γ-CD/CL-20 Complex (from water at a 1:1 mole ratio)	1.63
γ-CD/CL-20 Complex (from water at a 1:2 mole ratio)	1.63

Based on the measured density of CL-20 and γ-CD, the theoretical density of
a γ-CD/CL-20 complex at a 1:1 mole ratio was calculated as 1.62 g/cm^3, which
gives a value similar to the one measured for the 1:1 mechanical mixture. By
comparing the density of the complexes obtained with the density of the original
γ-CD and of its mechanical mixture with CL-20, it was demonstrated that the
complex was formed in all the three reactions. The density values were within
the range of 1.61-1.63 g/cm^3. The γ-CD/CL-20 complex made in aqueous
solution at a 1:2 mole ratio exhibits the same density as the complex obtained
under the same conditions but at a 1:1 mole ratio. This indicates that only one
CL-20 molecule is lodged inside the γ-CD molecule.

4   Conclusions

This study has provided substantial evidence to unambiguously indicate that, as
a result of the mixing of γ-CD solutions with CL-20, a γ-CD/CL-20 complex is
formed in a 1:1 mole ratio. This conclusion was confirmed by FTIR, ^{1}H NMR,
UV-Vis spectroscopic techniques and from the density measurement of the
complex obtained. In the FTIR spectra of the complex, characteristic bands of
both precursors are present. The band positions are shifted in relation to the
original precursors as a result of the interactions of the γ-CD OH groups with
the CL-20 NO$_2$ groups. The shift of the H5 hydrogen signal manifests itself in
the ^{1}H NMR spectrum of the complex, relative to pure γ-CD. From the UV-
VIS spectroscopic examination, the band positioned at 226 nm is assignable to
the N=O bond in the NO$_2$ groups. The complexes studied had a density (1.61-
1.63 g/cm^3) close to the density of the γ-CD/CL-20 mechanical mixture at a mole

ratio 1:1 (1.62 g/cm^3). The resulting complex of γ-CD/CL-20 is characterized by much lower sensitivity to friction and impact than CL-20 itself. An attempt to use β-CD to form an inclusion complex with CL-20 failed. A reason for that is that the cavity in the β-CD structure is too small in size to accommodate a CL-20 molecule.

Acknowledgements

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