Water-soluble polyesters from long chain alkylesters of citric acid and poly(ethylene glycol)

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Abstract

Long chain aliphatic alcohols have been used as model compounds to develop a preparative method for a water-soluble material, which could be a carrier for triacontanol, a highly hydrophobic plant growth regulator. New polyesters from long chain aliphatic (C = 12, 18 and 22) mono-1-alkyl citrates and poly(ethylene glycol) were synthesized and characterized by NMR spectroscopy. The polyester containing the triacontyl moiety was obtained from mono-1-triacontyl citrate, which was synthesized from the corresponding alcohol extracted from the *Agave fourcroydes*. The molecular weight $\overline{M}_n$ of the polyesters depends on experimental conditions during synthesis such as reaction time, atmosphere, catalyst concentration and temperature. The reaction is second order in the early stage of the polyester synthesis. The reaction rate constant is independent of the length of the aliphatic chain, but it decreases with increasing $\overline{M}_n$ of the poly(ethylene glycol) employed. Turbidity measurements have been used to study the polyester solubility. Solubility characteristics were found to depend on the $\overline{M}_n$ of poly(ethylene glycol), the aliphatic-chain length and the value of $\overline{X}_n$ for the polyester. These preparations could potentially be used to release triacontanol.

Keywords: Triacontanol; Polycondensation; Solubility; Mono alkyl citrates; Poly(ethylene glycol)

1. Introduction

The use of 1-triacontanol ($C_{30}OH$) as a stimulating agent for plant growth has been known since 1977 [1], and consequently, a great number of formulations have been proposed using this alcohol as a plant growth regulator [2,3]. Obviously, the main problem associated with the use of triacontanol is its low water solubility, thus several of these formulations contain surfactants, producing aqueous colloidal dispersions [1–4], some of which have not been successful in plant growth stimulation. This failure has been attributed to the preparative procedures used in these dispersions [2,3].

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The covalently attachment of $C_{30}OH$ to a hydrophilic polymeric matrix is an unexplored alternative, which could provide an attractive method for solubilizing $C_{30}OH$ in water. After product application the alcohol can be slowly released into the plant. The triacontanol content in a formulation requires several μg/L to exert a positive effect on plants, although 1 ng/L exhibits significant activity [2]. Thus, the quantity of triacontanol to be attached to the polymer can be rather low. The high cost of $C_{30}OH$ makes long chain aliphatic alcohols suitable as model compounds to obtain a useful polymeric carrier for $C_{30}OH$. A plant growth regulator (PGR) rich in 1-triacontanol has been developed in the University of Havana under the trade name 4M [5] and it has been targeted as the 1-triacontanol source in this study. The 4M contains a mixture of long chain aliphatic alcohols and it is mainly composed of 1-triacontanol, 1-octacosanol ($C_{28}OH$), 1-untriacontanol ($C_{31}OH$) and 1-dotriacontanol ($C_{32}OH$).

The matrix bearing the PGR can be either linear or non-linear. Polycondensation of citric acid with ethylene glycol, performed in the presence of a long-chain aliphatic alcohol, such as 1-decanol, 1-dodecanol or 1-octadecanol, has been described [6]. The proportions of the reagents were chosen such that the system should not reach the gel point. Under these synthetic conditions, oligomers were obtained, which were soluble in organic solvents and consisted of a mixture of oligomers, in which not all molecules were bound to an aliphatic alcohol moiety. Thus, low proportions of the products were soluble in water, and the rest formed stable colloidal dispersions. The proportion of soluble components decreased as the aliphatic alcohol chain length increased.

A linear polymer support can be prepared by the polycondensation of a suitable alcohol derivative and a hydrophilic comonomer. Mono-1-alkyl citrates are good candidates for the synthesis of linear polyesters, in which long chain aliphatic alcohols are attached to the polymer backbone. Poly(ethylene glycol) (PEG) is a highly hydrophilic polymer that can provide good solubility properties and has been widely used in the design of amphiphilic copolymers as spacers between hydrophobic groups [7–9].

The purpose of our work was to prepare and characterize water-soluble polymers containing long chain aliphatic moieties, of 12–30 carbon atoms. The preparation of amphiphilic materials that might be dispersed in water as stable colloidal dispersion was also considered because of the hydrophobic character that the aliphatic moieties confer to the polymer chain. In this way, polyesters prepared from mono-1-alkyl citrates and poly(ethylene glycol) have been prepared, using different reaction conditions. The water solubility of these polymers was studied in view of the future application of 1-triacontanol derivatives as plant growth stimulants.

2. Experimental

2.1. Materials

1-Docosanol, poly(ethylene glycol) 600, 1500, 2000 and 4000 were obtained from Sigma; 1-octadecanol, p-toluene sulfonic acid (PTSA) from Merck; 1-dodecanol, hexaethylene glycol, poly(ethylene glycol) dimethyl ether 1000 from Aldrich, and ethylene glycol and tetraethylene glycol from Acros. 4M was kindly supplied by the Department of Organic Chemistry (IMRE) at the University of Havana. It was extracted from the *Agave fourcroydes* as a mixture of long chain aliphatic alcohols (mainly composed of 35–46% of $C_{30}OH$, 15–20% of $C_{28}OH$, 16–19% $C_{32}OH$, 7–12% of $C_{31}OH$) [5]. In order to name this mixture, the notation 30M will be used, e.g., $C_{30M}OH$.

2.2. Monomers synthesis

Mono-1-alkyl citrates (CAC_x $x = 1$, 12, 18, 22 and 30M) were prepared using the method developed by Kotick [10]; transesterification of 1,3-dioxolan-4-ona-5,5-diacetic acid (DODA) with the corresponding alcohol and triethylamine at reflux temperature for 22 h (Fig. 1). The synthetic conditions are shown in Table 1.

Mono-methyl citrate (CAC_1), mono-1-dodecyl citrate (CAC_{12}) and mono-1-octadecyl citrate (CAC_{18}) were purified by evaporation of solvent, and the residual mixture was dissolved in ethyl acetate. The solution was washed three times with saturated sodium bicarbonate solution. The aqueous solution was washed twice with ethyl acetate and then adjusted to pH 2 by the drop-wise addition of concentrated HCl. The precipitate obtained was extracted with three portions of ethyl acetate. The organic phase was dried with magnesium sulfate, filtered and the solvent evaporated. The oily residue from CAC_1 was recrystallized several times from acetone and, in the case of CAC_{12} and CAC_{18}, from toluene. Purification of mono-1-docosyl citrate
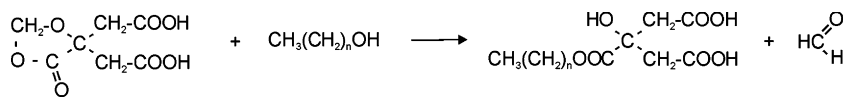
Fig. 1. Synthesis of CAC_x ($x = 1, 12, 18, 22$ and 30M); $n = x - 1$.

Table 1
Conditions of synthesis for mono-1-alkyl citrate (CAC_x $x = 1, 12, 18, 22$ and 30M), reaction time = 22 h

CAC_x derived from	x	DODA		Alcohol		Triethylamine		Chloroform	Yield
		g	mol	g	mol	mL	mol	mL	(%)
Methanol	1	15.0	0.073	4.7	0.147	22.0	0.161	150	45
1-Dodecanol	12	15.0	0.073	27.4	0.147	22.0	0.161	150	30
1-Octadecanol	18	15.0	0.073	39.7	0.147	22.0	0.161	150	28
1-Docosanol	22	4.70	0.023	15.0	0.046	7.0	0.050	50	25
4M	30M	0.45	2.2×10^{-3}	2.0	4.5×10^{-3}	0.7	0.005	10	18

(CAC_{22}) was performed by evaporation of chloroform and recrystallizing twice from ethyl acetate. The solid was dispersed in water and the solution was adjusted to pH 2 by drop-wise addition of concentrated HCl. The solid was filtrated and dried, and subsequently recrystallized from carbon tetrachloride several times until 1-docosanol had been totally removed. In order to prepare an equimolar mixture of CAC_{30M} and $C_{30M}OH$, mono-1-triacontyl citrate (CAC_{30M}) was purified by successive elimination of $C_{30M}OH$ from the reaction mixture according to the following procedure. The chloroform was evaporated and the remaining oil recrystallized twice from ethyl acetate and once from toluene. The solid was dissolved in hot pyridine and cooled, and the soluble fraction isolated. The pyridine solution was added to dilute HCl and that adjusted to pH 2. The precipitate was filtrated and washed several times with dilute HCl. These last steps were repeated until the desired composition was reached. The monomer composition was determined by comparison of the ratio of the integrals of CH_2OH and $COOCH_2$ triplet signals, from the alcohol and the monocitrate respectively, in the ^{1}H NMR (pyridin-d_5) spectrum.

CAC$_1$: FTIR (cm^{-1}): 3384 (ν_{O-H} alcohol), 3207 (ν_{O-H} acid), 1747 ($\nu_{C=O}$ ester), 1716 ($\nu_{C=O}$ acid). ^{1}H NMR (D_2O, δ in ppm): 2.81 (d, H_k^I and H_n^I), 3.03 (d, H_k^{II} and H_n^{II}), 3.78 (s, 3H$_a$). ^{13}C NMR (CDCl$_3$, δ in ppm): 45.4 (C_k and C_n), 54.5 (C_a), 75.3 (C_t), 173.5 (C_j and C_p), 175.9 (C_h) (Fig. 2a).

CAC$_{12}$ and CAC$_{18}$: T_m (CAC$_{12}$) = 80.7 °C, T_m (CAC$_{18}$) = 92.3 °C. FTIR (CAC$_{12}$, CAC$_{18}$, cm^{-1}): 3471 (ν_{O-H} alcohol), 3030 (ν_{O-H} acid), 2951, 2915, 2846 (ν_{CH} CH$_2$), 1744 ($\nu_{C=O}$ ester), 1698 ($\nu_{C=O}$ acid), 723 (ρ_{CH2}). ^{1}H NMR (CAC$_{12}$, CAC$_{18}$,
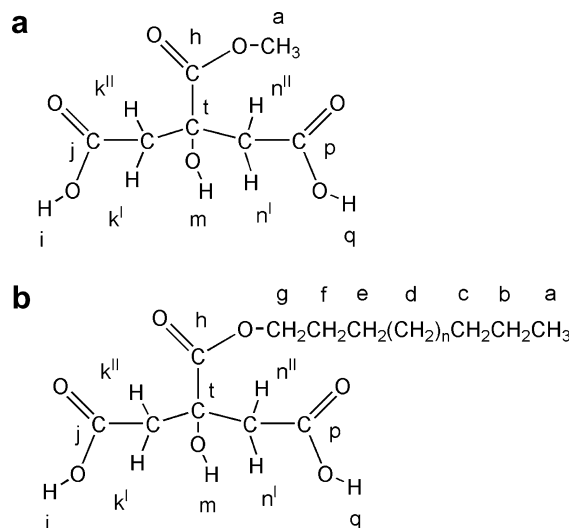

Fig. 2. Scheme of the chemical formulas used to assign the signals in the NMR spectra of monomers. (a) CAC$_1$, (b) CAC$_x$ ($x = 12, 18, 22$ and 30M); $n = x - 6$.

CDCl$_3$, δ in ppm): 0.89 (t, 3H$_a$), 1.27 (m, 2H$_b$, 2H$_c$, 2nH$_d$ and 2H$_e$), 1.66 (m, 2H$_f$), 2.88 (d, H_k^I and H_n^I), 2.96 (d, H_k^{II} and H_n^{II}), 4.22 (t, 2H$_g$). ^{13}C NMR (CAC$_{12}$, CAC$_{18}$, CDCl$_3$, δ in ppm): 14.5 (C_a), 23.1 (C_b), 26.1 (C_e), 28.8, 29.5, 29.7, 29.8, 29.9, 30.1 (C_d), 32.3 (C_c), 43.2 (C_k and C_n), 67.2 (C_g), 73.3 (C_t), 173.4 (C_j and C_p), 175.4 (C_h), where $n = 6$ for CAC$_{12}$ and $n = 12$ for CAC$_{18}$ (Fig. 2b).

CAC$_{22}$: T_m = 75.0 °C, FTIR: 3442 (ν_{O-H} alcohol), 2919, 2849 (ν_{CH} CH$_2$), 1739 ($\nu_{C=O}$ ester), 1721 ($\nu_{C=O}$ acid), 721 (ρ_{CH2}). ^{1}H NMR (pyridin-d_5, δ in ppm): 0.87 (t, 3H$_a$), 1.31 (m, 2H$_b$, 2H$_c$, 2nH$_d$ and 2H$_e$), 1.73 (m, 2H$_f$), 3.51 (d, H_k^I and H_n^I), 3.64 (d, H_k^{II} and H_n^{II}), 4.44 (t, 2H$_g$), 6.84 (H$_i$ and H$_q$). ^{13}C NMR (pyridin-d_5, δ in ppm): 14.4

(C_a), 23.1 (C_b), 26.4 (C_e), 29.1, 29.7, 29.8, 30.0, 30.2 (C_d), 32.3 (C_c), 44.8 (C_k and C_n), 65.9 (C_g), 74.7 (C_t), 173.5 (C_j and C_p), 174.9 (C_h), where $n = 16$ (Fig. 2b).

CAC$_{30M}$: $T_m = 79$–82 °C, FTIR (CAC$_{30M}$, cm^{-1}): 3441 (ν_{O-H} alcohol), 2917, 2849 (ν_{CH} CH$_2$), 1731 ($\nu_{C=O}$ ester), 719 (ρCH$_2$). ^{1}H NMR (pyridin-d_5, δ in ppm): 0.85 (t, H_a), 1.28 (m, H_b, H_c, H_d and H_e), 1.70 (m, H_f), 3.48 (d, H_k^I and H_n^I), 3.60 (d, H_k^{II} and H_n^{II}), 3.87 (t, C$\underline{H}_2$OH from alcohol), 4.41 (t, H_g), 6.84 (H_i and H_q). ^{13}C NMR (pyridin-d_5, δ in ppm): 14.3 (C_a), 22.9 (C_b), 26.2 (C_e), 28.9, 29.5, 29.6, 29.8, 29.9, 30.0 (C_d), 32.1 (C_c), 44.7 (C_k and C_n), 65.7 (C_g), 74.6 (C_t), 173.3 (C_j and C_p), 174.7 (C_h) (Fig. 2b).

2.3. Polymerization

Polyesters from CAC$_{18}$ and ethylene glycol (EG), tetraethylene glycol (TEG) and hexaethylene glycol (HEG) with p-toluenesulfonic acid as a catalyst were prepared by bulk polymerization under the experimental conditions of method I shown in Table 2. Fig. 3 presents the reaction scheme. Similarly, polyesters from CAC$_x$ ($x = 1$, 12, 18 and 22) and poly(ethylene glycol) were prepared under conditions summarized in Table 2. Reactions according to methods I to IV were performed at atmospheric pressure in the presence of air during the first hour of the reaction. The [CAC$_{30M}$ and PEG 1500 (1:1 mol)] polyester was synthesized according to method V and taking into account that CAC$_{30M}$ contains equimolar quantity of C$_{30M}$OH.

2.4. Characterization

The degree of conversion of the polycondensation reaction was determined by ^{13}C NMR from the intensity of the signals of carbonyl groups at 169.3 ($-$COOPEG, $I_{169.3}$) and 171.2 ppm ($-$COOH, $I_{171.2}$) in the spectra ($p = I_{169.3}/(I_{169.3} + I_{171.2})$), and by potentiometric titration of initial and final carboxylic end-group content ([COOH] in eq/g) with a 0.01 N NaOH standard solution, using a MTW pMX 3000 pH-meter. Values of $\overline{X}_n$ were calculated according to $\overline{X}_n = [\text{COOH}]_o/[\text{COOH}]$ by potentiometric titration and $\overline{X}_n = (I_{169.3} + I_{171.2})/I_{171.2}$ by ^{13}C NMR. ^{1}H and ^{13}C NMR spectra were recorded with a Bruker AC300 FT NMR spectrometer. The nature of each atom was determined using the distortionless enhancement by polarization transfer (DEPT) technique with proton pulses at 135°. Heteronuclear Multiple Quantum Coherence (HMQC) spectra were used to assign the signals in ^{13}C NMR spectrum of poly(CAC$_{12}$–PEG 600). Gel Permeation Chromatography (GPC) was measured on a PSS system with a HPLC TSP P100 pump, Waters 717plus autosampler inyector, Shodex RI-71 refractive index detector and PSS-SDV 5 μ combined columns with porosities of 100, 1.000 y 10.000 Å. THF

Table 2
Conditions of synthesis for the polyester of mono-1-alkyl citrate with the respective diol

Method	CAC$_x$/diol[a] (mol ratio)	[PTSA] %[b]	Reaction time (h)	Temperature (°C)	Atmosphere
I	1	1.25	8	135	Reduced pressure[c]
II	1	1.25	**25**	135	Reduced pressure[c]
III	1	1.25	8	**180**	Reduced pressure[c]
IV	1	**6.25**	8	135	Reduced pressure[c]
V	1	6.25	8	135	**Nitrogen flow[d]**

[a] $x = 1$, 12, 18, 22 and 30M. Diol = ethylene glycol, tetraethylene glycol, hexaethylene glycol or poly(ethylene glycol). In the case of CAC$_{30M}$, an equimolar mixture of CAC$_{30M}$ + C$_{30M}$OH was used.
[b] [PTSA] % = 100 × PTSA mol/CAC$_{xx}$ mol.
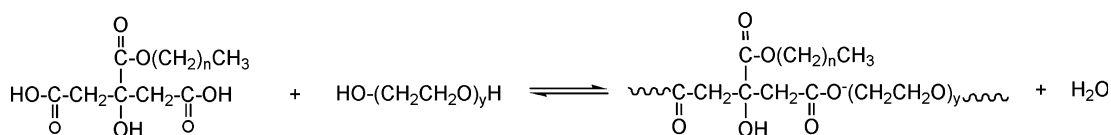[c] $P = 5$ mbar.
[d] Flow = 50 mL/min.

Fig. 3. Scheme of the polycondensation reaction of CAC$_x$ ($x = 1$, $x = 12$, $x = 18$, $x = 22$ and $x = 30M$; $n = x - 1$) and EG ($y = 1$), TEG ($y = 4$), HEG ($y = 6$) or PEG ($y = 13$ (PEG 600), $y = 34$ (PEG 1500) and $y = 45$ (PEG 2000)).

was used as eluent at a flow rate of 1 mL/min. Calibration was undertaken using PSS polystyrene standards with molecular weights from 374 to 1,000,000. The software used was PSS-WinGPC 6.20. Matrix-assisted laser desorption ionization-Time of flight (MALDI-TOF) measurements were performed using a Micromass TOF Spec-E instrument, equipped with a 337 nm nitrogen laser, capable of measuring both in linear and reflectron mode. Dithranol was used as the matrix and THF as the solvent. Measurement of the melting temperatures were undertaken in a Mettler Toledo differential scanning calorimeter, model DSC 822. Samples were heated from 25 to 120 °C at a heating rate of 10 °C/min. Samples were subsequently cooled to 25 °C and heated again to 120 °C, at 10 °C/min. The melting temperature (T_m) was determined from the second heating cycle. The colloidal dispersions of polyesters were sonicated before turbidity measurements were carried out. The turbidity of colloidal dispersions was determined in a UV–Visible spectrophotometer Unicam UV-3 at 500 nm.

3. Results and discussion

The main focus of this work was the incorporation of $C_{30M}OH$ into hydrophilic oligomers, which could be used in solution or in colloidal dispersion to apply in the future as a plant growth stimulant. We were led to work with this alcohol mixture by the fact that 4M gives excellent results as a PGR. An important problem associated with this aim is reaching an appropriate balance between the hydrophobic character of the CAC_{30M} and the hydrophilic contribution of PEG. The triacontanol content in a formulation requires around $1 \, \mu g/L = 2.3 \times 10^{-5} \, mol/L$ to exert a positive effect on plants. Hence, polyesters derived from CAC_{30M} and PEG should have a solubility of around $10^{-5} \, mol/L$ in order to be suitable. This condition can be achieved more easily if polymers of low $\overline{M}_n$, for instance between 10^3 to 10^4 g/mol, are prepared.

The design of the oligomers was based on the use of alcohols with increasing aliphatic chain length to address in a stepwise manner the problems related to synthesis, purification and characterization of the products. The approach to the synthesis was directed at oligomers of low $\overline{M}_n$ in order to achieve suitable solubility and consequently the influence of reaction conditions on molecular weight was studied. The highly hydrophobic character of the alcohol moieties was compensated to some extent by

using PEGs of different $\overline{M}_n$ as comonomers. However, the length of the PEG chain influences the kinetics of polycondensation as well as the solubility of the products. An investigation of both aspects has also been carried out.

3.1. Structural characterization of polyesters

^1H NMR spectra of all polyesters from mono-1-alkyl citrate and PEG showed the same pattern, except for the difference in the methylene signal intensities (e, d, c and b) of the aliphatic chain at 1.22 ppm, and those of the methylenes from PEG (s, u and v) at 3.50 ppm (Fig. 4b). To assign the signals in the ^{13}C NMR spectrum, the HMQC of poly(CAC_{12}–PEG 600) was recorded. This is shown in Fig. 5 as well as the results of DEPT 135° spectra. The ^{13}C NMR spectra can be assigned completely from the correlation between proton and carbon signals. Methylene groups of the aliphatic chain appear at the cross peaks ($^1H/^{13}C$) δ 1.22/22.2, 1.22/25.4, 1.22/28.8, 1.22/29.1, 1.22/31.4 ppm corresponding to b, e, f, d and c, respectively. PEG methylene groups (s, u and v) resonate at the cross peaks ($^1H/^{13}C$) δ 3.50/60.3, 3.50/69.9, 3.56/68.0, 3.39/72.4 ppm. Methylene groups from the citrate moiety (k and n) resonate in the interval 2.62–2.90 ppm (^1H), that correlates with the ^{13}C signal at 42.9 ppm. The signal at 4.08 ppm (H_g) correlates
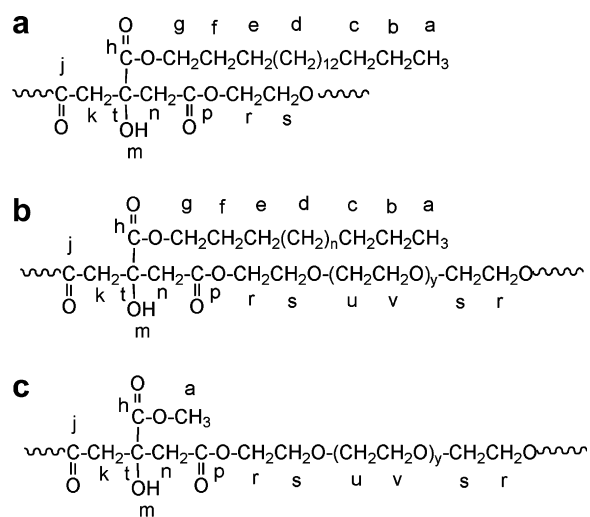
Fig. 4. Scheme of the chemical formulas used to assign the signals in the NMR spectra of polymers. (a) Poly(CAC_{18}–EG), (b) poly(CAC_{18}–TEG) ($n = 12$, $y = 2$), and poly(CAC_{18}–HEG) ($n = 12$, $y = 4$), poly(CAC_x–PEG) ($x = 12$, $x = 18$, $x = 22$ and $x = 30M$; $n = x − 6$; $y = 11$ (PEG 600), $y = 32$ (PEG 1500) and $y = 43$ (PEG 2000)). (c) Poly(CAC_1–PEG 1500) ($y = 32$).
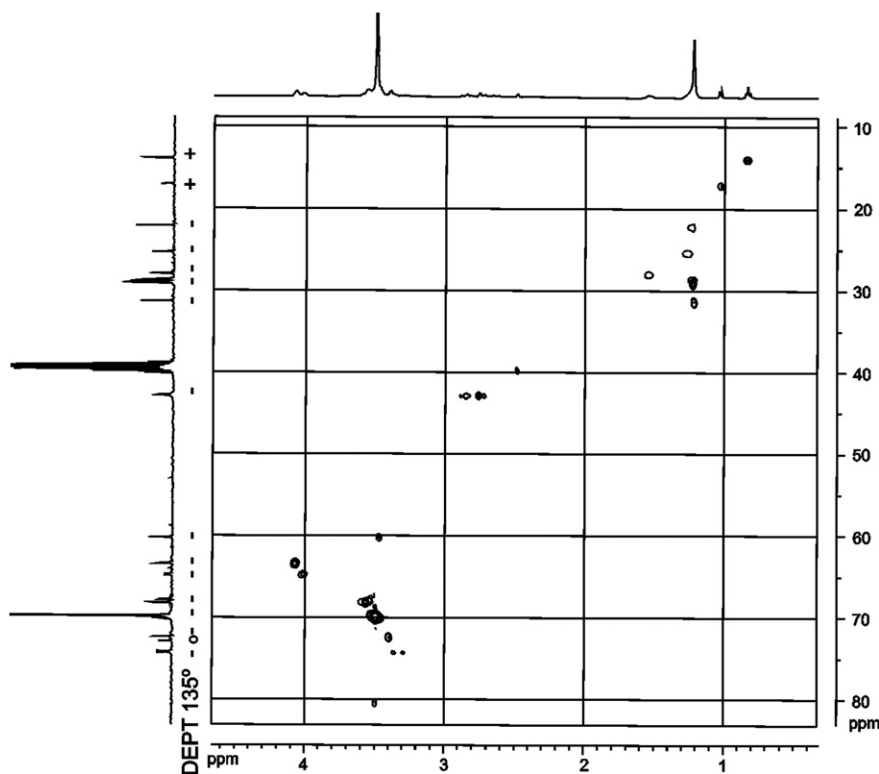
Fig. 5. HMQC of poly(CAC$_{12}$–PEG 600) in DMSO-d_6 combines with the results of DEPT 135° spectrum.

with that at 63.4 ppm (C$_g$) and the signal at 4.18 ppm (H$_r$) with that at 64.8 ppm (C$_r$). The quaternary carbon (C$_t$) atom appears at 72.9 ppm. The ^{1}H doublet at 1.02 ppm, which correlates with the ^{13}C signal at 18.5 ppm corresponds to CH$_3$ groups from isopropyl ethylene units due to imperfections in the PEG structure. This signal did not appear, when PEG 600 from other sources was used. Further experiments were carried out in order to complement the signal assignation of the CH$_2$ groups (r, s, u and v). A doublet in the ^{1}H NMR spectrum corresponds to each geminal proton H^I_k, H$^{II}_k$, H^I_n, H$^{II}_n$. When the citrate unit is symmetrical, (H^I_k, H^I_n) and (H$^{II}_k$, H$^{II}_n$), are equivalent and the spectrum shows two doublets arising from each geminal proton. When the citrate unit is asymmetrical, (H^I_k, H^I_n) and H$^{II}_k$, H$^{II}_n$) are not equivalent, the spectrum shows multiple signals.

The end chains of polyesters having high $\overline{X}_n$ contribute less to the symmetry than those with lower degree of polymerization. Therefore, proton signals of H^I_k, H$^{II}_k$, H^I_n, H$^{II}_n$ can be used as a qualitative test to analyze the degree of polymerization of the polyesters. ^{1}H NMR signals of the geminal protons k and n of poly(CAC$_{12}$–PEG 600), prepared by meth-

ods I and V are shown in Fig. 6. The method V uses higher PTSA concentration than method I and nitrogen flow instead of reduced pressure. Signals from polyesters prepared by method V appear as two doublets, while those from polyesters obtained from method I, as multiple signals. This result indicates that method V produces a polyester with higher degree of polymerization $\overline{X}_n$ than that prepared by method I, as can be expected when a higher concentration of catalyst is used.

The carbonyl region of the ^{13}C NMR spectra has been used in previous work to determine the extent of polyester formation [11]. Citric acid polyesters showed four signals, corresponding to carbonyl bonds of symmetrical and asymmetrical acids and ester groups. All these carbon atoms exhibit similar nuclear Overhauser effects and spin-lattice relaxation times [12]. Therefore, the fraction of carboxylic acid carbonyl groups and the percentages of ester carbonyl groups can be calculated from the intensities of the signals of the carbonyl groups in the proton broad band decoupled ^{13}C NMR spectra. ^{13}C NMR spectra of polyesters prepared from mono-1-alkyl citrates display only three carbonyl signals because there is no free asymmetric acid
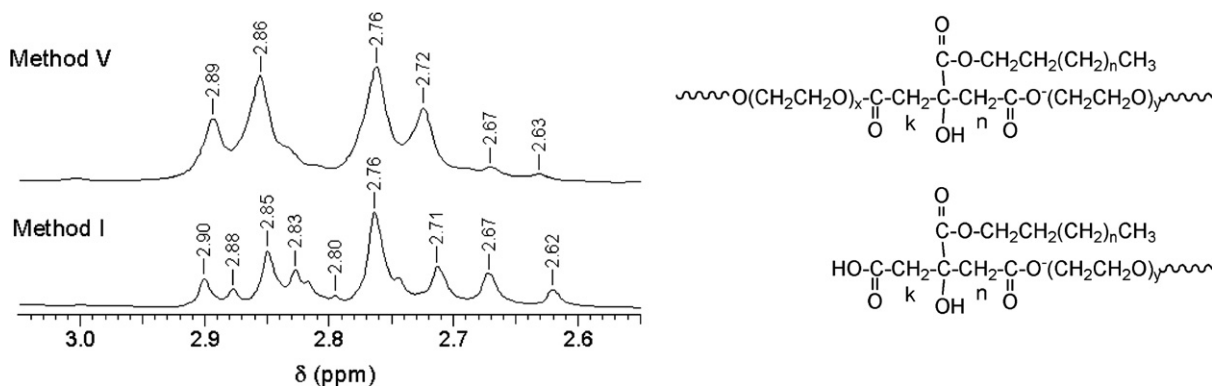
Fig. 6. Expanded ^{1}H NMR spectra (in DMSO-d_6) of poly(CAC$_{12}$–PEG 600) prepared by methods I and V showing methylene proton signals "k" and "n".

group. Fig. 7 shows the carbonyl region of the ^{13}C NMR spectrum of poly(CA$_{12}$–PEG 600) prepared by method I and the multiplicity of the carbon signals which is due to the different statistical distribution of the neighboring atoms in the polymer chain. The chemical shifts of the central position of the signals corresponding to the carbonyl carbon atom (–COOPEG), (–COOH) and (–COOR), where R represents the aliphatic chain, are observed at 169.4, 171.2 and 172.6 ppm, respectively.

In order to complete the assignation of the methylene ^{1}H NMR signals derived from CH$_2$CH$_2$O unities, several polyesters were synthesized; poly-(CAC$_{18}$–EG), poly(CAC$_{18}$–TEG) and poly(CAC$_{18}$–HEG). These polymers have no interest as carriers for long chain aliphatic alcohols because EG, TEG and HEG do not provide adequate hydrophilic character to the polymer and are insoluble in water. The carbonyl region in the ^{13}C NMR spectra of these polyesters provided information about the degree of polymerization. Comparison with the polyesters derived from PEG is described later.

Poly(CAC$_{18}$–EG) contains two symmetric CH$_2$ groups (r and s, Fig. 4a) between two monocitrate moieties. Consequently, resonance of signals from H$_r$ and H$_s$ occurrs at the same frequency (4.24 ppm, Fig. 8). Nevertheless, poly(CAC$_{18}$–TEG) and poly-(CAC$_{18}$–HEG), containing more than two CH$_2$ groups (r, s, u and v), show two signals at 4.17 and 3.58 ppm. The first is assigned to H$_r$ and the second to the rest of the CH$_2$ groups (H$_s$, H$_u$ and H$_v$) in accordance with previous NMR experiments on polyurethanes derived from PEG and diols [13,14]. The H$_g$ signal from aliphatic CH$_2$ linked to a carboxyl group, also appears at 4.17 ppm and is overlapped with the H$_r$ signal in the spectra of poly (CAC$_{18}$–TEG) and poly(CAC$_{18}$–HEG). A fourth molecule which does not contain g groups, was synthesized: poly(CAC$_1$–PEG 1500), and it exhibits a multiplet at 4.10 ppm, which can only be assigned
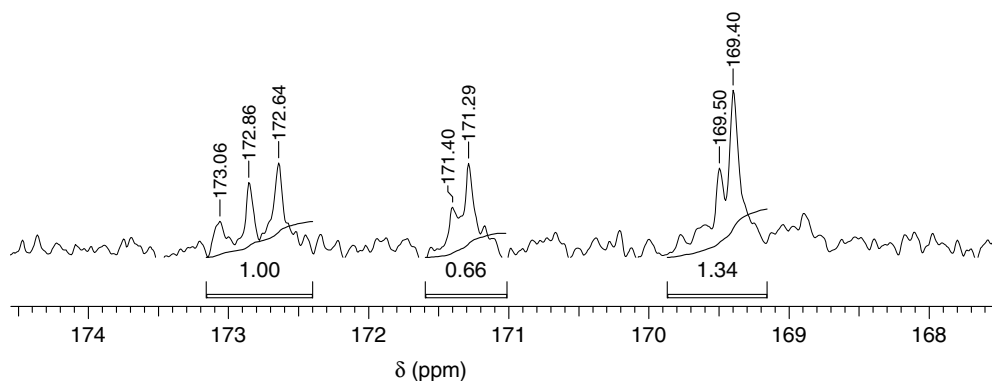

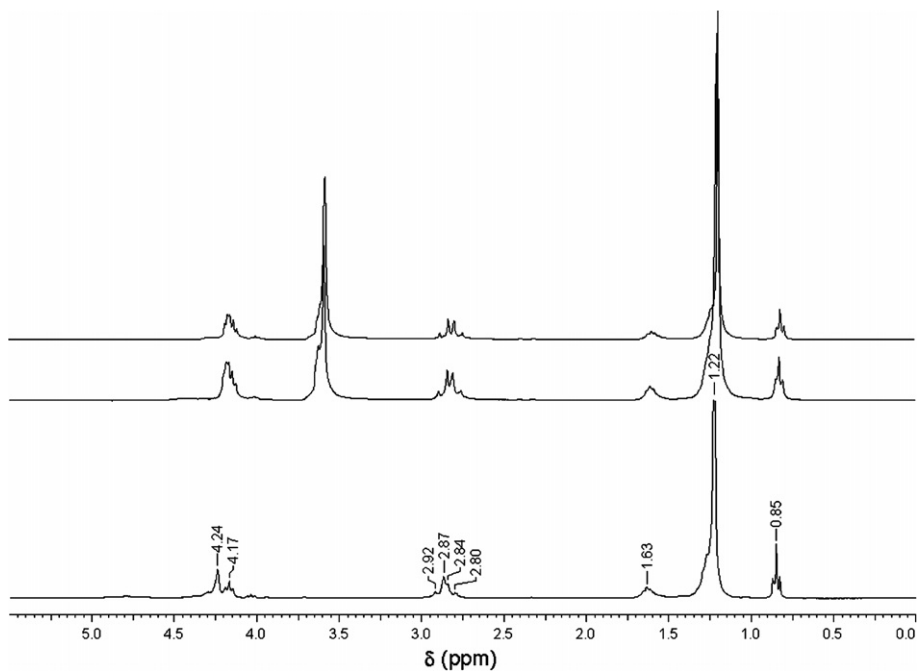Fig. 7. ^{13}C NMR spectrum of carbonyl carbons (in DMSO-d_6) of poly(CAC$_{12}$–PEG 600) prepared by method I.

Fig. 8. ^{1}H NMR spectra (from the bottom) of poly(CAC$_{18}$–EG), poly(CAC$_{18}$–TEG) and poly(CAC$_{18}$–HEG) in CDCl$_3$.
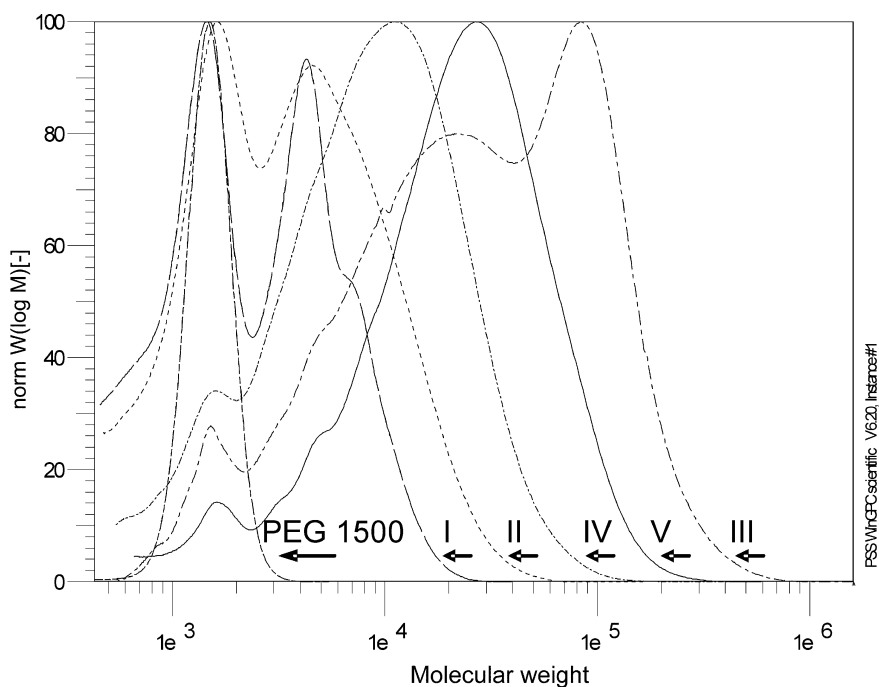

Fig. 9. GPC of PEG 1500 and poly(CAC$_{18}$–PEG 1500) prepared by methods I, II, III, IV and V (Mobile phase: THF).

to r groups. The complete assignment of ^{1}H and ^{13}C NMR signals of the abovementioned poly- esters is described below:

Poly(CAC$_{18}$–EG): ^{1}H NMR (CDCl$_3$, δ in ppm): 0.85 (t, H$_a$), 1.22 (m, H$_b$, H$_c$, H$_d$ and H$_e$), 1.63 (m, H$_f$), 2.82 (d, H$_k^I$ and H$_n^I$), 2.89 (d, H$_k^{II}$ and H$_n^{II}$),

4.17 (t, H_g), 4.24 (m, H_r, H_s). ^{13}C NMR (CDCl$_3$, δ in ppm): 14.1 (C_a), 22.6 (C_b), 25.7 (C_e), 28.3 (C_f), 29.7 (C_d), 31.9 (C_c), 43.1 (C_k, C_n), 62.3 (C_g), 66.6 (C_r, C_s), 73.0 (C_t), 169.3 (–COOEG), 173.2 (–COOR). R = aliphatic chain, C_{18} (Fig. 4a).

Poly(CAC$_{18}$–TEG) and poly(CAC$_{18}$–HEG): ^1H NMR (CDCl$_3$, δ in ppm): 0.81 (t, H_a), 1.19 (m, H_b, H_c, H_d and H_e), 1.60 (m, H_f), 2.76 (d, H_k^I and H_n^I), 2.85 (d, H_k^{II} and H_n^{II}), 4.17 (m, H_g, H_r), 3.58 (m, H_s, H_u, H_v). ^{13}C NMR (CDCl$_3$, δ in ppm): 14.1 (C_a), 22.6 (C_b), 25.7 (C_e), 28.3 (C_f), 29.6 (C_d), 31.8 (C_c), 43.2 (C_k, C_n), 63.9 (C_g), 66.4 (C_r), 70.5 (C_s, C_u, C_v), 72.9 (C_t), 169.5 (–COOTEG or –COO-HEG), 173.3 (–COOR). R = aliphatic chain, C_{18} (Fig. 4b).

Poly(CAC$_1$–PEG 1500): ^1H NMR (DMSO, δ in ppm): signal group from 2.68 to 2.93 (H_k and H_n), 3.66 (s, H_a), 3.51 (m, H_s, H_u, H_v), 4.10 (t, H_r). ^{13}C NMR (DMSO, δ in ppm): 44.0 (C_k, C_n), 51.9 (C_a), 63.3 (C_r), 69.0, 70.6, 73.2 (C_s, C_u, C_v), 73.9 (C_t), 170.0 (–COOPEG), 171.8 (–COOH), 173.9 (–COOCH$_3$) (Fig. 4c).

3.2. Influence of reaction conditions on molecular weight

Polycondensation of CAC$_{18}$ with PEG 1500 was carried out under different experimental conditions. Modifications in the reaction time, catalyst concentration, atmosphere and temperature allow the synthesis of products with different degree of polymerization. The GPC-results shown in Fig. 9 show the molecular weight distribution of PEG 1500 and the polyesters obtained according to the experimental conditions given in Table 2. The degree of polymerization, $\overline{X}_n$ of these products appears in Table 3. Only polyesters derived from EG, TEG and HEG reached high conversion and correspondingly high values of molecular weight. These are overestimated by ^{13}C NMR due to the error in calculating the –COOH intensities ($I_{171.2}$). This error increases as acid groups are consumed in polycondensation. The molecular weights of these polyesters, determined by GPC, were poly(CAC$_{18}$–EG): $\overline{M}_n = 3.1 \times 10^3$ g/mol, $\overline{M}_w = 1.3 \times 10^4$ g/mol, PD = 4.1; poly(CAC$_{18}$–TEG): $\overline{M}_n = 2.9 \times 10^3$ g/mol, $\overline{M}_w = 1.6 \times 10^4$ g/mol, $PD = 5.4$ and poly(CAC$_{18}$–HEG): $\overline{M}_n = 3.5 \times 10^3$ g/mol, $\overline{M}_w = 2.5 \times 10^4$ g/mol, PD = 7.1.

GPC of products obtained from methods I and II show the residues of PEG 1500 in agreement with MALDI-TOF mass spectrometry (Fig. 10). The

Table 3
Reaction conversion and degree of polymerization of mono-1-alkyl citrate with different chain length and poly(ethylene glycol) of different $\overline{M}_n$

Polyester	By ^{13}C NMR		By titration	
	p	$\overline{X}_n$	p	$\overline{X}_n$
Method I				
Poly(CAC$_1$–PEG 1500)	0.52	2.2	–	–
Poly(CAC$_{12}$–PEG 600)	0.69	3.2	0.83	5.9
Poly(CAC$_{12}$–PEG 1500)	0.46	1.8	–	–
Poly(CAC$_{18}$–EG)	1[a]	[a]	–	–
Poly(CAC$_{18}$–TEG)	1[a]	[a]	0.91	11.1
Poly(CAC$_{18}$–HEG)	1[a]	[a]	0.90	10.0
Poly(CAC$_{18}$–PEG 600)	–	–	0.76	4.1
Poly(CAC$_{18}$–PEG 1500)	0.52	2.1	0.50	2.0
Poly(CAC$_{18}$–PEG 2000)	0.30	1.4	–	–
Method II				
Poly(CAC$_{12}$–PEG 600)	0.80	5	–	–
Poly(CAC$_{18}$–PEG 1500)	0.57	2.3	–	–
Method IV				
Poly(CAC$_{18}$–PEG 1500)	0.98	50	–	–
Method V				
Poly(CAC$_1$–PEG 1500)	0.87	7.7	–	–
Poly(CAC$_{12}$–PEG 600)	0.95	20	–	–
Poly(CAC$_{18}$–PEG 600)	0.98	50	–	–
Poly(CAC$_{18}$–PEG 1500)	0.99	100	–	–

[a] Signal intensity at 171.3 ppm, which corresponds to acid groups, is almost negligible giving p values of approximately 1 and high degrees of polymerization, which are not possible to determine by this technique.

GPC data showed three molecular weight distributions, two of them corresponding to PEG cationized with sodium and with potassium, respectively and the third one corresponding to the diester. Good agreement between both methods was also observed in all the samples examined.

The increase in temperature from 135 up to 180 °C (Method III, Table 2) accelerates the polycondensation and thus enhances molecular weights, but also leads to the occurrence of transesterification involving the OH end groups of PEG or oligomers (Fig. 11). Formation of octadecyl alcohol was clearly detected as a white solid deposited on the top of the reaction flask [^1H NMR spectrum in CDCl$_3$, δ in ppm: 0.86 (t, 3H, CH$_3$), 1.23 (m, 30H, (CH$_2$)$_{15}$), 1.55 (m, 2H, CH_2CH$_2$OH), 3.62 (t, 2H, CH$_2$OH)]. The substitution of C$_{18}$ by oligomers, as a consequence of transesterification, produces branched chains, which would lead to an increase of the molecular weight of the polyesters. The polydispersity of chains arising from condensation and transesterification reactions is reflected in the bimodal curve observed in Fig. 9.
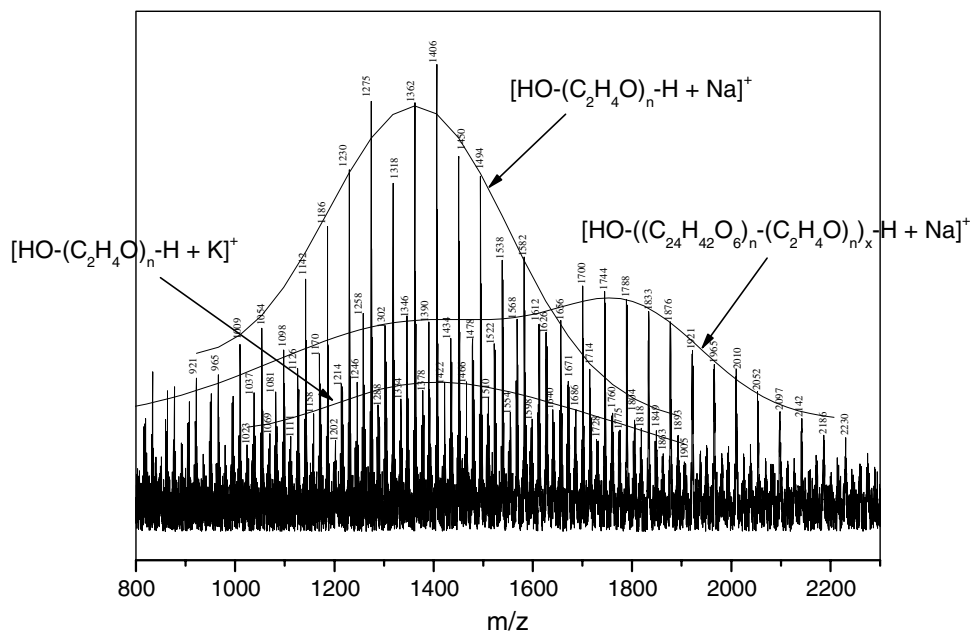
Fig. 10. MALDI-TOF mass spectrum of poly(CAC$_{18}$–PEG 1500) prepared by method I. Three distributions are observed: PEG + Na, PEG + K and poly(CAC$_{18}$–PEG 1500) + Na.
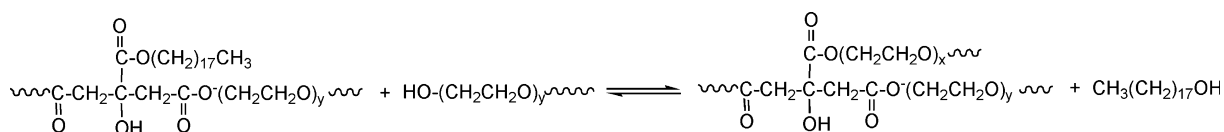

Fig. 11. Scheme of the transesterification reaction of poly(CAC$_{18}$–PEG) either with PEG or oligomers.

An increase in the reaction time from 8 (Method I) to 25 h (Method II) does not significantly alter the degree of polymerization, $\overline{X}_n$ of the products. An increase in the molecular weight is observed when higher catalyst concentration is used, and an additional enhancement of molecular weights is obtained when the reaction is carried out under nitrogen flow instead of reduced pressure.

GPC data of the polyester samples prepared by method V demonstrates a higher molecular weight than that for those obtained from method IV (Fig. 9). The effect of the increase of catalyst concentration is obvious. The substitution of reduced pressure by nitrogen flow eliminates the oxygen present in the early stage of reaction and precludes the formation of formic acid, from the reaction of oxygen with PEG [15–17]. Formic acid is responsible for a stoichiometric imbalance between the OH and CO$_2$H groups, leading to a reduction of the molecular weight of the polyester formed. Thus, it was possible to reach high conversion and high $\overline{X}_n$ values (see Table 3), when PEG was substituted by

ethylene glycol, tetraethylene glycol or hexaethylene glycol in the polycondensation with CAC$_{18}$ under method I conditions.

The ^{13}C NMR spectra of polyesters prepared by methods I, II and IV show a signal at 162.2 ppm arising from carbonyl carbon atom of poly(ethylene glycol) formiate (HCOOCH$_2$CH$_2$–) (Fig. 12). The spectrum of the oligomer obtained from method I was recorded one year after obtaining the sample. It presents an additional signal at 163.04 ppm corresponding to the carbonyl carbon of formic acid, which was probably formed as a consequence of the sample aging (Fig. 12), via a mechanism that was not studied. In accordance with this result, the same signal was observed in the ^{13}C NMR spectrum of a control sample of PEG 600 treated with p-toluenesulfonic acid that was recorded one year after its preparation. Spectra of the other products were recorded without delay. The spectrum of polyester prepared under nitrogen atmosphere (by method V) does not show these signals, indicating that oxidative degradation of PEG was prevented.
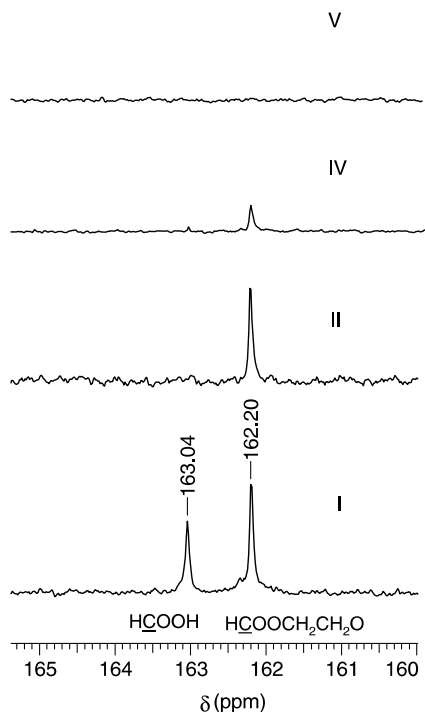
Fig. 12. ^{13}C NMR spectra of carbonyl carbons (in DMSO-d_6) of formate and formic acid produced by decomposition of PEG during the polycondensation reaction of poly(CAC$_{18}$–PEG 1500) prepared by methods I, II, IV and V.

Fig. 13. Kinetics of polycondensation of (■) poly(CAC$_{12}$–PEG 600), (▲) poly(CAC$_{18}$–PEG 600), (●) poly(CAC$_{18}$–PEG 1500) and (◆) poly(CAC$_{18}$-MeOPEG 1000) at 135 °C. Error bars represent the experimental error associated with each volume and mass used in the potentiometric titrations, which were used to calculate the acid concentrations.

Table 4
Rate constants for the polycondensation reaction

Reactions	k (g/eq min)	k' (g/eq min)
Poly(CAC$_{12}$–PEG 600)	9.4 ± 0.2	10.4 ± 0.2
Poly(CAC$_{18}$–PEG 600)	8.7 ± 0.4	9.0 ± 0.4
Poly(CAC$_{18}$–PEG 1500)	3.3 ± 0.2	3.5 ± 0.3

3.3. Kinetics of polycondensation

Kinetic measurements confirm the detrimental effect of the increase of the molecular weight of PEG on the course of the polyester formation. Fig. 13 points out that the reaction presents a deviation from the expected 2nd order kinetics, even at low conversion. Values of the rate constant k are summarized in Table 4. Considering that 2% of the end groups of the PEGs employed are not OH, the k' rate constant was also calculated according to:

$$\frac{1}{[COOH]'} - \frac{1}{[COOH]'_0} = k't\left(1 - \frac{\Delta^2}{4[COOH]'_0[COOH]'_f}\right)$$
(1)

where

$$\Delta = [OH]_0 - [COOH]_0$$

However, both constants are practically equal.

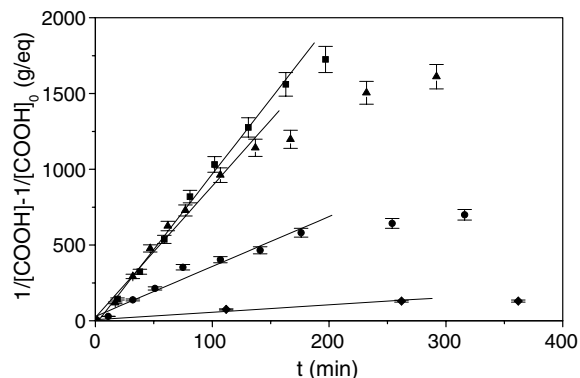The rate constant is independent of the length of the aliphatic chain of the alcohol, but decreases with increasing molecular weight of PEG. A similar effect on the polycondensation kinetics of maleic acid with PEG was observed by Nichifor et al. [18]. They reported the simultaneous formation of –OH groups due to the hydrolysis of the PEG chains, which eliminates the initial stoichiometric balance between –COOH and –OH groups, and delays the polycondensation. This behavior is more significant when higher $\overline{M}_n$ PEG is used.

The deviation from 2nd order kinetics observed by us agrees with the pattern described by Nichifor et al, and we consider that the kinetic behavior is a result of the rupture of PEG C–O bonds. As a consequence, an excess of hydroxyl groups is generated in the reaction medium and the stoichiometric condition is no longer fulfilled.

Further evidence of C–O scission is the reaction of CAC$_{18}$ with poly(ethylene glycol) dimethyl ether 1000 (MeOPEG) under method I experimental conditions. Small quantities of water contained in the reagent are sufficient to produce the hydrolysis of MeOPEG and the OH end groups generated react with the acid groups of CAC$_{18}$. Evidence for PEG ester formation is the appearance of a signal at
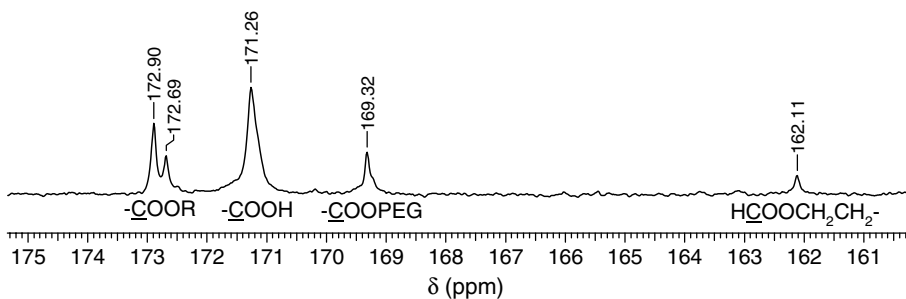
Fig. 14. ^{13}C NMR spectrum of carbonyl carbons (in DMSO-d_6) of poly(CAC$_{18}$–PEGMeO 1000).

169.33 ppm in the carbonyl region of the ^{13}C NMR spectrum of the product (Fig. 14), which corresponds to 13% esterification yield. This value was corroborated by potentiometry, giving 16% yield. This reaction occurs slower than the rest of the polycondensation reactions studied (Fig. 13).

3.4. Solubility of polyesters

All the polyesters spontaneously form turbid solutions ("sols"), and Table 5 shows the time at which flocculation was observed. The process is reversible, and redispersion of products can be achieved by agitation. Poly(CAC$_{12}$–PEG 600) does not flocculate and is completely soluble at 0.02 mol/L. The reversible character of the sols matches with the formation of lyophilic colloids and micelles. Flocculation of sols from poly-(CAC$_{22}$–PEG 1500), poly(CAC$_{22}$–PEG 4000) and poly(CAC$_{30M}$–PEG 1500) occurs in 12 h, while the others are stable for more than 1 month which may be a consequence of the presence of the corresponding alcohol, that does not form micelles.

Turbidity measurements represent a method to calculate the concentration range in which products

are soluble, but in this case only an estimate is possible because product purification is very difficult. Purification of polyesters was attempted by extraction with solvents, precipitation from non-solvents and preparative GPC. Extraction and precipitation give good results with polyesters containing C$_{12}$, but are not applicable to polyesters containing C$_{18}$. Poly(CAC$_{18}$–PEG 1500) was separated from PEG by preparative GPC, however, the yield was low. Dialysis was not attempted because of the low difference between the $\overline{M}_n$ (GPC) of PEG and the polyesters. The purification results become poorer as the chain length of the aliphatic moiety increases. The content of polyester and PEG in each sample was calculated from the deconvolution of their signals in the GPC chromatograms. The results are shown in Table 5 along with the slope of the curves of τ vs. C, and the values of the polyester concentration C$_T$, in which opalescence starts to increase markedly in the curves of turbidity versus $\log C$ (Fig. 15).

The influence of aliphatic chain length of the alcohol moiety (R) and the molecular weight of PEG on polyester solubility is observed in Fig. 15 and Table 5. Polyesters with higher R have lower

Table 5
Polyester concentration above which turbidity starts (C_T)

polyester	Method	$\overline{M}_n$ [a]	Polyester content in the sample (%)[b]	C_T (mol/L)	Slope (L/mol cm)	Flocculation	
						c (mol/L)	Stability
Poly(CAC$_{12}$–PEG 600)	I	960	90		1.8		
Poly(CAC$_{18}$–PEG 600)	I	1000	90	1.5×10^{-3}	116.5	0.02	>1 month
Poly(CAC$_{18}$–PEG 600)	V	6320		7.5×10^{-5}			
Poly(CAC$_{18}$–PEG 1500)	I	1100	88	4.5×10^{-3}	33.2	0.02	> 1 month
Poly(CAC$_{18}$–PEG 1500)	V	5170	99.7	3.3×10^{-4}	501.1		
Poly(CAC$_{22}$–PEG 1500)	I	1400	79	1.2×10^{-4}	862.4	0.01	12 h
Poly(CAC$_{22}$–PEG 4000)	I	3700	72	7.7×10^{-5}	1796.5	0.005	12 h
Poly(CAC$_{30M}$–PEG 1500)	V	2100	66	3.4×10^{-5}	6324.3	0.01	12 h

[a] $\overline{M}_n$ determined by GPC.
[b] Polyester content in (polyester and PEG) mixture was determined by deconvolution of GPC curves.
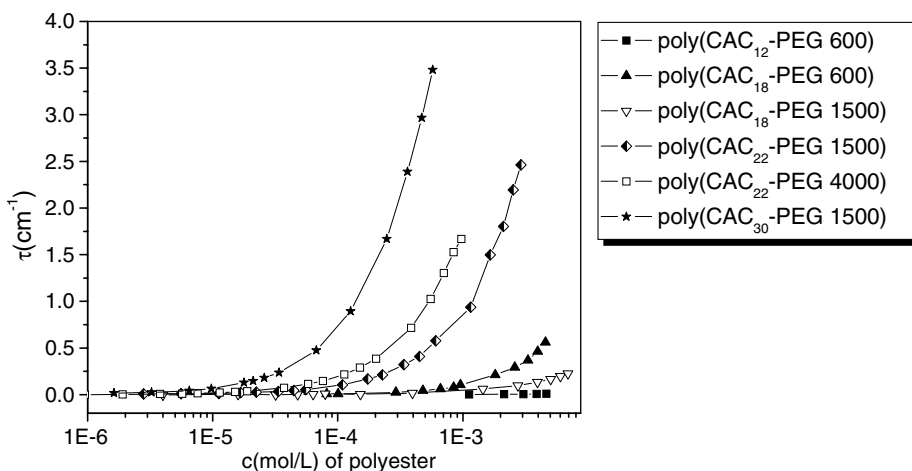
Fig. 15. Turbidity of colloidal dispersions of polyesters in water at 25 °C.

C_T values and higher slopes in the turbidity vs concentration curves due to the increase in the hydrophobic contribution of R to the polymer chain. Conversely, the effect of the molecular weight of PEG on product solubility follows the same trend as PEG solubility in water, which increases up to $\overline{M}_n = 1000 - 1, 450$ but decreases if $\overline{M}_n$ is higher [19]. Thus, the polyester solubility passes through a maximum. A positive effect was found for PEG, when $\overline{M}_n$ is increased up to 1500 while products derived from PEG 4000 were less soluble. Fig. 16 shows clearly that an increase of $\overline{X}_n$ is detrimental to the polyester solubility. Method V yields products with higher degree of polymerization that, however, were less soluble than those obtained from method I. The use of $C_{30M}OH$ monoalcohols, in the polycondensation of CAC_{30M} with PEG, gives the lowest M_n value possible, ca. 2×10^3 g/mol
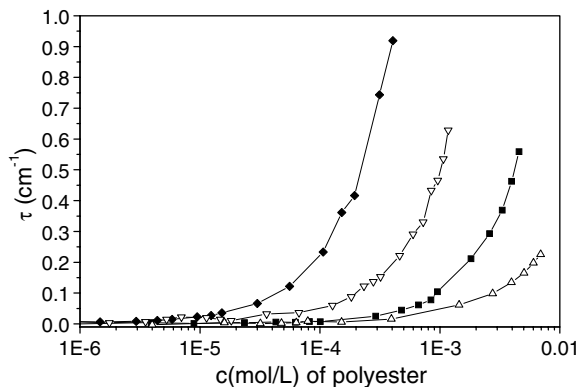

Fig. 16. Turbidity of colloidal dispersions of poly(CAC$_{18}$–PEG 600) prepared by method (■) I and (◆) V and poly(CAC$_{18}$–PEG 1500) prepared by method (△) I and (▽) V in water at 25 °C.

(GPC), which suggest that the condensation product of one monocitrate molecule with one PEG 1500 is predominant. Although the solubility of this product, ca. 3.4×10^{-5} mol/L, is the lowest of all polyesters, it could be useful for releasing the necessary quantity of $C_{30M}OH$, ca. 2.3×10^{-5} mol/L.

4. Conclusions

Water-soluble, amphiphilic polyesters from mono-1-alkyl citrates and PEG containing long aliphatic chains up to C_{30} can be obtained by controlling the reaction time, catalyst concentration, temperature and atmosphere of the reaction. Low molecular weights are obtained due to two main reasons. One is the influence of the experimental conditions. Only the use of method V yields larger chains. The other is the stoichiometric imbalance between the OH and CO_2H groups produced by PEG side reactions. The kinetic of the formation of poly(CAC$_{12}$–PEG 600), poly(CAC$_{18}$–PEG 600) and poly(CAC$_{18}$–PEG 1500) suggests the rupture of PEG C–O bonds that generates an excess of hydroxyl groups. When PEG is substituted by diols of low molecular weights (EG, TEG and HEG), which cannot produce the stoichiometric imbalance between the OH and CO_2H groups, it was possible to reach high conversion and high X_n values.

The solubility of the products depends on their degree of polymerization $\overline{X}_n$ as well as the $\overline{M}_n$ of PEG, which yields the best results for $\overline{M}_n = 1500$ g/mol. An increase of the degree of polymerization of the polyester is detrimental to its solubility. As expected, the length of the aliphatic chain moiety also

has an influence on the solubility, which decreases as the length of the aliphatic chain increases. Thus, solutions of 3.4×10^{-5} mol/L are achieved with poly(CAC_{30M}–PEG 1500) of $\overline{M}_n$ around 2000. This product can release the required amount of $C_{30M}OH$ (around $1\ \mu g/L = 2.3 \times 10^{-5}$ mol/L) to exert a positive effect on plants. Detailed studies concerning the release of triacontanol and its effect on plant growth are in progress.

Acknowledgements

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