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Ring Opening Polymerization of Organic Carbonates Using CO_2 - Carbene Adducts as Effective Organo Catalyst

*A. Reitz, R. Wilhelm, D. Kuckling**

Summary: In this study we successfully synthesized Poly(trimethylene carbonate) (PTMC) through carbene-catalysed ring opening polymerization. The use of CO_2-adducts decreases the air and moisture sensitivity of the carbene and improves the controllability of the reaction. The carbene is freed through dissolving and heating. The reaction can be done in bulk or in solution. Improvements to the system can be made by varying temperature and solvent. We could show that bulk polymerization allows the synthesis of PTMC in a short span of time and good yields.

Keywords: biodegradable; carbene; polycarbonate; ring opening polymerization

Introduction

Today, new materials for *in vivo* treatments, especially those with defined properties, are required. For polymeric materials this means carefully choosing both monomer and synthetic method. For a variety of combinations it is also possible to use controlled and living polymerization techniques to control size, form and functionality.[1] These methods yield monodisperse macromolecules with defined molecular weight and properties.[2] One of those methods is the ring opening polymerization showing further advantages, like being waste free and requiring only few components.[3] Ring opening polymerization can easily be combined with other polymerization techniques and allows the synthesis of a wide variety of molecular structures.[4] The monomers must be cyclic compounds with a cleavable C-X bond. Mainly esters are used and most of the polyesters are counted as biocompatible and biodegradable.[5] These qualities are of outmost importance for *in vivo* applications. The polymers are decomposed either by enzymes or chemically through hydrolytic cleavage. The oligomeric products of this step must not be toxic and has to be metabolized by the body.[6] Besides the long used polyesters like poly(lactid acid) and poly(ε-caprolactone),[7] aliphatic carbonates like PTMC gain increasing interest.[8] These organic compounds known as green solvents show great potential as monomers. On one hand they have melting points near room temperature and high boiling temperatures, on the other hand their polarity is similar to that of polar solvent like DMSO, DMF or acetonitrile.[9] Since their functional group, the carbonate group, resembles the ester group ring opening polymerization analog to this reaction is possible. Aliphatic carbonates form thermoplastic polymers with amorphous structures. They usually have a low glass transition temperature. As their degradation is slower than that of polyesters, medium term applications are possible.[10] Especially PTMC is now intensively studied as a nontoxic, biodegradable polymer which can be used as drug delivery system or as tissue replacement.[11] In such fields residue metals must not be present. To fulfill this requirement and avoiding complicated purification organocatalysis is used.[12] Organocatalysis only requires small organic molecules as catalyst and does not need metals. Mostly these catalysts

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[1] Department Chemie, Universität Paderborn, Warburger Str. 100, 33098 Paderborn, Germany
E-mail: dirk.kuckling@uni-paderborn.de

function as electron mobilisator. Famous examples are amines,[13] however, thioureas and carbenes have recently been reported to be used as catalyst.[14,15] Carbenes, a very reactive species owing to an electron sextet, are highly nucleophilic compounds. As such they were only known as intermediates for a long time. Since Arduengo first isolated crystals,[16] carbenes are often used as ligands and catalysts.[17] To avoid their still high reactivity especially towards water they can be reversibly masked as alcohol,[18] silver[19] or CO_2 adducts.[20] In this work we use carbene-CO_2 adducts which can easily be prepared from the free carbene. The active organo catalyst is freed *in situ* as seen in Figure 1 from the air-stable CO_2 adduct. This allows controlled and stoichiometric release avoiding additional bases which reduces side reactions.

Experimental Part

Materials

Trimethylene carbonate (TMC) was purchased from TCI and recrystallized thrice from ethyl acetate. Benzyl alcohol was distilled over CaH_2. 1,3-Bis(2,4,6-trimethylphenyl)-1,3-dihydro-2H-imidazol-2-ylidene was used as received (Aldrich). Solvents were dried using established procedures. The carbene-CO_2 adduct was prepared according to literature.[21]

Synthesis of PTMC

PTMC was prepared through bulk or solvent polymerization. The ratio of monomer:catalyst:initiator was kept at 100:1:1 while the temperature and solvent conditions were varied.

All polymerizations were carried out in a Schlenk tube equipped with a magnetic stirring bar and sealed with a septum. After the tube was repeatedly heated under vacuum and cooled under argon atmosphere the monomer and catalyst were added. The tube was again evacuated and flushed with argon twice. After tempering in an oil bath benzyl alcohol was added. After the polymerization the polymer was dissolved in chloroform and precipitated in methanol. The polymer was dried at room temperature in vacuum to constant weight.

Characterization

^1H and ^{13}C-NMR spectra were recorded on a Bruker AV 500 spectrometer in $CDCl_3$ at 500 MHz and 125 MHz, respectively. Molecular weights and polydispersity were analyzed employing size exclusion chromatography (SEC). As eluent chloroform with a flow rate of 0.75 mL/min was used with a Waters RI-Detector and toluene as internal standard at 30 °C. Columns used were PSS-SDV columns filled with 5 μm gel particles with a defined porosity of 10^6 Å (guard), 10^5 Å, 10^3 Å and 10^2 Å respectively molecular weight determination was based on narrow polystyrene standards.

Results and Discussion

For the ring opening polymerization of esters and carbonates many different mechanism are discussed. We expect this

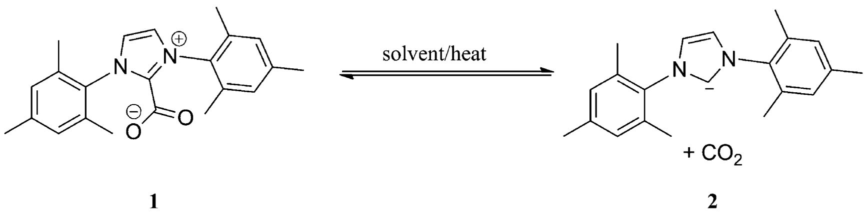

Figure 1.
Release of free catalyst by decomposition of dimesitylimidazol-CO_2 adduct.

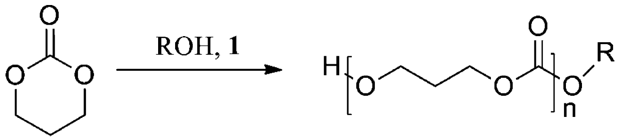

Figure 2.
Polymerization of TMC by the use of carbene-CO_2 adduct.

system of carbene and carbonate to use a route via a monomer activated mechanism. In a nucleophilic attack the carbene activates the monomer which in turn deprotonates the alcohol. The alkoxide substitutes the carbene, thereby the chain grows and the catalyst is released. This mechanism should show a low degree of decarboxylation in bulk polymerization and should lead to controlled reaction. Utilizing these characteristics the aim of this study was to polymerize TMC using dimesitylimidazol-CO_2 adduct and thereby avoiding any additional bases. This adduct could easily be synthesized by conducting CO_2 through a solution of bis(2,4,6-trimethylphenyl)-1,3-dihydro-2H-imidazol-2-ylidene in diethylether. This adduct is an effective precatalyst for the ring opening polymerization of TMC. With it PTMC can be obtained in good yields and high turnovers. Without a catalyst no reaction was observed. The reaction could be lead to high turnovers of 90–100% accepting polydispersities between 3–7. In Figure 3 the NMR spectra of PTMC is shown. To calculate the turnover, the ratio of the polymeric integrals to the sum of

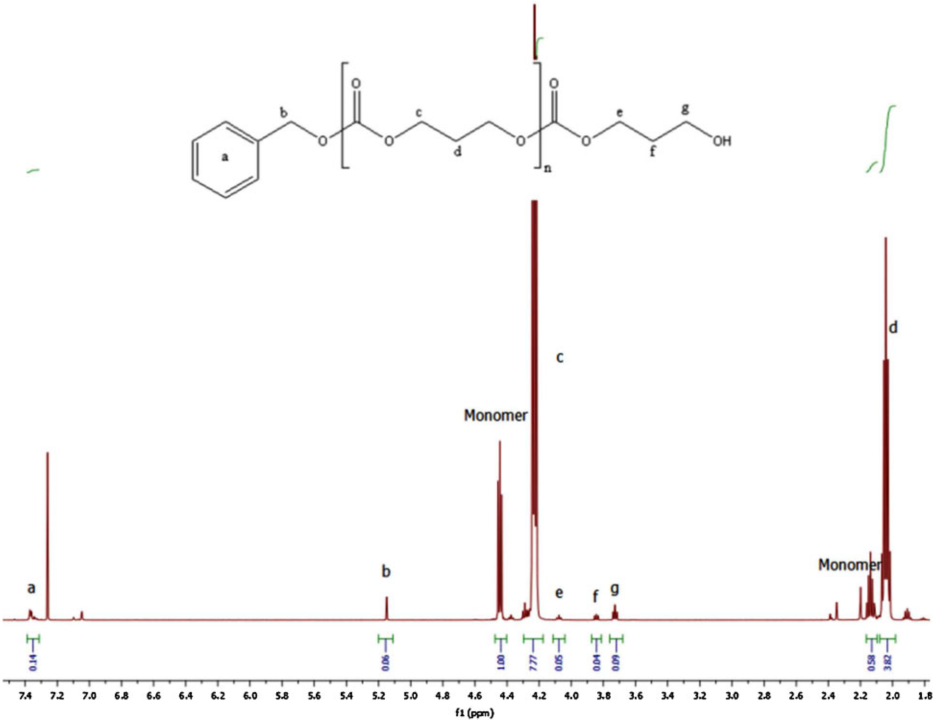

Figure 3.
^{1}H-NMR spectra of PTMC in $CDCl_3$.

monomeric (2.15 ppm and 4.45 ppm) and polymeric signals (d, c) is used. From the turnover the theoretical chain length can be obtained by multiplying the turnover with the number of monomers per initiator.

As TMC melts around 45 °C the reaction temperature of bulk polymerization must be above this temperature. For this study we investigated 60 °C, 80 °C and 100 °C. The reaction turnover as displayed in Figure 4 is mainly dependent on the temperature. All three temperatures show high molecular weight and good to acceptable polydispersities. While the polymerization products at 60 °C and 80 °C are quite similar with a low polydispersity of 1.4 and a molecular weight of 11,000–12,000 g/mol, the polymer synthesized at 100 °C showed a slightly higher molecular weight and broader but acceptable polydispersity.

For the bulk polymerization at 60 °C the diagram of time versus ln(1/(1-U)) shows a linear trend and therein affirms the controlled character of the ring opening polymerization of TMC. The reaction constant at this temperature is $k = 0{,}01494\,\text{min}^{-1} = 2{,}49 \cdot 10^{-4}\,\text{s}^{-1}$.

Besides bulk polymerization, polymerization in solvents is known and should lead to slower but better controlled reaction. We tested the polymerization in toluene, THF and diphenylether. While the polymerization in toluene and THF was slower than bulk polymerization but still effective, the reaction in diphenylether did not work. The polydispersities are acceptable but the molecular weight with 2,000–3,000 g/mol is considerably lower than expected. As the concentration of the monomer is lower than in bulk the turnovers are smaller, even after 6 h. Besides the low concentration there must be other reasons for comparably smaller molecular weights. As ESI-MS shows many polymers with propandiol ended chains the decarboxylation in solution appears to be higher than in bulk. Also the prolonged reaction time may allow side reactions to take place, so that transesterification can occur. One other unwanted side reaction could be the deactivation of the carbene through water traces being present even after careful drying of solvents.

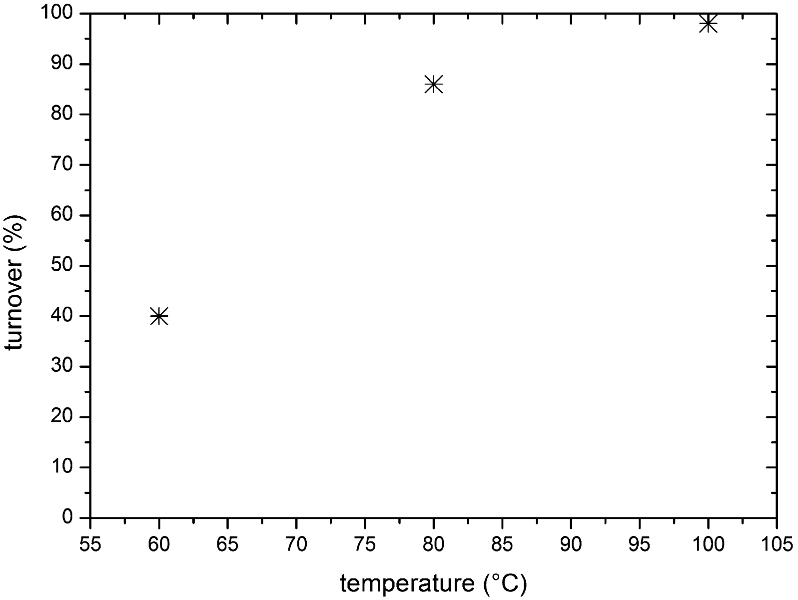

Figure 4.
Relationship between turnover and temperature for the bulk polymerization of TMC.

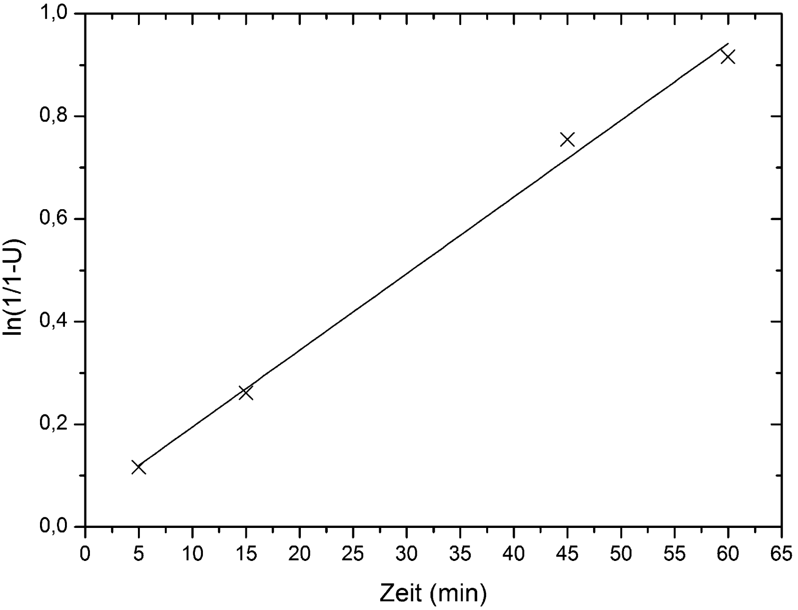

Figure 5.
Kinetics of bulk polymerization of TMC at 60 °C.

Table 1.
Polymerization results at different temperatures and in different solvents.

Temperature [°C]	Time [h]	Solvent	Molecular weight (M_n) [g/mol]	Polydispersity
60	4	–	11,470	1.4
80	4	–	11,500	1.4
100	4	–	13,400	1.7
60	6	THF	1,750	3.0
60	6	toluene	2,900	1.3
60	6	diphenylether	–	–

Conclusion

It has been shown that carbene-CO_2 adducts are effective catalysts for the ring opening polymerization of TMC. Both bulk and solvent polymerization show acceptable to good polydispersities. The reaction is highly temperature dependent. Bulk polymerization exhibits better control and higher molecular weight. For bulk polymerization a good agreement of theoretical and experimental molecular weight can be found.

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