Chemoselective Polymerization Control: From Mixed-Monomer Feedstock to Copolymers**

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In memory of Joachim Steinke (1965–2013)

Abstract: A novel chemoselective polymerization control yields predictable (co)polymer compositions from a mixture of monomers. Using a dizinc catalyst and a mixture of caprolactone, cyclohexene oxide, and carbon dioxide enables the selective preparation of either polyesters or polycarbonates or copoly(ester-carbonates). The selectivity depends on the nature of the zinc–oxygen functionality at the growing polymer chain end, and can be controlled by the addition of exogeneous switch reagents.

A key challenge for polymer science is to control the polymer sequence from mixtures of monomers. Sequence-controlled multiblock copolymers are of high interest, owing to their enhanced properties and their potential for designed functionality. Whereas Nature exerts sophisticated sequence control, for example, in peptide synthesis, synthetic methods are far less advanced. Generally, when using mixed-monomer feedstocks, the relative reactivities of the monomers, determined from homopolymerization experiments, are used to predict the sequence of the copolymer, that is, kinetic control.[3] Recently, this has been elegantly exploited using donor–acceptor monomers, to prepare sequence-controlled block copolymers.[2] Herein, we present a novel chemoselective control mechanism that is applicable to both the ring-opening polymerization (ROP) of lactones and the ring-opening copolymerization (ROCOP) of epoxides and carbon dioxide to yield copoly(ester-carbonates) (Figure 1).

Polyesters and polycarbonates are currently produced on a large scale (> 5 Mt/annum), mostly by condensation polymerization and using petrochemicals.[1] Such syntheses are hampered by precise monomer stoichiometry requirements, thermodynamic constraints, slow rates, and a total lack of polymerization control. These factors complicate, and even prevent, the preparation of copolymers.[1] In contrast, the ring-opening polymerization (ROP) of lactones[4]/cyclic car-

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exogeneous switch reagents to direct the polymerization pathway. It enables a single catalyst (1) to be used for both ROP and ROCOP, both sequentially and in one pot. It obviates the need for intermediate polymer isolation, complex rate balancing or compatibility testing.

Dizinc complex 1 is an efficient ROCOP catalyst, using cyclohexene oxide (CHO) and CO₂. 1 operates under CO₂ pressures as low as 1 bar and is highly selective, producing poly(cyclohexene carbonate) (PCHC) with a high fidelity of carbonate repeat units (> 99%). Given the strong precedent for zinc catalysts in lactone ROP,[4c] 1 was tested for the ROP of caprolactone (CL). However, 1 was completely inactive, even under forcing conditions (80°C, neat CL, with/without alcohol; Table 1; see also Table S1 in the Supporting Information).

Table 1: The formation of polyesters, polycarbonates, and copolymers using 1.

| Run | CHO | CL | CO₂ | t [h] | % conv. | Polymer | Mₙ (PDI) [g mol⁻¹] |
|-----|-----|----|-----|-------|---------|---------|-------------------|
| 1   |     | 100|     | 2     | >99     | PCL     | 11 780 (1.41)     |
| 2   | 20  | 200| 500 | 2     | >99     | PCL     | 60 20 (1.24)      |
| 3   | 900 | 100|     | 15    | >99 (CL)| PCHC    | 10 40 (1.08)      |
| 4   | 900 | 100| 1   | 21    | >99 (CL)| PCL-PCHC| 4810 (1.38)       |
| 5   | 900 | 100| 50  | 1     | >99 (CL)| PCHC-PCL| 3490 (1.48)       |
| 6   | 450 | 50 | 1   | 10    | >99 (CL)| PCHC-PCL| 560 (1.29)        |
| 7   | 450 | 50 | 1   | 5     | >99 (CL)| PCHC-PCL| 2350 (1.49)       |

[a] Determined by 1H NMR spectroscopy from the normalized integrals for resonances from CL (4.23 ppm), PCL (4.05 ppm), and PCHC (4.73–4.54 ppm). [b] Determined by SEC in THF, with a correction factor of 0.56 for PCL, as described in Ref. [16]. [c] Polymerization was monitored using in situ ATR-IR spectroscopy. [d] CO₂ removed after 3.5 h by application of six vacuum purge/nitrogen flush cycles.

[Figure 2. Chemoselective polymerization control. a) 1/CHO/CL = 1:900:100, 80°C, 16 h. Gases (CO₂ or N₂) are added to 1 bar total pressure.]

[Figure 3. Changes in the intensity of IR resonances (normalized) during the reaction in Figure 2, LHS (Table 1, run 3). The mixture of CL and CHO under CO₂ (1 atm) shows only the formation of PCHC, with no PCL formation.]
a continual increase in PCHC formation (1275 cm⁻¹). In contrast, there was no change in either PCL or CL concentrations (1374 and 694 cm⁻¹, respectively). In order to rationalize this selectivity, the CL ROP was investigated with CHO (10 mol%), under an atmosphere of CO₂ (1 bar). The polymerization was inhibited: there was no formation of PCL. This is proposed to be due to rapid insertion of CO₂ into the zinc alkoxide bond, coupled with the inability of the zinc carbonate to initiate ROP by analogy to the previous findings using I (Figure 4). The rate law for ROCOP using I, shows a zeroth order in carbon dioxide (1–40 bar), which is consistent with the rapid insertion of CO₂ into zinc alkoxide bonds. Thus, CO₂ inserts more rapidly into the zinc alkoxide bond than the rate of CL ROP (Figure 4). At first sight this could be counterintuitive, particularly if only the turn-over frequencies are considered: the TOFs for ROCOP (ca. 7 h⁻¹) are significantly lower than those for CL ROP (ca. 100 h⁻¹; Table S2).

The explanation lies in the relatively faster rate of the pre-rate-determining step (CO₂ insertion) which ensures that, from a mixture of monomers, catalyst I selects for ROCOP. Another finding is that the nature of the zinc chain end group controls selectivity, even from a mixture of different monomers. The zinc alkoxide chain end group catalyzes either ROCOP or ROP, whereas the zinc carboxylate/carbonate chain end groups only catalyze ROCOP. We have termed this selectivity, the CL ROP was investigated with CHO, CL, and CO₂ (1 bar), so as to initiate ROCOP and produce PCHC. In situ ATR-IR spectroscopy (Figure 6) showed PCHC formation (1280 cm⁻¹), with PCL/CL signals remaining constant (1420 and 694 cm⁻¹, respectively). After 3.5 h, the CO₂ was purged from the reaction, by application of six vacuum purge/nitrogen flush cycles over a period of 15 min, after which the intensity of the CO₂ resonance (2340 cm⁻¹) decreased to near zero. The CO₂ atmosphere was replaced with N₂, leading to rapid CL ROP. After this time, there was no significant change to the PCHC signal (1280 cm⁻¹).

The reaction was repeated with aliquot removal for SEC analysis (Table 1, run 7); thus after 4 h there was ca. 10% PCHC formation with an Mₙ of 530 g mol⁻¹ (PDI = 1.29; Figure S9) and after a further 2 h, there was > 99% con-

![Figure 4](image)

**Figure 4.** Chemoselective polymerization control, illustrating the importance of the zinc-oxygen chain end groups. The selectivity can be rationalized if the relative rates are: k₂ > k₁ > k₅. Where [Zn][Zn] is defined in Figure 1 and R = growing polymer chain (PCHC/PCL copolymer).
version into PCL-PCHC and the $M_n$ had increased to 2350 g mol$^{-1}$ (PDI = 1.49; Figure S9). Thus, the reverse monomer addition also enables one-pot sequential ROCOP and ROP, and yields PCHC-PCL (polycarbonate-ester). In this case, it is important to remove the excess CO$_2$, so that the zinc carbonate species can react with a further equivalent of CHO to generate the zinc alkoxide species required for CL ROP.

In summary, a means to bridge between two commonly applied polymerization pathways, ring-opening polymerization and ring-opening copolymerization, is described, which enables the selective synthesis of polysteres, carbones, and copoly(ester-carbonates). The two pathways are bridged by the addition of exogeneous switch reagents, either epoxide or carbon dioxide. The study also reveals that the chemical nature of the zinc-polymer chain end group plays a central role in controlling which monomer(s) are polymerized from a mixture. Such chemoselective polymerization control is unusual, yet the principles uncovered here are expected to apply more generally, including to other epoxides, heterocumulenes, and lactones. Future studies will focus on exploiting it to prepare a range of new polymers/copolymers.

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