Ring opening copolymerisation of lactide and mandelide for the development of environmentally degradable polyesters with controllable glass transition temperatures

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ABSTRACT

Environmentally degradable polyesters offer an interesting perspective for a vast number of applications. However, current front-runners like poly(lactide), poly(glycolide) and poly(ε-caprolactone) are either semi-crystalline excluding applications for which optical transparency is desired, or exhibit low glass transition temperatures (T_g) resulting in poor dimensional stability at temperatures exceeding the T_g. In the present work, copolymers of lactide and mandelide are explored as a method to obtain amorphous, environmentally degradable polyesters with a glass transition temperature exceeding 50 °C. Mandelide and lactide can be successfully copolymerised and the resulting copolymers revealed rising T_g values upon increasing the mandelide content. The obtained molecular weights were superior to the molecular weights previously obtained via polycondensation, but were limited by the epimerisation of the mandelide monomer, which passes through an enolic intermediate that is able to initiate the polymerisation.

1. Introduction

Environmentally degradable polymers are receiving increasing interest to allow novel applications of polymers in mostly (bio)medical and agricultural applications such as bioresorbable sutures [1,2], drug delivery applications [3–6], (implantable) tissue engineering scaffolds [7–9] and degradable mulch films [10–12]. In addition, these materials can be applied as bulk material for disposable devices, which are currently associated with the image of landfills and microplastics contaminating the oceans [13].

All of the above-mentioned applications directly benefit from materials that are engineered to degrade over a specific amount of time or after fulfilling their intended use, which has in turn led to an increase in the industrial interest for these materials. Moreover, degradable materials are becoming more and more competitive with traditional bulk plastics as a result of governmentally imposed regulations and levies.

Currently, biodegradable and bio-based polymers make up about 300,000 metric tons of the total plastics market, which only accounts for 1% of the global market of synthetic plastics [14,15]. However, the market for degradable and sustainable polymers grows about 20–30% each year, which is considerably higher than the total market growth. Although produced synthetically, polyesters make up a large fraction of the biodegradable plastics market and are often preferred over natural degradable polymers, as their properties can be tailored by simply selecting the appropriate monomers and polymerisation conditions. Moreover, the resulting materials have more predictable batch-to-batch uniformity than their natural counterparts [16].

Aliphatic polyesters like poly(lactic acid) (PLA), poly(glycolic acid) (PGA) and poly(ε-caprolactone) (PCL) are among the front-runners in the field of degradable materials [17–19], but are opaque due to the presence of crystalline domains or show low softening temperatures (e.g. approx. 40–50 °C) when amorphous grades are considered.

Mandelic acid with its bulky phenyl side-group has already been proposed as an interesting monomer to yield polyesters with an increased glass transition temperature in polycondensations [20]. This effect can be attributed to a reduction of the chain mobility as a result of the incorporation of the rigid aromatic side groups along the polymer backbone. However, the mandelic acid content of these polymers was limited (approx. 10%). Moreover, the molecular weights attainable via direct polycondensation of lactic acid and mandelic acid, were limited to approx. 5 kg/mol. In 2007, Liu et al. introduced a lactide-analogue derived from mandelic acid (i.e. mandelide) to allow the synthesis of poly(mandelic acid) via ring-opening polymerisation [21]. The current contribution continues on this earlier work and describes the first co-polymerisation of lactide and mandelide via ring-opening polymerisations with the aim to obtain amorphous polyesters with T_g exceeding 50 °C and molecular weights exceeding 10 kg/mol.

2. Materials and methods

2.1. Materials

All chemicals were used as received unless stated otherwise. Chloroform (HPLC grade), neohexanol, p-toluenesulfonic acid, Sn(2-ethylhexanoate)$_2$, toluene and mixed xylenes were purchased from Sigma Aldrich (Diegem, Belgium). Calcium hydride, rac-mandelic acid, sodium bicarbonate and sodium chloride were obtained from Acros Organics (Geel, Belgium). Ethyl acetate and methanol were obtained from Chem-Lab Analytical (Zedelgem, Belgium). Dichloromethane was purchased from TCI Europe (Zwijndrecht, Belgium). All NMR spectra were recorded in deuterated solvents obtained from Euriso-top (Saint-Aubin, France). Toluene was refluxed over Na/benzophenone until a deep blue colour persisted, distilled and subsequently stored over molecular sieves (4 Å). Neohexanol was distilled over calcium hydride and stored over molecular sieves (4 Å). R,S-lactide was recrystallised from hot ethyl acetate (approx. 77 °C) and dried in vacuo.

2.2. Synthesis procedures

2.2.1. Synthesis of mandelide

Mandelide was prepared following a slightly adapted procedure from literature [21]. In brief, 20 g (132 mmol) DL-mandelic acid and 0.68 g p-toluenesulfonic acid (3.96 mmol) were dissolved in 2 L toluene or mixed xylenes. Contrary to [21], the solution was degassed by passing a nitrogen stream through the solution for at least half an hour while stirring by means of a magnetic stirring bar. A Dean-Stark trap and condenser were mounted on the flask and the set-up was subsequently purged with nitrogen. The solution was refluxed for 3 days under nitrogen atmosphere. Next, the reaction was allowed to cool to room temperature during which precipitation occurred. The precipitated racemic mandelide (5.63 g, yield = 32%) was removed by filtration and dried in vacuo.

^{1}H-NMR (CDCl$_3$, ppm): 7.28 (5H, m), 6.15 (1H, s); ^{13}C-NMR (CDCl$_3$, ppm): 166.77, 132.43, 129.64, 128.94, 126.45 and 77.62; FT-IR (ATR, cm^{-1}): 3065 (ν(aromatic C−H)), 1754 (ν(C=O)), 1499 (ν(C=C)), 1071 (ν_{as}(C−O)), 743 (δ aromatic C−H); MS (EI, m/z): 268.

The filtrate was washed with a saturated sodium bicarbonate solution (3 × 100 mL) and brine (3 × 100 mL) and dried over anhydrous magnesium sulphate. After filtration, the solvent was removed by rotary evaporation and the formed meso-mandelide (4.46 g, yield = 25%) recrystallised from hot ethyl acetate (approx. 77 °C) and finally dried in vacuo.

^{1}H-NMR (CDCl$_3$, ppm): 7.47 (5H, m), 5.87 (1H, s); ^{13}C-NMR (CDCl$_3$, ppm): 164.96, 131.38, 130.21, 129.52, 126.73 and 78.11; FT-IR (ATR, cm^{-1}): 3066 (ν(aromatic C−H)), 1731 (ν(C=O)), 1498 (ν(C=C)), 1039 (ν_{as}(C−O)), 739 (δ aromatic C−H); MS (EI, m/z): 268.

Table 1
Amounts of reagents applied for the synthesis of the lactide-mandelide copolymers. Polymerisations were performed at 100 °C for 16 h at a total monomer concentration (lactide + mandelide) of 1 M.

	Lactide	Mandelide	Sn(II) Octoate	Neohexanol	Toluene
	[mmol]	[mmol]	[µmol]	[µmol]	[mL]
PLA	6	0	30	60	6
PLAMA 75/25	4.5	1.5	30	60	6
PLAMA 50/50	3	3	30	60	6
PLAMA 25/75	1.5	4.5	30	60	6
PMA	0	6	30	60	6

2.2.2. Reaction of mandelide with trichloroacetyl isocyanate

Meso-mandelide (10 mg, 40 µmol) was added to an NMR-tube and dissolved in 800 µL deuterated DMSO. After recording a ^{1}H-NMR spectrum, 14 µL trichloroacetyl isocyanate (TAIC, 120 µmol.) was added to the NMR-tube and another ^{1}H-NMR spectrum was subsequently recorded.

^{1}H-NMR (DMSO-d_6, ppm): 8.41 (1H, d) (10H, m), 6.62 (0.7H, s) 6.41 (0.3H, s);

2.2.3. Copolymerisation of lactide and mandelide

Copolymers of lactide and mandelide (target DP 100) were prepared by adding the appropriate amounts of all reagents (Table 1) in flame-dried Schlenk vials. Given the low required amounts of initiator and catalyst, 1 M stock solutions were prepared in toluene. All manipulations of these reagents were performed in an argon-filled glovebox to prevent the enclosure of moisture. The filled vials were closed by means of rubber septa and removed from the glovebox. The Schlenk vials' contents were frozen by means of liquid nitrogen after which the vials were connected to the Schlenk line and subjected to three freeze-pump-thaw-cycles (FPT) to remove traces of moisture and oxygen. After the final FPT-cycle, the vials were brought under Ar-atmosphere and placed in an oil bath at 100 °C. The solutions were stirred overnight (16 h), followed by the removal of the solvent in vacuo. The obtained product was redissolved in a minimal amount of dichloromethane and precipitated in cold methanol. The polymer was finally removed via filtration and dried in vacuo.

2.2.4. Comparison of polymerisation kinetics of lactide and meso-mandelide

To compare the polymerisation kinetics of lactide and mandelide, both monomers were polymerised with a target degree of polymerisation (DP) of 50. After the addition of 5 mmol of each monomer and 5 mL toluene to two separate Schlenk vials, these vials were sealed with a rubber septum. Both monomer solutions as well as the catalyst and initiator solutions were removed from the glovebox and immediately frozen in liquid nitrogen to allow three subsequent FPT-cycles. The appropriate amounts of initiator (100 µmol) and catalyst (50 µmol) were added to the Schlenk vials, which were then placed in an oil bath (100 °C) to initiate the polymerisation. At regular intervals, a drop of reaction medium (approx. 50 µL) was collected via dry and Ar-purged syringes and subsequently analysed via ^{1}H-NMR spectroscopy and size exclusion chromatography (SEC).

2.3. Methods

^{1}H-NMR spectra were recorded on a Bruker (Brussels, Belgium) AVANCE Ultrashield spectrometer (300 MHz). ^{13}C-NMR spectra were recorded on a Bruker AVANCE II Ultrashield spectrometer (400 MHz). Free induction decays were converted to NMR-spectra by means of the Topspin software package.

Attenuated total reflectance infrared (ATR-IR) spectroscopy was performed on a PerkinElmer (Zaventem, Belgium) BioRad FTS 575C combined with a specac (Orpington, United Kingdom) MKII Golden