at 25 C. If due allowance is made for the solvent viscosity and temperature differences then the normalised tetrachloroethylene data would be raised by 0.2. Insufficient data have been collected to confirm whether or not these data are in complete agreement with the extensions to the Benmouna theory (equation 5). It is hoped that additional data will be presented at the meeting. However the data do indicate that D_S is reduced in an equally poor solvent which is in agreement with equation 5. But the large second moments of these data suggest that the slow decay is further removed from a single exponential function contrary to the predictions of the Benmouna theory. This could be a manifestation of the slow relaxation behaviour observed in poor solvent binary polymer solutions[2].

References

1. Daivis P. J., Pinder D. N., Callaghan P. T., 1992, *Macromolecules* , 25, 170.
2. Nicolai T., Brown W., Johnsen R. M., 1990, *Macromolecules*, 23, 1165.

MACROMOLECULAR REPORTS, A31(SUPPLS. 6&7), 1127-1133 (1994)

MACROMOLECULAR ENGINEERING OF ALIPHATIC POLYLACTONES, POLYLACTIDES, AND POLYANHYDRIDES

Ph. DUBOIS, I. BARAKAT, N. ROPSON, Ph. DEGEE, R. JEROME and Ph. TEYSSIE.

Center for Education and Research on Macromolecules (CERM), University of Liege, SART-TILMAN B6 - B-4000 LIEGE - BELGIUM

INTRODUCTION

Polymers and copolymers of ϵ-caprolactone (ϵ-Cl), lactides (LA) and glycolide are used in medicine as biodegradable sutures, artificial skin and resorbable prostheses. They have also potentialities in the formulation of drugs, aiming at the sustained release of drugs and the targeting of tumors. The related aliphatic polyesters are known to be biocompatible and biodegradable.

Aliphatic polyanhydrides are another class of biocompatible polymers, which have been considered for use as erodible materials in medicine.

Although polycondensation is the traditional method of synthesis of polyesters and polyanhydrides, it has all the drawbacks of a step-growth polymerization. These disadvantages can however be overcome by the ring-opening polymerization of ϵ-CL, LA, glycolide and alicyclic anhydrides. If the polyaddition is living, it may provide molecular weight control, narrow MWD if initiation is fast enough and control of the molecular architecture, e. g. end-functionalization and block copolymerization.

This paper will report recent progress in the control of "living" ring-opening polymerization of ϵ-CL, LA and adipic anhydride (AA), using aluminum alkoxides as initiators.

LIVING POLYMERIZATION

Aluminum isopropoxide has proved to be a very effective initiator for the polymerization of ϵ-CL (in toluene, at 0 or 25°C)[1,4], LA (in toluene, at 70°C)[3,4] and AA (in toluene, at 20°C)[6]. The ring-opening proceeds through a "coordination-insertion" mechanism and the selective rupture of the acyl-oxygen bond of the monomer. The polymerization is typically "living", at least until a molecular weight of ca. 90,000 in the case of LA. Although undetermined, this upper limit is exceedingly higher for ϵ-CL, whereas the AA polymerization has only been

investigated in the range of low molecular weights until now. Loss in the "livingness" of the propagation step is observed when inter - and intramolecular transesterification reactions occur within the time required for the complete monomer (ϵ-CL and LA) conversion. Monomer and temperature have a critical effect on the average number of alkoxides per aluminum ($\bar{n}$) which participate in the polymerization. Accordingly, within the limits of a "living" propagation, the molecular weight can be predicted on the basis of $\bar{n}$ and the monomer/AL molar ratio. The polydispersity is then usually low (1.1 to 1.4). Interestingly enough, whenever added with triethyl Al, primary amines have been found to be effective initiators for the ϵ-CL polymerization in both toluene and THF at 40°C[7]. The alkyl Al activates the carbonyl group of the monomer and favors the nucleophilic attack of the amine, which is the actual initiation step. The opening of ϵ-CL is unchanged and the propagation is "living".

BLOCK COPOLYMERIZATION

Since ϵ-CL and LA can be polymerized in a living manner according to the same mechanism, their sequential polymerization is expected to lead to the related block copolymers. Two conditions have however to be fulfilled for the block copolymerization of ϵ-CL and LA to be successfull[5] (i) For a question of mutual reactivity, ϵ-CL must be first polymerized followed by the lactide. (ii) $\bar{n}$ must remain unchanged upon the addition of the second monomer to the solution of

living PCL chains. There are two possible ways of meeting the second condition : either Al isopropoxide is completely dissociated by 2-propanol from the very beginning of the sequential polymerization or a dialkyl Al monoalkoxide is used as the initiator.

Additional experiments have shown that living PCL chains in toluene are able to polymerize AA at 80°C and N-carboxyanhydrides at 25°C, with formation of a block copolymer[6,9]. Synthesis of macromonomers as precursors of graft copolymers is discussed in the next section.

END-FUNCTIONALIZATION

In agreement with the polymerization mechanism of ϵ-CL and LA, polyester chains are capped at one end by the radical derived from the initiating alkoxide group, whereas the second end-group is a hydroxyl function resulting from the hydrolysis of the chain-growing site. It has been shown that the characteristic features of the ϵ-CL and LA polymerization (mechanism, living propagation) remain unchanged when the alkyl group of Al alkoxides bear a functional group (x), e.g. a halogen, a tertiary amine, a methacryloyl unsaturation. Accordingly, asymmetric α - hydroxy, ω - X functional PCL and PLA chains, and particularly ω -methacryloyl chains or macromonomers, have been prepared with a predictable length and a narrow MWD[1,4]. Appropriate termination or coupling reactions of the living chains lead to the related telechelic polyesters

(symmetric α ,ω-functional chains). When AA is concerned, the nature of the end-groups is again under control : one chain extremity is capped by the alkoxy group of the initiator (initiation control) and the hydrolysis of the propagation site gives rise to an acid end-group (termination control). Functional Al alkoxides are thus expected to produce α - carboxylic acid, ω - X functional polyanhydrides. The particular case where x is a methacryloyl group has been reported[6].

Although Al monoalkoxides bearing a primary amine have been prepared, they have failed to provide the expected amino-terminaded polyester; rather α,ω-hydroxy chains have been obtained. This observation has to be related to the ability of primary amines to initiate the ϵ-CL and LA polymerization. An alternative approach has been proposed, which consists in attaching an alkylbromide end-group to PCL chains, via the appropriate initiator. The bromo end-group has been converted into an azidogroup which has subsequently been reduced into the expected primary amine[8]. ω-primary amine PCL chains have proved to be effective macroinitiators for the ring-opening polymerization of α - benzyl glutamate N-carboxyanhydride with the formation of PCL-b-peptide copolymers[9].

CONCLUSIONS

Al alkoxides are very powerful initiators for the polymerization of ϵ-CL, LA and AA. The great versatility of their structure paves the way to the macro-

molecular engineering of several families of biocompatible and biodegradable polymers (telechelic polymers, macromonomers, block and graft copolymers).

Characterization of the initiators by ^{27}Al and ^{13}C NMR spectroscopy is under the way in order to gain a deeper insight on their solution behavior and interaction with the monomer. Extension to other monomer (glycolide) and initiators (Zn and Sn derivatives) is currently investigated.

REFERENCES

1. Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Polym. Bull. 22, 475 (1989)

2. Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Macromolecules 24, 977 (1991)

3. Ph. DUBOIS, C. JACOBS, R. JEROME, Ph. TEYSSIE, Macromolecules 24, 2266 (1991)

4. Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Makromol. Chem., Macromol. Symp. 42/43, 103 (1991)

5. C. JACOBS, Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Macromolecules 24, 3027 (1991)

6. N. ROPSON, Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Macromolecules, to be published in 1992

7. Ph DUBOIS, Ph. DEGEE, R. JEROME, Ph. TEYSSIE, Macromolecules, to be published in 1992

8. Ph. DEGEE, Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, Macromolecules, accepted for publication

9. Ph. DEGEE, Ph. DUBOIS, R. JEROME, Ph. TEYSSIE, J. Polym. Sci., Polym. Chem., accepted for publication.