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A Study of Ring Strain and Polymerisability in Cyclic Esters
W. Saiyasombat, R. Molloy, I.M. Ward, A.F. Johnson, T.M. Nicholson
and S. Poshyachinda

International Conference on Materials Technology: Recent Developments and Future Potential, 9-10 January 1997, Chiang Mai, Thailand

2. POSTER PRESENTATION pages 331-332

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Ring Strain and Polymerizability of Cyclic Esters
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A STUDY OF RING STRAIN AND POLYMERISABILITY IN CYCLIC ESTERS

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ABSTRACT

The development of new biodegradable polyesters for use in biomedical applications (such as absorbable sutures and controlled drug delivery systems) is an area of considerable research interest at the present time. Of fundamental importance to this research is the development of a clear understanding of the factors affecting reaction control, and therefore polymer microstructure and properties, in the ring-opening polymerisation of cyclic esters. Ring strain is one of the most important factors affecting a cyclic monomer's polymerisability. In this work, the ring strains in γ-butyrolactone, δ-valerolactone and ε-caprolactone were studied by infrared spectroscopy, Raman spectroscopy and Molecular Simulation Incorporated (MSI). The thermodynamic polymerisabilities of these 3 lactones and other cyclic diesters in the glycolide series were studied by MSI. Ring strain and thermodynamic polymerisability for the 3 lactones increased with increasing ring size. Thermodynamic polymerisability for the glycolide series decreased with increasing substitution on the α-carbon.

Introduction

A detailed understanding of the factors affecting the ring-opening polymerisation of cyclic esters is the starting point for developing polymer properties relevant to the intended application. These factors are (i) ring size, (ii) ring strain, (iii) substitution on the ring, (iv) functionality within the ring, (v) type of initiator used and (vi) reaction conditions. Ring strain is particularly important. The major sources of ring strain are (i) bond angle distortion (angular strain), (ii) bond stretching or compression, (iii) repulsion between eclipsed hydrogen atoms (conformational strain, bond torsion) and (iv) non-bonding interactions between atoms or substituents attached to different parts of the ring (transannular strain, compression of the van der Waals radii) [1,2].

Strain energy can often furnish valuable information about the relative ring strain of organic compounds. Conventional strain energies are apparent in alicyclic compounds when the observed standard molar enthalpies of formation in the gaseous state are compared with values for strain-free structures calculated using modern bond-energy schemes [3]. Conventional strain-energies have been reported for cycloalkanes, cyclic ethers, cyclic thioethers, and cyclic imines, and, for all of these, minimum strain-energies are observed for the six-membered ring compounds [4]. For simple lactones, the standard molar enthalpies of combustion which have been reported are for two five-membered ring lactones : γ-butyrolactone and γ-valerolactone, and one six-membered ring lactone : δ-valerolactone [5]. However, if the necessary group equivalents or the heat of formation of the compound of interest are unknown, another approach is required. The ring strain in the cyclic esters studied here can be compared in terms of their internal energy from Molecular Simulation Incorporated (MSI) and also in terms of the frequencies of their respective O-C(=O) and O-CH_2 stretching bands from Fourier-transform infrared spectroscopy (FT-IR). Fourier-transform Raman spectroscopy (FT-Raman) and MSI (Biosym package).

Polymerisability refers to the thermodynamic feature of a given monomer and can be expressed by the extent to which the free energy of the polymerising system changes as it converts into polymer [6]. MSI was used to determine the polymerisability via calculation of the difference in internal energy between the polymer and the monomer.

Experimental

Materials

γ-Butyrolactone (Fluka), δ-valerolactone (Fluka), and ε-caprolactone (Fluka) were each purified by vacuum distillation from CaH_2.

Spectroscopy

FT-IR analyses were made on a Perkin-Elmer FT-IR 1720-X spectrometer with the sample placed between NaCl windows.

FT-Raman analyses were made on a Perkin-Elmer FT-Raman 2000 spectrometer with the sample placed between glass windows.

Determination of Vibrational Frequencies by MSI

From the minimized energy structure of a cyclic monomer, it was possible to calculate vibrational modes and frequencies via the second derivative of surface energy. The **Biosym** command was used to load the macro package that displayed the vibrational modes. The **Discover** module was then used to calculate normal modes and frequencies.

Calculation of Energies [7]

(a) Calculation of Monomer Energies

Monomer molecules were built from the fragment library by selecting the appropiate fragments and creating bonds between them. The **Discover_3** module was then selected to find the lowest energy structure for the monomer molecule.

(b) Calculation of Polymer Energies

Polymer molecules were built up from repeat units. This was done in a similar way to the fragments used to build small molecules except that two of the atoms were defined as the head and the tail of the unit. The units were then joined together to form the polymer. A repeat unit was built by selecting the appropriate fragments and creating bonds between them. The **Homopolymer/Polymerize** command was selected and the structure confirmed by clicking on the repeat unit that had been built. Either the number 4 or 5 was entered as **Polymerize Deg.** This generated a four or five-unit segment of the polymer. Finally, the lowest energy structure for the polymer chain was determined by selecting the **Discover_3** module.

(c) Calculation of $\Delta H_p'$

The difference in internal energy between the polymer and the monomer was calculated from Eq. 1

$$\Delta H_p' = P_5 - P_4 - M \qquad (1)$$

where P_5 : internal energy of polymer chain with degree of polymerisation = 5
P_4 : internal energy of polymer chain with degree of polymerisation = 4
M : internal energy of monomer

Results and Discussion

(a) Ring Strain

The vibrational frequencies of the cyclic ester monomers from the three different methods : FT-IR, FT-Raman and MSI, are compared in Table 1.

The frequencies show similar trends but slightly different values for each method. These differences may arise from the different calibration of the instruments and the forcefield used in the MSI. However, when comparing the changes at each vibrational frequency, the same trend is found in each of these three methods.

	γ-butyrolactone			δ-valerolactone			ε-caprolactone		
	FT-IR	FT-Raman	MSI	FT-IR	FT-Raman	MSI	FT-IR	FT-Raman	MSI
$-O-\overset{\overset{O}{\|}}{C}-$	1241	1240	1231.11	1279	1280	1262.39	1292	1297	1276.57
$-O-CH_2-$	1038	1045	1038.37	1056	1063	1033.47	1089	1088	1064.87
Ring Size	5			6			7		

As the ring becomes more strained, it becomes more rigid and the vibrational frequency increases. Thus, the ring strain in these cyclic esters can be compared in terms of the frequencies of their respective O-C(=O) (acyl-oxygen) and $O-CH_2$ (alkyl-oxygen) stretching bands, since the ring strain comes from the distortion of these O-C(=O) and $O-CH_2$ bonds. As a measure of these distortions, the bond angles in O-C(=O)-C, C(=O)-O-C and C-C-C and the bond lengths of O-C(=O), O-C and C-C, as determined by MSI, are compared with the equilibrium values in Table 2.

On comparing the internal energy of the cyclic ester monomer with the ring strain energy, the internal energy shows the same trend as the ring strain energy, as shown in Table 3.

When comparing both the frequencies of the three lactones with respect to their O-C(=O) and $O-CH_2$ stretching bands and their internal energies, the following conclusions can be drawn. For the three lactones studied, ring strain increases with increasing ring size, i.e.

ring strain : γ-butyrolactone < δ-valerolactone < ε-caprolactone
ring size : 5 < 6 < 7

Table 1 : Comparison of the vibrational frequencies of the lactone monomers studied in this work.

Comparison of the vibrational frequencies of γ-butyrolactone from FT-IR, FT-Raman and MSI.

FT-IR		FT-Raman		MSI	
frequency	% T	frequency	intensity	frequency	intensity
2992.0	30.9	2988	strong	2988.14	0.0186
2917.0	30.7	2930	strong	2967.41	0 0209
				2924.44	0.0082
				2911.21	0.0092
1762.0	-0.4	1757	medium	1714.1	0.0285
1462.0	32.0	1491	medium	1465.24	0 0126
1423.0	34.0	1467	medium	1447 69	0.0112
1377.0	6.0	1429	medium	1370.81	0.0162
1318.0	65.2			1307 42	0 0212
1280.0	45.9			1288.15	0.0018
1241.0	33.3	1240	medium	1231.11	0 0124
1175.0	-0.1	1217	weak	1171.64	0.0124
				1143.98	0.0053
1083.0	46.1			1072.08	0.0036
1038.0	0.2	1045	weak	1038.37	0.0015
992.0	1.2			981.297	0.0069
931.0	25.7	926	medium	942.342	0.0075
871.0	24.9			896.579	0.0057

Comparison of the vibrational frequencies of δ-valerolactone from FT-IR, FT-Raman and MSI.

FT-IR		FT-Raman		MSI	
frequency	% T	frequency	intensity	frequency	intensity
2961.0	40.1	2972	strong	2980.9	0.0173
2912.0	49.8	2911	strong	2960.05	0.0167
				2949.76	0.0188
				2943.15	0.0071
				2923 66	0.0078
				2900.09	0.0130
				2890.86	0.0055
1734.0	10.2	1731	medium	1716.04	0.0277
1491.0	61.0	1451	medium,broad	1446.07	0.01
1463.0	53.0			1433.68	0.015
1445 0	55.5			1423.03	0.0195
1402.0	35.8			1400 46	0.0139
1343.0	35.9			1364.69	0.0057
				1345 82	0 0291
				1331.75	0.0134
				1304 64	0.0096
1279.0	43.6	1280	medium,broad	1262.39	0.0081
1240.0	13.4			1209.16	0.0114
1159.0	19.5	1165	weak,broad	1173.83	0.0049
1079.0	21.7	1085	weak		
1056.0	11.4	1063	weak	1033 47	0 0026
				1013.56	0.0003
983.0	65.6			946.223	0.0056
931.0	35.7			925.79	0.0018
879.0	73.5	880	weak	893 443	0.0041
827.0	70.3	800	weak	867.117	0.0046
749.0	58.8	754	medium	745.324	0.011

Comparison of the vibrational frequencies of ε-caprolactone from FT-IR, FT-Raman and MSI.

FT-IR		FT-Raman		MSI	
frequency	% T	frequency	intensity	frequency	intensity
				2946.64	0.0175
2936.0	20.6	2930	strong	2937.49	0.0055
				2923.01	0.0096
2863.0	43.0	2860	medium	2900.49	0.0157
1729.0	4.6	1733	medium	1714.33	0.0264
1477.0	47.7	1463	medium	1486 58	0.0125
1439.0	33.6			1436.48	0.0181
				1426 3	0.0117
				1412.67	0.0162
1393.0	33.8			1374 34	0.0208
				1361.82	0.0135
1348.0	29.5	1342	weak	1348.75	0 0196
				1325.38	0.0079
				1313.03	0.0003
1292.0	16.3	1297	weak	1276.57	0 0078
1252.0	23.0			1253 68	0 0082
1226.0	37.6			1221.5	0.0102
1168.0	6.0	1165	very weak	1138.79	0.0004
1100.0	30.4				
1089.0	24.6	1088	weak	1064.87	0.0006
1056.0	12.1			1050 98	0.0019
1016.0	24.4	1023	weak	1002.3	0.0006
988.0	43.1				
963.0	49.2			958.738	0.0005
				938.392	0.0014
892.0	73.6			888.602	0.0049
863.0	55.4				
850.0	52.5			827 143	0 0052
				809.556	0.0039
				760.784	0.0143
735.0	69.8	743	medium	729.014	0.0107
696.0	56.0	709	medium	693.129	0.0125
				605.666	0.004

Table 2 : Comparison of the bond angles and bond lengths of the cyclic ester monomers studied in this work.

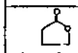
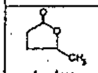
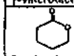
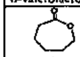
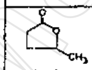
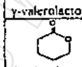
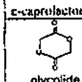
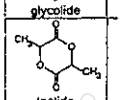
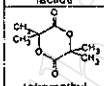
	strain energy	bond angle			bond length		
	(kJ/mol)	$\text{C-O-}\overset{O}{\text{C}}$	$\text{O-}\overset{O}{\text{C}}\text{-C}$	C-C-C	O-C	$\text{O-}\overset{O}{\text{C}}$	C-C
 γ-butyrolactone	32.2 (4)	108 9900	110 35	102.08	1.4400	1.3800	1.53
 γ-valerolactone	30.5 (4)	109 0330	110.4402	102.09	1.4361	1,3780	1.5275
 δ-valerolactone	39 7 (4)	121 0450	114,9411	113.8-114.0	1 4620	1 4025	1 5480-1 6505
 ε-caprolactone	-	125 5423	177,6563	113 7-115.21	1 4559	1 4003	1 5425-1 5477
equilibrium value		109 5	110	110 5	1 425	1 37	1 526

Table 3 : Comparison of strain energies and energy changes from Biosym and heats of polymerisation of the cyclic ester monomers studied.

	strain energy (kJ/mol)	internal energy of polymer (5 repeat units) (kJ/mol), P_5	internal energy of polymer (4 repeat units) (kJ/mol), P_4	internal energy of monomer (kJ/mol), M	$\Delta H'_p$ (kJ/mol)	$\Delta H^o_{p\infty}$ (kJ/mol)	$\Delta S^o_{p\infty}$ (J/mol K)	$\Delta G^o_{p\infty}$ (kJ/mol)
 γ-butyrolactone	32.2 (4)	51.68	39.79	27 32	-15.43	-8.8	-65	12.6
 γ-valerolactone	30 5 (4)	91.36	70.78	27.64	-7 06	-	-	-
 δ-valerolactone	39,7 (4)	54 48	42 15	39.16	-26.83	-27 4	-65	-8 0
 ε-caprolactone	-	60.65	44 57	51 97	-35 69	-28.8	-53 9	-12 8
 glycolide	31.0 (6)	94 89	73.30	44.62	-23 03	-34 0	-0.3	-32 1
 lactide	-	154 14	119.32	55 74	-20 92	-	-	-
 tetramethyl glycolide	-	290 01	227.34	76 13	-13 46	-	-	-

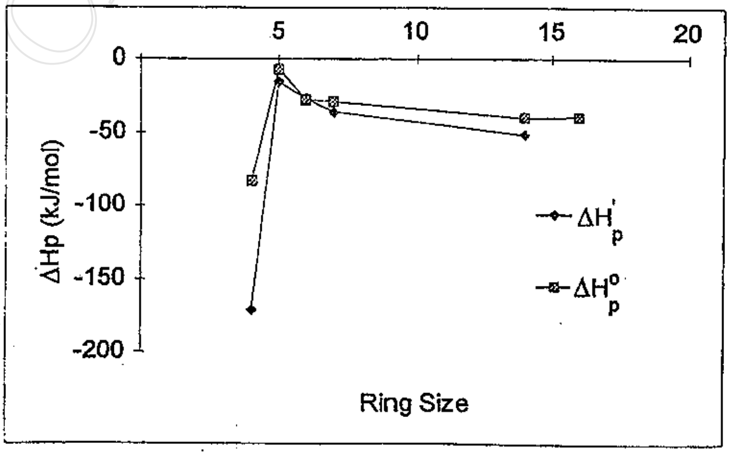


Figure 1 : Comparison of ΔH^o_p and $\Delta H'_p$ for different ring sizes.

(b) Thermodynamic Polymerisability

The thermodynamic polymerisability of a cyclic ester monomer can be estimated from its change in free energy during ring-opening. Using MSI, the internal energy of the polymer chain with different degrees of polymerisation (4 or 5) and also of the monomer were determined. The difference in internal energy between the polymer and the monomer was then calculated from Eq.1. The energy change, $\Delta H'_p$, corresponds to the heat of polymerisation. These $\Delta H'_p$ values are compared with the standard enthalpy changes ΔH°_p, as shown in Table 3 and Figure 1.

Although they have the same trend, their values are quite different for small ring sizes. From the $\Delta H'_p$ values obtained in this work, the following conclusions can be drawn :

(1) for the 3 lactones studied, $\Delta H'_p$ increases with increasing ring size and ring strain

$\Delta H'_p$: γ-butyrolactone < δ-valerolactone < ε-caprolactone

ring strain : γ-butyrolactone < δ-valerolactone < ε-caprolactone
ring size : 5 < 6 < 7

(2) for the glycolide series studied, $\Delta H'_p$ decreases with increasing substitution on the α-carbon atom

$\Delta H'_p$: glycolide > lactide > tetramethyl glycolide

number of substituents : 0 < 2 < 4

From

$$\Delta G^o_p = \Delta H^o_p - T\Delta S^o_p \qquad (2)$$

when ΔS^o_p is nearly constant, ΔH^o_p can be used instead of ΔG^o_p. Thus, $\Delta H'_p$ can be used to indicate the thermodynamic polymerisability of the cyclic esters studied here.

Interactions between substituents are generally more pronounced in linear than in cyclic molecules. Thus, substitution, mostly affecting the enthalpy of polymerisation, usually decreases polymerisability. The effect of substitution is also demonstrated in the conformational strain (transannular strain) caused by the interaction of groups located either in the immediate neighbourhood or across the ring. The conformational strain in the macromolecule formed may, however, be higher than the conformational strain in the monomer. A typical case where the substituents are kept apart in the monomer but may interact in the macromolecule may be shown schematically as follows.

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ชื่อ-สกุล ผู้อธิบายงานวิจัย วิมล ไสยสมบัติ

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A STUDY OF RING STRAIN AND POLYMERISABILITY IN CYCLIC ESTERS

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Ring strain is one of the most important factors affecting the polymerisability of a cyclic monomer. In this work, the ring strains in γ-butyrolactone, δ-valerolactone and ε-caprolactone were studied by infrared spectroscopy, Raman spectroscopy and molecular modelling. The thermodynamic factors influencing the ability to polymerise of these three lactones and other cyclic diesters in the glycolide series were also studied by molecular modelling. It was found that ring strain increased with ring size for the three lactones studied as did the thermodynamic scope for polymerisation whereas, for the glycolide series, these properties decreased with increasing substitution on the α-carbon.

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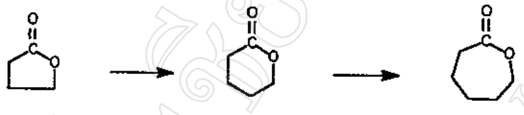
ความเครียดของวงเป็นปัจจัยหนึ่งที่มีอิทธิพลอย่างสูงต่อ ความสามารถในการพอลิเมอไรซ์ของไซคลิกมอนอเมอร์ ในงานวิจัยนี้ได้ศึกษาความเครียดของวงใน แกมมา-บิวทิโรแลคโทน เดลต้า-วาเลอโรแลคโทน และ เอปไซลอน-คาโพรแลคโทน โดยใช้อินฟราเรดสเปคโตรสโคปี รามานสเปคโตรสโคปี และ โมเลกุลลาร์โมเดลลิ่ง วิธีโมเลกุลลาร์โมเดลลิ่งยังได้ใช้ศึกษาเทอร์โมไดนามิคแฟคเตอร์ซึ่งเป็นตัวบ่งบอกถึง ความสามารถในการพอลิเมอไรซ์ของแลคโทนทั้งสามชนิด และ ของไซคลิกไดเอสเทอร์ในอนุกรมของไกลคอไลด์ ในแลคโทนทั้งสามชนิดพบว่า ความเครียดของวงจะเพิ่มขึ้นเมื่อขนาดของวงเพิ่มขึ้น ซึ่งสอดคล้องกับผลการศึกษาทางเทอร์โมไดนามิคส์ของการพอลิเมอไรเซชัน ในขณะที่ในอนุกรมของไกลคอไลด์นั้น ความสามารถในการพอลิเมอไรซ์ลดลงเมื่อหมู่แทนที่บนแอลฟา-คาร์บอนเพิ่มขึ้น

INDEX KEY WORDS: ring strain, thermodynamic polymerisability, lactones, glycolides

ชื่อเรื่อง (ไทย) การศึกษาความเครียดของวงและความสามารถในการเกิดปฏิกิริยาพอลิเมอไรเซชันในไซคลิกเอสเทอร์

การศึกษาความเครียดของวง และความสามารถในการพอลิเมอไรซ์ของไซคลิกมอนอเมอร์ โดยใช้ อินฟราเรดสเปคโตรสโคปี รามานสเปคโตรสโคปี และ โมเลกุลลาร์โมเดลลิ่ง ในอนุกรมของแลคโทนพบว่า เมื่อขนาดของวงเพิ่มขึ้น จาก 5 เหลี่ยม เป็น 7 เหลี่ยม ตามลำดับคือ



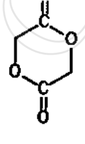
แกมมา-บิวทิโรแลคโทน เดลต้า-วาเลอโรแลคโทน เอปไซลอน-คาโพรแลคโทน

ความเครียดของวงและความสามารถในการพอลิเมอไรซ์จะเพิ่มขึ้น ข้อสรุปนี้ ได้จากการพิจารณาร่วมกันระหว่าง ขนาดของมุมระหว่างพันธะ (bond angle) ความเครียดของวง และ ΔH_p ดังแสดงในตารางที่ 1 และความถี่ของการสั่น (vibrational frequencies) ของพันธะ O-C(=O) และ O-CH_2

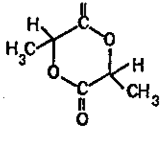
<u>ตารางที่</u> 1 เปรียบเทียบพลังงานความเครียด (strain energies) กับปริมาณความร้อนของปฏิกิริยาพอลิเมอไรเซชัน (heats of polymerisation) ที่ได้จากการคำนวณ และ จากเอกสารอ้างอิง

	พลังงานความเครียด (กิโลจูลต่อโมล)	ΔH_p (คำนวณ) (กิโลจูลต่อโมล)	ΔH_p (เอกสารอ้างอิง 3) (กิโลจูลต่อโมล)	ΔS_p (เอกสารอ้างอิง 3) (จูลต่อโมลต่อองศาเคลวิน)	ΔG_p (เอกสารอ้างอิง 3) (กิโลจูลต่อโมล)
แกมมา-บิวทิโรแลคโทน	32.2 [1]	-16.4	-6.8	-65	12.6
แกมมา-วาเลอโรแลคโทน	30.6 [1]	-7.1			
เดลต้า-วาเลอโรแลคโทน	39.7 [1]	-26.8	-27.4	-66	-8.0
เอปไซลอน-คาโพรแลคโทน		-35.9	-28.8	-64	-12.8
ไกลคอไลด์	31.0 [2]	-23.0	-34.0	-0.3	-32.1
แลคไทด์		-20.9			
เตตระเมทิลไกลคอไลด์		-13.6			

เมื่อพิจารณาอนุกรมของไกลคอไลด์ ซึ่งมีขนาดของวงเท่ากัน แต่มีหมู่แทนที่บนแอลฟา-คาร์บอนต่างกันดังนี้



ไกลคอไลด์



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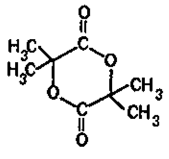

เตตระเมทิลไกลคอไลด์

พบว่าเมื่อหมู่แทนที่บนแอลฟา-คาร์บอนเพิ่มขึ้น ความสามารถในการพอลิเมอไรซ์จะลดลง ข้อสรุปนี้ได้มาจากการพิจารณาการลดลงของค่า ΔH_p ดังแสดงในตารางที่ 1

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polymer papers

Ring strain and polymerizability of cyclic esters

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Ring strain is one of the most important factors affecting the polymerizability of a cyclic monomer. In this work, the ring strains in γ-butyrolactone, δ-valerolactone and ϵ-caprolactone were inferred on the basis of infrared and Raman spectroscopy data. The thermodynamic factors influencing the ability to polymerize of these three lactones and other cyclic diesters in the glycolide series were studied using molecular modelling methods. The ring strain was observed to increase with increasing ring size for the three lactones studied increasing the thermodynamic scope for these monomers to polymerize. For the glycolide series, ring strain and polymerizability decreased with increasing substitution on the α-carbon. © 1998 Elsevier Science Ltd. All rights reserved.

(Keywords: cyclic esters; ring strain; polymerizability)

INTRODUCTION

The development of new biodegradable polyesters for use in biomedical applications such as absorbable sutures and controlled drug delivery systems is an area of considerable interest at the present time[1,2]. Of fundamental importance are the development of a clear understanding of the factors affecting the chemistry of the ring-opening polymerization of cyclic esters and the influence of polymer microstructure on properties, for both academic and technical reasons.

A detailed understanding of the factors affecting the ring-opening polymerization of cyclic esters is the starting point for developing polymer properties relevant to the intended application. The main factors to consider are ring size, ring strain, the nature and extent of substitution on the ring, functionality within the ring and the polymerization conditions used, including the nature of the initiator. Of these factors ring strain is particularly important. The major contributions to ring strain are bond angle distortion (angular strain), bond stretching or compression, repulsion between eclipsed hydrogen atoms (conformational strain, bond torsion) and non-bonding interactions between substituents attached to different parts of the ring (transannular strain)[3,4].

Strain energy calculations furnish valuable information about the relative ring strain in organic compounds, even when the absolute magnitudes obtained are uncertain because of assumptions made in the method and process of computation. Conventional strain energies are apparent in alicyclic compounds when the observed standard molar enthalpies of formation in the gaseous state are compared with values for strain-free structures calculated using modern bond-energy schemes[5]. Such strain energies have been reported for cycloalkanes, cyclic ethers, cyclic thioethers and cyclic imines, and, for all of these, minimum strain-energies are observed for the six-membered ring compounds[6]. For simple lactones, the standard molar enthalpies of combustion which have been reported are for two five-membered rings: γ-butyrolactone and γ-valerolactone, and one six-membered ring lactone: δ-valerolactone[7]. However, if the necessary group equivalents or the heat of formation of the compound of interest are unknown, another approach is required. The ring strains in the cyclic esters studied here can be compared in terms of their internal energies as calculated from molecular modelling and also in terms of the frequencies of their respective O–C(=O) and O–CH_2 ring stretching bands from Fourier transform infrared spectroscopy (*FT*i.r.), Fourier transform Raman spectroscopy (*FT*-Raman) and molecular modelling.

The polymerizability of a cyclic monomer is generally expressed by the extent to which the free energy of the polymerizing system changes as it converts into polymer[8]. Molecular modelling was used to calculate the difference in internal energy between the polymer and the monomer in each case and thus obtain an estimate of polymerizability.

EXPERIMENTAL

Materials

The structures of the cyclic esters studied in this work are illustrated in *Figure 1*.

γ-Butyrolactone, γ-valerolactone, δ-valerolactone and ϵ-caprolactone were supplied by Fluka and were each purified by vacuum distillation from calcium hydride. Glycolide, L-lactide and tetramethyl glycolide were synthesized and purified by recrystallization.

Spectroscopy

All *FT*i.r. analyses were performed on a Perkin-Elmer *FT*i.r. 1720-X Spectrometer with the sample placed between polished sodium chloride windows.

FT-Raman analyses were made on a Perkin-Elmer *FT*-Raman 2000 Spectrometer with the sample held between glass windows.

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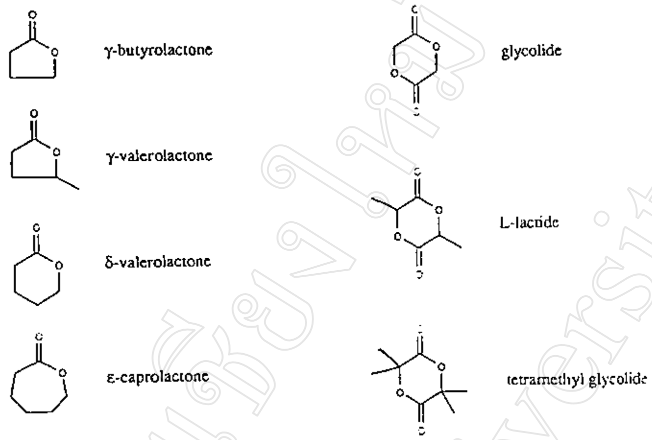

Figure 1 Chemical structures of the cyclic esters studied in this work

Molecular modelling

Molecular modelling was performed using the *Discover* software package[9] running on a SGI Indigo R4000 workstation, using the *Insight* interface to construct the models. The minimized energy of both the monomer (*M*) and the 4- and 5-mers of the polymer (P_4 and P_5) were obtained. The internal energy of a single polymer unit was estimated as the difference in energy between the 5- and 4-mers and so the change in internal energy upon polymerization (ΔH_p) could be calculated from:

$$\Delta H_p = (P_5 - P_4) - M$$

The normal modes of vibration, together with infrared frequencies, were calculated with *Discover*[9] using a method which involves the diagonalization of the second derivative of the energy function (the Hessian) at the calculated minimum energy conformation.

RESULTS AND DISCUSSION

Table 1 shows calculated bond lengths and bond angles for a series of cyclic esters studied. As the ring size increases from 5 to 7, the deviations from the forcefield equilibrium values (which would be close to those found in a non-cyclic molecule) increase. This correlates with the reported increases in strain energy[7] which are listed in *Table 2*.

Reported values of the change in free energy (ΔG_p) and entropy (ΔS_p) during the ring opening of cyclic esters[11] are included in *Table 2*. It can be seen that ΔS_p remains essentially constant over the series of lactones studied, which is as would be expected since the dominant factor in ΔS_p is the loss of translational entropy brought about by the large reduction in the number of molecules present, a factor which is relatively constant from system to system. Therefore, the variations in ΔH_p can be used to indicate the relative thermodynamic polymerizabilities in place of ΔG_p. Even though the thermodynamic parameters given in *Table 2* are not standard state values, their trends still allow for valid conclusions to be drawn since the various systems studied are closely comparable in physical terms.

Results from our molecular modelling calculations are compared with previous work[11] in *Figure 2* and the good agreement is evident for ring sizes in the range 5–7. It can be seen that, as the ring size increases from 5 to 7, the magnitude of ΔH_p changes significantly in a manner to be expected until it becomes essentially constant (values in the range − 35 to − 50 kJ/mol) for ring sizes of 8 to 16. From a thermodynamic standpoint, the larger cyclic monomers (more than eight units in the ring) can be more readily polymerized.

For the glycolide series, ΔH_p decreases with increasing substitution on the α-carbon atom. Interactions between substituents are generally more pronounced in linear than in cyclic molecules. Thus, substitution, mostly affecting the enthalpy of polymerization, usually decreases polymerizability. Substituents are kept well separated in cyclic monomers but once they are in the linear polymer chain, chain flexibility allows a greater probability of close proximity.

The frequencies of the O–C(=O), O–CH$_2$ and C=O stretching vibrations for the cyclic ester monomers obtained by the different methods employed are compared in *Table 3*. The frequencies show similar trends in all cases but slightly different values depending on the method. In the case of the spectroscopic results, these differences can be attributed to

Table 1 Comparison of the calculated bond angles and lengths of the cyclic esters studied

	Bond angle (deg.)			Bond length (Å)		
	C–O–(C=O)	O–(C=O)–C	C–C–C	O–C	O–(C=O)	C–C
γ-butyrolactone	109.0	110.3	102.1	1.44	1.38	1.53
γ-valerolactone	109.0	110.4	102.1	1.44	1.38	1.53
δ-valerolactone	121.0	114.9	113.9	1.46	1.40	1.55
ε-caprolactone	125.5	117.6	114.4	1.46	1.40	1.54
Forcefield equilibrium value	109.5	110.0	110.5	1.425	1.370	1.526

Table 2 Comparison of strain energies with calculated and reported heats of polymerization

	Strain energy (kJ mol^{-1})	ΔH_p (calc) (kJ mol^{-1})	ΔH_p (Ref. 11) (kJ mol^{-1})	ΔS_p (Ref. 11) (J mol^{-1} K^{-1})	ΔG_p (Ref. 11) (kJ mol^{-1})
γ-butyrolactone	32.2 (Ref. 7)	− 15.4	− 6.8	− 65	12.6
γ-valerolactone	30.5 (Ref. 7)	− 7.1			
δ-valerolactone	39.7 (Ref. 7)	− 26.8	− 27.4	− 65	− 8.0
ϵ-caprolactone		− 35.9	− 28.8	− 54	− 12.8
Glycolide	31.0 (Ref. 10)	− 23.0	− 34.0	− 0.3	− 32.1
Lactide		− 20.9			
Tetramethyl glycolide		− 13.5			

Table 3 Comparison of vibrational frequencies of the cyclic ester monomers from three different methods (all frequencies expressed as cm^{-1})

	γ-butyrolactone (ring size = 5)			δ-valerolactone (ring size = 6)			ϵ-caprolactone (ring size = 7)		
	*FT*i.r.	*FT*-Raman	Molecular modelling	*FT*i.r.	*FT*-Raman	Molecular modelling	*FT*i.r.	*FT*-Raman	Molecular modelling
C=O	1762	1764	1714	1734	1728	1716	1729	1728	1714
O–(C=O)	1241	1245	1231	1279	1280	1262	1292	1286	1276
$O–CH_2$	1038	1038	1038	1056	1055	1033	1089	1091	1065

instrumental limitations or calibration methods or to difficulties in accurately measuring the centre of the band. This error is estimated to be ± 2 cm^{-1}. Examples of the *FT*i.r. and *FT*-Raman spectra are shown in *Figure 3* for δ-valerolactone as evidence of spectral quality.

Molecular modelling calculations are very dependent on the accuracy of the forcefield used and in calculations of the type carried out here the functional form used produces a large difference in the absolute values of the calculated frequencies. However, trends within the molecular modelling data are more accurately calculated.

The absorption frequencies of the carbonyl (C=O) group in cyclic esters have been reported[12]. However, these reported values do not correlate well with ring strain because this bond is not part of the ring. On the other hand, the O–C(=O) and $O–CH_2$ vibrations are for groups within the ring and so may be expected to be more directly affected by the ring strain. As the ring size increases from 5 to 7, it becomes more strained, as discussed above. This leads to a more rigid structure and hence the vibrational frequencies increase.

The experimental results shown in *Table 3* show a reduction in the frequency of the carbonyl group as the ring size increases. This suggests that the group becomes held less rigidly as the ring size increases, which may be expected as the internal O–(C=O)–C angle is increasing. In the force field used in the molecular modelling results, this interaction is not included and so these data show no such effect.

CONCLUSIONS

As mentioned at the outset of this paper, a detailed understanding of the factors affecting the ring-opening polymerization of cyclic esters is essential for tailoring polymer properties to meet specific requirements in specialist applications. Central to this understanding is the study of ring strain and thermodynamic polymerizability of the cyclic monomer, properties which this work has shown are determinable through a combination of experimental (*FT*i.r./Raman spectroscopy) and simulation (molecular modelling) methods.

The foregoing results have demonstrated that, for the lactone series, as the ring size increases from 5 to 7 in the order:

γ-butyrolactone → δ-valerolactone → ϵ-caprolactone

the ring strain and the thermodynamic polymerizability also increase. The observed trends in bond angle (*Table 1*), strain energy and ΔH_p (*Table 2*) and C–O bond stretching frequencies (*Table 3*) all combine to support this view.

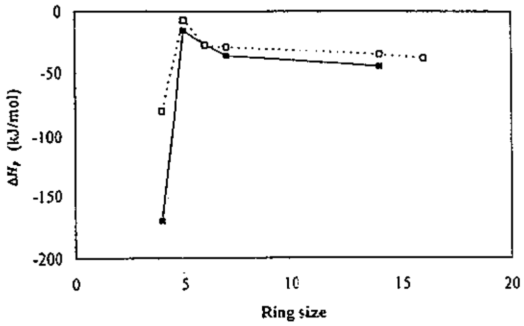

Figure 2 ΔH_p values calculated in this work (——) and from Ref. 11 (- - -) for a series of lactones of different ring sizes

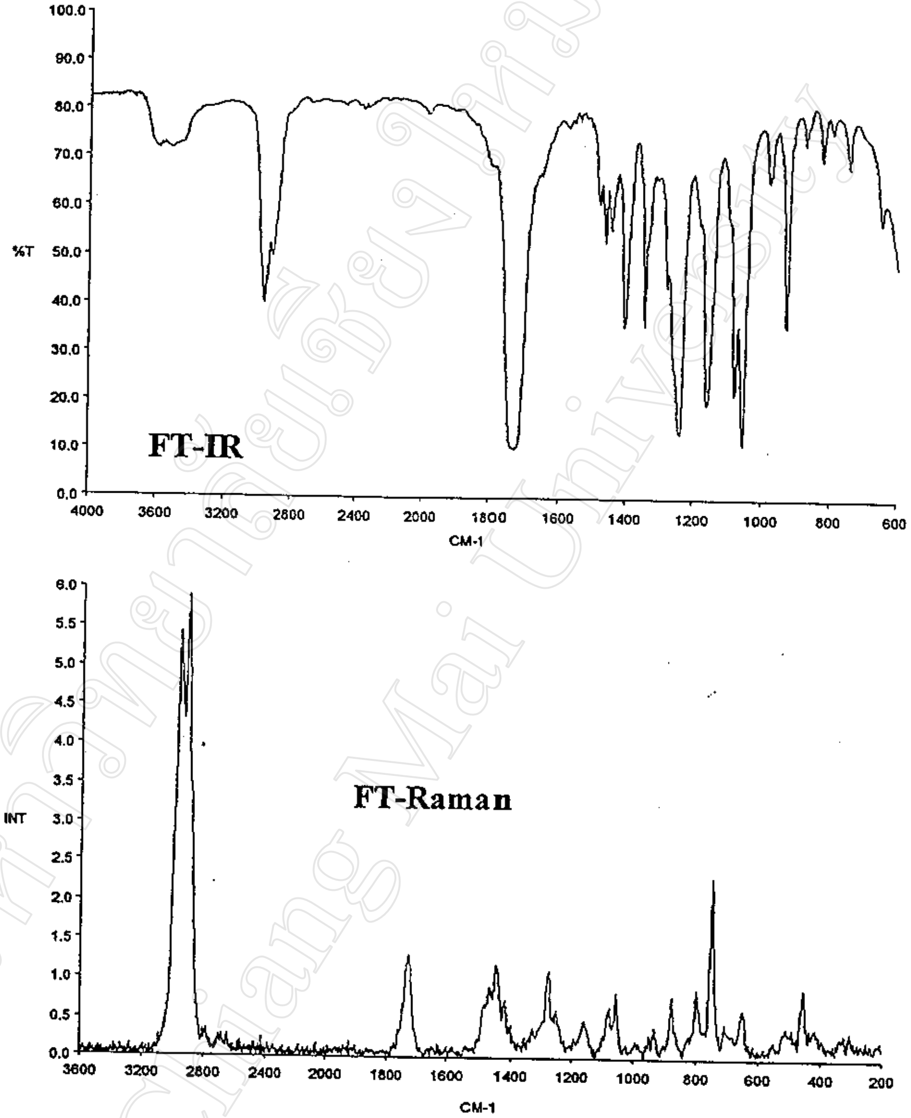

Figure 3 The *FT*i.r. (above) and *FT*-Raman (below) spectra of δ-valerolactone

When the ring size is kept constant, as in the glycolide series, increasing substitution on the α-carbon decreases polymerizability, mainly due to a decrease in ΔH_p. This serves to emphasize the fact that, while ring strain is obviously an important factor, ring substitution also exerts a powerful influence. Increasing either the number or size of the substituents decreases polymerizability as a result of increased intramolecular steric repulsions in the chain relative to the ring. Indeed, this steric effect is so influential that tetrasubstituted glycolides, such as tetramethyl glycolide, are found not to polymerize.

Despite the long history of previous work in the field of ring-opening polymerization, there are still certain aspects of ring-chain inter-conversion which remain unclear. For example, which molecular features in different systems might stabilize chains more than rings, or *vice versa*? What roles do the mechanisms of polymerization (and hence the choice of initiator or catalyst) and thermal depolymerization play? Answers to these and other questions that still remain may possibly be provided in the near future by a combination of methods such as those which have been employed in this study.

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