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POLYCYCLOACETALS FROM RENEWABLE RESOURCES

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Succes met het doorworstelen van deze thesis!

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Abbreviations

ADMET	Acyclic diene metathesis
AIBN	Azobisisobutyronitrile
AMP	Acetal metathesis polymerization
BCD	4,4'-Bicyclohexanone diketal glycerol
BuOAc	Butyl acetate
CALB	Candida Antarctica lipase
$CHCl_3$	Chloroform
CHD	1,4-Cyclohexanedione diketal glycerol
Đ	Dispersity
Da	Dalton
DA	Diels-Alder
DBTL	Dibutyltin dilaurate
DBTO	Dibutyltin oxide
DBU	1,8-Diazabicyclo[5.4.0]undec-7-ene
DCE	Dichloroethane
DCM	Dichloromethane
DI	Diisocyanate
DiAcD	Acetonylacetone diketal glycerol
di-TMP	Di-trimethylolpropane
DGA	Diglycerol bisacetonide
DMA	Dimethyl acetamide
DMF	Dimethyl formamide
DMFDC	Dimethyl furan dicarboxylate
DMPA	2,2-Dimethoxy-2-phenylacetophenone
DMS	Dimethyl succinate
DMSO	Dimethyl sulfoxide
DMTA	Dynamic and mechanical thermal analysis
DP	Degree of polymerization
DPC	Diphenyl carbonate

DSC	Differential scanning calorimetry
E	Young modulus
EtOAc	Ethyl acetate
Et_3N	Triethylamine
Et_2O	Diethylether
FDCA	Furan dicarboxylic acid
FT-IR	Fourrier transform infrared spectrometer
HDI	Hexamethylene diisocyanate
HFIP	Hexafluoroisopropanol
hMDI	Hydrogenated methylene diphenyl diisocyanate
5-HMF	5-Hydroxymethyl furfural
^1H-NMR	Nuclear magnetic resonance
HPA	Hydroxypivaldehyde
HPLC	High pressure liquid chromatography
HR-MAS	High resolution- magic angle spinning
HSQC	Heteronuclear single quantum correlation experiment
IPDI	Isophorone diisocyanate
IR	Infrared spectroscopy
KTFA	Potassium trifluoroacetate
LC-MS	Liquid chromatography - mass spectroscopy
Maldi-*ToF*	Matrix-assisted laser desorption/ionization-time of flight mass spectrometer
m-CPBA	m-Chloroperoxybenzoic acid
MDI	Methylene diphenyl diisocyanate
MeOH	Methanol
2-MeTHF	2-Methyl tetrahydrofuran
$MgSO_4$	Magnesium sulfate
M_n	Number average molecular weight
M_w	Weight-average molecular weight
MW	Molecular weight
NaOH	Sodium hydroxide
NIPU	Non-isocyanate polyurethanes
NMP	N-methyl-2-pyrrolidone

PA	Polyamide
PC	Polycarbonate
PDI	Phenyl diisocyanate
PE	Polyethylene or polyester
PEF	Polyethylene furanoate
PET	Polyethylene terephtalate
PLA	Polylactic acid
PMMA	Poly(methyl methacrylate)
POM	polyoxymethylene
p-TsOH	*p*-Toluenesulfonic acid
PU	Polyurethane
r	Stoichiometric ratio
RAFT	Reversible addition fragmentation chain transfer
SEC	Size exclusion chromatography
SGP	Step-growth polymerizations
TAD	1,2,4-triazoline-3,5-dione
TBD	Triazabicyclodecene
T_d	Degradation temperature
TDI	Toluene diisocyanate
TFA	Trifluoroacetic acid
T_g	Glass transition temperature
TGA	Thermogravimetric analysis
THF	Tetrahydrofuran
TLC	Thin-layer chromatography
T_m	Melt temperature
TMDI	2,4,4-Trimethyl-hexamethylene diisocyanate
TPU	Thermoplastic polyurethane
UTS	Ultimate tensile strength
XDI	Xylene diisocyanate

Chapter 1: Introduction, aim and outline

1.1 Introduction and aim

It is almost impossible to imagine our modern world without polymers as these materials can be found in all kinds of applications like clothing, construction materials and cosmetics. They also led to major breakthroughs in the medical field and the evolution of electrical devices. Due to the versatility of polymers, their properties can be tailored to meet the specific demands of any application. When polymer materials are compared to non-synthetic materials, they offer ecological and economic benefits because of their low weight, small carbon footprint, straightforward processability and useful lifetime.

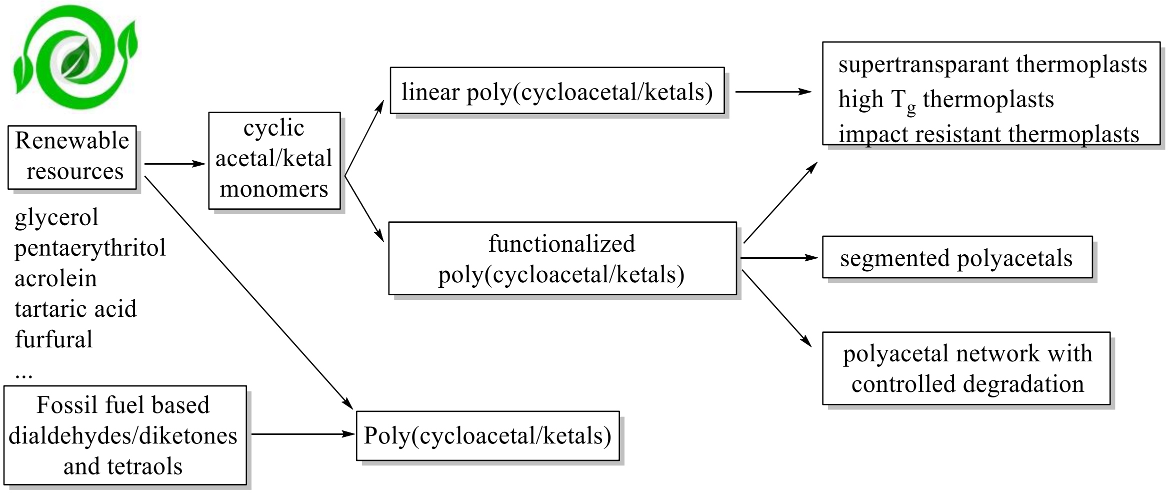
However, due to the depletion of fossil resources, the polymer industry is more and more challenged to develop sustainable and biobased polymers.[1-3] Next to this, the governments' and the public awareness has increased when it comes to sustainable products, which resulted in increased interest for the development of "green" plastics.[4-7] Nowadays, a limited number of biobased polymers is commercially available of which poly(lactic acid) and green polyethylene are well-known examples.[8-10] With the introduction of the PlantBottle of Coca-Cola and the associated large marketing campaigns, renewable polymers were really introduced to the society.[11]

At the moment, packaging is an important opportunity for the application of biobased polymers. However, it is challenging for such materials to compete economically with petrochemical derived polymers.[12-14] Instead, biobased polymers should seek to compete in higher value and higher performance application areas like thermoplastic elastomers and engineering plastics. One of the clear challenges in biobased polymers is the search for rigid polymer structures with resulting good thermal and mechanical properties. Moreover, understanding and engineering the degradation profiles of biobased polymers, for example by combining long-term durability with a triggered degradation, represents a challenge for researchers today. It is this area of high performance biobased polymers with triggered degradation that forms the foundation of this thesis.

A possible solution for the above-mentioned challenges in biobased polymers are poly(cycloacetal/ketals) as these polymers are rigid and can be degraded in an acid environment.[15] Moreover, by the introduction of multiple aliphatic cycles in the polymer chain, amorphous and therefore transparent polymers should be realized, which can have an added value.

The goal of this PhD research was to synthesize poly(cycloacetal/ketals) from renewable resources. In our research effort, the starting point was always to strive for transparent materials with high glass transition temperatures ($T_g > 100$ °C) and degradation temperatures. Moreover, the materials should be ductile and have good elastic moduli when implemented in high-end applications.

An overview of the different pathways that will be followed in this thesis is presented in Scheme 1.1. Fully and partially renewable poly(cycloacetal/ketals) can be synthesized depending on the used monomers. When tetraols and dicarbonyls are combined in a direct fashion, poly(cycloacetal/ketals) can be obtained as such. Another pathway consists of the synthesis of cyclic acetal/ketal containing bifunctional monomers from renewable feedstock, followed by a polycondensation reaction. On the one hand, linear poly(cycloacetal/ketals) can be synthesized, while on the other hand polymers, functionalized in a post-polymerization reaction, could be obtained. Depending on the properties of the different poly(cycloacetal/ketals), a variety of applications can be aimed for.



Scheme 1.1. Overview of the possible pathways to make poly(cycloacetal/ketals) for different applications.

1.2 Outline

Chapter 2 is an introduction to renewable monomers and the biobased polymers hereof. First, some definitions will be given and it will be explained why the society is turning towards renewable resources and sustainable development. Then, a short overview will be given of the different families of renewable monomers and their pros and cons. To explain how popular biobased polymers are at this time, a few examples of commercially available biobased polymers are presented. Their synthesis and properties are explained thoroughly and the biobased carbon content is compared for the different examples.

Chapter 3 situates polyacetals and polyketals in the world of polymers. The possible methods to make polyacetals and polyketals will be discussed, followed by an in-depth study of poly(cycloacetal/ketals). The reported literature on poly(cycloacetal/ketals) is presented in three sub-chapters divided based on their synthesis method. These three methods are polyacetalization/ketalization, the polymerization of a difunctional molecule containing cyclic acetal/ketal moieties and polytransacetalization/ketalization. As the goal of this thesis is concerned with the synthesis of poly(cycloacetal/ketals) from renewable resources, the state-of-the-art on this topic is discussed in the final section of this chapter.

Chapter 4 gives an introduction on step-growth polymerizations as this is the class of polymerizations to which poly(cycloacetal/ketals) belong. Attention will be given at the molecular weight distribution and control of these kind of polymerizations. In the second half of the chapter, a small overview is presented of the four major sub-classes of step-growth polymerizations and their synthesis. Thus, polyesters, polyamides, polycarbonates and polyurethanes will be discussed in more detail here.

Chapter 5 reports the synthesis of poly(cycloacetal/ketals) *via* polyacetalization/ketalization. Initially, a model study was performed on several commercially available dicarbonyls to check their reactivity towards acetalization/ketalization. After this model study, the most reactive dicarbonyls were chosen and they were reacted on the one hand with pentaerythritol as tetraol and on the other hand with di-trimethylolpropane. The polymerizations were performed *via* reported synthesis methods. The resulting polymers were investigated chemically, thermally and mechanically and their properties were compared. Next to this, also various renewable dialdehydes were synthesized from hydroxyaldehydes, e.g. 5-hydroxymethylfurfural. The synthesis of these compounds was optimized and also here, a model study was performed prior to the polymerization with a tetraol. The thermal properties of these renewable poly(cycloacetals) were examined more profoundly.

Chapter 6 presents the step-growth polymerization of acetal containing monomers. The idea was to synthesize difunctional compounds that contain acetalized pentaerythritol in their structure. An attempt was done to synthesize a diol, diamine, diester and dithiol from our starting compound. The procedure to obtain each monomer was optimized and for some, an upscaling could be done. Subsequently, these monomers were used in step-growth polymerizations to make polyurethanes, polyamides, polyesters and polythioethers. For each class of polymers, the synthesis was fine-tuned and the thermal and mechanical properties were measured.

Chapter 7 addresses the step-growth polymerization of ketal containing monomers. Diols were synthesized from commercially available diketones and glycerol to obtain (partially) renewable monomers. The experimental procedures were optimized and the synthesis was upscaled. From these diols, polyurethanes, polycarbonates and polyesters were synthesized with respectively available diisocyanates, diphenylcarbonate and renewable diesters. The polymers were extremely well characterized and the resulting thermal and mechanical properties were compared.

Chapter 8 explores transketalization as a polymerization method as this was rarely reported. First, a bisketal of diglycerol was synthesized. Due to the limited amount of papers on this subject[16-17], a general method was defined in this chapter. Thereafter, the bisketal from diglycerol was reacted with (renewable) diketones in order to obtain poly(cycloketals) with a high biobased content. Moreover, copolymers were synthesized with di-trimethylolpropane to combine the advantages of both tetraols.

Chapter 9 presents the versatility of poly(cycloacetal/ketals) since functionalities can be built in the polymer chain, which can be reacted in a post-polymerization modification reaction. Diethyl tartrate was acetalized with acrolein into an alkene containing diester, after which this diester was polymerized with 1,4-butanediol. Optimization of the polymerization was crucial for these kind of monomers. The resulting poly(cycloacetal-esters) with pending double bonds were modified with a variety of thiol compounds *via* a thiol-ene reaction. As such, a very hydrophilic or hydrophobic polyester could be obtained. Moreover, these type of polyesters could also be crosslinked with dithiols and the resulting networks were tested on their acid degradability.

Chapter 10 will give a general conclusion and addresses some perspectives for follow-up research.

Chapter 11 provides a summary of this thesis in Dutch.

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Chapter 2: Biobased polymers and their challenges

2.1 Introduction and definitions

Most of the bulk polymers are derived from petrochemicals. Although only 6% of the worldwide produced oil is used in the fabrication of polymers, there are environmental concerns associated with both the raw materials used to make them and their end-of-life options.[1-4] Therefore, sustainable polymers are investigated and besides, the development for sustainable polymers is stimulated by policy, legislation and international agreements.[5] Research has mainly focused on replacing fossil raw materials with renewable alternatives and on developing materials with recyclable or biodegradable end-of-life options.[6] Although renewability and biodegradability are often used in a similar context, Figure 2.1 shows that it does not mean automatically that a biobased polymer is biodegradable and vice versa.[7] For example, biobased polyethylene has the same properties as conventional polyethylene, which means that they both do not biodegrade.

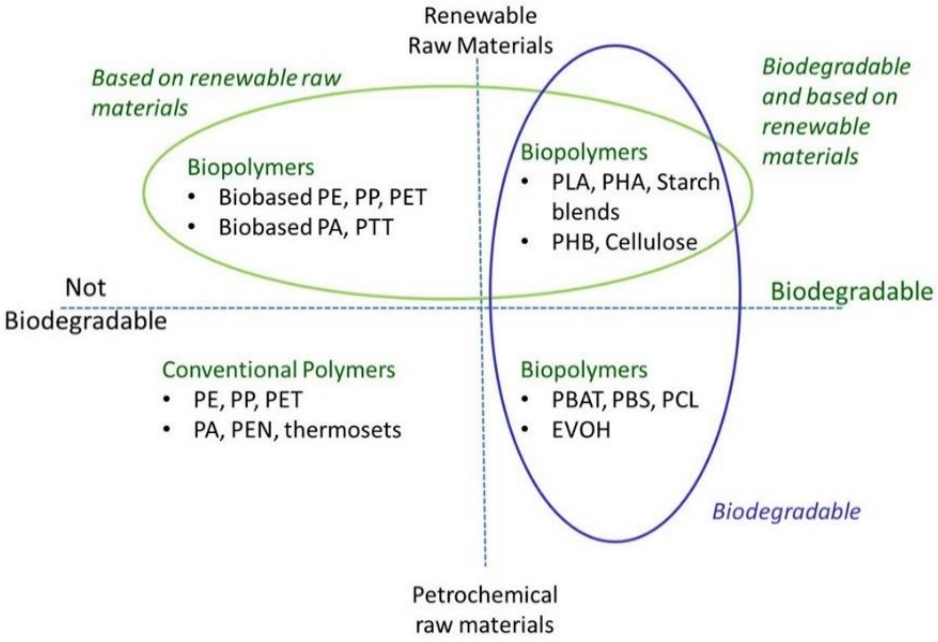


Figure 2.1. Overview of polymers from renewable and fossil raw materials and their ability to biodegrade.[7]

In this chapter, we will focus on polymers from renewable resources, as these were the main target of this thesis. There are four working philosophies when dealing with polymers from renewable resources.[8]

1. The preparation of monomers, which are already widely used
2. The manufacture of novel materials with new properties and applications
3. The synthesis of polymers that simulate the performance of existing polymers
4. Chemical or physical modification of natural polymers

The first philosophy is also known as the *drop-in* strategy, which is highly wanted by industry as it usually requires a lower amount of investments and has the added benefit of an already existing, fully mature market.[9] The second philosophy corresponds with the emerging strategy, in which a completely new value chain needs to be build up. Moreover, the final product does not necessarily competes with already existing products. However, this strategy usually requires larger investments and more technological developments compared to the *drop-in* strategy. The third strategy is a combination of the *drop-in* and emerging strategy and works with new renewable monomers that can be introduced in already existing polymer processing technologies. An example of a polymer which is produced with this strategy is PEF.[10] In this analogue of PET, the classic terephtalic acid is replaced with a completely new monomer, 2,5-furandicarboxylic acid. This example looks like it belongs to the emerging strategy; however, it can be introduced in the same processing facilities of PET, which resembles the *drop-in* strategy. The fourth strategy is probably the oldest strategy of working with renewable polymers. The most famous example is the chemical modification of cellulose to gain polymers with different properties.

At the moment, sustainable polymers only present a minor fraction in the global plastics market (< 1%), but a significant increase is predicted over the next decades.[11] Although bioderived polymers show to be environment friendly and can benefit from supportive policy or legislation, favorable economics and superior material properties will be required to invoke the expected increase. These polymer materials will need to outshine in material properties such a mechanical strength, thermal resistance and processability. These tough criteria explain why there are only few commercially successful sustainable polymers up until now.

In the following paragraphs, an overview of the available renewable monomers will be presented after which the commercial biobased polymers of today will be highlighted. Finally, the challenges for biobased polymers will be discussed in order to give an insight in the foundation of this thesis.

2.2 Renewable monomers

Renewable resources represent the obvious answer to the quest for macromolecular materials that could replace fossil-based polymer materials. This is not an original idea, as apart from natural polymers, the first synthetic polymer commodities were developed during the second half of the 19th century. Among these polymers, cellulose esters, vulcanized natural rubber, terpene resins etc., could all be synthesized. The last decade, the use of renewable resources gained a lot of attention as witnessed by the spectacular increase in the number of publications, reviews and symposia. Moreover, public and industrial sectors are getting more and more involved in this broad field of research.

The purpose of this chapter is to provide a concise overview of the state of the art related to monomers from renewable resources. Two categories are defined; first, the monomers replacing fossil counterparts will be discussed, after which other monomers from biomass are described.

2.2.1 Monomers replacing existing counterparts from fossil fuels

This section deals with efforts to prepare well-known monomer structures, traditionally prepared from fossil resources, using renewable counterparts. The research and technological activities in this context are rapidly growing and some of these processes are already industrially implemented.

2.2.1.1 Ethylene and propylene

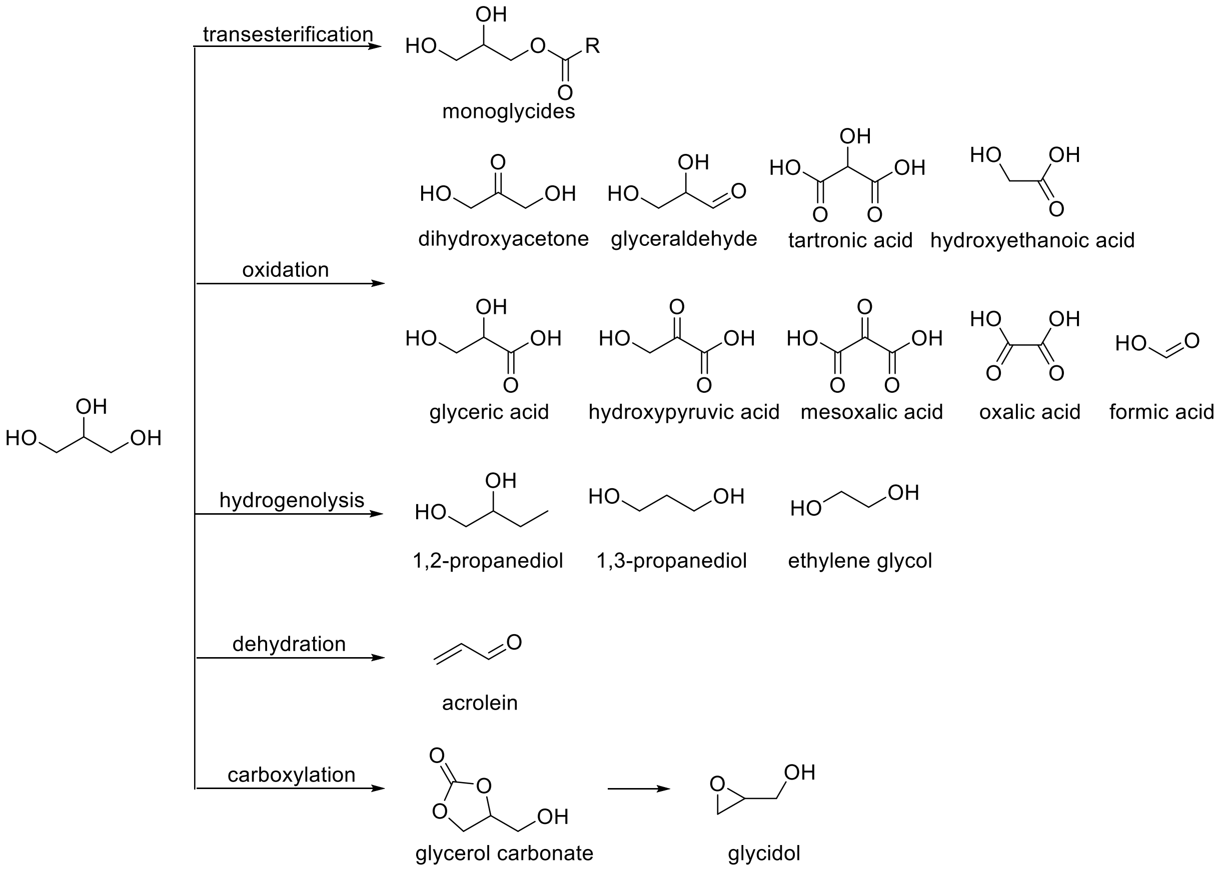
When sugar cane or other sugar rich crops is fermented, this results in bio-ethanol. This ethanol can then be further dehydrated to obtain biobased ethylene. [12] Since 2010, Braskem, a Brazilian company, uses this process to produce 'green ethylene' and also poly(ethylene) on ton scale.[13] Recently, they started investigating the synthesis of ethylene from ethanol, derived from non-edible cellulose sources.[8] As such, ethylene could be produced from renewables everywhere in the world. The production of ethylene from renewable resources is an important milestone as it is one of the most important monomers on the planet.

The next step is to prepare all major olefin monomers from renewables, like for example propylene. Braskem performed the necessary research in order to optimize the synthesis of propylene from ethanol, to make polypropylene in the end.[14] Now, a venture with other companies is concerned with the upscaling and catalyst implementation of this pathway.[15] It is expected that 'green propylene' will soon be on the market.

2.2.1.2 Glycerol and monomers derived therefrom

When producing biodiesel, triglycerides are converted by transesterification to the methylesters of its various fatty acids, leaving glycerol as a byproduct. As a consequence of the biodiesel revolution, the availability of glycerol increased, while the price dropped significantly (0.1 \$/kg).[16] Because of the availability and low price, research institutions are looking for novel utilizations for glycerol itself, as well as possible transformations into a variety of compounds.

Glycerol can be polymerized to a linear or highly branched structure, which can be applied in cosmetics, food additives and lubricants.[17] Next to this, glycerol can be applied for the production of a wide range of value added chemicals. The low glycerol price makes it interesting to look for the production of other chemicals via different pathways.[8, 18-19] A few examples will be presented here and an overview is given in Scheme 2.1.



Scheme 2.1. Overview of the chemicals derived from glycerol.

A first reaction is the transesterification with fatty acids to obtain monoglycide compounds that can be applied as food emulsifiers or non-ionic surfactants.[20] The oxidation of glycerol can result in a large variety of hydroxyesters/acids, which have great potential as intermediate for polymer synthesis.[21-23] When glycerol is selectively hydrogenated via metal-catalysis, diols like propanediol and ethylene glycol can be obtained. These diols are well-known polycondensation monomers, which can be incorporated in polymers for different applications, e.g. polyester resins, cosmetics, paint and anti-freeze.[18] Acrolein can be synthesized from glycerol via a sustainable, cost-effective dehydration route, different from the commercial process from fossil sources.[24-25] Acrolein is an important intermediate for the production of acrylic esters that when polymerized can be used as superabsorbents and detergents. Glycerol can also be transformed into glycerol carbonate, which is on the one hand a solvent for plastics and resins. On the other hand, it is an intermediate to make glycidol, which is an important source for hyperbranched macromolecules and dendrimers.[26]

In the future, the production of glycerol will most probably further increase with consequently even lower prices. The application of glycerol as a feedstock for the synthesis of polymers, in replacement of some classical petrochemical routes, is crucial in the context of sustainable development.

2.2.1.3 Other monomers from biomass

In addition, some renewable counterparts can already replace other monomers used in the polymer production. Isoprene is an important monomer for the synthesis of elastomers and the tire industry. Next to the renewed interest in natural rubber (polyisoprene) exploitation, the perspective to produce large quantities of isoprene from renewables is very attractive.[27] Both academic and industrial efforts were made to study the biosynthesis of isoprene from isopentenyldiphosphate using different bacterial sources.[28-29]

Next to isoprene, the synthesis of succinic acid from fermentation of sugars has been investigated by various companies like BASF and DSM, as there is a yearly demand of about 40 000 tons.[30-31] On the one hand, succinic acid is an important precursor for the polyester and polyamide synthesis, while on the other hand it shows to be a potential source to other monomers like 1,4-butanediol, tetrahydrofuran and maleic/fumaric acid.

Furthermore, cellulose can be seen as a potential platform for the synthesis of small molecules (e.g. 1,2-alkanediols).[32] Cellulose could exist as a feed for biorefineries where the feed is separated into useful compounds.[33] Biorefineries are thought to function like their petroleum counterparts, whereby an optimized balance must be achieved between energy sources and chemical commodities, including monomers.

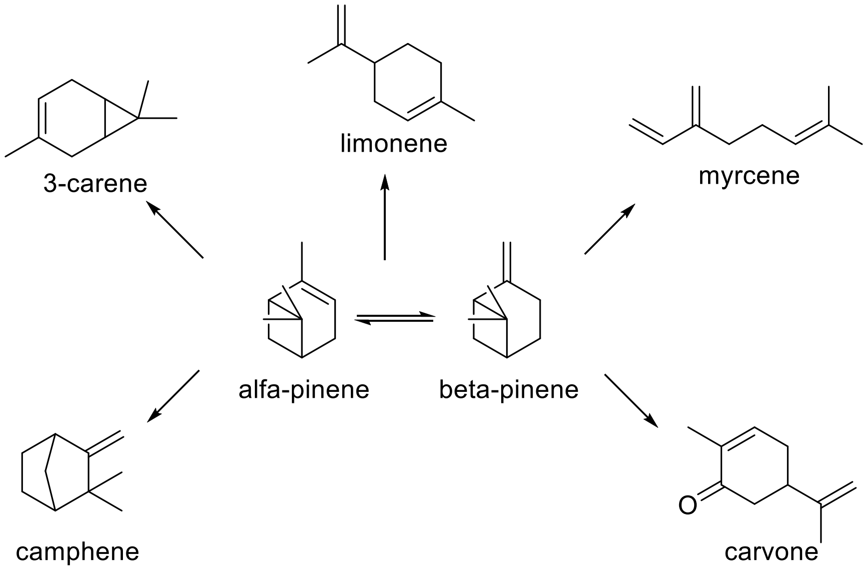
Finally, lignin could deliver precursors for aromatic monomers by selective depolymerization.[34] Methoxy- and hydroxyl styrenes and substituted hydroxyl-benzoic acids are the specialty monomers that could be derived from lignin.[35] As the synthesis of these monomers from fossil resources is associated with high costs, the alternative preparation from cheap lignin could be a nice implementation of renewables. However, the persisting problem with lignin is the difficulty in addressing a specific monomer structure, rather than a mixture of homologues, whose applications in polymer synthesis can provide well-defined macromolecular structures rather than random copolymers.

2.2.2 Original monomers, not currently available from fossil resources

A rich pallet of monomer structures arise from renewable resources where some can be applied as such, while others need to be transformed first. This section describes both types, together with their link to macromolecular materials.

2.2.2.1 Terpenes

Terpenes are unsaturated aliphatic structures, mainly derived from turpentine, the volatile fraction of resins from conifers. Most terpenes share isoprene as a common building block and can be classified according to the number of isoprene units. Monoterpenes, bearing the general isoprene-dimer formula $C_{10}H_{16}$, are the only relevant members as they can polymerize in a relatively controlled fashion. The global turpentine production amounts to more than 300 000 tons per year and its major constituents are α-pinene (45–97%) and β-pinene (0.5–28%) (Scheme 2.2).[36] R-limonene is a byproduct of the citrus industry, with a yearly world production of 70 000 tons. The pinenes and limonenes are cheap and abundant natural products, extensively used as chemical precursors to a wide variety of chemicals for the pharmaceutical, fragrance and flavor industry.[8] The pinenes are also exploited as a source for other less common, but interesting terpenes, through selective isomerization processes, as sketched in Scheme 2.2.

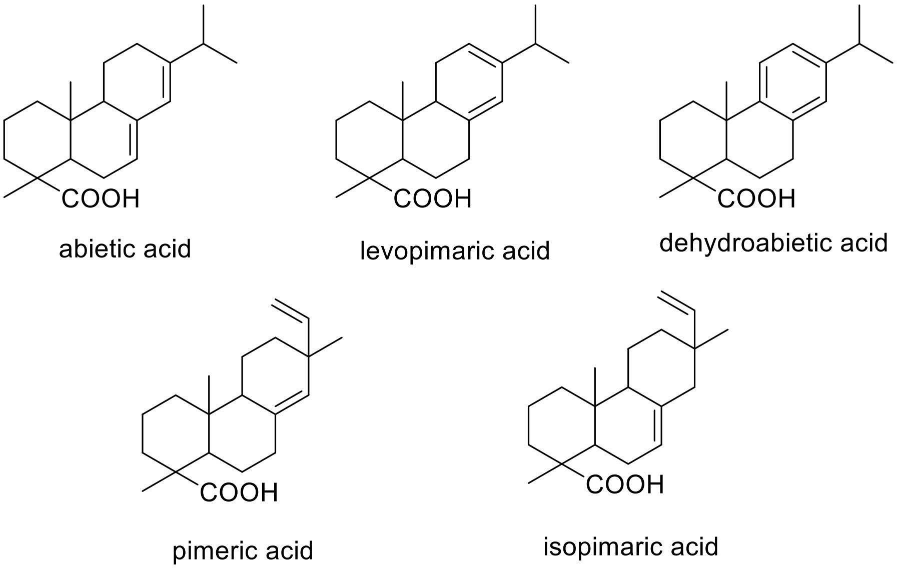


Scheme 2.2. Isomerization and oxidation processes for converting pinenes into other terpenes.

Among the terpenes, β-pinene is by far the most viable monomer because of being cheap and only bearing one alkenyl unsaturation, which leads to less side-reactions. Its cationic polymerization has been extensively studied, first with classical Lewis-acid initiators, then using quasi-living systems.[36-37] Free radical polymerization of terpenes is of little interest as only low degree of polymerization and yields could be realized. However, the radical copolymerization of β-pinene with acrylates via controlled reversible addition fragmentation chain transfer (RAFT) produced interesting materials.[36] Moreover, acyclic diene metathesis (ADMET) was used to polymerize myrcene.[38] Many articles report renewable polycarbonates from limonene oxide when copolymerized with CO_2.[39] A disadvantage of terpenes is the shortage of functional groups. This could however be circumvented by introduction of functionalities via thiol-ene chemistry. [40] For example, alcohol and ester groups were introduced and polyesters could be obtained from these structures.

2.2.2.2 Rosins

Rosin, one of the most common natural products, is the non-volatile fraction of pine resin with a production volume of more than 1Mt yearly worldwide.[36] Rosin consists of hydrophenthrene structures like abietane-type and pimarane-type “resin acids”, five of which are shown in Scheme 2.3. Rosin and its derivatives are used as emulsifiers, tacifiers and additives to printing inks and varnishes.[41]

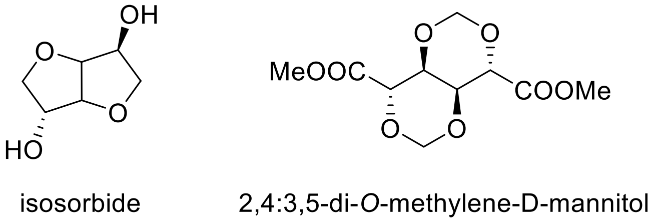


Scheme 2.3. The most representative structures found in rosin.

A large variety of chemical modifications have been applied to rosin in order to obtain polymerizable structures for both linear and crosslinked materials.[41] Mostly, reactions were performed on the olefin moiety like oxidation, hydrogenation, dehydrogenation, isomerization and Diels-Alder reactions.[42-43] Also, reactions concerning the carboxyl function were performed including the preparation of salts and acrylates, esterification and alkoxylation. Many of these derivatizations are aimed at the synthesis of monomers for both polycondensation and polyaddition reactions, e.g. rosin-based structures containing two carboxylic acids or anhydrides for polyester and polyamide synthesis. Then again, the diene moieties can be functionalized, for example via Diels-Alder reactions with maleimides. The recent synthesis of rosin-based oxiranes and acid anhydrides suitable for epoxy resins showed that this renewable resource could readily replace fossil-derived monomers in the preparation of an important family of materials.[44-46]

2.2.2.3 Sugars

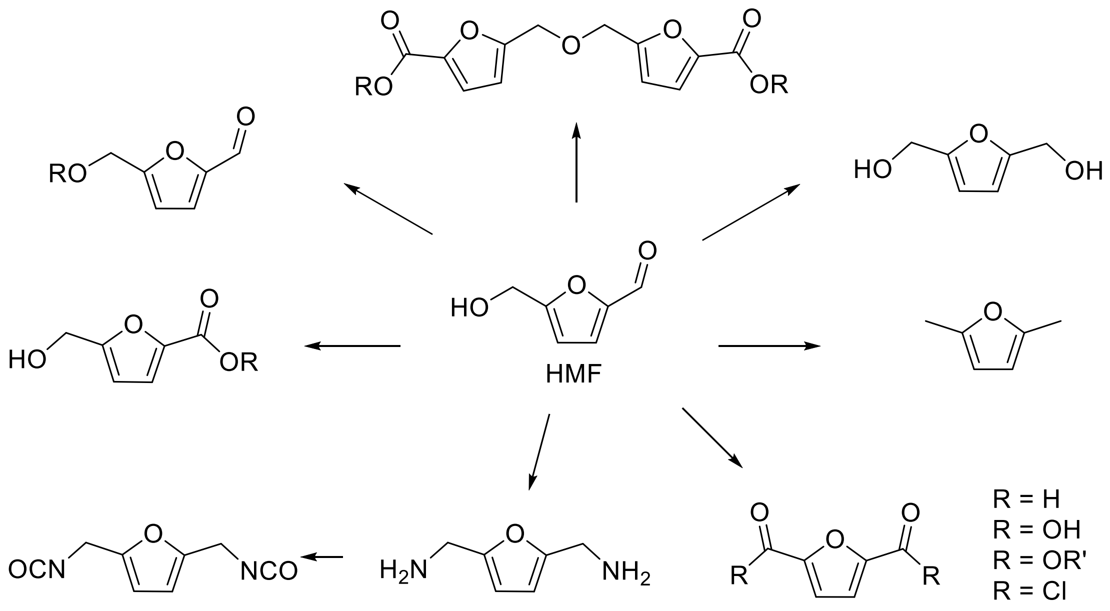
Carbohydrate-based building blocks have become highly relevant to the field of polymers from renewable resources. Macromolecular materials incorporating these monomer units can exhibit high chain stiffness, but can also be promising in biomedical applications.[47] The most well-known monomer derived from sugars to be used in polymerizations, is isosorbide and its stereoisomers. Isosorbide (Scheme 2.4) is prepared by the double dehydration of sorbitol, which can be obtained from the hydrogenation of glucose.[48] Isosorbide has already been used in the synthesis of polyesters, polycarbonates, polyurethanes and polyethers and results in high T_g polymers with low crystallinity due to the asymmetric position of the diols.[48-51] Industrially, isosorbide-based plastics are already produced by Roquette to obtain materials like food containers and other kitchen supplies.[52] Muñoz-Guerra *et al.* published multiple articles on carbohydrate-based bicyclic (CBB) compounds in polyester and polyurethane synthesis.[49, 53-62] A general strategy is applied; a carbohydrate derivative, like mannitol, galacteric acid and glucitol, is reacted with formaldehyde to form the acetal containing diester or diol, an example is presented in Scheme 2.4. Hereafter the synthesized monomer is used in the polyester or polyurethane synthesis. The main goal of their research is to compete with PET and mimic or outshine in thermal and mechanical properties.



Scheme 2.4. Examples of sugar derived monomers, namely isosorbide and 2,4:3,5-di-*O*-methylene-D-mannitol.

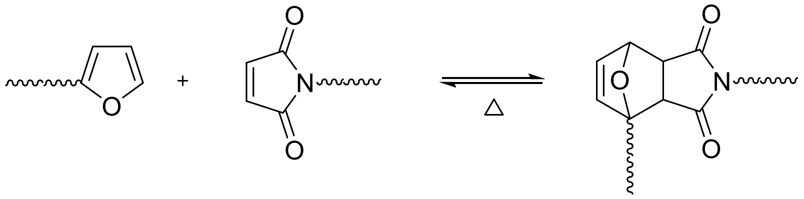
2.2.2.4 Furans

In the case of furan, a whole spectrum of small molecules can be explored as monomers in polymer synthesis. The peculiar chemical properties of this heterocycle opens the way for the synthesis of macromolecules with special properties. However, the presence of a furan cycle can, in some cases, give rise to problems such as lower chemical stability compared to its aliphatic or aromatic counterparts.[63] It all starts from two building blocks that can be prepare from dehydration of any saccharide source, namely furfural, prepared from pentoses, and 5-hydroxymethylfurfural (5-HMF), prepared from hexoses. Furfural has been an industrial commodity for nearly a century, whereas 5-HMF, and its corresponding diacid, is presently reaching that stage. A comprehensive series of monomers can be prepared from furfural and 5-HMF, some of which are given in Scheme 2.5.[64]



Scheme 2.5. Overview of possible compounds that can be prepared from 5-HMF.

All these monomers are associated with step-growth polymerizations and thus polyesters, polyamides, polyurethanes and others were prepared. Their properties were assessed and some of the novel furan containing macromolecules displayed features comparable or even more promising than their conventional petrochemical counterparts. Some of the materials showed to exhibit remarkable properties like Kevlar-type PET-like behavior and polyurethanes with self-extinguishing flame resistance.[65] The most significant contribution to furan polymers is the application of the Diels-Alder (DA) reaction, a reversible process, involving monomers like furan (diene) and maleimide (dienophile).[66] The combination of furan and maleimides can be applied for the synthesis of thermoreversible polymers, i.e. materials that can be readily recycled, possess self-mending properties and can alternatively be converted into heat-resistant macromolecules.[67] The DA reaction is shown in Scheme 2.6, where the forward reaction, resulting in the DA adduct predominates up to about 65 °C, whereas the equilibrium is heavily shifted in favor of the retro-DA reaction that breaks the couplings above 110 °C. Both linear and branched architectures have been constructed, including reversibly crosslinked materials.[68]

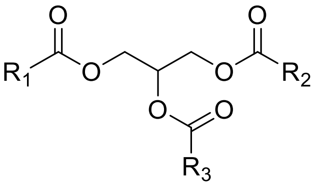


Scheme 2.6. The DA equilibrium when combining furan and maleimide.

In conclusion, furan monomers and the peculiarities of furan chemistry already showed to have a high potential in macromolecular synthesis. Novel materials could be synthesized that span a comprehensive set of properties and possible applications.

2.2.2.5 Vegetable oils

The exploitation of vegetable oils as a source of materials is an old principle, for the application in coatings and the production of soap. More recently, they are applied for progressively wider and more sophisticated applications including inks, plasticizers, alkyd resins, agrochemicals, etc.[19] With the production of biodiesel, the availability of vegetable oils has increased enormously. This resulted in the continuous development of crosslinked and linear macromolecules from triglycerides. On the one hand, triglycerides can substitute petro-derived products, while on the other hand also materials from vegetable oils that do not have a petrochemical counterpart could be synthesized. Moreover, the synthesis of monomers and polymers from plant oils is being implemented in an increasing number of industrial applications. [69]



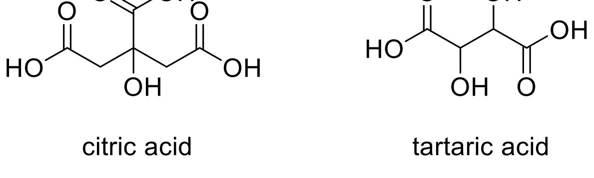
Scheme 2.7. Structure of a triglyceride.

Vegetable oils exist out of multiple triglycerides, which are formed from glycerol and various fatty acids. In the structure of a triglyceride like in Scheme 2.7, R_1, R_2 and R_3 represent the fatty acid chains, which are linear aliphatic structures that can vary in length (12-22C), unsaturations (0-6) and sometimes contain functional groups like hydroxyl groups and epoxides. Vegetable oil represent 80% of the global oil and fat production, whereas 20% is of animal origin, with this share decreasing. About 25% is soybean, followed by palm oil, rapeseed, and sunflower oil. The abundant output of reviews and articles on polymers derived from plant oils in the last few years is an indication for the growth of this area of research.[70-72]

The internal double bonds can directly react with free radical or cationic polymerization reactions.[73] The former is known to be used in drying oils, paints and coatings. The cationic copolymerization of triglycerides results in thermosetting materials ranging from rubbers to hard plastics. Next to the direct reaction of the double bonds, also the preparation of polyols from fatty acids and oils for general polyurethane applications has been the subject of many studies.[74] However, the low reactivity of the unsaturated aliphatic chains makes these compounds ineffective monomers. Therefore, different chemical modifications were performed on vegetable oil to obtain useful monomers. The most popular modification is the epoxidation of the double bond.[75] For example, acrylated epoxidized soybean oil is already commercially available from UCB Chemical Company and serves as a photosensitive coating material.[76] A new efficient route for the implementation of renewables is the olefin metathesis of vegetable oils or fatty acids derived hereof.[77] Hydrothiolation of the double bond (thiol-ene) has also been profoundly investigated for the successful preparation of many polymers and is still growing in popularity.[78] Also, “click” chemistries concerning the double bond were explored. Azide-alkyne and triazolinedione (TAD) chemistry could successfully be applied onto vegetable oils resulting in highly crosslinked polymers without the use of a catalyst or solvent.[79-81]

2.2.2.6 Polycarboxylic acids and aminoacids

Citric acid (Scheme 2.8) is a low cost commodity produced industrially via fermentation of biomass with a yearly industrial production of over a million tons.[8] Its use in polymer science was concentrated mostly on its role as a chemical modifier and plasticizer of starch. In more recent years citric acid has been employed as a monomer in the synthesis of polyesters, like crosslinked materials for controlled drug release and biodegradable polyesters for tissue engineering applications.[82-83] Tartaric acid (Scheme 2.8) is an equally widespread and cheap natural product and its use as a monomer is particularly explored in the group of Muñoz-Guerra.[84-85] An interesting study handles the synthesis of polyurethanes with different diisocyanates bearing COOH side groups, which displayed a unique proneness to degrade with water upon incubation under physiological conditions.[86] Tartaric-acid based polyesters, synthesized by the transesterification of OH-protected dimethyl tartrate with aliphatic diols, gave materials with controlled hydrophilicity.[87] After deprotection, these highly hydroxylated polyesters became soluble in polar solvents, including water.



Scheme 2.8. Structure of citric acid and tartaric acid.

The polymerization of natural amino acids generates proteins. A different situation arises if an amino acid is used as a source for polymers other than its own polyamide, as in the case of L-lysine and L-phenylalanine.[88-89] This approach describes the synthesis of hyperbranched poly(ester urethanes) based on D,L-alanine using an isocyanate-free process.[90]

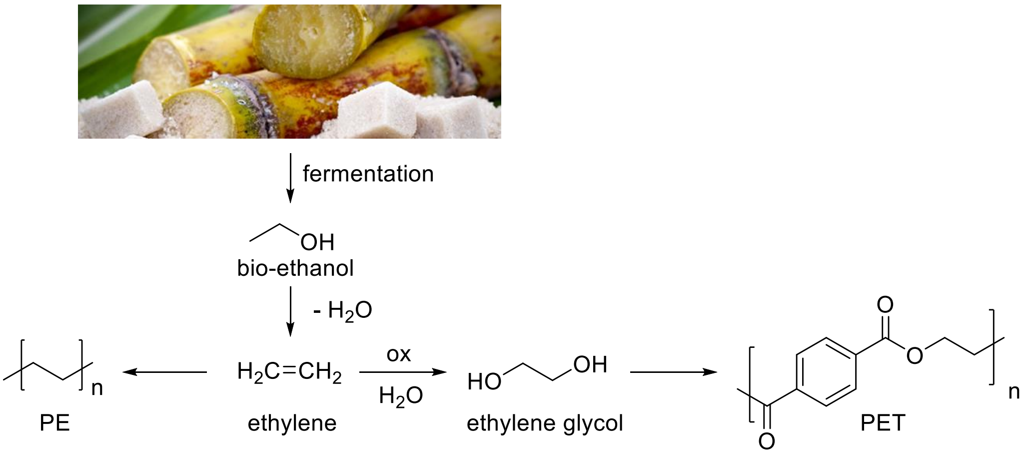
2.3 Commercial biobased polymers

As can be seen from the paragraph on renewable monomers, there is a wide variety of renewable monomers available. However, only a limited amount of these biobased monomers is already commercially applied. An overview of the most famous commercially available polymers from these renewable monomers will be presented.

2.3.1 Green PE and PET

In this paragraph, two very different renewable polymers, bio-PE and bio-PET, are described together as at least one of their monomers can be synthesized from renewable resources and substitutes a petrochemical counterpart.

Ethylene can be produced from the dehydration of ethanol, coming from sugar cane as discussed in paragraph 2.2.1.1. PE is synthesized via radical polymerization of ethylene and a 100% renewable polymer is obtained when bio-ethylene is used. Furthermore, ethylene can be transformed to ethylene oxide and when reacted with water, ethylene glycol is obtained.[91] This renewable ethylene glycol can then be used in the synthesis for renewable PET, which has been applied in the plant bottle of Coca-Cola.[92] In bio-PET only 20% of the carbon content is bio-based, thus improvement is still necessary. This can maybe be realized by changing terephtalic acid by furan dicarboxylic acid (*vide infra*). The bio-based carbon content is calculated by dividing the amount of biobased carbons by the total amount of carbons in the structure.[93] In Scheme 2.9, an overview of the synthesis of bio-PE and bio-PET from renewable feedstock is presented.



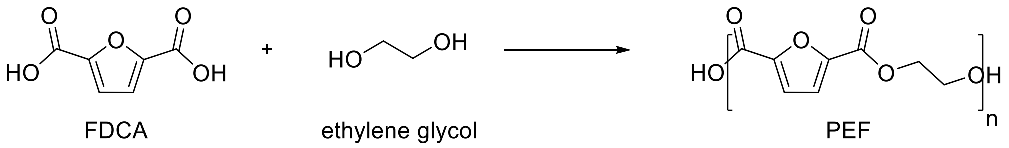
Scheme 2.9. Overview of the synthesis of bio-PE and bio-PET from ethanol fermented from sugar cane.

An advantage of developing monomers from renewable resources as direct substitutes is that the polymerization process, processing and applications of the resulting polymers are identical, which simplifies their integration. These biobased polymers are front-runners in the commercialization of sustainable polymers.

The method of making bio-PE is rather controversial as the polymer is not recycled at the moment and usually persists in, and pollutes the environment. Moreover, an edible feedstock is necessary in order to prepare the polymers and this may have a social impact. The European Union performed a detailed study on the potential land-use requirements for bioderived polymers. They concluded that 1-5% of the land used at the present moment to grow wheat as a source of starch would be needed.[94] Life-cycle assessment of the present generation of bio-PET shows a reduction of 20-50% in the emission of greenhouse gasses compared to petrochemical derived PET.[2, 95]

2.3.2 PEF

Polyethylene furanoate (PEF) is an attractive fully biobased polymer that could substitute PET, as it has similar properties. Fully bioderived PEF can be synthesized from the polycondensation of bioderived ethylene glycol and furan dicarboxylic acid (FDCA) as can be seen in Scheme 2.10. This diacid is produced from 5-hydroxymethyl furfural (5-HMF), which is sugar-derived.[96] An already improved route, to HMF ethers, is reported because of the instability of 5-HMF which resulted in side products.[97] Next, 5-HMF or the HMF ethers are oxidized to FDCA.[98] It is important to note that the polymerization reaction is compatible with the PET manufacturing process, therefore PEF has the potential to use existing infrastructure. These characteristics of PEF have resulted in the fast commercialization of this biobased polymer.[2]

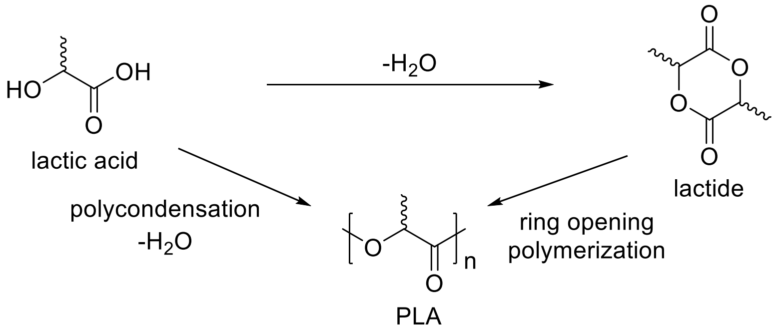


Scheme 2.10. Synthesis of polyethylene furanoate (PEF) from FDCA and ethylene glycol.

When comparing PEF to PET, it is observed that PEF has a higher T_g and improved barrier properties and in addition, PEF is less likely to undergo cold crystallization. All these advantages of PEF make this polymer an ideal polymer material to use in packaging such as bottles. A life-cycle assessment that benchmarked bioderived PEF against petrochemical-derived PET showed a reduction in greenhouse-gas emissions of up to 55%.[96, 99] Until now, the cost of PEF is still higher than that of PET, but it is expected to reduce when produced on a larger scale.

2.3.3 PLA

Polylactic acid is a commercial polymer, which is produced through the fermentation of starch to lactic acid, followed by the preparation of lactide and its subsequent polymerization.[100] In the manufacturing process, an efficient microbial fermentation towards lactic acid is essential. Research showed that better efficiency and profitability can even be achieved with cheap substrates like agricultural waste and glycerol and the utilization of cheaper fermenters.[101] Dehydration of lactic acid results in cyclic lactide which is polymerized in a next step through ring-opening polymerization (Scheme 2.11). PLA can also be synthesized directly from lactic acid in a stepwise polycondensation reaction.[102]



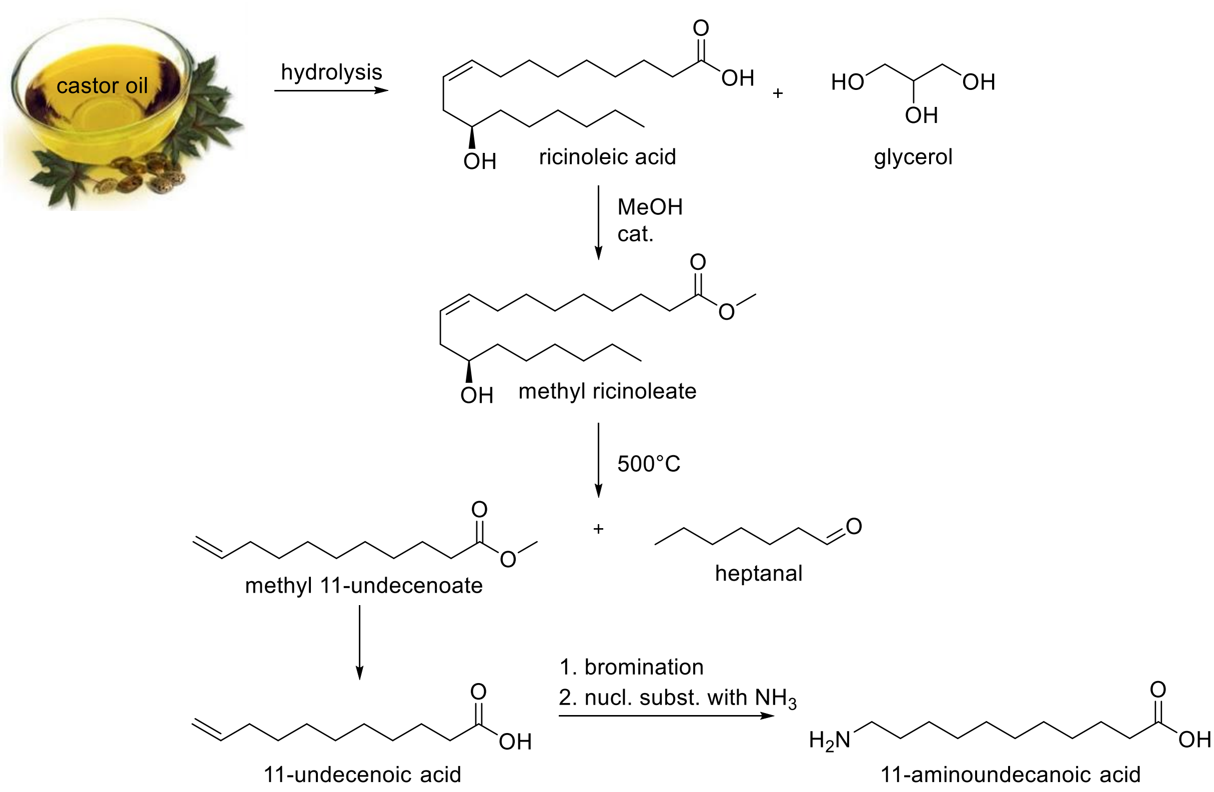
Scheme 2.11 . Synthesis of PLA from lactic acid and lactide.

Polylactic acid has the properties that enable it to replace petrochemical-derived plastics in the area of packaging and fibres.[2, 103] It has reached a global capacity exceeding 250 kilo tons per year with a steady decline in price.[104] PLA is considered as a commodity material and it still has some inferior characteristics like brittleness and mediocre thermal properties like a low heat resistance.[105] Therefore, PLA is often copolymerized or blended with other polymers in order to play with the end properties of the material. In terms of end-of-life, PLA can be recycled and degraded. It is industrially compostable (at high temperatures and humidity) to lactic acid, which can be metabolized naturally. Life-cycle assessment has shown reductions of up to 40% in greenhouse gas emissions compared to petrochemical-derived polymers such as polyethylene or PET.[106] However, the production of PLA may have other environmental impacts, such as the large amounts of water and fertilizer necessary for the production, which is difficult to compare with the impact of fossil fuel extraction and storage.

2.3.4 Engineering plastics

2.3.4.1 Polyamides from castor oil

Different polyamides are already produced from castor oil but the oldest and most known polyamide is Rilsan®. It is a high-performance polyamide 11 (PA 11) produced from a natural raw material, namely from castor oil extracted from the castor plant.[107-108] For 60 years already, Rilsan is known for its extraordinary properties like low density, low moisture uptake, which results in high dimensional stability, high elongation at break and high tensile strength, good abrasion resistance and even high impact resistance. It is used in applications such as fittings, pneumatic and hydraulic tubes and medical devices like catheters. The monomer to make PA 11 is 11-aminoundecanoic acid, which is an AB monomer and is polymerized using a catalyst.



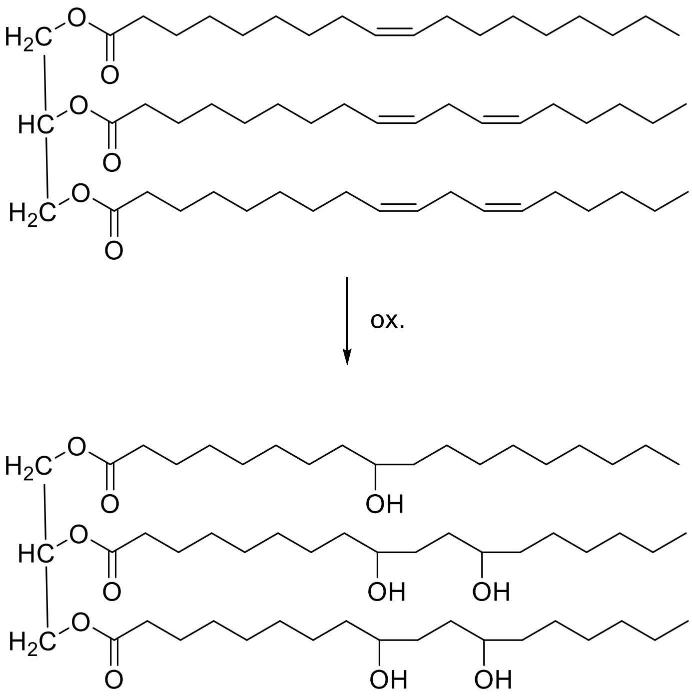
Scheme 2.12. Synthesis of 11-aminoundecanoic acid from castor oil.

The pathway to synthesize 11-aminoundecanoic acid is presented in Scheme 2.12.[109] First, castor oil is hydrolyzed, which results in ricinoleic acid and glycerol. Subsequently, ricinoleic acid is methylated and heated (thermal cracking) after which methyl 11-undecenoate and heptanal are obtained. After hydrolysis, 11-undecenoic acid is obtained and the double bond was brominated after which the amine was made with a nucleophilic substitution.

2.3.4.2 Others

Vegetable oils, BiOH®

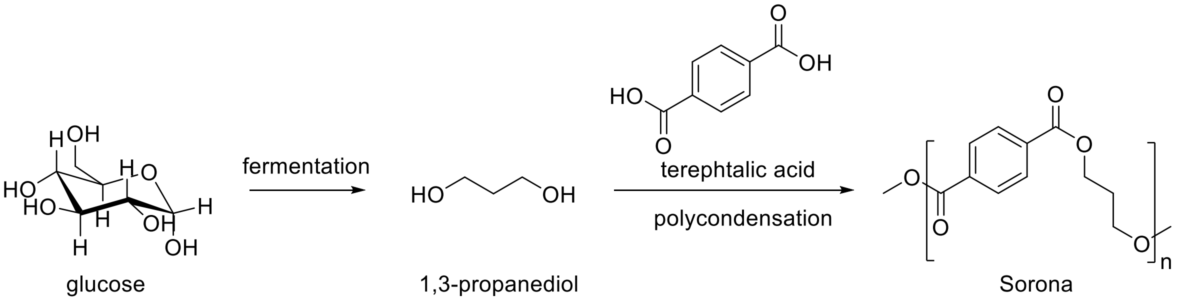
BiOH® is a partially renewable flexible foam made from soybean oil.[110] Flexible foams are polyurethanes, with applications such as furniture, mattresses and automotive seats. These polyurethanes are manufactured via the combination of diisocyanates with polyols. Cargill decided to use a renewable polyol in their polyurethane synthesis that was created from soybean oil.[111] Soybean oil is preferred because of its high level of unsaturation compared to other vegetable oils and it is less expensive than for example corn and sunflower oils. The double bonds are transformed into secondary hydroxyl groups which can react with diisocyanates (Scheme 2.13).[112] Of course, any unsaturated triglyceride can be used resulting in polyurethanes with different properties. As such, a high biobased carbon content can be realized, which is more than 50% depending on the formulation. A preliminary life-cycle assessment showed 36% less greenhouse gas emissions for the synthesis of the polyol.[111] Of course the use of diisocyanates still limits the sustainability of the foams.



Scheme 2.13. Oxidation of soybean oil into a polyol.

1,3-Propanediol, Sorona

Dupont produces a partially renewable polyester that is called Sorona.[113] This polyesters is made up from 1,3-propanediol, obtained from corn, and terephtalic acid. The glucose present in corn is fermented and transformed in 1,3-propanediol as shown in Scheme 2.14.[114] A titanium catalyst promotes the reaction of 1,3-propanediol with terephtalic acid, with the formation of polyesters.[115] Hereafter, the polyester pellets are extruded into fibers, which are mainly used as fibers for carpets and apparel.[116] The manufacture of biobased 1,3-propanediol results in 40% less greenhouse gas emission compared to the synthesis of petrochemical 1,3-propanediol. Moreover, when compared to PET and nylon, Sorona can be recycled more easily because of the absence of heavy metals in the product.[115, 117] Of course, terephtalic acid is still petroleum based, thus only 27% of the carbon content in Sorona is biobased. Other companies also use the renewable 1,3-propanediol as a *drop-in* chemical in their synthesis of, for example, polyurethanes and polycarbonates.



Scheme 2.14. Production of Sorona from glucose harvested from corn.

2.4 Challenges in biobased polymers

First, it important to mention that the use of oil in plastics manufacturing represents the most sustainable and effective use of oil and gas, this in stark contrast to burning oil to generate energy. Moreover, plastics innovations in lightweight engineering, food packaging and thermal insulation of buildings, contribute significantly to energy savings, amounting to more than twice the amount of energy needed to produce the plastics. Polymers play an active role in securing the energy supply as electrical insulators, components of batteries and in rotor blades of windmills. In industrialized countries, polymer packaging secures the food supply chain, whereas in less developed countries 50 percent of the food is lost in transportation.[6] These facts prove that plastics, unlike any other class of materials, already play a key role in sustainable development.[118] Then again, sustainable polymers from renewable resources are gaining importance as society wants to reduce our ecological footprints. These biobased polymers are already commercially available in packaging and fibers but there are still multiple challenges that need to be overcome.

One of the major challenges in the area of biobased polymers is the identification of building blocks that can easily be prepared from abundant feedstocks that do not compete with the food chain. Additionally, agricultural methods for crop production and harvesting need to be improved. Also, the waste from agricultures and industry should be redirected and used for the preparation of monomers. Next to the optimization of the resource extraction, it is also crucial to prioritize the design of routes to monomers and polymers that are compatible with existing industrial infrastructure in order to reduce cost and accelerate the implementation of biobased polymers. Finally, the end-of-life of renewable polymers and the impacts associated with their disposal needs to be considered.[2]

Nowadays, packaging is an important opportunity for the application of biobased polymers. However, it is challenging for such materials to compete economically with petro-chemical derived polymers. Instead, biobased polymers should seek to compete in higher value and performance application areas like thermoplastic elastomers and engineering plastics where the price can be higher. For example, the synthesis of biobased polymers with higher thermal resistance would enable them to compete with existing semi-aromatic polyesters and nylons. Moreover, understanding and engineering the degradation profiles of biobased polymers, for example by combining long-term durability with a triggered degradation, represents a challenge for researchers today. It is this area of high performance biobased polymers with triggered degradation that forms the foundation of this thesis.

2.5 References

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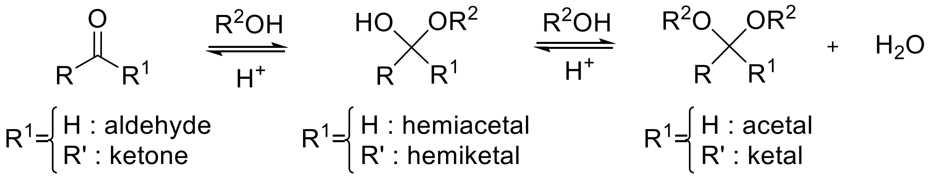
Abstract

This chapter highlights the details on poly(cycloacetal/ketals) reported in the literature. The methods of preparation and the resulting properties will be reviewed and at the end of this chapter an overview of the prior art on poly(cycloacetal/ketals) from renewable resources will be given.

Chapter 3: Polyacetals/ketals: theoretical introduction

3.1 Introduction

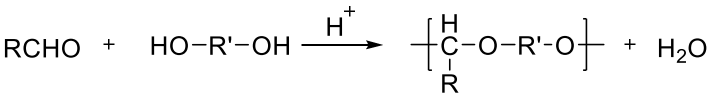
A polyacetal/ketal is defined as a polymer where the repeating unit comprises an acetal/ketal. An acetal/ketal can be obtained from the reaction of an aldehyde or ketone with two hydroxyl groups, respectively. The reaction proceeds via a less stable hemiacetal/ketal as can be seen from Scheme 3.1. It is important to note that the acetalization/ketalization reaction is an equilibrium reaction that is acid catalyzed.[1] Moreover, water is formed, which can be eliminated from the reaction mixture to push the reaction to completion. When combining an aldehyde/ketone with a diol, a cyclic acetal/ketal is synthesized. In case of aldehydes, the formation of six membered cyclic acetals is favored whereas in the case of ketones the formation of a five membered ring is favored.[2]



Scheme 3.1. Synthesis of an acetal/ketal by reaction of an aldehyde/keton with an alcohol.

There are four general methods for synthesizing polymers containing acetal or ketal groups: (1) the reaction of diols with carbonyl compounds, which is an extension of the classical acetal/ketal synthesis, (2) acetal/ketal exchange, (3) addition of diols to divinyl ethers and (4) the polymerization of an acetal/ketal containing monomer with a standard polymerization method.[3] Recently, a fifth method was developed by Miller *et al.*[4] in which polyacetals are synthesized via acetal metathesis polymerization.

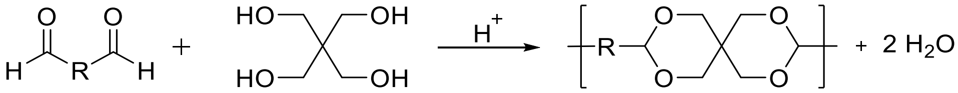
By reacting equimolar amounts of an aldehyde and a diol and removing the condensate, water, polyacetals are formed (Scheme 3.2). A commonly employed method to remove water from the reaction method is by azeotropic distillation, performed with a Dean-Stark apparatus.[5] A serious limitation to this technique is the tendency to form cyclic acetals.



$$RCHO + HO{-}R'{-}OH \xrightarrow{H^+} \left[\overset{H}{\underset{R}{C}}{-}O{-}R'{-}O\right] + H_2O$$

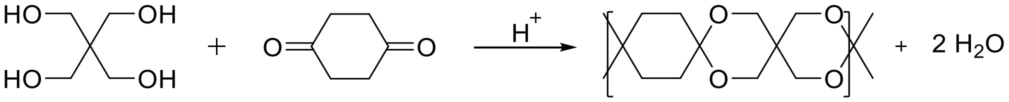
Scheme 3.2 . Synthesis of polyacetals from an aldehyde and diol by azeotropic distillation.

Advantage can be taken of this tendency to form cyclic acetals by reacting tetrols such as pentaerythritol with dialdehydes to form cyclic acetal containing polymers (Scheme 3.3).[6-15] The polymer prepared from glutaraldehyde and pentaerythritol (R = -(CH_2)$_3$-), for example, has been investigated for fiber and wire coating applications.[7]



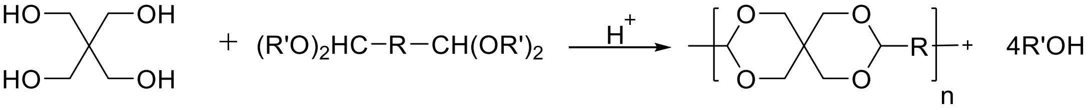
Scheme 3.3 . Synthesis of a poly(cycloacetal) from pentaerythritol and a dialdehyde.

The reaction of pentaerythritol with 1,4-cyclohexanedione to form a *spiro* polyketal (Scheme 3.4) is of particular interest.[16] Spiro polymers are polymers having reoccuring ring units joined through a common carbon atom. These kind of polymers are known for their very rigid backbone and consequently high thermal stability.[17]



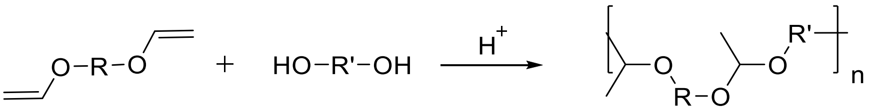
Scheme 3.4. Synthesis of a spiro poly(cycloketal) from 1,4-cyclohexanedione and pentaerythrithol.

Acid-catalyzed acetal or ketal exchange reactions, also called transacetalization/transketalization, result in the same polyacetal and polyketal structures as shown above but instead of water, an alcohol is formed as the by-product (Scheme 3.5). When an alcohol is formed as the condensate, the polymerization can often proceed at lower temperatures as alcohols generally have lower boiling points than water. Thus, polyacetals can be prepared by reacting a tetrol with the acetal/ketal of a dialdehyde/diketone.[7, 10, 18-19]



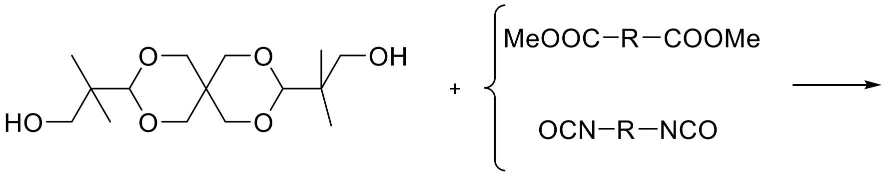
Scheme 3.5. Acetal exchange reaction to prepare a polyacetal.

Linear polyacetals can also be prepared by an entirely different route, namely the acid catalyzed stepwise addition polymerization of diols to divinyl ethers (Scheme 3.6).[20] Polymers of this type have sparked interest as biodegradable polymers for controlled drug release.[21]



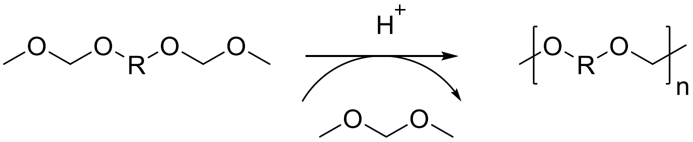
Scheme 3.6 . Acid-catalyzed stepwise addition polymerization of diols to divinyl ethers.

A fourth method to make polyacetals is synthesizing an acetal/ketal monomer, which already contains the acetal/ketal unit and possesses two additional functionalities that can for example be used in a conventional polycondensation reaction. An example for this type of monomers that is already industrially used is spiroglycol, a pentaerythritol based diol. This diol can then be polymerized in polyester and polyurethane synthesis and thus contains acetal, and ester or urethane functionalities (Scheme 3.7).[22-23]



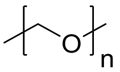
Scheme 3.7 . Polycondensation/addition of spiroglycol to obtain polyesters or polyurethanes.

In 2012, Miller *et al.* reported the synthesis of polyacetals via acetal metathesis polymerization (AMP). In order to prepare a polyacetal via AMP, the reaction mixture has to consist of bis-acetal monomers. The metathesis of the acetal units is promoted by an acid catalyst (Scheme 3.8) and the driving force of the reaction is the removal of a volatile acetal as the condensate. The bis-acetal can be obtained from the acid catalyzed exchange between a mono-acetal with a diol. Up till now, only two types of diols were tested in the AMP procedure, namely biobased linear α,ω-diols and isohexides, such as isosorbide. They also reported that the polyacetals based on AMP are sensitive to hydrolysis, which was expected as the acetal is present in the linear chain.



Scheme 3.8. Acid catalyzed acetal metathesis polymerization of a bisacetal.

The most famous polyacetal is polyoxymethylene (Scheme 3.9), known as POM, which is made by anionic polymerization of formaldehyde.[24] POM is used as an engineering thermoplastic in precision parts, which require high stiffness, low friction and excellent dimensional stability. As a tough, solvent and fuel resistant plastic it is used for example in gears, zips, lighters, aerosol valves, fasteners and furniture components.



Scheme 3.9. Structure of POM.

Another possible application of polyacetals/ketals is in drug delivery as the polymer structure can be tuned to easily degrade in acid conditions.[25-26] Linear polyacetals are already broadly investigated, but because of their sensitivity toward hydrolytic degradation, poly(cycloacetal/ketals) may be of interest as a more stable alternative.

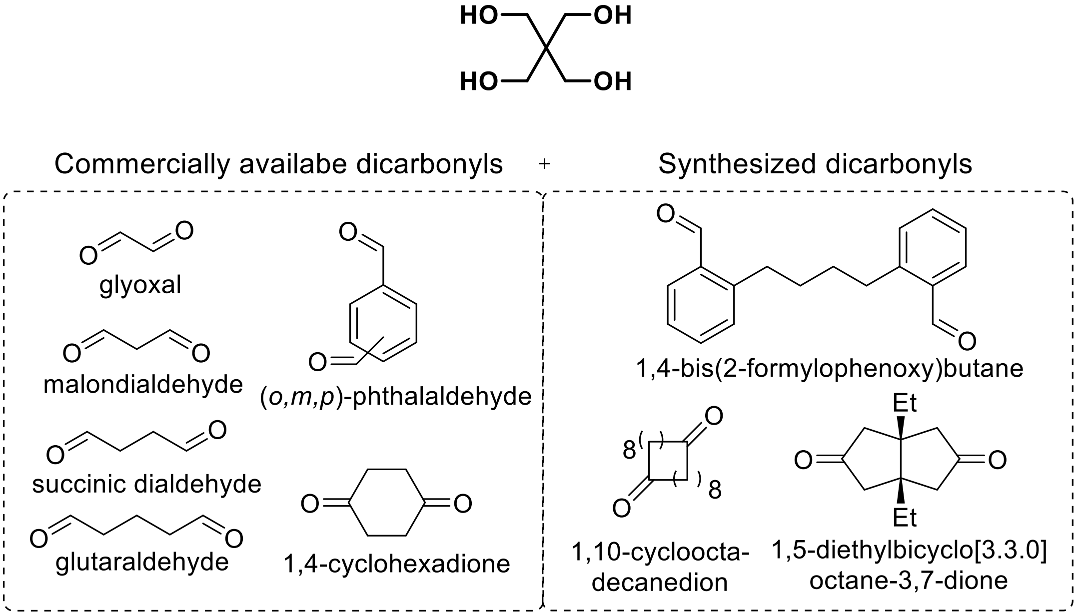
3.2 Poly(cycloacetals)

A poly(cycloacetal/ketal) is a polymer with cyclic acetal/ketal units in the main chain. Three methods to make poly(cycloacetal/ketals) have been reported in the literature. The acetals/ketals can be formed directly during the polymerization, an acetal/ketal exchange reaction can occur, or a monomer already containing acetal/ketal moieties can be polymerized.

3.2.1 Polyacetalization/ketalization

In the polyacetalization/ketalization reaction, a dicarbonyl is combined with a tetraol. This condensation reaction is reversible and can reach high conversion when the condensate, water, is removed during the reaction. The reports on polyacetalization/ketalizations can be divided in two classes. On the one hand, there are reports on the use of commercially available pentaerythriol as the tetraol, while on the other hand tetraols were specially synthesized for the use in polyacetals.

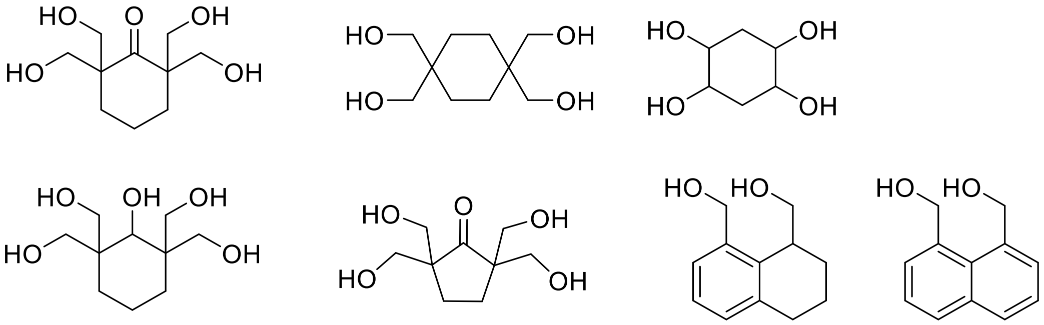
Pentaerythritol was mostly combined with commercially available dialdehydes or diketones like glyoxal, glutaraldehyde, phthalaldehydes and 1,4-cyclohexanedione.[7, 9-10, 12, 14, 16, 27-28] Alternatively, dialdehydes or diketones were synthesized in order to alter the polymer properties.[27-30] In Scheme 3.10 the dicarbonyls, which have been used in poly(cycloacetal/ketals) with pentaerythritol as the co-monomer are displayed.



Scheme 3.10. Overview of the reported polyacetalization/ketalizations from pentaerythritol.

Initially, poly(cycloacetal/ketals) were synthesized from pentaerythritol and commercially available dicarbonyls resulting in spiropolymers. Mostly, low molar mass polymers (max. 8 kDa) were obtained, which were highly crystalline and not soluble in common organic solvents. Although the obtained molecular weights were low, the polymeric structures are described as thermally stable, hard and sometimes transparent. In order to increase the solubility of the polymers, new dicarbonyls were synthesized to allow for a more targeted alteration of the polymer properties. When introducing the synthesized dicarbonyls in the polymer backbone, polymers soluble in for example DMSO, THF and chlorinated solvents were obtained. With 1,5-diethylbicyclo[3.3.0]octane-3,7-dione, the polymers with the highest molecular weights (14 kDa) were produced.[28] Moreover the polymer was characterized with NMR techniques and the T_g (= 180 °C) was determined. This high T_g material was amorphous, as a result of the bicyclic nature of the diketone. However, the synthetic effort to make the dicarbonyl monomer is a drawback.

As pentaerythritol based poly(cycloacetal/ketals) result in very rigid spiro polymers, other tetraols were investigated as well, in order to avoid the high crystallinity that limits the stirring of the reaction mixture, low molecular weights and poor solubility, typically associated with a high rigidity. Seven different specially synthesized tetraols are reported and are presented in Scheme 3.11.[6, 16, 31] They were combined with commercially available terephtaldehyde, isophthaldehydes, and 1,4-cyclohexanedione as well as the synthesized 1,4 cyclohexanedicarbaldehyde. Only the polymers with isophthalaldehyde and 1,4 cyclohexanedicarbaldehyde as comonomers were soluble in hexafluoroisopropanol (HFIP). No molecular weights, T_gs or T_ms are reported, but the thermal stability of the polymers was confirmed with TGA measurements. Thus, changing the tetraol is a promising approach, but the tetraols used so far still seemed too rigid to result in easily processable poly(cycloacetal/ketals).



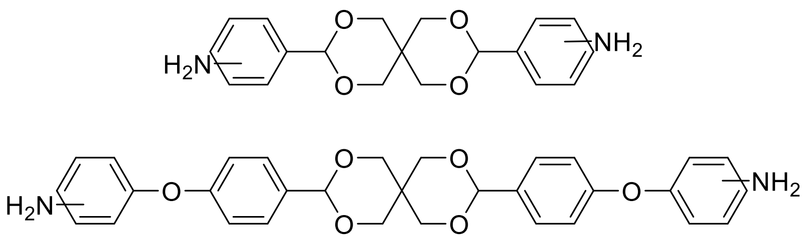
Scheme 3.11. Tetraols synthesized for the polyacetalization/ketalization.

So far, the reports on polyacetalization and polyketalization do not include the processing of the polymers or their mechanical properties. Establishing these properties will play a role in the further investigation of these kind of polymers.

3.2.2 Cyclic acetal/ketal containing monomers

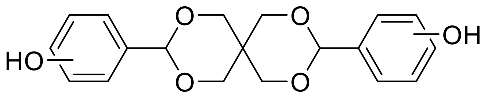
A second way to prepare poly(cycloacetal/ketals) is to start from monomers that already contain cyclic acetal/ketals in their structure, and are then incorporated in the polymer backbone. Most of the studies on poly(cycloacetals) synthesized in this way start from pentaerythritol based diols, diamines, diesters or dienes, and there are only a few reports on AB type cycloacetal/ketal monomers and cycloacetal/ketal containing acrylates.

For pentaerythritol based diamines, only aromatic monomers were reported (Scheme 3.12).[32-35] Pentaerythritol was reacted with an amine functional benzaldehyde to obtain an aromatic cycloacetal containing diamine. Mostly, polyamides were synthesized by interfacial polymerization but rather low molecular weight polymers were reported (M_n < 7.5 kDa). Yet, the low molecular weight polymers already displayed high T_gs (105-250 °C) depending on the comonomer. When bis(4-chlorocarboxyphenyl)dimethylsilane was used as comonomer, T_g values of 210-240 °C could be obtained with the diamine at the top in Scheme 3.12 while T_g values of around 180 °C were measured when the other diamine was applied. Lower T_g values could be reached when these diamines were combined with 2,5-dialkoxyterephthaloylchlorides with varying alkoxy chain lengths. The longer the chain of these alkoxy substituents, the lower the T_g value. Next to thermal analysis, tensile tests were performed on these polyamides, which showed high moduli (2-13 GPa).

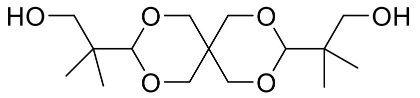


Scheme 3.12. Reported pentaerythritol based diamines.

Two different pentaerythritol based diols were reported (Scheme 3.13) and from those diols polyesters, polycarbonates and polyurethanes were synthesized. An aromatic diol was synthesized from pentaerythritol and 2- or 4-hydroxybenzaldehyde in order to obtain a diol.[30, 34, 36-37] Next to this, an aliphatic diol was synthesized from pentaerythritol and 3-hydroxy-2,2-dimethylpropanal. The latter diol is more commonly known under the commercial name spiroglycol and is produced by Mitsubishi.[22-23]



4,4'-(2,4,8,10-Tetraoxaspiro[5,5]undecane-3,9-diyl)diphenol

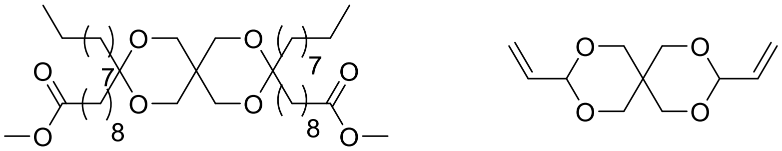


Spiroglycol

Scheme 3.13. Reported pentaerythritol based diols.

The polyesters made from the aromatic diols were synthesized via polycondensation with acid chlorides in solution or in an interfacial polymerization set-up. When polycondensation in solution was used only low molecular weight polymers (M_n < 5 kDa) were obtained. With interfacial polymerization higher molecular weight polymers could be realized (M_n < 15 kDa). The diol was combined with different 2,5-dialkoxyterephthaloylchlorides and depending on the length of the alkoxy chain, T_gs of 60-125 °C were obtained. Moreover, the synthesized polymers were semi-crystalline as determined by DSC measurements. Spiroglycol was applied in polyester, polycarbonate and polyurethane synthesis. The polyester, a copolyester of PET, is produced commercially under the name Altester. Altester is a copolymer, which contains up to 40% of the aliphatic diol and shows improved properties compared to PET homopolymer. Higher T_gs and transparency, and a lower crystallinity and density are reported, while the same mechanical properties are maintained. Next to the Altester, polyurethanes and polycarbonates were reported based on spiroglycol but these polymers are not yet commercialized.

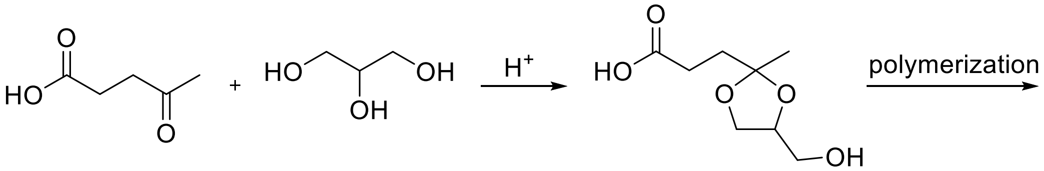
Pentaerythritol was also acetalized with methyl 9(10) formylstereate in order to obtain a diester (Scheme 3.14, left) that can be polymerized with ethylene glycol.[38] Because of the longer alkyl side chains these polyesters were soluble in common organic solvents like chloroform. Molecular weights up to 7 kDa were obtained for these polyesters but no thermal data was determined for these structures.



Scheme 3.14. Reported diester from pentaerythritol and metyl 9(10) formylstereate (left) and a reported diene (right).

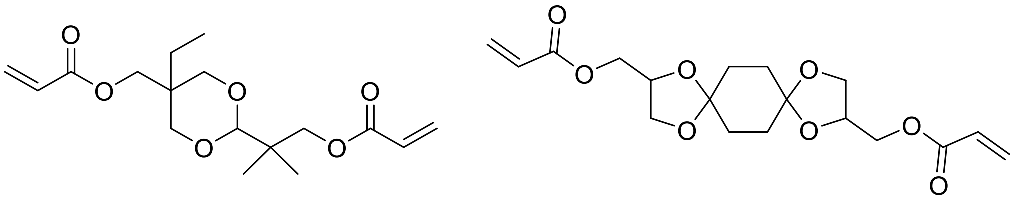
The diene presented in Scheme 3.14 (right), made from pentaerythritol and acrolein, was copolymerized in a radical fashion with acrylates like hydroxyethylmethacrylate (HEMA).[31, 39] The introduction of the cycloacetal containing diene had a positive effect on the degradation temperature and the resulting polymers consisted of a hydrophobic and hydrophilic part, which resulted in the formation of particles.

In addition to the pentaerythritol-based monomers, AB monomers that contain a cyclic acetal/ketal functionality were synthesized as well. These monomers were all synthesized according to the same strategy. A carboxylic acid with a ketone or aldehyde in the structure was reacted with glycerol, resulting in an AB monomer containing a cyclic acetal/ketal moiety (Scheme 3.15).[38, 40-42] In a next step, these monomers can be homopolymerized with an acid catalyst. This strategy led to oligomers that proved to be thermally stable.



Scheme 3.15. Example of an AB monomer from levulinic acid and glycerol.

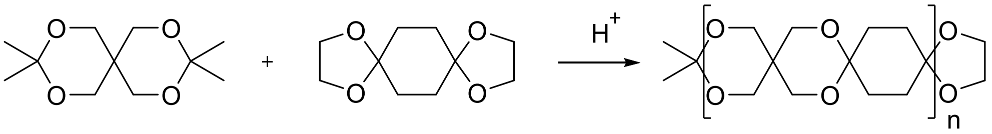
Finally, two bisacrylates containing a cyclic acetal/ketal moiety were synthesized and subsequently crosslinked via a radical process. When a diol is available, the transformation to a bisacrylate is straightforward. The first monomer was synthesized from trimethylolpropane and 3-hydroxy-2,2-dimethylpropanal (Scheme 3.16, left), while the second monomer was made from 1,4-cyclohexanedione and glycerol (Scheme 3.16a, right).[43-44] The latter was used for nanoimprint lithography while the first monomer was used for tissue-engineering biomaterials. In fact, both applications require similar properties such as mechanical strength and degradability, which can be introduced by the cyclic acetal/ketal structure in the backbone.



Scheme 3.16. Reported cyclic acetal/ketal containing bisacrylates.

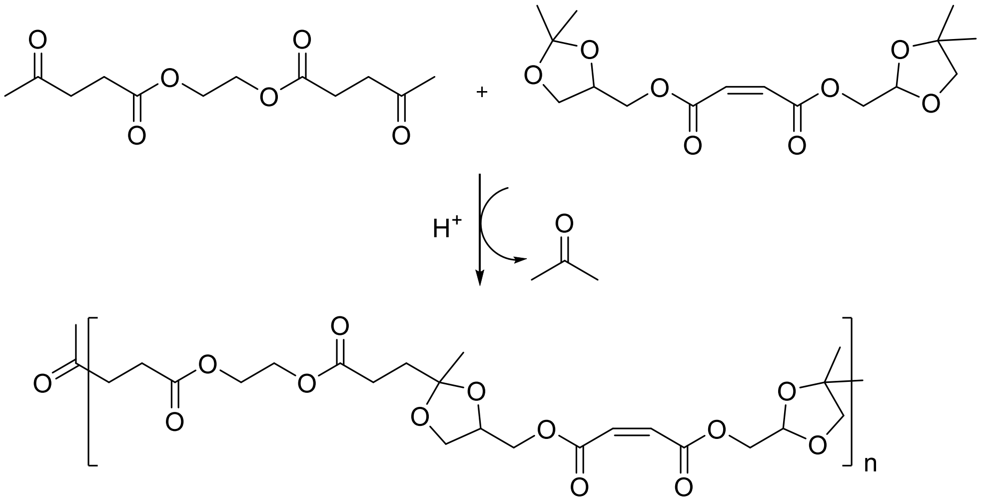
3.2.3 Polytransacetalization/ketalization

Polytransacetalization/ketalization reactions are based on acid-catalyzed acetal or ketal exchange reactions (Scheme 3.5). The use of this method to obtain poly(cycloacetals) or poly(cycloketals) is scarcely investigated. Alder *et al.*[18] reported an attempt to obtain spiropolymers from 1,4-cyclohexanedione and pentaerythritol via transketalization (Scheme 3.17). The acetonide of pentaerythtritol was reacted with the bisketal of 1,4-cyclohexanedione and ethylene glycol under acid conditions and unsoluble oligomers were obtained.



Scheme 3.17. Transketalization of 1,4-cyclohexanedione and pentaerythritol.

More recently, Segetis, an American chemical company filed a few patents on transketalization to make poly(ester-acetal/ketals) from glycerol and levulinic or maleic acid.[45-46] An example of such a synthesis is presented in Scheme 3.18. No molecular weights, thermal and mechanical properties or potential applications of these materials were described in the patents.



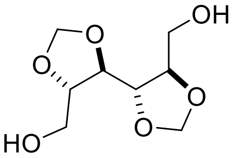
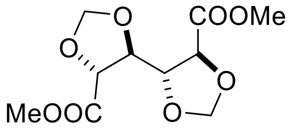
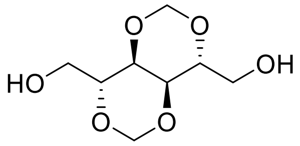
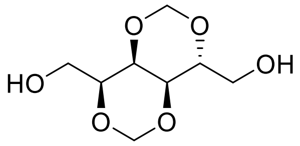
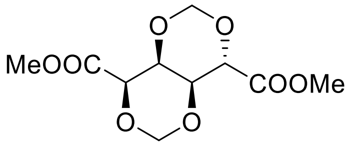
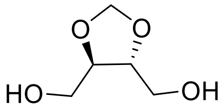
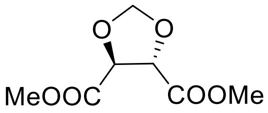
Scheme 3.18. Polytransketalization of bis(levulinic acid) and glycerol bisacetonide maleic acid diester.

3.3 Poly(cycloacetal/ketals) from renewable monomers

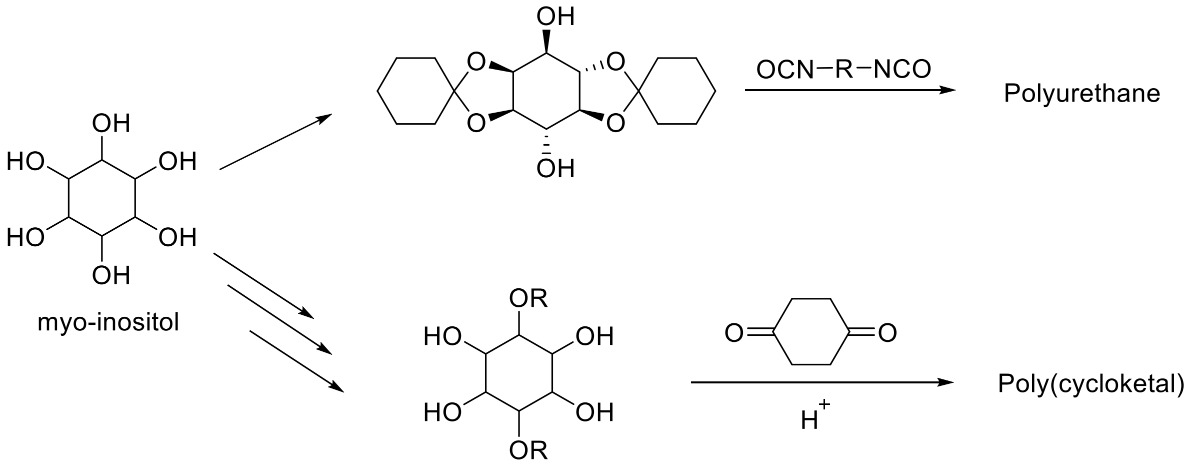
Poly(cycloacetal/ketals) are a class of polymers that can easily be made from renewable resources. Moreover, because of the cyclic moieties in the backbone, good thermal and mechanical properties can be achieved, which makes this class of polymers highly interesting. Some of the examples in paragraph 3.2 were made from biobased monomers but not a lot of attention was given to this matter. In recent years, more attention is given to this renewable aspect and a few examples of renewable poly(cycloacetal/ketals), with the emphasis on the biobased character, were reported. An overview of all the reported building blocks for poly(cycloacetal/ketals) coming from biobased sources are presented in Table A1 in the Appendix. Some of these renewable monomers will be highlighted here as they formed an inspiration to this thesis.

Munoz-Guerra *et al.* published multiple articles on carbohydrate-based bicyclic (CBB) compounds, such as isohexides and diacetals in polyester and polyurethane synthesis.[47-57] For the preparation of different monomers, the same principle is used every time, and a carbohydrate is reacted with formaldehyde to form an acetal containing diester or diol. Hereafter the synthesized monomer is used in the polyester or polyurethane synthesis. The main aim of the authors' research is to compete with PET. Mostly, molecular weights with a M_n above 15 kDa could be achieved and a large variety of properties was accessible depending on which diester and diol were combined. In Table 3.1, an overview of the cyclic acetal containing diols and diesters, prepared from sugars or other renewable resources reported by Munoz-Guerra, can be found.

Table 3.1. Overview of the biobased acetal containing diesters and diols.

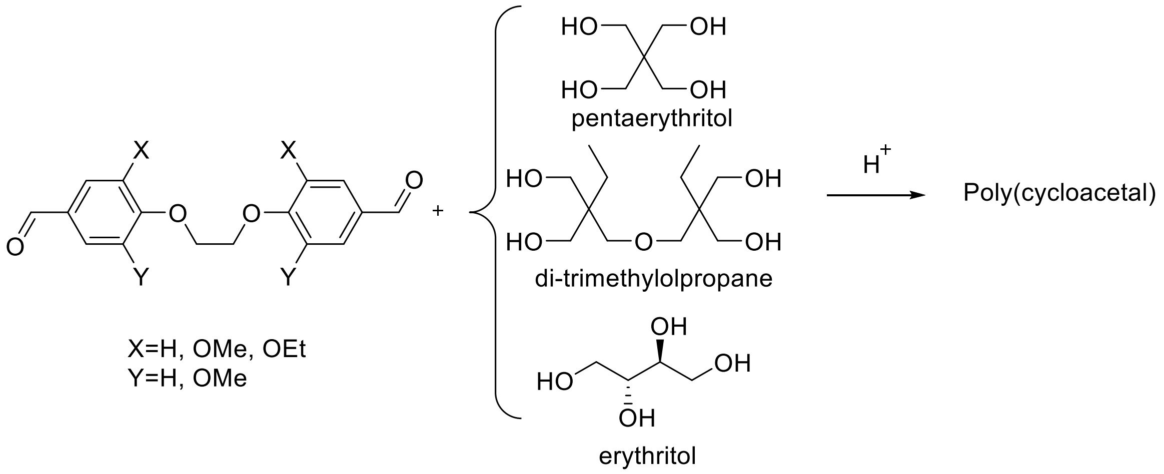
Natural source	Chemical structure diol	Chemical structure diester
D-Galactose		
D-Fructose		
D-Glucose		
Tartaric acid		

Sudo *et al.* reported poly(cycloacetals) based on naturally occurring myo-inositol *via* two different approaches.[58-59] Myo-inositol contains six hydroxyl groups. Thus, in a first step, a tetraol or diol is synthesized and the polymerization with a diketone or diisocyanates, respectively, is performed in a second step (Scheme 3.19). A disadvantage of this method is the synthetic effort required to make a diol or tetraol from myo-inositol.



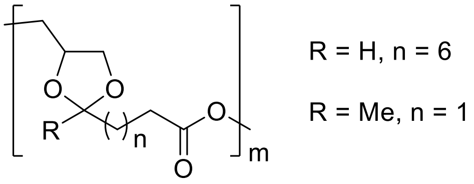
Scheme 3.19. Polyketals and polyurethanes from myo-innositol.

Polyacetalization was also combined with renewable monomers from lignin derivatives. Miller *et al.* synthesized dialdehydes from vanillin, 4-hydroxybenzaldehyde and syringaldehyde, which were polymerized with pentaerythritol, erythritol or di-trimethylolpropane (di-TMP) (Scheme 3.20).[60-61]



Scheme 3.20. Poly(cycloacetal)s from vanillin, syringaldehyde and 4-hydroxybenzaldehyde.

Another strategy that was explored, was the synthesis of an AB monomer containing an acetal/ketal, a hydroxyl and an ester group (paragraph 3.2.2). In 1966 this strategy was employed for glycerol monoazelaaldehydate, more recently levulinic acid and glycerol were combined to form an AB monomer.[40-41] Both monomers can homopolymerize and contain an ester and cyclic acetal/ketal functionality (Scheme 3.21). Mostly, the difficulty associated with this method lays in the synthesis of the AB type of monomer in an easy and straightforward way.



Scheme 3.21. Polyester containing cyclic acetal/ketal moieties from an AB monomer.

3.4 Conclusion

Poly(cycloacetal/ketals) are a class of polymers that was not yet extensively investigated but already showed interesting properties such as thermal stability and good mechanical properties, even for polymers of relatively low molecular weight. Moreover, for these kind of polymers, the monomers are often accessible from Nature, which results in biobased polymers. The challenges for making poly(cycloacetal/ketals) are to find other renewable monomers than the reported ones, such as tetraols, diketones and dialdehydes, or to synthesize new cycloacetal/ketal containing monomers in an easy and scalable way. Moreover, there is a need for higher molecular weight polymers (M_n > 20 kDa) to ensure chain entanglements, which are necessary for good mechanical properties. In this thesis, step-growth polymerization will be used as the main route to poly(cycloacetal/ketals), and this strategy will be highlighted in more detail in the next chapter.

3.5 References

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Abstract

Step-growth polymers have been known since the discovery of synthetic polymers as useful materials within wide application areas. Various polymer materials like polyesters, polyamides, polycarbonates and polyurethanes are synthesized by step-growth polymerizations and find important applications in textiles, car industry, packaging, coatings and many others. As described in chapter 3, most poly(cycloacetal/ketals) are obtained via step-growth polymerizations. In this chapter, the basics of step-growth polymerization will be handled, after which more information will be given on molecular weight control and distribution. Finally, a number of the most popular polymers prepared by this technique will be discussed and examples of synthesis methods, properties and applications will be given.

Chapter 4: Step-growth polymerization: theoretical introduction

4.1 Introduction and definitions

One of the first useful polymeric materials, Bakelite, was synthesized via a step-growth process. Bakelite is a resin formed from the condensation of phenol and formaldehyde and was invented by Leo Baekeland in 1907.[1-2] However, it was not until the pioneering work of Wallace Carothers and his research group at DuPont during the 1930's that the fundamental principles of step-growth processes were elucidated.[3-4] The first polymer commercialized by Du Pont was based on the step-growth polymer of adipic acid and hexamethylene diamine, known as nylon 6,6.[5] Even though Carothers was the pioneer in step-growth polymerizations, it was not until the work of Whinfield and Dickson that polyesters became commercially viable.[6] They patented polyesters based on terephtalic acid, better known as PET.

Step-growth polymerization (SGP) refers to a type of polymerization mechanism where only one kind of reaction is involved in the formation of the polymer and this reaction proceeds step by step with bi- or multifunctional molecules.[7] As a consequence, the reaction takes place between any of the species in the system, e.g. monomers, dimers, trimers,…, oligomers, eventually yielding long polymer chains.[8-9] As long as the two complementary functional groups of reactants encounter each other, the reaction can occur. This is illustrated in Figure 4.1, where the single dots represent the bifunctional monomers and the black chains represent dimers, oligomers and polymers.

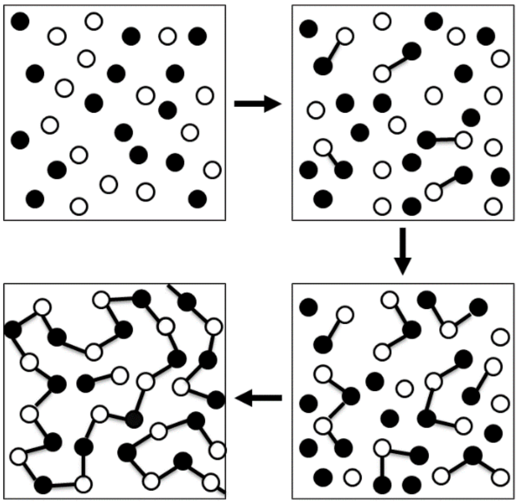


Figure 4.1. Generic representation of SGP.[10]

Furthermore, it is assumed that the reactivity of the functional groups is the same for both monomer and polymer chain independent of its size. In other words, the reaction is independent on the degree of polymerization.[7-8]

Characteristic to step-growth polymerizations is the slow molecular weight build-up, even at high conversion, due to this step-by-step mechanism in which first dimers are formed by the reaction of two monomers, then tetramers, hexamers etc.[8] The monomers usually disappear from the reaction mixture long before high molecular weight compounds are formed.[7] The slow pace by which the average molecular weight increases as a function of conversion can be derived from the Carothers equation and is visualized in Figure 4.2. The conversion is depicted by p and is plotted against the degree of polymerization (DP). A high conversion is needed to obtain high molecular weights; therefore, it is extremely important to have an exact stoichiometric balance, thus equimolarity is indispensable. [7-8, 11-12]

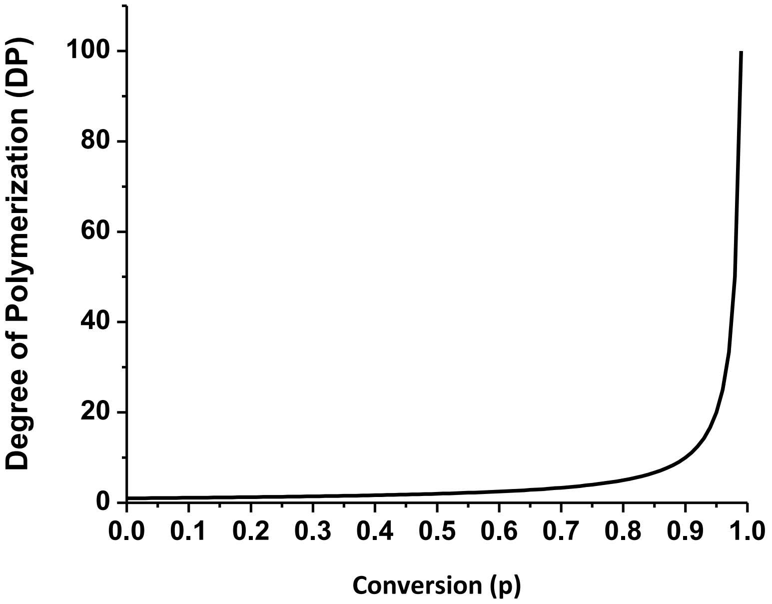


Figure 4.2. Carothers equation visualized for step-growth polymerization.

In 1929 Carothers proposed a general differentiation for two classes of SGP, in which he made a distinction between condensation polymerization and addition polymerization. Condensation polymerizations are equilibrium reactions, where a small molecule is eliminated from the growing chain to shift the equilibrium to completion.[7] When no small molecule is eliminated, the reaction is called a polyaddition, which is irreversible. Polyaddition reactions are often very fast and lead to high degrees of polymerization.[7]

All SGPs can be divided into two groups, depending on the type of monomer used. If the monomer has two identical functional units, the process is called AABB-type SGP (eq. 4-1). Mixtures of at least two different types of monomers, bearing the complementary functional groups, are required. When every monomer bears both complementary functional groups, the process is called AB-type SGP (eq. 4-2). In general, these two groups can be represented by the two following equations, where A and B are two different functional groups.

$$n\,A - A + n\,B - B \rightarrow (A - AB - B)_n \tag{4-1}$$
$$n\,A - B \rightarrow (A - B)_n \tag{4-2}$$

4.2 Molecular weight properties for SGP: control and distribution

4.2.1 Molecular weight

In order to prepare step-growth polymers with high molecular weights, only organic reactions that proceed in a quantitative way are suitable. During the synthesis of polyesters, polyamides, polyurethanes and polycarbonates, which will be discussed in paragraph 4.3, the mechanism that results in chain growth is the attack of a nucleophile to the electrophilic carbonyl. Moreover, in order to obtain step-growth polymers with high molecular weight, a few criteria must be taken into account.[12]

- High reaction conversions (99.9%)
- Monomer functionality equal to 2.0
- Functional group stoichiometry equal to 1.0
- Absence of side reactions that lead to loss of monomer functionality
- Efficient removal of the condensate side products
- Accessible reactive groups

These criteria will be discussed more thoroughly to understand their impact during step-growth polymerization reactions.

High reaction conversions (99.9%)

The Carothers equation (eq. 4-3) relates the degree of polymerization (DP) to the monomer conversion (p).

$$DP = \frac{1}{1-p} \tag{4-3}$$

This equation shows that high molecular weight (or high DP) is not achieved until high monomer conversions are reached. For example, at 95% conversion of the monomers, only a DP of 20 can be realized. Only when *p* approaches the value of one (100%), higher molecular weight polymers are obtained (see Figure 4.2).

Monomer functionality equal to 2.0

If bifunctional monomers of identical functionality per molecule (eq. 4-1) or monomers possessing two different functionalities (eq. 4-2) react with each other, linear polymers are obtained. When monomers contain multiple functional groups or have a functionality higher than two, branched polymers or networks are formed.[13] As the focus of this thesis is based on the synthesis of linear polymers, the attention will only be put on the linear SGP, which means that the monomer functionality must be equal to two.

Functional group stoichiometry equal to 1.0

The previously mentioned equations include the requirement for very pure monomers in order to ensure the 1:1 stoichiometry. However, in SGP there are two important aspects with regard to the control of molecular weight. When a polymer of very specific molecular weight is desired, the polymerization reaction can be quenched, e.g. by diluting or cooling the reaction mixture. However, even after quenching, the reactive functional end groups can still react with each other, leading to a different molecular weight than desired.[13] To avoid this, the concentrations of the two monomers can be adjusted, so that they are slightly non-stoichiometric and one of the reactants is in slight excess. Thus, the molecular weight is also related to the imbalance r, which is normally defined to be less than 1.0. The extension of the Carothers equation (eq. 4-4) shows the variation of DP with *r* and *p*.

$$DP = \frac{1+r}{1+r-2rp} \tag{4-4}$$

The polymerization proceeds to a point where one of the reactants is completely depleted and all the chain ends possess the same functional group of the monomer that is in excess. The polymerization is quenched and the polymer is stable to any molecular weight changes.[13] However, there are two situations when this equation can be simplified. If the two bifunctional monomers A-A and B-B are present in stoichiometric amounts (r = 1), the eq. 4-4 reduces to the previously discussed Carothers equation (eq. 4-3). When 100% conversion is achieved, p = 1 and eq. 4-4 changes to eq. 4-5.

$$DP = \frac{1+r}{1-r} \tag{4-5}$$

When plotting DP as a function of the stoichiometric ratio *r* for different conversions *p* (Figure 4.3), it is necessary to use pure monomers in stoichiometric amount in order to obtain high molecular weight polymers. Moreover, the conversion needs to be as high as possible in order to get high molecular weight polymers.

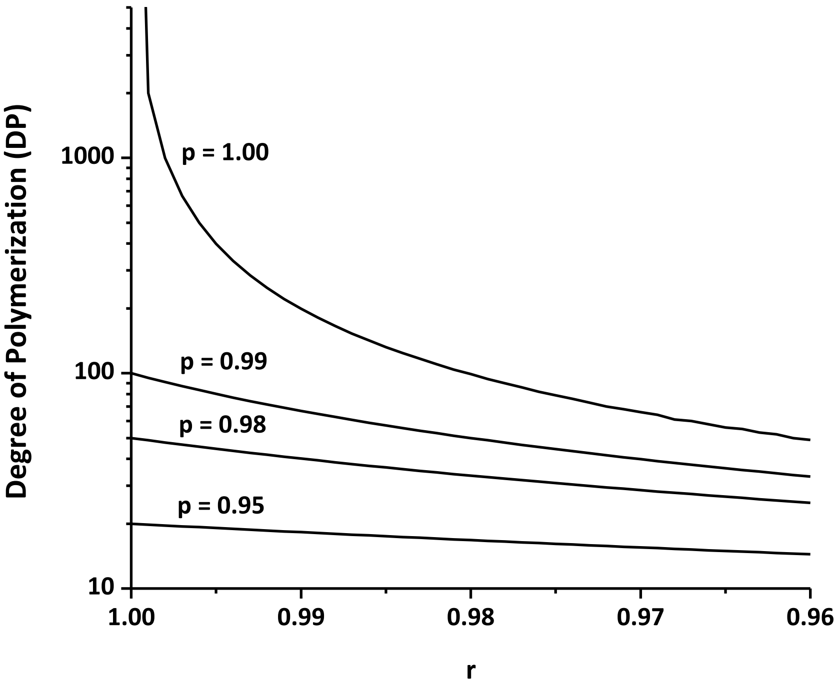


Figure 4.3. Degree of polymerization as a function of r for different conversions (*p*) in a SGP.

Another method of controlling molecular weight is by adding a small amount of a monofunctional monomer. This monomer contains only one functional group and is often referred to as a chain stopper.[7] A chain stopper controls and limits the SGP of bifunctional monomers as by incorporation of this monofunctional compound the chain ends with no functional group are not able to react further. However, in many occasions monofunctional compounds are unwanted in the reaction mixture of SGP because of their stopping behaviour, resulting in low molecular weight compounds.

Absence of side reactions that lead to loss of monomer functionality

In addition, it is important that the polymerization is a very high yielding reaction with the absence of side reactions in order to achieve high molecular weight polymers. Therefore, using highly pure monomers, thus avoiding contamination of the reaction mixture with (mono functional) impurities is evident. When a monofunctional impurity adds to the end of a molecule, that end can no longer participate in the polymerization reaction, with low molecular weight polymers as a result.[14]

Efficient removal of the condensate side products

In the condensation reactions, an elimination product is formed which needs to be removed from the reaction mixture to shift the equilibrium to the product and thrive the reaction to completion, or in other words to obtain high molecular weight polymers. Often, the condensate can be efficiently removed by applying lowered pressures and/or a dry nitrogen flow at high temperatures. To facilitate the removal even more and to ensure the accessibility of the reactive functional groups, vigorous stirring and reactor engineering is of crucial importance.[12]

Accessibility of reactive groups

In order for SGP to yield high molecular weight polymers, the functional end groups present in the polymer must be accessible to each other. Therefore, it is essential that the polymer does not precipitate from the reaction mixture before the desired molecular weight is reached and that good mixing is maintained. This precipitation can be avoided by using a good solvent, a strong and steady stirrer and/or high temperatures.

In conclusion, reaction conditions in SGP must be carefully chosen to avoid undesirable consumption of the functional groups (e.g. by side reactions or evaporation), and 1:1 stoichiometry must be maintained throughout the polymerization process.[12]

4.2.2 Molecular weight distribution

The product of a polymerization reaction is a mixture of polymer molecules of different length and molecular weight. This range of molecular weights is referred to as the molecular weight distribution. Flory derived this molecular weight distribution by a statistical approach based on the concept of equal reactivity of functional groups.[15] This concept states that both the probability of the reaction and the reaction rate of two functional groups are independent of the sizes of the involved molecules (monomers or growing chains). The number-distribution function N_x and the weight-distribution function w_x for SGP at a certain conversion p can be calculated and are given respectively by eq. 4-6 and eq. 4-7.

$$N_x = N_0 p^{x-1}(1-p)^2 \tag{4-6}$$

$$w_x = x p^{x-1}(1-p)^2 \tag{4-7}$$

The dispersity (Đ) is a measure for the distribution of the molecular weight in a polymer and is given by M_w / M_n. The number- and weight-average molecular weights M_n and M_w can be derived from respectively the number- and weight-distribution functions. M_n is defined as the statistical average molecular weight of all the polymer chains in the sample, and is given by eq. 4-8, where the summations are over all values of x. M_x is the molecular weight of a chain and N_x is the number of chains of that molecular weight

$$M_n = \frac{\sum M_x N_x}{\sum N_x} = \sum x M_0 p^{x-1}(1-p) \tag{4-8}$$

Evaluation of the summation results in the following formula for M_n, with M_0 as the mass of the repeating unit.

$$M_n = \frac{M_0}{1-p} \tag{4-9}$$

The definition of M_w is given by eq. 4-10. For M_w, it is taken into account that a larger molecule will have a larger contribution to the molecular weight than a smaller molecule.

$$M_w = \sum M_x w_x = \sum x^2 M_0 p^{x-1} (1-p)^2 \tag{4-10}$$

Evaluation of the summation results in the following formula for M_w.

$$M_w = M_0 \frac{1+p}{1-p} \tag{4-11}$$

The dispersity given by M_w / M_n presents the width of the molecular weight distribution in SGP and results in eq. 4-12.

$$Đ = \frac{M_w}{M_n} = 1 + p \tag{4-12}$$

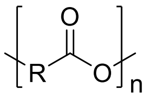
The value of the dispersity increases with the extent of the reaction and approximates a value of two when high conversions are realized (p = 1).

4.3 Classes of step-growth polymerizations and synthesis methods

Nowadays, step-growth polymers cover an enormous industrial market and are indispensable in daily life. In this part, the different classes of step-growth polymers that are relevant for this thesis and their properties, main applications and synthesis methods are outlined. Compared to AB-type SGP, AABB-type SGP can introduce more variation in the polymer chain because of the wide availability of monomers. Only AABB-type SGP are considered in this thesis.

4.3.1 Polyesters

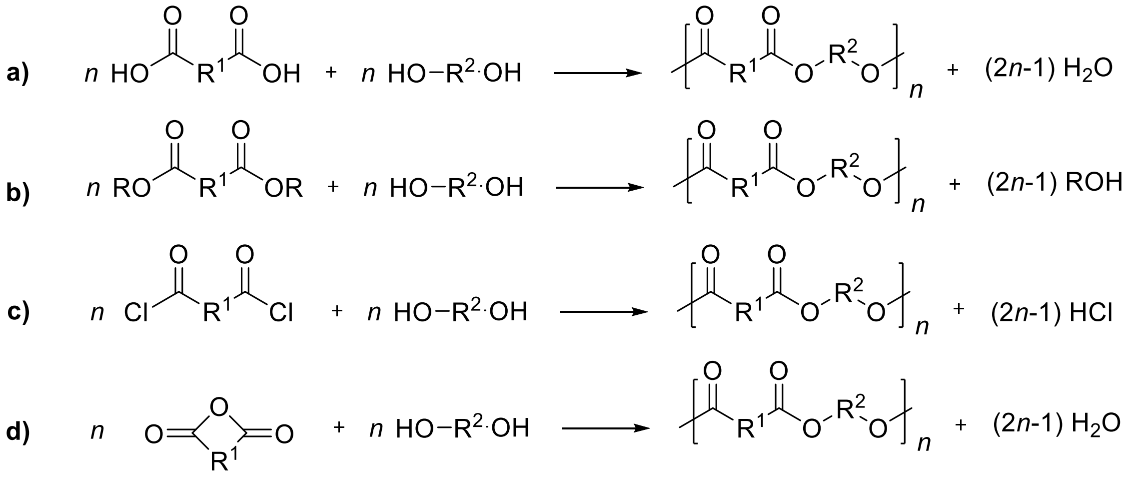
Polyesters are polymers that contain ester moieties in their main chain as can be seen from Scheme 4.1. [16]



Scheme 4.1. General structure of a polyester.

Poyesters can be synthesized using different combinations of reactants and multiple process conditions. Specifically, AABB-type polyesters can be prepared by the following commonly used methods.[16-22]

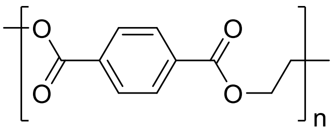
- Esterification reactions between diols and dicarboxylic acids (Scheme 4.2 (a))
- Transesterification reactions between diols and diesters (Scheme 4.2 (b))
- Reaction of diols with diacid chlorides (Scheme 4.2 (c))
- Reaction of diols with cyclic diacid anhydrides (Scheme 4.2 (d)).



Scheme 4.2. Frequently used synthetic routes for polyester synthesis.

Since all above-mentioned routes are condensation reactions, they lead to the production of small condensates. To obtain high molecular weights, this condensate needs to be removed constantly from the reaction mixture. For the removal of this condensate, the polymerizations are mostly performed in bulk at high temperatures and under reduced pressure.

Polyesters are one of the most versatile classes of polymers ever produced. The most prominent example is polyethylene terephthalate (PET), which is a linear aromatic polyester (Scheme 4.3).[17] PET is known to display high mechanical strength, transparency and good thermal stability.[23] The discovery of PET has led to a tremendous development in polyester fibers, resins and films due to their strong demand for textile applications, food packaging and bottle markets for glass replacement.[24]

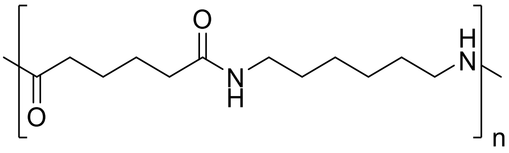


Scheme 4.3. Structure of poly(ethylene terephtalate).

Up till a few years ago, the reactants for polyesters were mostly derived from fossil resources. The use of fossil resources in combination with the increasing amount of polyester consumables was an incentive for research to make polyesters more renewable and/or degradable.[25-26] Nowadays, more and more (partially) renewable polyesters are commercially produced with building blocks coming from feedstock, like e.g. sugar cane or are produced via fermentation of biomass, like dimethyl succinate. In 2015, Coca cola presented their partially renewable PET Plantbottle[27], with one of its two major reactants, ethylene glycol, now coming from sugarcane (paragraph 2.3.1). The challenge, however, is to find a biobased alternative for its second major reactant, terephtalic acid. In addition, this alternative needs to be cheap and readily available. At the moment, only one aromatic diacid is already used in polyester synthesis, which is 2,5-furandicarboxylic acid.[28]

4.3.2 Polyamides

Polyamides are polymers, which have amide bonds incorporated into the polymer backbone. When the backbone consists of amino acids, the polymers are referred to as polypeptides or proteins[29], in all other cases, the polyamides are identified as nylons (Scheme 4.4).[30]



Scheme 4.4. Structure of nylon 6,6.

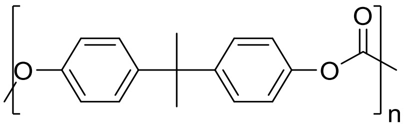
The first nylon (nylon 6,6) was synthesized by Carothers *via* the reaction of a diamine and a dicarboxylic acid (derivative).[31-32] It is a non-toxic polymer, which has low gas and vapour permeability, is resistant to most solvents and chemicals, has very good wear resistance and has a good combination of mechanical properties like strength, stiffness and toughness.[33]

Three polymerization methods are frequently used to make polyamides: interfacial, solution and melt polycondensation. Melt polycondensation is most often used when dicarboxylic acids are reacted with diamines.[12] In some occasions, the high temperatures needed to keep everything in a molten state, approach the degradation temperature and then solution polymerization is preferred. Polyamides can be made from diamines and acid chlorides at room temperature in solution. Polymerization in solution is more frequently used in a laboratory environment as large amounts of solvents are necessary and great amounts of byproducts (salts) are formed. The backbone of polyamides synthesized via interfacial polymerization, is built via a different mechanism than SGP. In this polymerization method, monomers diffuse to the interface where they react with polymer chain ends instead of with other monomers. The reaction rates are so high that the monomers will react with the growing polymer chain ends before they can penetrate through the polymer film to start the growth of new chains.[13] The polycondensation can only continue when this film is continuously pulled away from the interface, which is called the ‘nylon rope trick’.[34] Consequently, higher molecular weight polyamides can be synthesized with the interfacial process compared to the other methods.

In the last decade, renewable monomers are already used to produce polyamides. The most known example is Rilsan, which is made from castor oil.[35] Also here, the challenge of finding renewable aromatic diacids or diamines still needs to be fulfilled.

4.3.3 Polycarbonates

Polycarbonates are polymers comprised of carbonate groups in their backbone. The best well-known polycarbonate is made up of bisphenol A molecules connected with carbonate moieties (Scheme 4.5).[36]



Scheme 4.5. Polycarbonate with bisphenol A.

The most common manufacturing process is based on the reaction of bisphenol A with phosgene.[36] Due to phosgene's toxicity research has been conducted to find alternatives for phosgene or phosgene-free synthetic routes or procedures. This has resulted in an alternative production method making use of diphenylcarbonate.[36-37] During the reaction of diphenylcarbonate and a diol, phenol is released as a high boiling condensate. Therefore, high temperatures and reduced pressure are necessary to remove the phenol from the reaction mixture to obtain high molecular weight polymers.[37] Another method to synthesize polycarbonates uses cyclic carbonates, such as ethylene carbonate, which are polymerized *via* ring-opening polymerizations.[38] However, the latter process is not yet industrially applied.

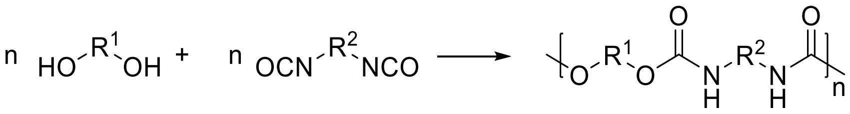
The general properties of polycarbonates are transparency, excellent toughness and very good thermostability.[39-40] However, next to phosgene, bisphenol A is the subject of many scientific debates concerning its possible endocrine disrupting and other toxic properties.[41-44] This has resulted in a quest to find (renewable) alternatives for bisphenol A.[45-46]

4.3.4 Polyurethanes

Conventional polyurethane synthesis proceeds via a step-wise polyaddition reaction between an isocyanate and an alcohol. In contrast to polycondensation, a polyaddition is a fully atom efficient reaction, since no small molecule is eliminated.[7, 47]

Otto Bayer and his coworkers, first made polyurethanes in 1937.[48] The new polymers had some advantages over existing plastics that were made by polymerizing olefins or by polycondensation. Early work focused on the production of fibres and flexible foams and polyurethanes were applied on a limited scale as aircraft coating during World War II.[49]

Linear polyurethanes are synthesized by the reaction of diisocyanates with diols (Scheme 4.6).[50] The synthesis of polyurethanes can be performed in bulk or solution and rather low reaction temperatures are necessary (room temperature to 80 °C). These mild synthesis conditions to make polyurethanes, compared to for example polyesters and polyamides, is the result of the high reactivity of the diisocyanates. However, this high reactivity of the isocyanates makes them prone to react with water, which interferes with the 1 to 1 equimolarity.[51] Linear polyurethanes offer high mechanical strength, high elasticity, high abrasion resistance and a controllable hardness.[50]



Scheme 4.6. General polyurethane synthesis.

The properties of a polyurethane are greatly influenced by the types of isocyanates and polyols used to make it. Long, flexible segments, contributed by the polyol, give soft, elastic polymers, while high amounts of crosslinking give tough or rigid polymers. Long chains and low crosslinking will result in a polymer that is very stretchy, short chains with lots of crosslinks produce a hard polymer while long chains and intermediate crosslinking results in a polymer useful for making foam.

Nevertheless, polyurethanes show some disadvantages, the most prominent one being the toxicity of the used reactants. Diisocyanates, which are toxic compounds, are commonly made using the Hetschel method, which involves the reaction of amines with phosgene that is extremely toxic.[52] Furthermore, polyurethanes can have low thermal stability. Temperatures as low as 200 °C have been reported for the start of the decomposition.[53] Research is being conducted to minimize the stated disadvantages of polyurethanes. This includes the search for methods to produce polyurethanes without the use of isocyanates and the improvement of the thermal stability.[54-55]

Several production methods to produce non-isocyanate polyurethanes (NIPU) are described in the literature.[54, 56] The methods, using the polycondensation reaction of chloroformates with amines or carbamates with alcohols, are used for the production of linear polyurethanes.[54] For the production of polyurethane networks, the reaction between cyclocarbonate oligomers and amine oligomers is used, which is not in the scope of this thesis.[56]

4.4 Conclusion

Step-growth polymerization is the method of choice for the industrial synthesis of a variety of polymers. We could not imagine life without polyesters, polyurethanes, polyamides and polycarbonates. The methods for preparing these polymers exist already for more than 50 years and are easily applicable. Moreover, a large variety of monomers can be polymerized with step-growth polymerizations, which is a great advantage. Poly(cycloacetal/ketals) are mostly obtained via polycondensation, but they can also be combined with ester, amide, carbonate or urethane linkages.

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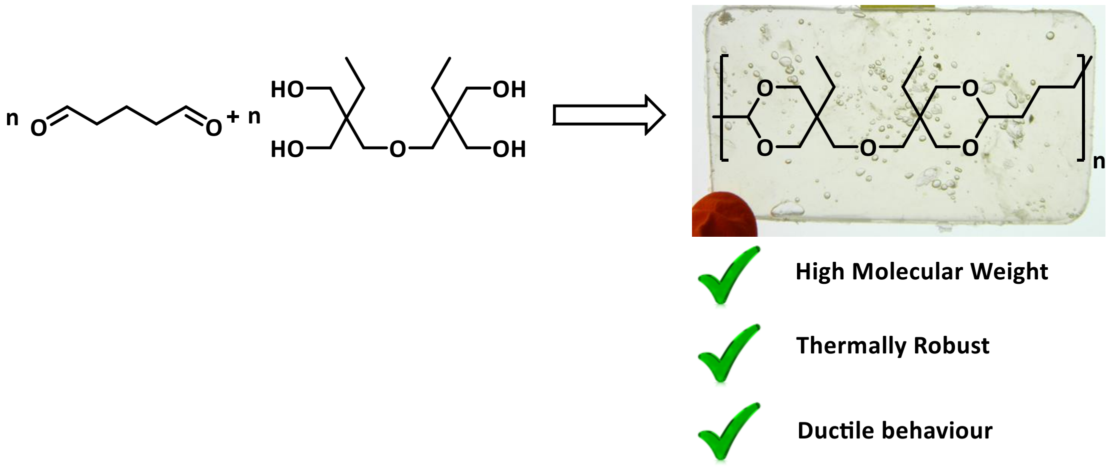

Graphical abstract in Polymer

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Abstract

Initially, polyacetalizations/polyketalizations were executed with commercially available dialdehydes and diketones. At first, a model study on several commercial dicarbonyls was performed to compare them in terms of reactivity after which they were further exploited for polyacetalization/polyketalization. To obtain the targeted polymers, two different polymerization methods were explored and several solvents were tested. The influence of the various dicarbonyls on the properties of the poly(cycloacetal/ketals) was examined systematically. In order to tune the thermal and mechanical properties, new dialdehydes starting from renewable building blocks were synthesized. To obtain the intended dialdehydes, both the synthesis method and the purification procedure were optimized. The green building blocks were commercially available hydroxyaldehydes. After this, a model study of the synthesized dialdehydes was carried out, assessing their reactivity in the acetalization reaction. Eventually, the synthesized dialdehydes were polymerized and characterized.

Chapter 5: Polyacetalization/ketalization

5.1 Poly(cycloacetals) and poly(cycloketals) from commercially available dialdehydes and diketones

5.1.1 Introduction

Poly(cycloacetals) and poly(cycloketals) are a class of polymers that are generally formed by the acetalization/ketalization reaction between a tetraol and a dialdehyde[1-3] or diketone[4-7]. During this process, cyclic acetal/ketal moieties are formed in the backbone, which results in the synthesis of a rigid polymer backbone. Poly(cycloacetals) were first reported in 1912, yet only limited attention was given to this class of polymers despite their promising properties.[8] Different poly(cycloacetals) were reported from the reactions of pentaerythritol as tetraol and commercial dialdehydes, such as glyoxal, glutaraldehyde and terephthaldehyde.[1-3, 8-14] Only a few papers describe the synthesis of poly(cycloketals) via polyketalization. The two polymers that were investigated consisted of pentaerythritol as tetraol and 1,4-cyclohexanedione or 1,5-dialkylbicyclo[3.3.0]-octane-3,7-diones as bicarbonyl.[4-7] When introducing pentaerythritol in the polymer backbone, the presence of spirocenters results in the formation of spiropolymers (see Chapter 3).

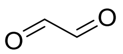
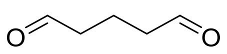
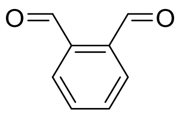
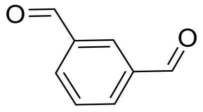
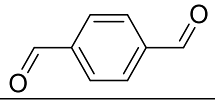
The majority of the reported poly(cycloacetals) and poly(cycloketals) had low molar masses (max. 8 kDa) and were not soluble in common organic solvents. Although the molecular weights were low, the obtained polymeric structures are described as being thermally stable, hard and sometimes transparent. More recently, this class of polymers has regained interest, but with the focus on the synthesis of new dialdehydes and/or tetraols in order to vary the final polymer properties.[9, 15-16] In general, the synthesis of the monomers is associated with a large synthetic effort. To our knowledge, no useful materials, displaying desired physical properties, could be obtained based on the polyacetalization or polyketalization from commercially available dialdehydes and diketones up till now.

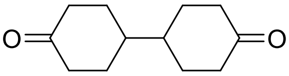
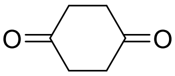
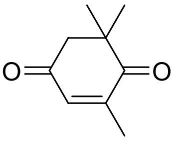
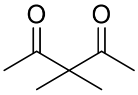
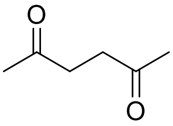
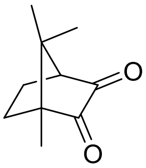
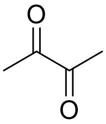
The goal of this chapter was to systematically synthesize processable, high molecular weight poly(cycloacetals) and poly(cycloketals) starting from commercially available dialdehydes and diketones. This gave us the opportunity to understand and become familiar with the different techniques. A model study on several dialdehydes and diketones was performed to compare them in terms of reactivity. To obtain the targeted polymers, two different polymerization methods were explored and were performed in different solvents.[17-20] The synthesis of poly(cycloacetals) and poly(cycloketals) with pentaerythritol as tetraol, as previously reported [1, 8, 10-13], was first repeated and in a next step, the dialdehydes were reacted with a more flexible tetraol, namely di-trimethylolpropane (di-TMP). In this way, the formation of spiropolymers can be avoided, unlike with pentaerythritol, which enhances the solubility of the polymer structures while keeping rigid, cyclic structures in the backbone. Di-TMP was used once by Miller *et al.* in poly(cycloacetals) from synthesized lignin based dialdehydes, which resulted, among other things, in a better solubility of the polymer structures.[18, 21] The influence of the various dialdehydes' and diketones' chemical structures on the thermal, optical and mechanical properties of the poly(cycloacetals) and poly(cycloketals) was examined in a systematic way to provide us with a deeper insight in the material properties. Finally, since the polymers contain acid-labile acetal/ketal functionalities, hydrolytic stability tests were performed.[22-23]

5.1.2 Model study

Initially, five dialdehydes and seven diketones (Table 5.1) were subjected to a model study for a reactivity check. The acetalization of the selected compounds was already investigated with 1,3-propanediol[24-26] or ethylene glycol[27-28], but in most cases different methods were used, which makes the comparison of their reactivity not possible. In order to determine and compare the difference in reactivity of the selected dicarbonyl compounds, the model acetalization and ketalization reaction with 1,3-propanediol and ethylene glycol was explored in the presence of *p*-TsOH as catalyst. Ketones and aldehydes can form both 5-membered rings and 6-membered rings depending on the diol structure with which they react. However, as mentioned in Chapter 3, aldehydes prefer to form the six membered ring while diketones prefer the formation of 5-membered rings. This preference results in a higher reactivity towards 1,2-diols in the case of diketones compared to 1,3-diols in the case of dialdehydes.[29] The reaction conversion was followed by measuring the amount of water in the Dean-Stark apparatus and NMR analysis of the raw reaction mixture. For example, the conversion of the model reaction of *p*-phthalaldehyde with 1,3-propanediol, which is displayed in Figure 5.1 (the NMR spectra at one, three and six hours reaction time), could be followed via the integration of the disappearing aldehyde signal (h).

Table 5.1. Reaction times and conversion for reactions of the selected dialdehydes and diketones with ethylene glycol and 1,3-propanediol.

Dialdehydes		Diol	Time	Conversion
	glyoxal*	ethylene glycol	/	/[a]
		1,3-propanediol	/	/[a]
	glutaraldehyde	ethylene glycol	2h	100%
		1,3-propanediol	2h	100%
	*o*-phthalaldehyde	ethylene glycol	8h	100%
		1,3-propanediol	6h	100%
	*m*-phthalaldehyde	ethylene glycol	8h	100%
		1,3-propanediol	6h	100%
	*p*-phthalaldehyde	ethylene glycol	8h	100%
		1,3-propanediol	6h	100%

Diketones		**Diol**	**Time**	**Conversion**
	4,4'-bicyclohexanone	ethylene glycol	1h	100%
		1,3-propanediol	2h	100%
	1,4-cyclohexanedione	ethylene glycol	1h	73%
		1,3-propanediol	2h	82%
	4-ketoisophorone	ethylene glycol	2h	86%
		1,3-propanediol	5h	33%
	3,3'-dimethylpentadione*	ethylene glycol	4h30	/[b]
		1,3-propanediol	4h	/[b]
	Acetonylacetone	ethylene glycol	2h	100%
		1,3-propanediol	2h	75%
	camphorquinone	ethylene glycol	24h	100%
		1,3-propanediol	24h	100%
	diacetyl	ethylene glycol	2h	100%
		1,3-propanediol	2h	43%

[a] A complex mixture of compounds was formed which could not be clarified.

[b] A mixture of both monomer as monoketal was formed in this timeframe.

*These compounds were not selected for polymerization.

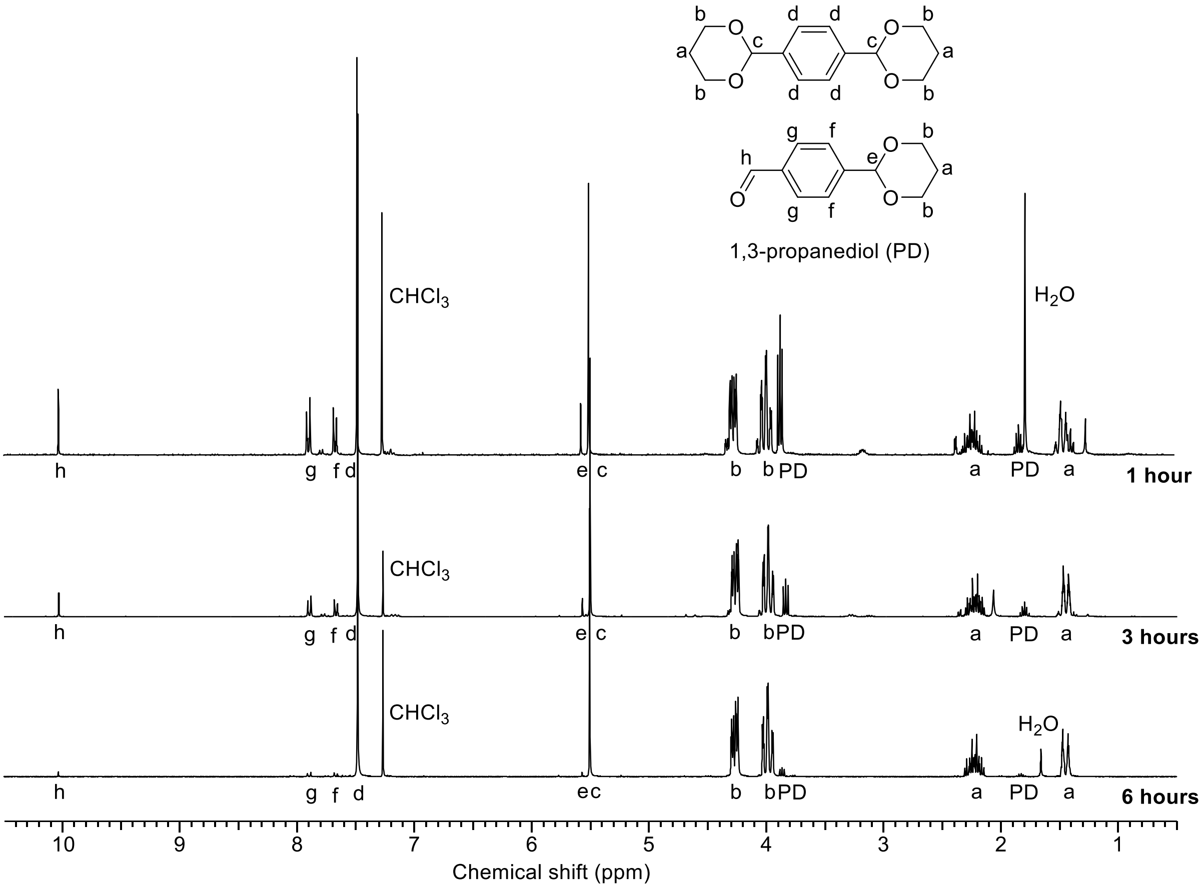


Figure 5.1. ^{1}H NMR-spectra of the acetalization of *p*-phthaldehyde with 1,3-propanediol ($CDCl_3$-d, 300 MHz) after one hour, 3 hours and 6 hours in order to follow the conversion.

5.1.2.1 Model study on the dialdehydes

The selected dialdehydes are cheap bulk chemicals with limited flexibility, except for glutaraldehyde, to ensure good material properties in the polymer end product. Glyoxal is the smallest possible aliphatic dialdehyde and can originate from biobased sources, since it is present in bio-oil.[30-31] A pure bisacetal of glyoxal could not be isolated from the residual mixture after the reaction, which was expected since this dialdehyde is a mixture of hydrated oligomers.[32] Glutaraldehyde, which is an aliphatic, more flexible and also potentially biobased dialdehyde, obtained full conversion after 2 h, yielding the corresponding diacetal.[33] Three aromatic dialdehydes (*p*-phthalaldehyde, *m*-phthalaldehyde and *o*-phthalaldehyde), which have the same chemical formula but differ in the positioning of the substituents, were also examined in order to see the role of regio-isomerism on the reactivity of the compounds and thus the speed of the reaction.

Unlike the fast reaction of glutaraldehyde, the acetalization of these phthalaldehydes with 1,3-propane diol took 6 h to reach full conversion. This delay is ascribed to the presence of a conjugated electron system in the phthalaldehydes, in contrast to the aliphatic glutaraldehyde. Due to this conjugation, one aldehyde group is deactivated after acetalization of the other aldehyde functionality. Since acetalization of the three aromatic dialdehydes was completed within similar reaction times, regio-isomerism did not seem to have a notable influence on the reactivity. Glyoxal was left out of the further study due to the presence of dimers and oligomers in the starting mixture, which would presumably result in crosslinked materials. Moreover, glutaraldehyde appeared to be more reactive than the phthalaldehydes towards the acetalization process, which will reflect on the polymerization process.

5.1.2.2 Model study of the diketones

There is a clear difference between the reaction times needed to form diketals with either a 1,2-divalent alcohol or a 1,3-divalent alcohol. The diketones prefer to react with 1,2-divalent alcohols, which is represented in shorter reaction times. Despite the shorter reaction times with a 1,2-divalent alcohol, it is also necessary to look at the reaction time with a 1,3-divalent alcohol as the tetraols, that will be used for the polyketalization reactions, have their alcohol moieties positioned in a 1,3-position instead of a 1,2-position.

Furthermore, there is a noticeable difference in the reactivity of the investigated diketones. This difference in reactivity was used as a basis for the decision on whether to select or discard diketones for further investigation. The diketone 3,3'-dimethylpentadione was discarded from the testing set because of several reasons. It is not cheap (€210/25g), not biobased and after a reaction time of 4.5 h with a 1,2-diol, a mixture of mono and non-reacted diketone was obtained. It was determined that there is too much steric hindrance for the formation of diketals, which would also be a problem in polymerization reactions. Furthermore, camphorquinone and 4-ketoisophorone showed low reactivity. The low reactivity of 4-ketoisophorone is the result of the deactivating effect of the double bond and the steric hindrance caused by the methyl groups. Camphorquinone, on the other hand is a bridged system in which the ketone functionality is also hindered because of the methyl groups. Although these diketones show low reactivity towards 1,3-diols, they are included in the polyketalization reactions because of their rigid structure and biobased content. The other diketones also looked promising enough to be used for further testing in polyketalization reactions. The diketones used as model compounds to test the feasibility of new reactions were 1,4-cyclohexanedione and 4,4’-bicyclohexanone since they were the most reactive ones in the tested set.

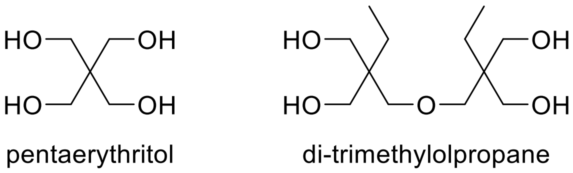
5.1.2.3 Conclusion of the model study

The dicarbonyl compounds with the shortest reaction times were selected for polymerization. Thus, glutaraldehyde, 4,4’-bicyclohexanone, 1,4-cyclohexanedione, acetonylacetone and diacetyl were chosen. Next to this, it was also decided to try to polymerize the different phthaldehydes as this can show some structure property relations. Also two renewable diketones (4-ketoisophorone and camphorquinone), which were less reactive towards the diols, were used in the polymerization process, as this allows to make different renewable poly(cycloketals).

5.1.3 Polyacetalization and polyketalization

5.1.3.1 Introduction

As the selection of the dicarbonyls was made based on the model study, only the choice of tetraols needed to be made. The choice of cheap, commercially available tetraols is rather limited and for this study we chose for pentaerythritol and di-trimethylolpropane (di-TMP) (Scheme 5.1). Pentaerythritol is a much more rigid tetraol compared to di-TMP, which could result in better thermal and mechanical properties of the polymers in the end. The resulting polymers will also always contain at least one spiro centre, the one of pentaerythritol itself.



Scheme 5.1. Structure of the two tetraols chosen for this chapter.

The poly(acetalization/ketalization) is a polycondensation reaction from which water needs to be removed to achieve high molecular weight polymers. Here, two techniques for water removal are applied; one uses a physical drying agent while the other method works via azeotropic distillation. From now on, we will refer to the techniques as protocol A and B, respectively. In protocol A, first the chlorinated solvent dichloromethane (DCM) was selected based on a literature report.[18] In a second approach, ethylacetate (EtOAc) and 2-methyl tetrahydrofuran (2-MeTHF) were selected as solvent because of their more renewable character and higher reflux temperatures.[19-20] In protocol B, only toluene was considered as solvent, due to the limited solubility of the monomers in petroleum ether.

5.1.3.2 Pentaerythritol as tetraol

As a starting point of this study, the selected dicarbonyls were reacted with pentaerythritol in a polymerization reaction via protocol A, with $MgSO_4$ as drying agent[18], and protocol B. As was expected from literature examples, no polymers or only low molecular weight polymers could be synthesized. [1, 3, 10-11, 13] Only glutaraldehyde, 1,4-cyclohexanedione and 4,4-bicyclohexanone, when reacted with pentaerythritol, resulted in polymers (Table 5.3). The polymers were in all cases white solids, which precipitated early from the reaction mixture, with low molar masses up to 5 kDa. The polymers were only soluble in HFIP and multi-modal SEC traces reveal that branching might have occurred. The polymers were stable up to 360 °C if the polymers show to have higher molecular weights, but no glass transition could be observed from DSC analysis within a temperature range of 0 °C till 350 °C. In literature, the high crystallinity of the poly(cycloacetal/ketals) from pentaerythritol was always stated but not proven. Our DSC measurements (0-350 °C) did not show melting points but XRD measurements proved the crystallinity of these polymers. We think that the melting point of these polymers is close to the degradation temperature and is therefore not observed in the DSC graph. As a final step, attempts were made to prepare polymer films but they resulted in white, turbid and very brittle materials (Figure 5.2). Consequently, no mechanical properties could be obtained from the pentaerythritol-derived samples.

Table 5.2. Overview of poly(cycloacetal/ketals) from dicarbonyls and pentaerythritol.

Dicarbonyl	Protocol	Drying agent	M_n (kDa)/ Đ	$T_{d5\%}$ (°C)	% biobased
Glutaraldehyde	A	$MgSO_4$	4.5/1.4	360	50
	B		2.4/2.3	300	
Cyclohexanone	A	$MgSO_4$	2.2/1.0	260	100
	B		2.0/ 1.0	240	
Bicyclohexanone	A	$MgSO_4$	4.8/1.0	330	30
	B		2.4/1.4	280	

Figure 5.2. Spiropolymer from glutaraldehyde and pentaerythritol in EtOAc.

5.1.3.3 Di-TMP as tetraol

In order to obtain processable poly(cycloacetal/ketals) with potential applicability, pentaerythritol was replaced by the tetraol di-TMP as it has a more flexible structure. The polymerization of the above described dicarbonyls with di-TMP in the presence of *p*-TsOH as catalyst was studied. The generated water could be eliminated from the reaction mixture with the two previously described protocols, but also a third method will be explored here. The water can also be removed by applying vacuum but therefore it is necessary to be able to work in the melt, which can be done with di-TMP (T_m = 105 °C) and not with pentaerythritol due to the high melting point (T_m = 260 °C).

After the reaction it was easy to evaluate if polymerization occurred. When di-TMP flakes were still present in the reaction mixture nothing had happened. After work-up and purification it was clear that only glutaraldehyde, the phthalaldehydes, 1,4-cyclohexanedione, 4,4’-bicyclohexanone and acetonylacetone resulted in polymers when reacted with di-TMP. The other diketones only formed oligomers with molar mass values below 1 kDa. NMR-analysis of the resulting products showed that the aimed poly(cycloacetals) originating from glutaraldehyde (Figure 5.3, A) and the phthalaldehydes (Figure 5.3, B) as well as the poly(cycloketals) from 1,4-cyclohexanedione (Figure 5.4, C), 4,4’-bicyclohexanone (Figure 5.4, D) and acetonylacetone (Figure 5.4, E) were successfully synthesized and isolated. The molecular weights of the poly(cycloacetal/ketals) derived from the mentioned dicarbonyls, along with the thermal and mechanical analysis results, can be found in Table 5.3. This table compares results obtained by the different protocols. It is important to note that polymerization *via* protocol B was around ten times faster than reaction *via* protocol A. This means that protocol B is preferred in terms of reaction time necessary to obtain high conversion. Besides this observation, Table 2 shows that the poly(cycloacetal/ketals) often have high molar masses (between 10 and 38 kDa), to our knowledge reported for the first time.

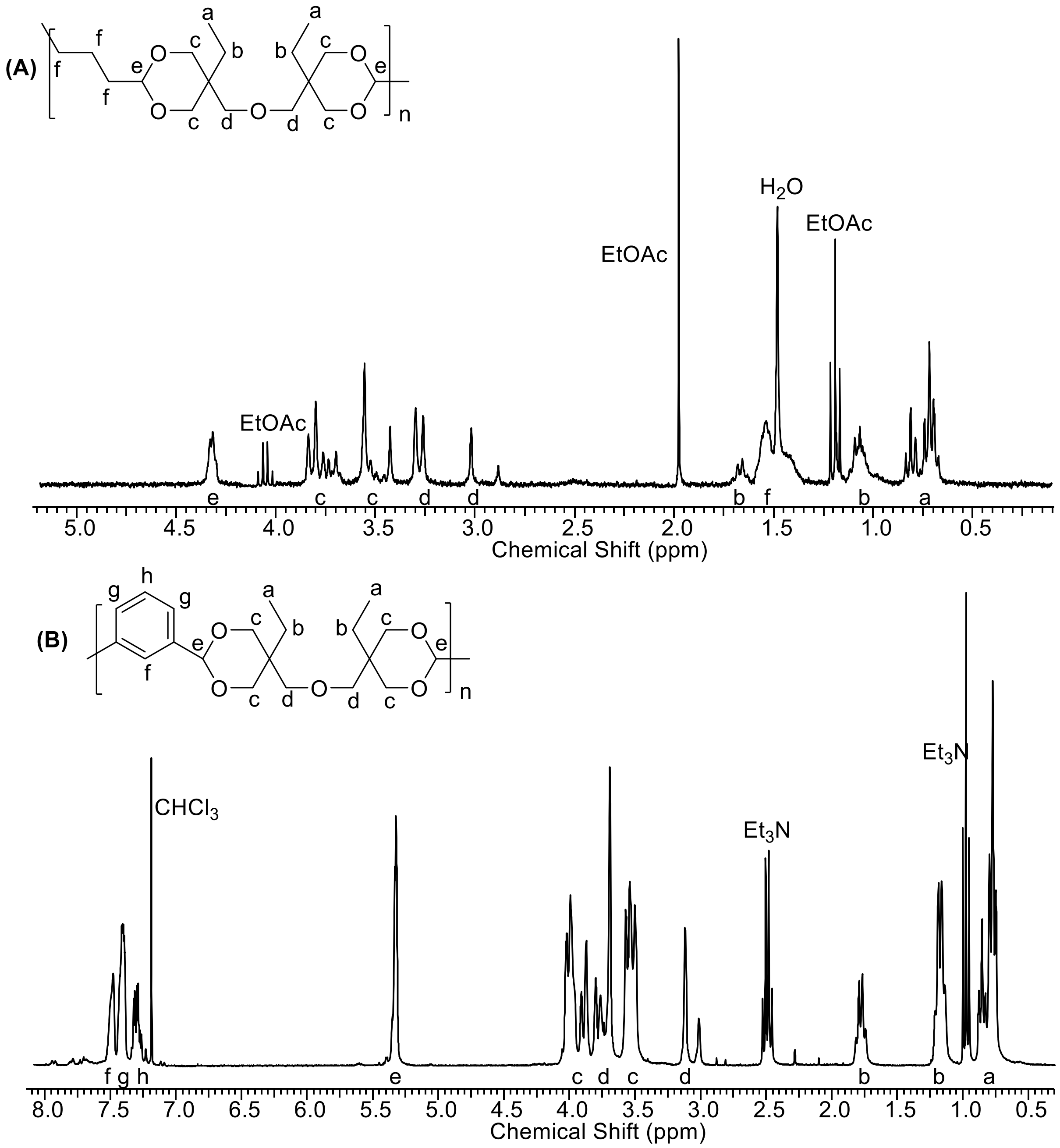


Figure 5.3. ^{1}H-NMR of the poly(cycloacetals) obtained from glutaraldehyde and di-TMP (A) and from *m*-phthalaldehyde and di-TMP (B) (CDCl$_3$-d, 300 MHz).

Since the poly(cycloacetal/ketals), showed striking differences in terms of their molecular weights on the one hand and thermal, mechanical and optical properties on the other hand, they are discussed separately hereafter.

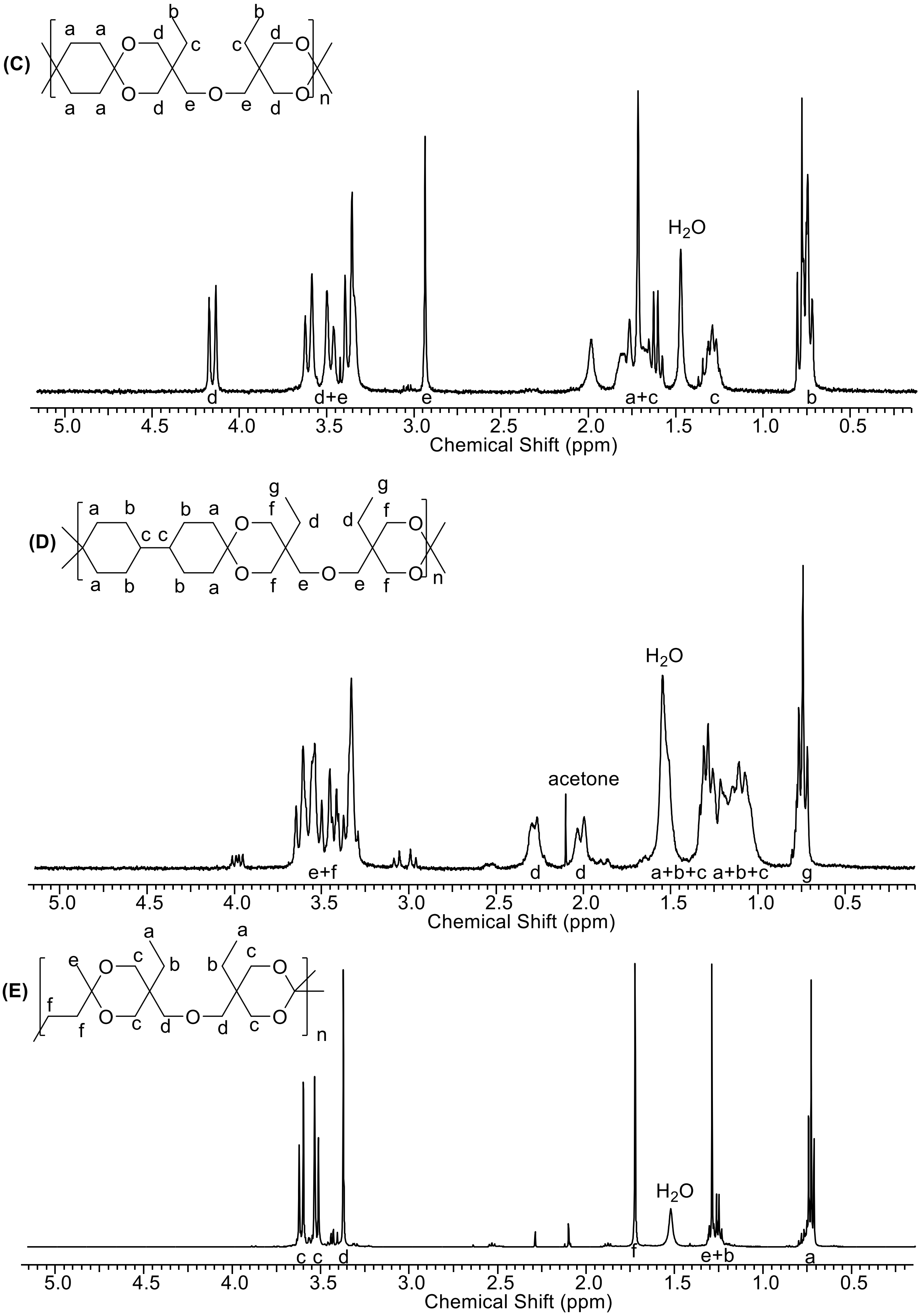


Figure 5.4. ^{1}H-NMR of the poly(cycloketals) from 1,4-cyclohexanedione and di-TMP (C), 4,4’-bicyclohexanone and di-TMP(D) and acetonylacetone and di-TMP (E) ($CDCl_3$-d, 300 MHz).

Table 5.3. Molar masses and dispersities as well as thermal and mechanical properties of the synthesized poly(cycloacetals) and poly(cycloketals) with di-TMP as tetraol.

Dicarbonyl	Solvent	M_n / Đ (kDa)	T_d (°C)	T_g[e] (°C)	T_g[f] (°C)	E (GPa)	Yield strength (MPa)	Tensile strength (MPa)	% Bio based
Glutaraldehyde	**DCM (A)**	34 / 4.0	270	30	35	0.4	7.1	14.8	30
	EtOAc (A)	38 / 2.6	370	31	34	0.7	10.4	16.6	
	2-MeTHF (A)	8 / 1.2	390	21	/[a]	/[a]	/[a]	/[a]	
	Toluene (B)	38 / 3.1	370*	30	39	0.5	11.0	16.5	
***p*-phthaldehyde**	**DCM (A)**	/[b]	305	115	/[c]	/[c]	/[c]	/[c]	0
***m*-phthaldehyde**	**DCM (A)**	20 / 1.4	343*	86	/[d]	/[d]	/[d]	/[d]	0
	EtOAc (A)	3 / 1.2	360	80	/[d]	/[d]	/[d]	/[d]	
	2-MeTHF (A)	11 / 1.2	370	93	/[d]	/[d]	/[d]	/[d]	
	Toluene (B)	16 / 1.9	340	95	/[d]	/[d]	/[d]	/[d]	
***o*-phthaldehyde**	**DCM (A)**	18 / 1.4	327*	102	/[d]	/[d]	/[d]	/[d]	0
	2-MeTHF (A)	15 / 1.4	350*	106	/[d]	/[d]	/[d]	/[d]	
	Toluene (B)	15 / 1.7	275*	103	/[d]	/[d]	/[d]	/[d]	
Cyclohexadione	**DCM (A)**	25 / 1.8	315	106	/[d]	/[d]	/[d]	/[d]	33
	2-MeTHF (A)	12 / 1.3	340	100	/[d]	/[d]	/[d]	/[d]	
	Toluene (B)	14 / 1.4	330	100	/[d]	/[d]	/[d]	/[d]	
Bicyclohexanone	**DCM (A)**	14 / 1.6	325	110	/[d]	/[d]	/[d]	/[d]	0
	2-MeTHF (A)	12 / 1.3	330	105	/[d]	/[d]	/[d]	/[d]	
	Toluene (B)	13 / 1.4	330	110	/[d]	/[d]	/[d]	/[d]	
Acetonylacetone	**DCM/ 2-MeTHF (A)**	-	-	-	-	-	-	-	33
	Toluene	9 / 1.2	240	30	/[c]	/[c]	/[c]	/[c]	

A = Polymerization protocol A, B = protocol B, *T_d determined at 10% weight loss instead of 5% due to presence of water, / = Absent results because of a) low yield, b) insolubility in DMA and HFIP for SEC, c) difficulties of processing or d) brittleness.

The T_g was measured with DSC (e) and DMTA (f). For DMTA analysis, the T_g is defined as the maximum in the Tanδ-T curve.

Glutaraldehyde + di-TMP

When analyzing the results of poly(cycloacetals) originating from glutaraldehyde, it can be observed that DCM, EtOAc and toluene as solvent resulted in higher yields and molecular weights. The polymers were thermally stable (up to 360 °C) and showed to have a rather low glass transition temperature (T_gs around 30 °C), which was expected due to the flexible structure of glutaraldehyde. These poly(cycloacetals) could easily be processed into colourless and transparent materials (Figure 5.5), which could be mechanically tested in a next step.

Figure 5.5. Picture of a processed poly(cycloacetal) from glutaraldehyde and di-TMP obtained via protocol A.

Figure 5.6 depicts the stress-strain curves of a material obtained by polymerization of glutaraldehyde *via* protocol B. Besides the relatively high elastic modulus (±0.6 GPa) and tensile strength (±16 MPa) at room temperature, these poly(cycloacetals) also showed ductile behaviour (strain at break up to 70%).

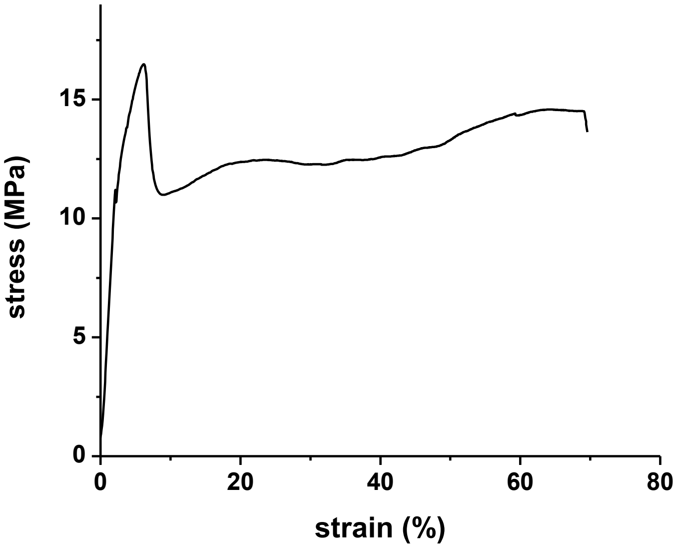


Figure 5.6. Stress-strain curve of a glutaraldehyde-based poly(cycloacetal) obtained via protocol B.

For glutaraldehyde, one other method was attempted in order to make poly(cycloacetals). Theoretically, it should be possible to make poly(cycloacetals) when combining glutaraldehyde, di-TMP, an acid catalyst and low pressure. As such, the water is continuously removed and the equilibrium is pushed to completion which could lead to high molecular weight polymers. The polymerization was executed in the melt, so at least a temperature of 105 °C was necessary (T_m of di-TMP). After 10 minutes, the reaction could not be stirred anymore and a non-soluble polymer was formed. Lower vacuum and even a N_2 flow were used in order to keep the reaction mixture liquid enough to stir. Unfortunately, in all cases a crosslinked polymer was formed. However, with the milder method (N_2 flow) it was possible to solubilize a fraction of the polymer in DMF, which showed to be a poly(cycloacetal) from glutaraldehyde and di-TMP with molecular weights not higher than 8 kDa. It was decided to not further investigate this method as crosslinking seemed to be inevitable.

Phthalaldehydes + di-TMP

In this section, the results of poly(cycloacetals) originating from the phthalaldehydes will be discussed. First of all, it should be noted that polymers based on *p*-phthalaldehyde precipitated early from the reaction mixture and were unsoluble in common organic solvents or HFIP, while the poly(cycloacetals) from *o* and *m*-phthalaldehyde as well as the poly(cycloacetals) from glutaraldehyde were soluble at room temperature in high boiling solvents such as DMSO, DMA and DMF. Consequently, molecular weights of the *p*-phthalaldehyde could not be determined and these poly(cycloacetals) were not considered for further analysis. Table 5.3 also shows that the polymerization of *m*-phthalaldehyde was difficult in EtOAc and even impossible for the polymerization of *o*-phthalaldehyde. Presumably, EtOAc is able to react with di-TMP in an acid catalyzed transesterification reaction as a result of the delay in the reaction caused by deactivation of the dialdehyde (*vide supra*). Furthermore, molecular weights of phthalaldehyde-based poly(cycloacetals) were lower than those of glutaraldehyde-based poly(cycloacetals). From the model study, it could be concluded that the deactivation of the phthalaldehyde (*vide* supra) limits the polyacetal to reach higher molecular weights. The poly(cycloacetals) based on phthalaldehydes are more rigid compared to the glutaraldehyde based poly(cycloacetals), which is shown by higher T_g values.

In Figure 5.7, the DSC results of the three different phthalaldehyde-based poly(cycloacetals) polymerized in DCM are shown. It is clear that the T_gs of the different poly(cycloacetals) strongly depend on the specific phtalaldehyde used. This dependence is ascribed to regioisomerism, since the substitution pattern of the phthalaldehyde determines how the aromatic ring can stack in the polymer backbone. This results in a difference in flexibility of the poly(cycloacetal) and consequently an obvious discrepancy in the observed T_gs. The polymers derived from *p*-phthalaldehyde show the highest T_g because of the *para* position of the aldehyde-groups and thus better stacking of the symmetric structural unit.

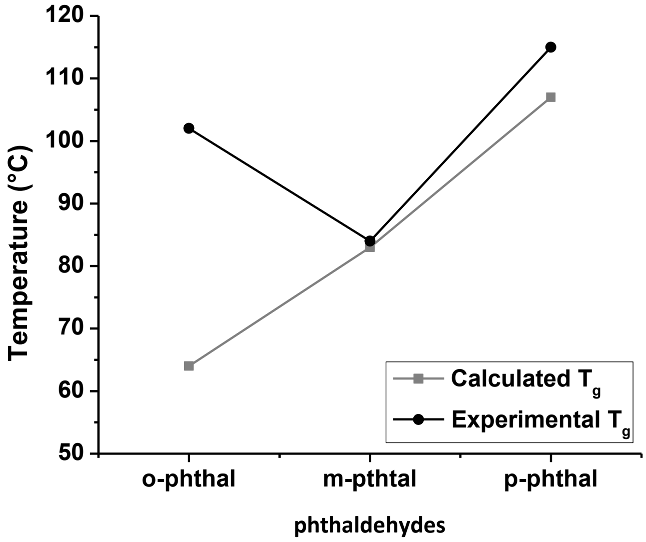


Figure 5.7. T_g values (DSC) of the phthalaldehyde-based poly(cycloacetals), compared to the calculated T_g values (group contribution calculations).

These experimental results were compared to theoretical T_g values, calculated with group contribution methods[34], which show a clear trend in T_g that can be related to the relative position of the aldehydes on the aromatic ring. Only for the *o*-phthalaldehyde-derived polymers, the calculated result clearly differs from the experimental one, which is ascribed to the fact that the theoretical method probably takes large free volume, and therefore bad packing of the *o*-phthalaldehyde-derived polymer chains, into account.

On the other hand, a 3D structure of the *o*-phthalaldehyde and *m*-phthaldehyde based polymers shows that the meta substitution creates more free volume in comparison to the ortho-substituted polymer. Mechanical properties of these phthalaldehyde-based poly(cycloacetals) could not be determined since they were too brittle for tensile or DMTA tests. The resulting materials were non-transparent and had a light yellow colour (Figure 5.8).

Figure 5.8. Picture of a poly(cycloacetal) from *m*-phthalaldehyde and di-TMP.

1,4-cyclohexanedione + di-TMP

First, it should be noted that polymerizations in 2-MeTHF (protocol A) and in toluene (protocol B) did not result in high molecular weight polymers. Clearly, dichloromethane is the solvent of choice for the reaction of 1,4-cyclohexanedione and di-TMP as the polymer was only soluble in this solvent. Thermally stable amorphous polymers with high T_gs (T_g = 106 °C) could be obtained. The processed materials were white (opaque), unfortunately, no mechanical tests could be performed as air bubbles were still present in the material.

4,4'-Bicyclohexanone + di-TMP

The synthesis of poly(cycloketals) from 4,4'-bicyclohexanone and di-TMP did not result in high molecular weight polymers. Both protocols and all tested solvents gave molecular weights of around 13 kDa. The polymers were thermally stable up to 330 °C and high T_gs with a value of 110 °C were obtained. Processing of these materials was done, although not high enough molecular weights were obtained to ensure entanglements. A white opaque and brittle material was obtained, which could not be measured on the tensile machine due to the brittleness.

Acetonylacetone + di-TMP

Poly(cycloketals) from acetonylacetone and di-TMP could only be realized with protocol B in toluene. Rather low molecular weights could be obtained and as expected a low T_g polymer was synthesized. Moreover, the thermal stability of these polymers was low as degradation already started at 240 °C. When processed, a transparent elastic brown coloured film could be realized. However, the molecular weights were too low to ensure entanglements and therefore good enough mechanical properties.

Hydrolytic stability and biobased content

When the content of renewable carbon in the di-TMP based poly(cycloacetal/ketals) is calculated only low values are obtained. Di-TMP is not renewable at the moment, and only when it is combined with a renewable diketone, it results in a partially (30%) renewable poly(cycloacetal/ketal).

In a final experiment two polymers were subjected to stability tests in order to investigate the hydrolytic stability of the acetal/ketal functionalities, which are part of the polymer backbone.[35] The poly(cycloacetal) based on glutaraldehyde and di-TMP as well as the poly(cycloketal) of 1,4-cyclohexanedione and di-TMP were subjected to these stability tests. The polymers were immersed in an aqueous solution for two weeks, after which the samples were weighted and SEC analysis was performed to investigate if degradation took place.[22] The percentage of mass loss and the SEC measurements are presented in Table 5.4. For both polymers no significant decrease in mass was observed as more than 96% of the polymer weight was recovered. Moreover, the molar masses only decreased very little when immersed in lower pH media. It can be concluded that these poly(cycloacetal/ketals) are stable in hydrolytic media up to pH 1 for at least two weeks.

Table 5.4. Molecular weights and dispersities before and after degradation tests with glutaraldehyde-based poly(cycloacetals).

	Glutaraldehyde + di-TMP 65 / 2.9		**1,4-cyclohexanedione + di-TMP 25 / 1.8**	
pH	**Mass loss (%)**	**M_n / Đ (kDa)**	**Mass loss (%)**	**M_n / Đ (kDa)**
1	4	61.2 / 2.7	3	21.8 / 1.8
3	4	65.0 / 2.3	2	21.8 / 1.8
5	2	63.7 / 2.2	2	22.2 / 1.8
7	2	65.0 / 2.5	2	24.0 / 1.7

5.1.4 Conclusion

Poly(cycloacetal/ketals) were synthesized from pentaerythritol and di-TMP as tetraols and various commercially available cheap and rigid dialdehydes and diketones. Polymerizations with pentaerythritol only resulted in low molecular weight and crystalline materials. With di-TMP, high molecular weight polymers were obtained with glutaraldehyde, *o*- and *m*-phthaldehyde and 1,4-cyclohexanedione. High T_gs (80-110 °C) were obtained for all polymers except for the glutaraldehyde ($T_g = 30$ °C) one. Only the glutaraldehyde poly(cycloacetal) could be processed into transparent and ductile materials. Despite the promising results, not all of the desired criteria for poly(cycloacetal/ketals) could be achieved. In order to get high T_g, transparent and ductile materials with a high biobased carbon content, it was decided to synthesize our own dialdehydes and to make poly(cycloacetals) thereof.

5.2 Poly(cycloacetals) from synthesized dialdehydes

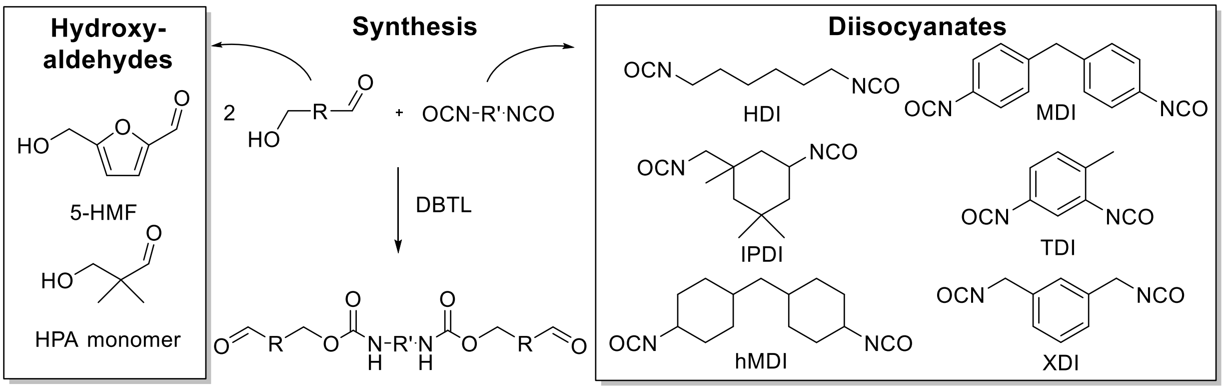
5.2.1 Introduction

In the former paragraph, it is shown that poly(cycloacetals) could be obtained from commercially available dialdehydes like glutaraldehyde and phthalaldehyde. Since the availability of commercial dialdehydes is limited, new partially biobased dialdehydes containing rigid moieties were synthesized. Recently, it was proven that this strategy can lead to polymers with extraordinary properties.[9, 15, 18, 36] Through structural optimization of the dialdehyde, a high rigidity of the polyacetal was targeted resulting in thermally and chemically stable polymers. Different procedures can be used to obtain the envisaged dialdehydes, for example Miller *et al.* started from 4-hydroxybenzaldehyde, vanillin, and syringaldehyde, all derived from lignin, thus being partially renewable. [18]

Our strategy to obtain partially renewable dialdehydes was based on a nucleophilic addition reaction. Biobased hydroxyaldehydes, hydroxymethylfurfural[37] and hydroxypivaldehyde[38], were reacted with six different diisocyanates to ensure a variety in the dialdehyde structures. After optimizing the synthesis and purification, a model study of the prepared dialdehydes was performed, gaining valuable knowledge with respect to their reactivity in the acetalization reaction. In a next step, poly(cycloacetals) were obtained from the acetalization with di-TMP. Finally, thermal, mechanical and optical properties were evaluated.

5.2.2 Synthesis of biobased dialdehydes

A partially biobased dialdehyde was obtained via the classic formation of urethane linkages and the general method is depicted in Scheme 5.2. Two building blocks were modified via this synthesis method in order to get a series of dialdehydes enabling a range of properties on the obtained poly(cycloacetals). Two different and rigid, green hydroxyaldehydes were used, 5-HMF, containing a furan ring, and hydroxypivalaldehyde (HPA), containing a quaternary carbon. For the diisocyanate part, six different diisocyanates were applied, three aliphatic (HDI, IPDI and hMDI) and three aromatic (MDI, TDI and XDI) ones, giving theoretically twelve different backbones. The synthesized dialdehydes were given trivial nomenclature, e.g. bisHMF-HDI consisting of two 5-HMF molecules and one HDI molecule. The choice of diisocyanate determined the biobased content.[39]



Scheme 5.2.Synthesis of biobased dialdehydes starting from hydroxyaldehydes and diisocyanates.

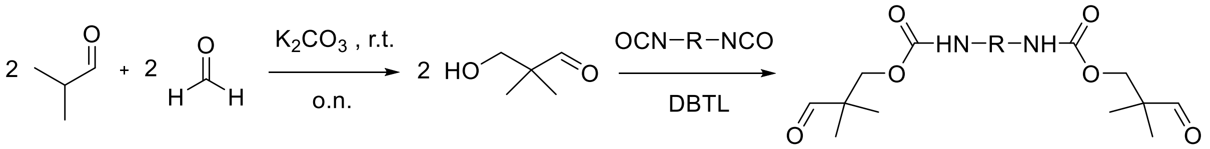
The synthesis of HMF-based dialdehydes turned out to be high yielding facing, no difficulties to purify. Only the yield of bisHMF-HMDI was surprisingly low due to mass loss during purification. Moreover, these synthesis reactions were reproducible and upscaling was effortless. Reaction times depended strongly upon the used diisocyanate. The high reactivity of the aromatic diisocyanates led to a fast synthesis (15 min) of the corresponding HMF-based dialdehyde, opposing reaction time increased due to steric congestion in the aliphatic diisocyanates (1 h) (Table 5.5). Despite the use of oil-based diisocyanates, an overall biobased content of around 50% could be achieved. Nevertheless, measures have been taken for the synthesis of diisocyanates from sugars or from other biomass which could potentially increase the biobased content of these monomers in the future.[40]

Table 5.5.Overview of the reaction time, yield, melting point (T_m) and the biobased content of the different HMF based dialdehydes.

Dialdehyde	MW (g mol^{-1})	Yield (%)	Reaction time (min)	T_m (°C)	Biobased content (%)
bisHMF-HDI	420	83	15	147	60
bisHMF-IPDI	475	91	60	15	50
bisHMF-hMDI	514	14	90	155	44
bisHMF-MDI	502	91	15	160	44
bisHMF-TDI	426	64	15	150	57
bisHMF-XDI	440	87	15	131	55

The synthesis of the HPA-based dialdehydes was less straightforward since HPA occurs as its dimer at room temperature.[41-42] This means that an extra synthesis step had to be performed prior to the nucleophilic addition reaction, in order to obtain the desired HPA monomer. In literature, two different methods are described to achieve the HPA monomer respectively via the aldol reaction between isobutyraldehyde and formaldehyde, and via the thermal treatment (cracking) of the HPA dimer.[41-48]

Synthesis of the HPA monomer via aldol reaction. Isobutyraldehyde was reacted with formaldehyde in the presence of potassium carbonate as the catalyst (Scheme 5.3, step 1). After overnight stirring at room temperature, the product was purified.



Scheme 5.3. Synthesis of the HPA-based dialdehyde via the aldol reaction of isobutyraldehyde with formaldehyde.

As can be seen from the ^{1}H-NMR (Figure 5.9) the HPA dimer is present next to the HPA monomer in a 2 to 3 ratio. It was not possible to obtain pure HPA monomer as the monomer-dimer equilibrium is favourable for the dimer at room temperature.[41-42] The second step, addition of the diisocyanate, was not performed, as a complicated mixture of compounds was anticipated. The rational behind this, is that the presence of hydroxyl moieties on the HPA dimer counterpart would also react. Therefore, a second method to obtain the HPA monomer was investigated.

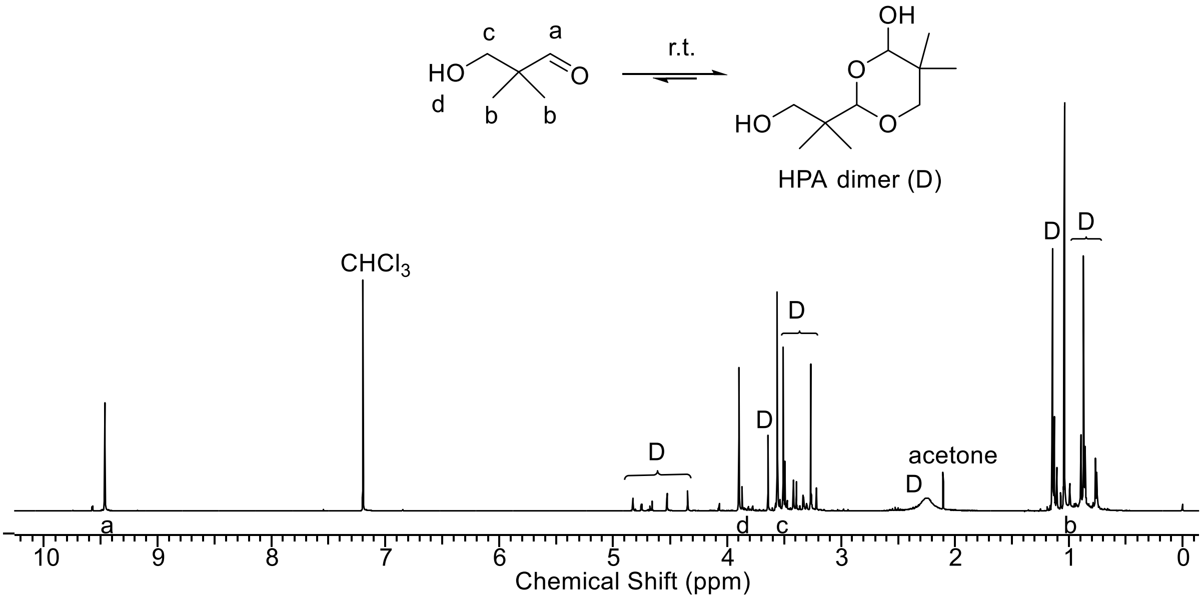


Figure 5.9. ^{1}H-NMR spectrum of HPA via the aldol reaction ($CDCl_3$-d, 300 MHz).

Thermal treatment of the HPA-dimer. When heating the HPA dimer, the cycle opens and the HPA monomer is released (Figure 5.10). Initially, online IR revealed the time and temperature needed for the HPA monomer to reach the maximum amount. Eventually, BuOAc was chosen as the preferred solvent due to its high boiling point (126 °C), its green character[49] and because it is regarded as a good solvent for urethane formation.

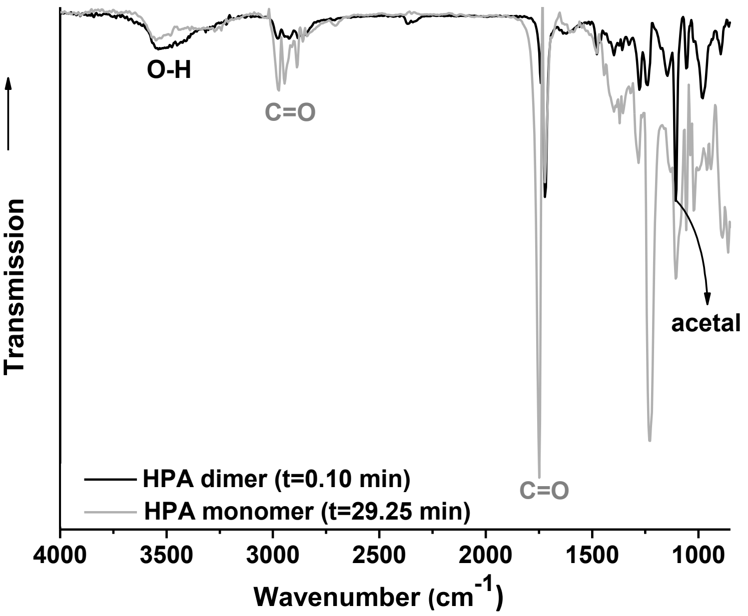


Figure 5.10. the IR spectra of the initial and final reaction mixture is displayed. In the beginning, only HPA dimer is present in the solution, while after 30 minutes clearly only HPA monomer is present. This is confirmed by the aldehyde signals of the HPA monomer at 1750 cm^{-1} (C=O, stretch) and 3000-2800 cm^{-1} (C=O, stretch). Next to this, the IR signal of the acetal in the fingerprint diminishes, which proves that the amount HPA dimer reduces with time at 110 °C.

Furthermore, the point at which the amount of HPA stabilizes can be investigated with online IR. In Figure 5.11, a 3D representation of the IR spectra as a function of time can be seen. When the focus is set at 1750 cm^{-1} (stretch signal of the aldehyde group), it can be observed that the signal stabilizes after 10 minutes. This means that the maximum amount of HPA monomer is formed at 110 °C after only 10 minutes. Thus, the thermal treatment method seems to be more successful than the aldol reaction in order to obtain the HPA monomer.

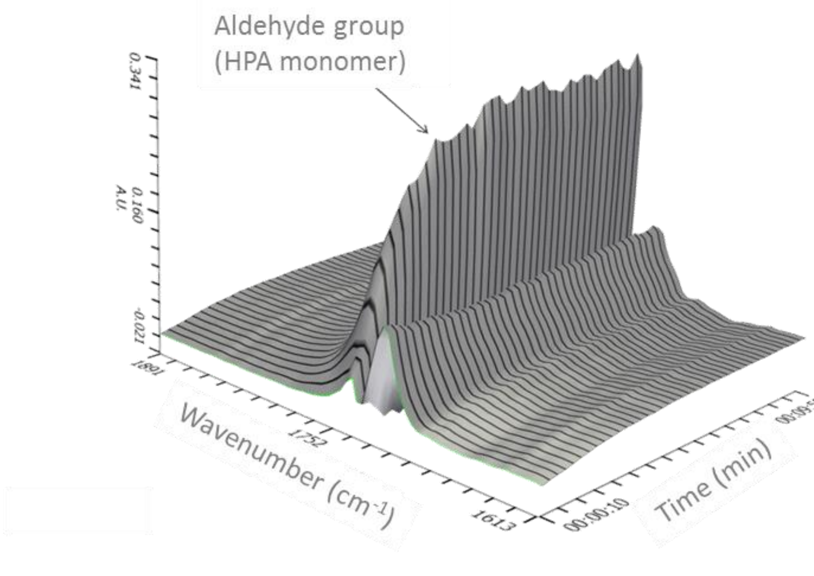
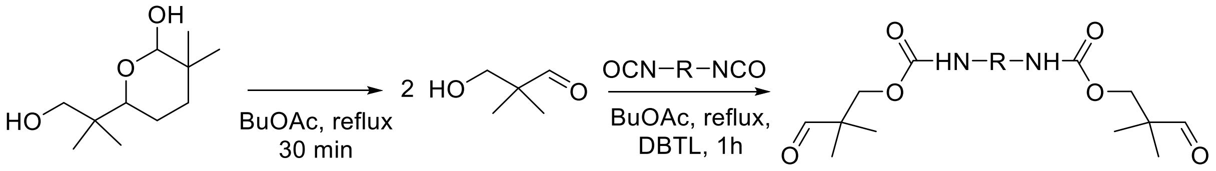


Figure 5.11. 3D graph of the online IR measurement of the equilibrium reaction between the HPA dimer and monomer as a function of time.

This information can then be used to synthesize the HPA-dialdehyde in a one-pot procedure (Scheme 5.4). First, the thermal treatment of the HPA dimer was executed for 30 minutes to be sure that the maximum amount of HPA monomer is formed. Next, a diisocyanate was added to the reaction mixture together with DBTL as the catalyst. This is kept under reflux to avoid HPA dimer formation. It is known that diisocyanates react fast and reactions are often easily upscalable.[22, 50-51]



Scheme 5.4. Synthesis of the HPA-dialdehyde via thermal treatment of the HPA dimer.

First, only MDI was used as diisocyanate in the synthesis, since this bulk chemical is one of the most rigid and showed good reactivity in the synthesis of bisHMF-MDI (reaction time of 15 min.). Analysis (^{1}H-NMR) confirmed that the aimed HPA-based dialdehyde was synthesized (Figure 5.12). However, the reaction mixture still contained minor traces of HPA dimer (D signals in the ^{1}H-NMR spectrum). While the synthesis of bisHPA-MDI appeared to be fast and high yielding, this reaction also seemed to be less reproducible than for the HMF-based dialdehydes. This clearly results from the incomplete conversion from the HPA dimer to its monomer. Given the fact that the HPA dimer and monomer are in constant equilibrium, partial reaction with the HPA dimer and diisocyanate is unavoidable. Despite testing different purification methods , it was impossible to obtain a HPA dimer free fraction.

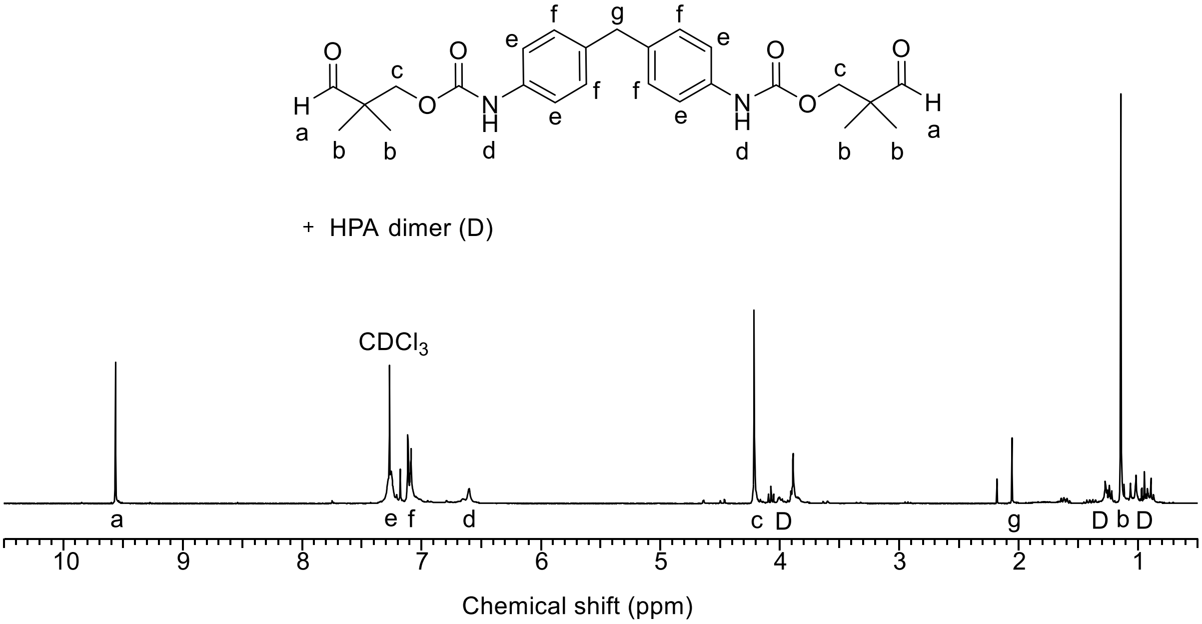


Figure 5.12. ^{1}H-NMR spectrum of the synthesized HPA based dialdehyde (bisHPA-MDI) ($CDCl_3$-d, 300 MHz).

Parallel to the synthesis of bisHPA-MDI, also dialdehydes from IPDI, hMDI and PDI were envisioned as they would most likely ensure enhanced rigidity to the polymer backbone. Also for these monomers, HPA dimer still seemed to be present.

With the dialdehydes in hand, we performed a model study to verify whether these dialdehydes are suitable for polyacetalization.

5.2.3 Model compound synthesis of the synthesized dialdehydes

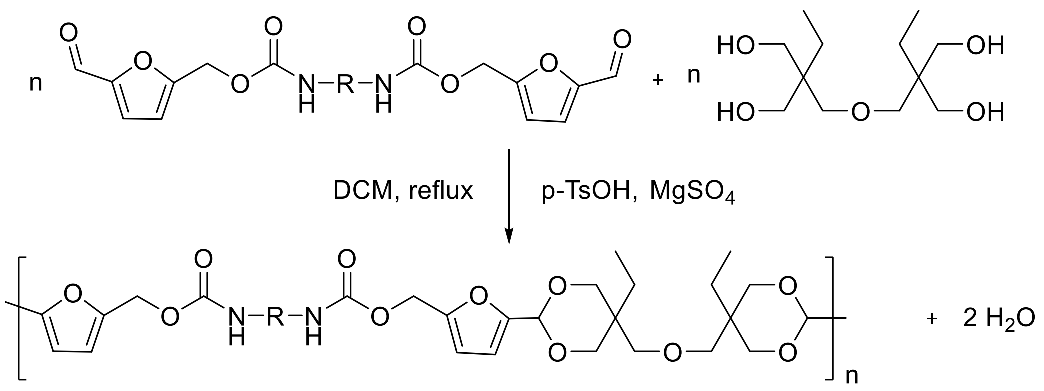
A model study, similar to the comparison of commercial dialdehydes in 5.1.2, was engaged to examine to what extent acetalization is possible. First, it should be noted that petroleum ether was used instead of toluene for the acetalization of the HMF-based dialdehydes. The reason for this is that the HMF-based dialdehydes were less thermally stable, as a result of the presence of furan rings in their structure.[37] Not only the building block, 5-HMF, is unstable at high temperatures, also the resulting furan rings in the dialdehydes are very reactive and are able to undergo a broad range of (side-)reactions at elevated temperatures.[52] ^{1}H-NMR analysis of the reaction mixture obtained after eight hours, showed that the acetalization was still not completed. Thus, reactivity is significantly slower compared to the glutaraldehyde and phthalaldehyde compounds, respectively being two and six hours. The ^{1}H-NMR spectra showed that acetalization had taken place, however unambiguous assignment of the signals deemed impossible due to the presence of both mono- and bis-acetalized dialdehydes and bisHMF-DI.

Analogous to the acetalization of the HMF-based dialdehydes, the acetalization of bisHPA-MDI was performed with 1,3-propanediol in toluene, since thermally induced side reaction were not anticipated. In contrast to the acetalization of HMF-based dialdehydes, ^{1}H-NMR analysis showed that already after one hour the desired product was obtained.

In conclusion, all the synthesized dialdehydes showed the ability to undergo acetalization. HMF-based dialdehydes needed more time for acetalization and thus will most probably require longer reaction times to polymerize.

5.2.4 Polyacetalization of the synthesized dialdehydes with di-TMP

In this section, polymerization of the partially biobased, synthesized dialdehydes with di-TMP in the presence of *p*-TsOH as catalyst, was studied. Due to the presence of a rigid element in the monomers, poly(cycloacetals) with high rigidity were expected. It was chosen to only react the dialdehydes with di-TMP as this gave the best results with glutaraldehyde. A few polymer reactions with pentaerythritol as tetraol were performed but no polymer could be obtained.



Scheme 5.5. Polyacetalization of HMF based dialdehydes and di-TMP.

Firstly, the polymerization of HMF-based dialdehydes will be discussed. In this polymer synthesis the formed water (see Scheme 5.5) was eliminated from the reaction mixture via protocol A, using $MgSO_4$ as a physical drying agent, in the presence of DCM as a solvent. No other solvents were tested as they are higher boiling solvents and the HMF-based dialdehydes are thermally less stable, as stated above. Additionally, this polymerization was executed during 90 h, since the model compound study showed that the HMF-based dialdehydes needed more time for acetalization than the commercially available dialdehydes. NMR-analysis of the resulting products showed that the targeted poly(cycloacetals) starting from the HMF-based monomers were synthesized. In Figure 5.13, a ^{1}H-NMR spectrum is presented of the polyacetal made from bisHMF-TDI and di-TMP where broadening of the signals is evident. Results of the molecular weights and thermal analyses of the poly(cycloacetals) derived from these dialdehydes can be found in Table 5.6.

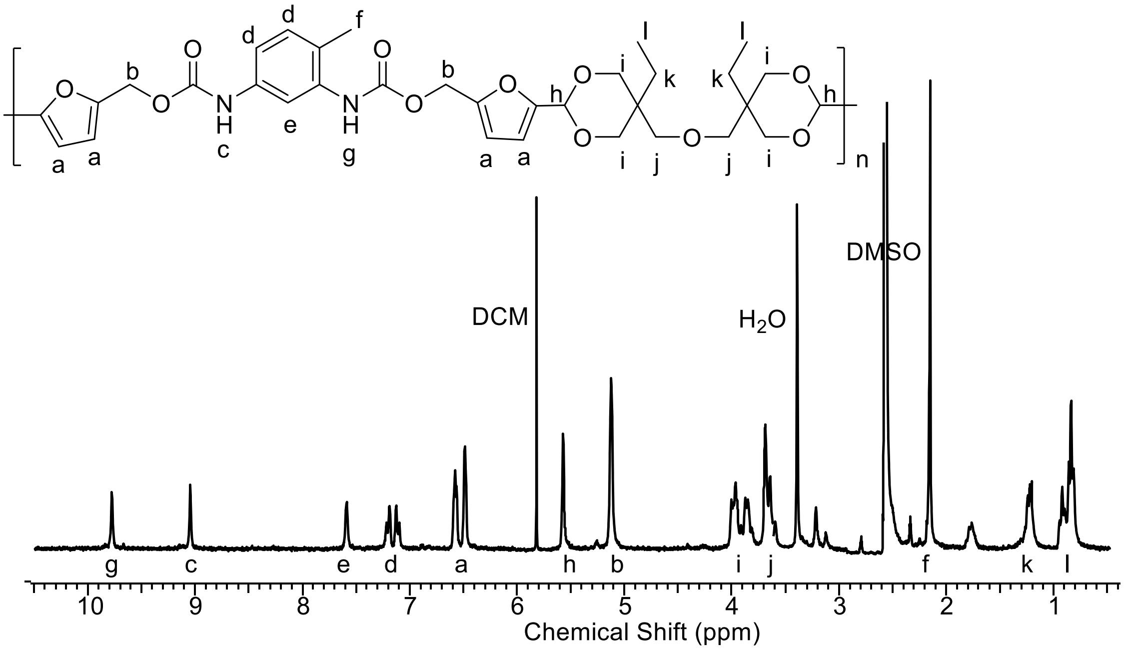


Figure 5.13. ^{1}H-NMR spectrum of the polyacetal out of BisHMF-TDI and di-TMP ($CDCl_3$, 300 MHz).

First of all, the table below depicts that the molecular weights of the HMF-based poly(cycloacetals) were generally lower than those measured for the poly(cycloacetals) made from commercial dialdehydes (> 15 kDa). An explanation for the low molecular weight polymers was found in the low reactivity of the dialdehydes as proven in the model study (*vide supra*).

Table 5.6.Results of the analysis of the HMF-based poly(cycloacetals).

	DMA-SEC	*TGA*	*DSC*	*DMTA*
Dialdehyde	**M_n / Đ (kDa)**	**T_d (°C)**	**T_g (°C)**	**T_g (°C)**
bisHMF-HDI	2 / 2.2	245	27	/[a]
bisHMF-IPDI	8 / 1.5	270*	88	/[b]
bisHMF-hMDI	15 / 1.7	280	104	116
bisHMF-MDI	7 / 1.9	190	96	108
bisHMF-TDI	14 / 3.0	175	108	95
bisHMF-XDI	9 / 1.8	250	69	77

/ = Results lacking as a result of a) too low molecular weight or b) brittleness of the material

*T_d determined at 10% weight loss instead of 5% due to presence of water

Furthermore, the T_ds of the synthesized poly(cycloacetals) were remarkably lower than those of the poly(cycloacetals) based on commercial dialdehydes (>300 °C). This was an expected result due to the presence of the reactive furan rings in the polymer backbone causing accelerated decomposition. If the corresponding T_gs are considered, it can be stated that they are relatively high and comparable to those of phthalaldehyde based poly(cycloacetals). In Figure 5.15, the DSC-results of all HMF-based dialdehydes gave a wide spread in transition temperature and could be ascribed to the difference in flexibility of the six applied diisocyanates and consequently the divergence in the induced degrees of freedom in the resulting poly(cycloacetal). However, due to the small temperature range between the higher T_gs and lower T_ds, these poly(cycloacetals) rapidly showed degradation and therefore the possibilities to process these polymers were limited.

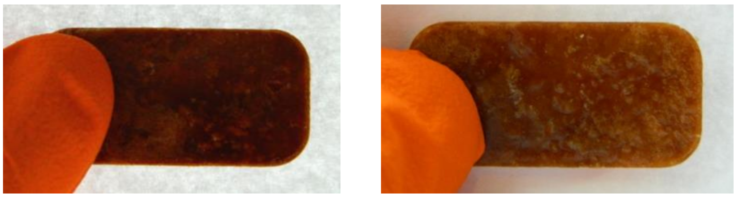


Figure 5.14. Poly(cycloacetals) based on BisHMF-TDI (left) and BisHMF-hMDI (right).

When eventually materials were made out of these poly(cycloacetals), no mechanical analyses could be performed on these samples due to brittleness. Yet, it was possible to perform tensile tests on the material of bisHMF-TDI, which yielded an elastic modulus of 0.2 GPa, a yield strength of 0.4 MPa and a tensile strength of 2.0 MPa. These values were significantly lower than those of the glutaraldehyde based poly(cycloacetals), which was expected since the material was brittle compared to the ductile and flexible glutaraldehyde based poly(cycloacetals). The obtained materials were brown and non-transparent compared to the colorless, transparent glutaraldehyde based materials (Figure 5.14).

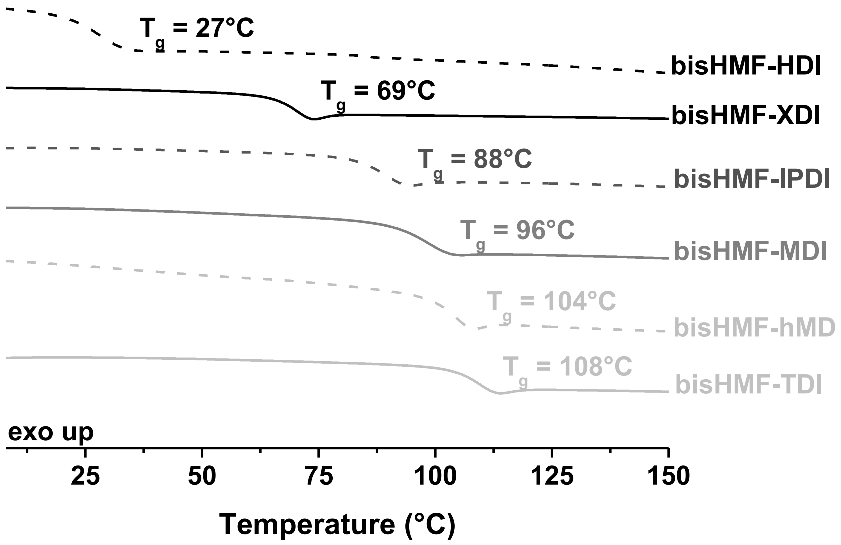
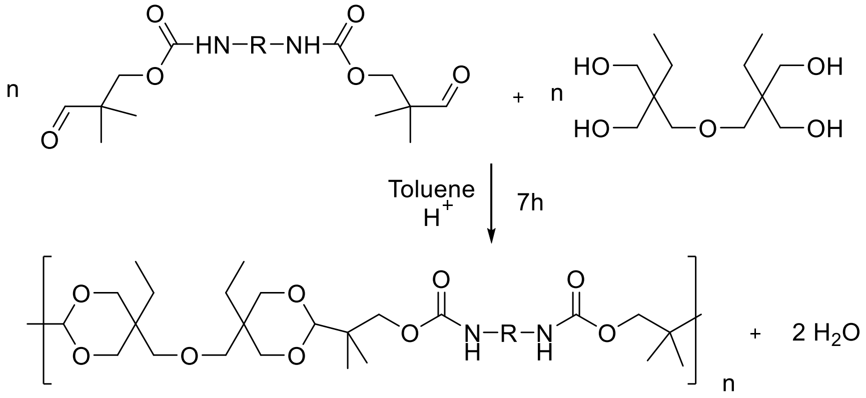


Figure 5.15. DSC results of the HMF based poly(cycloacetals).

In the following section, the polymerization of the HPA based dialdehydes will be discussed (Scheme 5.6). These polymers will not contain a furan ring, which would avoid low degradation temperatures and brittleness.

Initially, the polymerization of bisHPA-MDI with di-TMP was performed. Protocol A (physical drying agent) and B (Dean-Stark) were tested. No polymers could be obtained via protocol A. The results of the polymerization using a Dean-Stark in toluene can be found in Table 5.7.



Scheme 5.6. Polyacetalization of the HPA based dialdehydes with di-TMP.

Except for one polymer based on bisHPA-MDI, no high molecular weights could be realized. This was on the one hand the result of a bad stoichiometry due to HPA dimer still present in the monomer batch. On the other hand, during the polymerization, residual HPA dimer can resolve into HPA monomer which is a chain stopper. The glass transition temperatures are comparable to the bisHMF based polymers and even for bisHPA-MDI a value of 113 °C could be reached. No processing was performed on these samples as low molecular weight almost always result in brittle materials. As the results of the HPA based polymers were not fulfilling our objectives and the monomer synthesis was time consuming, it was decided to look for other methods in obtaining cyclic acetal/ketal containing polymers.

Table 5.7. Results of the analysis of the HPA-based poly(cycloacetals).

Monomer	M_n / Đ (kDa)	T_g (*via* DSC)
bisHPA-IPDI	2/1.4	70
bisHPA-hMDI	4/1.6	81
bisHPA-PDI	2/1.2	92
bisHPA-MDI	13/2.6	113

5.3 Conclusion

New dialdehydes could be synthesized from renewable resources via the nucleophilic addition of diisocyanates to hydroxyaldehydes. The synthesis of bisHPA-DI was more time-consuming as the HPA dimer needed to be cracked before use. It was not possible to obtain the bisHPA-DI as pure as the bisHMF-DI. A model study was performed on the synthesized dialdehydes to investigate the reactivity of the aldehyde towards alcohols. The reactivity of the bisHMF-DI (8 h reaction time) was much lower than that of the bisHPA-DI (1 h reaction time). It was not possible to reach high molecular weight polymers with the bisHPA based dialdehydes due to HPA dimer still being present in the monomer batch. The bisHMF based dialdehydes could be polymerized with di-TMP, but were not thermally stable to survive processing. There are still some possibilities in making renewable dialdehydes but in this project the focus will be shifted to another method of obtaining poly(cycloacetal/ketals), namely by the synthesis of cycloacetal/ketal containing monomers and introduction in polymers via known polycondensation methods.

5.4 Experimental part

5.4.1 Materials

Acetone (≥99.8%), dichloromethane (DCM, ≥99.5%), 3,3-Dimethyl-2,4-pentanedione (97%), di-trimethylolpropane (di-TMP, 97%), ethyl acetate (EtOAc, ≥99.7%), ethylene glycol (EG, ≥99%), glyoxal (40% in H_2O), hexane (≥97%), methanol (MeOH, ≥99.9%), 2-methyltetrahydrofuran (2-MeTHF, ≥99.5%), 1,3-propanediol (98%) and toluene (99.9%) were purchased from Sigma Aldrich. Acetonylacetone (>95%), 4,4'-Bicyclohexanone (>98%), (±)-Camphorquinone (98%), 1,4-Cyclohexanedione (>98%), di-trimethylolpropane (di-TMP, >98%), Diacetyl (98%), glutaraldehyde (50% in H_2O), 4-Ketoisophorone (>95%), *o*-Phthalaldehyde (>99%), *m*-phthalaldehyde (>98%), pentaerythritol (>98%) and *p*-phthalaldehyde (>98%) were purchased from TCI. $CDCl_3$(Euriso-Top, 99.8%), dimethylsulfoxide-d_6 (Euriso-TOP, 99.8%), magnesium sulfate ($MgSO_4$, Carl Roth), molecular sieves (4 Å, type 514 pearls, Carl Roth), petroleum ether (Acros Organics, pure), p-toluenesulfonic acid monohydrate (p-TsOH, Acros Organics, 99%), triethylamine (Et_3N, Acros Organics, 99%) and all previously mentioned substances were used as received without further purification.

5.4.2 Synthesis

5.4.2.1 General Synthesis of HMF-based dialdehydes

A two-neck-flask of 50 mL was charged with 5-hydroxymethylfurfural (HMF) (20 mmol), diisocyanate (10 mmol) and dry EtOAc (20 mL). Then, dibutyltinlaurate (0.10 mL, 1 mol%) was added and mixing was continued for 15 - 90 minutes depending on the used diisocyanate. The product (bisHMF-DI) was filtered and washed with EtOAc. Except for bisHMF-IPDI, which was precipitated (hexane), filtered and washed (hexane). All the products were dried overnight at 50 °C under lowered pressure.

BisHMF-HDI. Isolated yield: 83 %. **Brutoformula:** $C_{20}H_{24}N_2O_8$. **Molecular weight:** 420.42 g mol^{-1}. **LC-MS (m/z):** 438.20 $[M+NH_4]^+$. **^{1}H-NMR (300 MHz, DMSO-d_6):** δ (ppm) = 9.58 (s, 2H, 2xC*H*O), 7.51 (d, 2H, 2xCHOCC*H*CH), 7.35 (t, 2H, 2xCON*H*), 6.74 (t, 2H, 2xCHOCCHC*H*), 5.06 (s, 4H, 2xC*H₂*OCO), 2.96 (q, 4H, NHC*H₂*CH₂CH₂CH₂CH₂C*H₂*NH), 1.45-1.13 (band, m, 8H, NHCH₂C*H₂*C*H₂*C*H₂*C*H₂*CH₂NH)

BisHMF-IPDI. Isolated yield: 91 %. **Brutoformula:** $C_{24}H_{30}N_2O_8$. **Molecular weight:** 474.51 g mol^{-1}. **LC-MS (m/z):** 492.30 $[M+NH_4]^+$. **^{1}H-NMR (300MHz, DMSO-d_6):** δ (ppm) = 9.59 (s, 2H, 2xC*H*O), 7.51 (d, 2H, 2xCHOCC*H*CH), 7.40 (t, 1H, N*H*CH), 7.28 (m, 1H, N*H*CH₂C), 6.75 (d, 2H, 2xCHOCCHC*H*), 5.07 (d, 4H, 2xC*H₂*OCO), 4.03 (q, 1H, NHC*H*), 3.60 (m, 1H, NHC*H₂*), 3.33 (s, 1H, NHC*H₂*), 1,55-0.75 (band, t+2xm, 15H, NHCHC*H₂*C(C*H₃*)₂C*H₂*CC*H₃*C*H₂*NH)

BisHMF-hMDI. Isolated yield: 14 %. **Brutoformula:** $C_{27}H_{34}N_2O_8$. **Molecular weight:** 514.00 g mol^{-1}. **LC-MS (m/z):** 532.30 [M+NH$_4$]$^+$. **^{1}H-NMR (300MHz, DMSO-*d*$_6$):** δ (ppm) = 9.57 (s, 2H, 2xC*H*O), 7.50 (d, 2H, 2xCHOCC*H*CH), 7.29 (d, 2H, 2xCON*H*), 6.74 (d, 2H, 2xCHOCCHC*H*), 5.05 (s, 4H, 2xC*H*$_2$OCO), 3.19 (m, 2H, 2xNHC*H*), 1.85-0.75 (band, m+dd, 20H, NHCH(C*H*$_2$C*H*$_2$)$_2$C*H*C*H*$_2$C*H*(C*H*$_2$C*H*$_2$)$_2$CHNH)

BisHMF-MDI. Isolated yield: 91 %. **Brutoformula:** $C_{27}H_{22}N_2O_8$. **Molecular weight:** 502.48 g mol^{-1}. **LC-MS (m/z):** 520.20 [M+NH$_4$]$^+$. **^{1}H-NMR (300MHz, DMSO-*d*$_6$):** δ (ppm) = 9.79 (s, 2H, 2xCON*H*), 9.60 (s, 2H, 2xC*H*O), 7.53 (d, 2H, 2xCHOCC*H*CH), 7.35 (d, 4H, 2xC*H*CHCCH$_2$CCHC*H*), 7.11 (d, 4H, 2xC*H*CCH$_2$CC*H*), 6.83 (d, 2H, 2xCHOCCHC*H*), 5.21 (s, 4H, 2xC*H*$_2$OCO), 3.80 (s, 2H, CHCC*H*$_2$CCH)

BisHMF-TDI. Isolated yield: 64 %. **Brutoformula:** $C_{21}H_{18}N_2O_8$. **Molecular weight:** 426.38 g mol^{-1}. **LC-MS (m/z):** 444.20 [M+NH$_4$]$^+$. **^{1}H-NMR (300MHz, DMSO-*d*$_6$):** δ (ppm) = 9.81 (s, 1H, N*H*CCCH$_3$), 9.61 (d, 2H, 2xC*H*O), 9.09 (s, 1H, N*H*CCHCHCCH$_3$), 7.57-7.49 (m, 3H, NHCC*H*C+2xCHOCC*H*CH), 7.12 (dd, 2H, NHCC*H*C*H*), 6.83 (t, 2H, 2xCHOCCHC*H*), 5.20 (d, 4H, 2xC*H*$_2$OCO)and 2.11 (s, 3H, C*H*$_3$Ar).

BisHMF-XDI. Isolated yield: 87 %. **Brutoformula:** $C_{22}H_{20}N_2O_8$. **Molecular weight:** 440.41 g mol^{-1}. **LC-MS (m/z):** 458.20 [M+NH$_4$]$^+$. **^{1}H-NMR (300MHz, DMSO-*d*$_6$):** δ (ppm) = 9.59 (s, 2H, 2xC*HO)*, 7.51 (d, 2H, 2xCHOCC*H*CH), 7.26 (m, 2H, 2xN*H*CH$_2$C), 7.12+7.94 (d+t, 4H, CH$_2$CC*H*CC*H*C*H*C*H*), 6.76 (d, 2H, 2xCHOCCHC*H*), 5.11 (s, 4H, 2xC*H*$_2$OCO), 4.18 (d, 4H, 2xNHC*H*$_2$)

5.4.2.2 Synthesis of a HPA-based dialdehyde

A two-neck-flask of 50 mL was filled with HPA dimer (4.90 mmol) and BuOAc as a solvent (20 mL). The mixture was stirred and refluxed. After 30 minutes, MDI (4.9 mmol) and DBTL (0.10 mL) were added. One hour later, the product (bisHPA-MDI) was precipitated (hexane), filtered and washed (hexane). This was dried overnight at 50 °C under lowered pressure.

BisHPA-MDI. Isolated yield: 90 %. **Brutoformula:** $C_{25}H_{30}N_2O_6$. **Molecular weight:** 454.52 g mol^{-1}. **LC-MS (m/z):** 472.20 [M+NH$_4$]$^+$. **^{1}H-NMR (300MHz, CDCl$_3$):** δ (ppm) = 9.56 (s, 2H, 2xC*H*O), 7.26 (m, 4H, 2xNHC(C*H*)$_2$), 7.10 (d, 4H, 2xCH$_2$C(C*H*)$_2$), 6.63 (m, 2H, 2xCN*H*CO), 4.21 (s, 4H, 2xOC*H*$_2$C), 2.05 (s, 2H, CC*H*$_2$C), 1.14 (s, 12H, 4xCC*H*$_3$)

5.4.2.3 Model compound synthesis

A flask of 250 mL was charged with a dicarbonyl (1 equiv), diol (2.2 equiv) and *p*-TsOH (5 mol%). After this toluene or petroleum ether (40-60 °C, 100 mL) was added to the mixture which was stirred and refluxed under argon atmosphere in a Dean-Stark set-up.[17] After 2 to 24 h, depending on the used dialdehyde, trimethylamine (Et$_3$N) was added and the bulk solvents were removed under reduced pressure, followed by drying overnight at 50° under lowered pressure.

5.4.2.4 Polymer synthesis

Protocol A. A flask of 50 mL was filled with the dicarbonyl (1 equiv), di-TMP (1 equiv) and *p*-TsOH (2 mol%) as the catalyst. After this, the solvent DCM, EtOAc or 2-MeTHF (50 mL) was added to the mixture, which was stirred and refluxed under argon atmosphere. A glass filter adapter was installed in between the condenser and reaction flask. Into this adapter a physical drying agent, $MgSO_4$, was put. After 65 to 90 h, depending on the used dicarbonyl, the formed polymer was precipitated in ice cold of Et_3N:MeOH (2:5). Then, the precipitate was filtered, washed and dried overnight at 40 °C under reduced pressure.

Protocol B. A flask was charged with the dicarbonyl (1 equiv), di-TMP (1 equiv) and *p*-TsOH (2 mol%) as the catalyst. After this toluene (100 mL) was added as a solvent to the mixture which was stirred and refluxed under argon atmosphere in a Dean-Stark set-up. After 6 to 8 h, the formed polymer was precipitated ice cold Et_3N:MeOH (2:5). Then, the precipitate was filtered, washed and dried overnight at 40 °C under lowered pressure.

5.4.3 Methods

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analyses were performed using a Mettler Toledo instrument 1/700 under nitrogen atmosphere at a heating rate of 10 °C min^{-1} and a temperature gradient of 200 °C The STARe software of Mettler-Toledo was used to analyze the results.

DMA-SEC

Size Exclusion Chromatography (SEC) measurements were performed on a Waters instrument, with a Waters 2414 Refractive Index detector, equipped with 3 Polymer Standards Services GPC serial columns - one GRAM Analytical 30 Å, 10 µm and two GRAM Analytical 1000 Å, 10 µm - at 35 °C. PMMA standards (690 g mol^{-1} and 1 944 000 g mol^{-1}) were used for calibration and N,N-Dimethylacetamide (DMA) containing 0.42 g mL^{-1} LiBr was used as a solvent at a flow rate of 1 mL min^{-1} . Furthermore a Hitachi Column Oven L-7300, a Waters 600 controller and a Waters 610 Fluid Unit were used. The Molecular weight and dispersities were determined using Empower software.

HFIP-SEC

Size Exclusion Chromatography (SEC) measurements were performed using a Agilent HPLC and a 1260 refractive index detector. The used eluens was HFIP containing 20 mM sodium trifluoroacetate with a flow rate of 0.3 mL min^{-1}. Two PSS PFG 100 Å gel 5 µm mixed D columns connected in series with a similar precolumn (Agilent) were utilized at 35 °C. The instrument was calibrated using PMMA standards and Agilent Chemstation software was used to analyse the resulting chromatograms.

LC-MS

An Agilent Technologies 1100 series LC/MSD system equipped with a diode array detector (DAD) and a single quad MS was utilized to perform LC-MS analyses. Analytical Reversed Phase HPLC-analyses were performed using a Phenomenex Lunca C18 (2) column (5µm, 250 mm x 4.6 mm) and a solvent gradient (0-100% acetonitrile in water in 15 minutes). A UV-detector ($\lambda = 214$ nm) was used to detect the eluting compounds. The electrospray mass spectra recordings were made using a single quad MS detector (VL) with electrospray ionisation.

Nuclear Magnetic Resonance

Proton and carbon nuclear magnetic resonance (^{1}H and ^{13}C NMR) measurements were performed using a Bruker Avance 300 (300 MHz) and a Brucker Avance II 400 (400Mhz) instrument at room temperature. ADC/NMR Processor Academic Edition software of ACD/Labs, which is online available, was used to analyse the recorded spectra.

Online Attenuated total reflection Fourrier Transform InfraRed spectroscopy (ATR FT-IR)

Time-resolved online ATR FT-IR spectra were recorded on a React-IR 4000 Instrument (Mettler Toledo AutoChem ReactIR) equipped with a silicon ATR probe (SiComp, optical range 4400–650 cm-1). For online monitoring, the silicon probe was introduced into a two-necked glass flask containing the reaction mixture and spectra were recorded every minute. The solvent spectrum was recorded at the reaction temperature and subtracted to enhance the signal of the reaction species. Curve-fittings of FT-IR spectra were performed using Bruker OPUS software (version 4.2).

Press

The used materials were processed using a mould, which was pressed together using a 7.5 ton Manual Rubberstamp Press.

Thermogravimetric Analysis (TGA)

Thermogravimetric Analyses were performed with a Mettler-Toledo TGA/SDTA 851e instrument. The measurements were performed under nitrogen atmosphere with a heating rate of 10 K min^{-1} from 25 °C to 800 °C on samples with sizes of 5-10 mg. Mettler-Toledo's STARe software was used to analyse the thermograms.

Tensile Testing

Tensile tests were performed on a Tinius-Olsen H10KT tensile tester, equipped with a 100N load cell. A flat dog bone type specimen with an effective gage length of 13 mm, a width of 2 mm and a thickness of 1.3 mm was used in the tests. A Ray-Ran dog bone cutter was utilized to cut out the samples. A speed of 10 mm min^{-1} was used to perform the tensile tests.

Group contribution calculation methods

Van Krevelen *et al.* [34] describe a theoretical method that allows for estimation of polymer properties by using empirical and semi-empirical methods. It can predict various thermodynamic and mechanical properties of both amorphous homopolymers and statistical copolymers (for molecular weight values fixed at 10^6 Da). The model uses connectivity indices as opposed to group contributions in its correlations, thus no database of group contributions is required, and properties may be predicted for most of the polymers.

Hydrolytic stability study

A hydrolytic stability study was performed by placing 0.1 g of polymer into test tubes, to which 10 mL of an aqueous solution of a specific pH was added. Parallel experiments were carried out with four polymer samples immersed in water (pH 7), sodium hydroxide solution (pH 10) and hydrochloric acid solution (pH 3) at temperatures of 50 °C. The test tubes were sealed to avoid evaporation of the solutions. After one month, the samples were rinsed with water and dried. The degradation was followed by sample weighing and SEC measurements.

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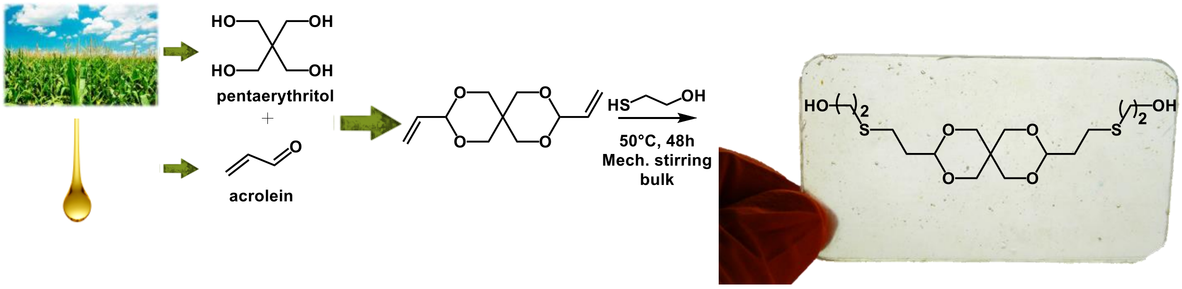


Graphical abstract in European Polymer Journal

(Volume 70, 232-239, 2015)

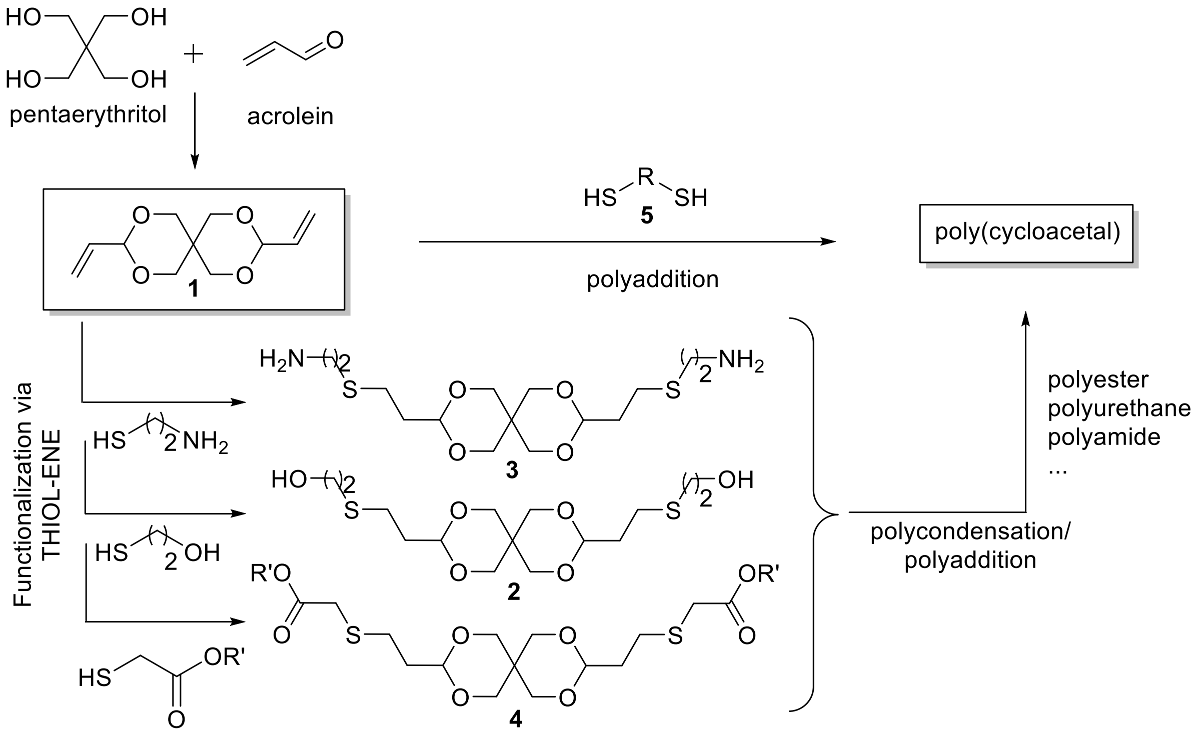
Abstract

Polyacetalization and polyketalization (Chapter 5) only resulted in a few high molecular weight polymers with limited biobased content. Moreover, the thermal and mechanical properties were not that satisfying. Di-TMP was the only tetraol that gave good results while pentaerythritol was rather hard to handle and gave rise to crystalline and low molecular weight polymers. Another way of making poly(cycloacetal/ketals) is by polymerizing bifunctional monomers which already contain cycloacetal/ketal moieties with a known and straightforward polymerization method. In this chapter, cyclic acetal-containing bifunctional monomers based on renewable pentaerythritol were synthesized. A diol, diamine and dithiol were synthesized *via* a straightforward thiol-ene reaction. The synthesis procedures were optimized and the monomers were up-scaled. Subsequently, the synthesized monomers were polymerized *via* a step-growth polymerization technique, which resulted in polyurethanes, polyamides and polythioethers. Eventually, a systematic characterization of the different polymers was performed.

Chapter 6: Step-growth polymerization of pentaerythritol-containing monomers

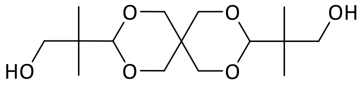
6.1 Introduction

A renewable diene containing two cyclic acetal moieties served as the start of the synthesis of several bifunctional monomers. 3,9-Divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (**1**) is made from pentaerythritol, which is a renewable tetraol, and acrolein, which can be prepared renewably from glycerol.[1-2] This diene allows for the creation of a whole platform of bifunctional compounds, which can then be used in different polymerization reactions (Scheme 6.1). In the end, poly(cycloacetals) with additional functionalities in the polymer backbone such as ester, urethane, thioether and amide bonds can be synthesized and the properties can be investigated systematically.



Scheme 6.1. Overview of the possible pentaerythritol based poly(cycloacetals). 3,9-Divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (1) is made from pentaerythritol and acrolein, after which this dialkene could be modified with thiol-ene to a dithiol, diamine, diol or diester. These monomers are then polymerized in a polycondensation/polyaddition reaction.

A similar monomer to the ones we wanted to synthesize was already described and is referred to as spiroglycol (Scheme 6.2).[3] It is prepared *via* the aldol condensation of pentaerythritol and hydroxypivaldehyde. Spiroglycol is already industrially used by Mitsubishi in the polyester synthesis and results in a polymer with better physical properties than PET.[4] The higher T_g and better transparency were caused by the introduction of the spirocenter and cyclic acetal units in the polymer backbone. From this example, we know that polymers with cycloacetals in the backbone can result in high T_g, high performance and transparent polymers.



Spiroglycol

Scheme 6.2. Chemical structure of spiroglycol.

The diene (**1**) can be easily transformed into a diol, dithiol, diamine or diester *via* thiol-ene chemistry.[5-8] First, the thiol-ene mechanism was investigated to determine the radical or nucleophilic character of the reaction.[7] In a next step, four different monomers could be synthesized. Efforts were also put in the optimization and upscaling of those reactions. Eventually, the different monomers could be used in various polymerization reactions and the properties of the obtained polymers were investigated systematically.

6.2 Synthesis of pentaerythritol based bifunctional monomers

6.2.1 Reaction mechanism

First, we wanted to determine if the thiol-ene reaction with the diene (**1**) would follow a nucleophilic or a radical mechanism. Usually, if the double bond is electron-poor, the mechanism will be nucleophilic, while a radical thiol-ene occurs if the double bond is electron-rich.[7] For the radical reaction, heat or UV light and an initiator are necessary to introduce radicals, whereas the nucleophilic reaction requires a catalyst (tertiary amine) to proceed.[7]

Two test reactions with mercaptoethanol were performed on the available diene in order to establish the mechanism and the reaction conditions. To test a possible radical reaction, the diene and mercaptoethanol were dissolved in THF, and DMPA was added as initiator. Alternatively, the reaction was also attempted in DCM for 24 h with trimethylamine as the catalyst to test a possible nucleophilic mechanism. Figure 6.1 (a) presents the LC-MS spectrum of the products obtained from the "nucleophilic reaction" in DCM and (b) the one from the "radical reaction" in THF. The products were not purified, but in the presence of radicals (Figure 6.1 (b)), a clear signal at 4.4 minutes showed the mass of the desired product, attesting the occurrence of the thiol-ene reaction. This signal was totally absent in the other case (Figure 6.1 (a)). Moreover, a large signal corresponding to the diene (starting compound) was still present in the presence of trimethylamine. From LC-MS measurements, it could thus be concluded that the thiol-ene reaction of mercaptoethanol with (**1**) proceeds *via* the radical mechanism.

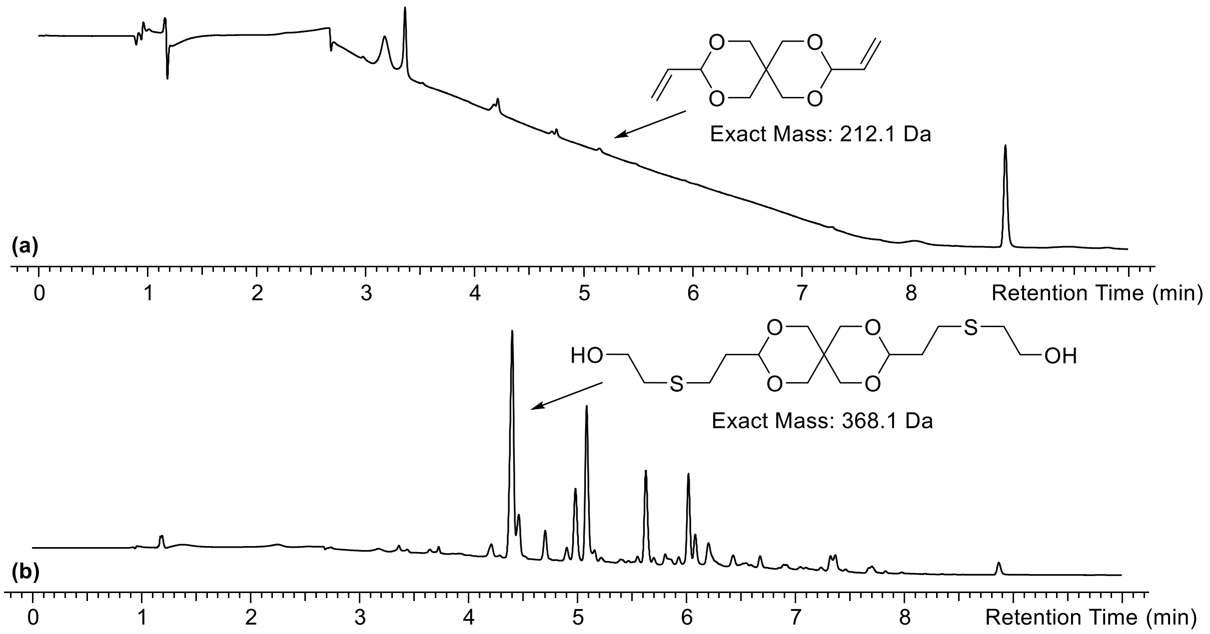
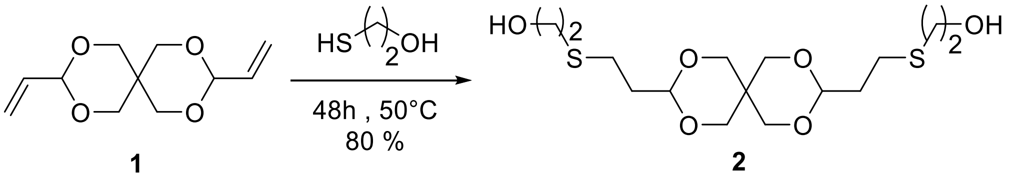


Figure 6.1. LC-MS spectrum of the crude nucleophilic reaction mixture (a) and radical reaction mixture (b) after thiol-ene reaction.

6.2.2 Synthesis of a diol

3,9-Divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (**1**) was first transformed into a novel, partially biobased spiroacetal diol (**2**). As just described in the previous paragraph, thiol-ene chemistry with 2-mercaptoethanol was used to turn (**1**) into a dihydroxyl-functionalized compound (**2**) (Scheme 6.3).[5] A short alcohol-containing thiol (two carbon atoms) was selected to ensure enough rigidity of the corresponding polymers later on.



Scheme 6.3. Synthesis of the partially biobased spiroacetal diol (2), starting from 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (1) and 2-mercaptoethanol.

As the reaction was proven to follow a radical mechanism, the initial attempts to prepare (**2**) were thus conducted photochemically with 2,2-dimethoxy-2-phenylacetophenone (DMPA) as photoinitiator. The photochemical reaction stopped after one hour but yields were limited to 30 % and the column chromatography, necessary to remove the residual initiator fragment adducts, made the upscaling of this synthesis too challenging. In order to improve the procedure, the thiol-ene reaction was tested without the use of an initiator, as already reported elsewhere.[7] Although the reaction took longer (48 hours at 55 °C; above melting point of both compounds), a highly pure product was obtained with an isolated yield of 80%, without need for column chromatography, typically on a 30 g scale**.** LC-MS analysis of the purified product revealed its high purity, which is critical for the subsequent polycondensation reactions (Figure 6.2).

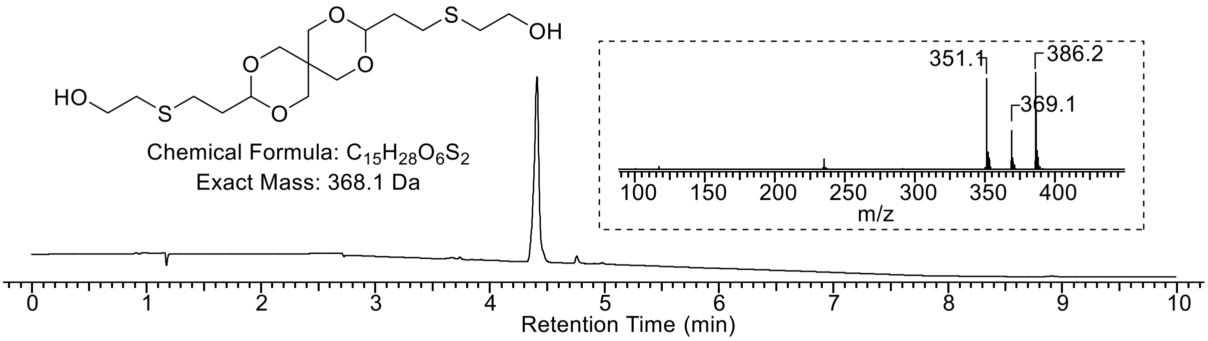


Figure 6.2. HPLC trace with MS analysis (insert, positive mode) of the purified diol (2) including M+1 (369.1 Da), M-H$_2$O (351.1 Da) and M+NH$_4^+$ (386.2 Da).

Furthermore, the chemical structure of the diol monomer (**2**) was evidenced by 2D-NMR-analysis (Figure 6.3).

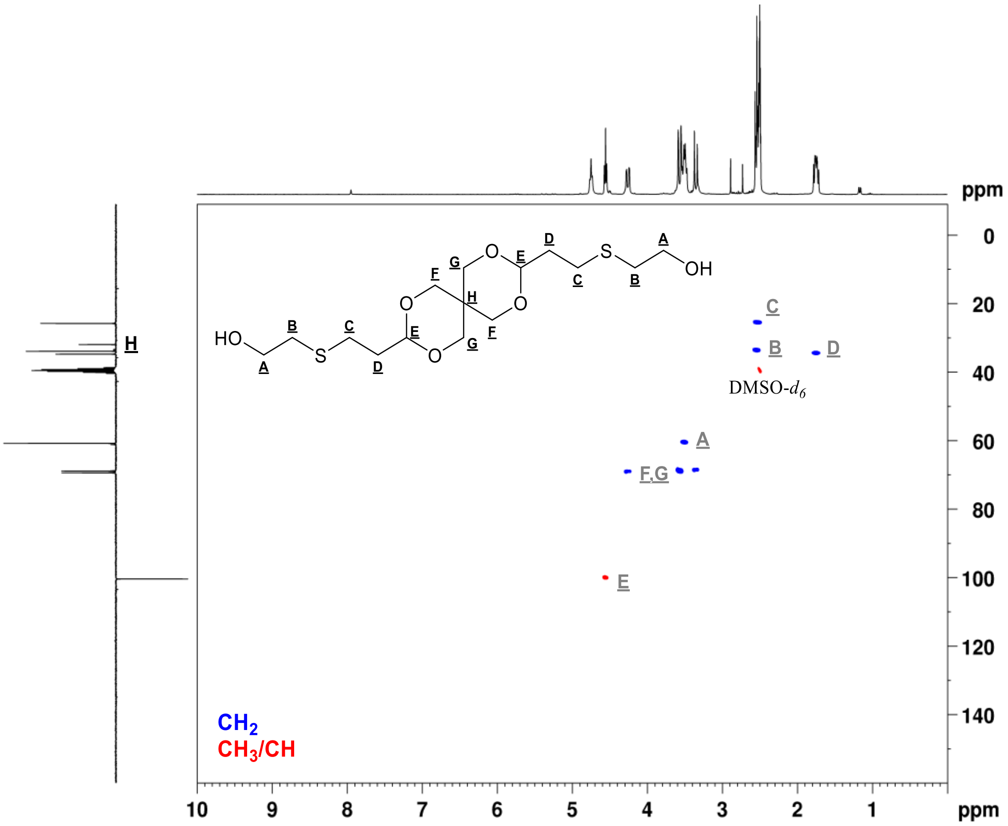
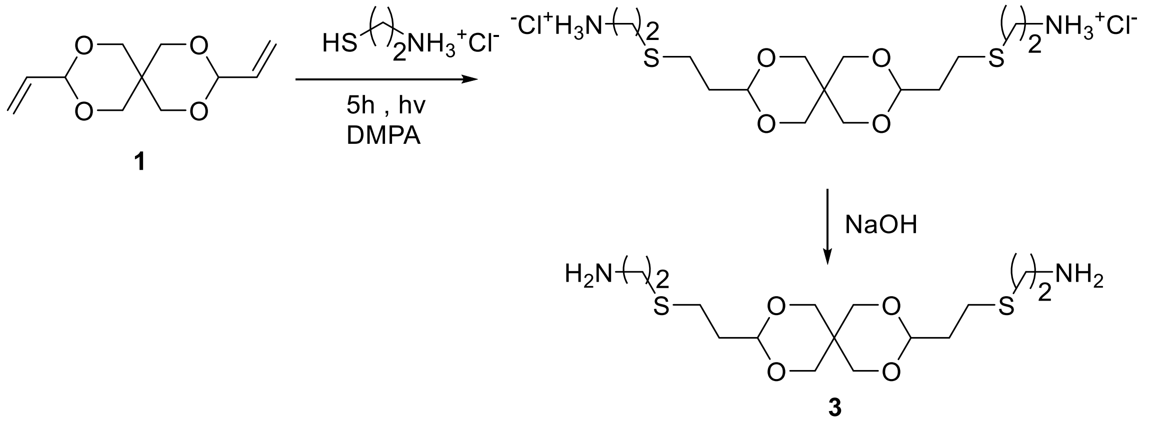


Figure 6.3. HSQC spectrum showing multiplicity editing (300 MHz, DMSO-d$_6$) of the purified diol (2) and peak assignment.

The anti-Markovnikov product was absent in the isolated diol, as methyl signals are not present in the HSQC spectrum.

6.2.3 Synthesis of a diamine

A new diamine monomer, similar to the diol one, was also synthesized *via* thiol-ene chemistry.[5] 3,9-Divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (**1**) was reacted photochemically with cysteamine hydrochloride and DMPA as initiator (Scheme 6.4). It was necessary to first make the protonated diamine in order to avoid side reactions (formation of disulfides). The synthesis was straightforward and the product could easily be purified by filtration.



Scheme 6.4. Synthesis of the partially biobased spiroacetal diamine (3), starting from 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (1) and cysteamine hydrochloride followed by a deprotection with NaOH.

As seen from Figure 6.4, all the signals of the protonated diamine could be assigned and no double bond or thiol signals are present anymore. The purity of the product was confirmed by LC-MS measurements (M-2HCl = 369 Da). To obtain the diamine (**3**), a basic step is needed. An extraction with NaOH was thus performed before polymerization could take place.

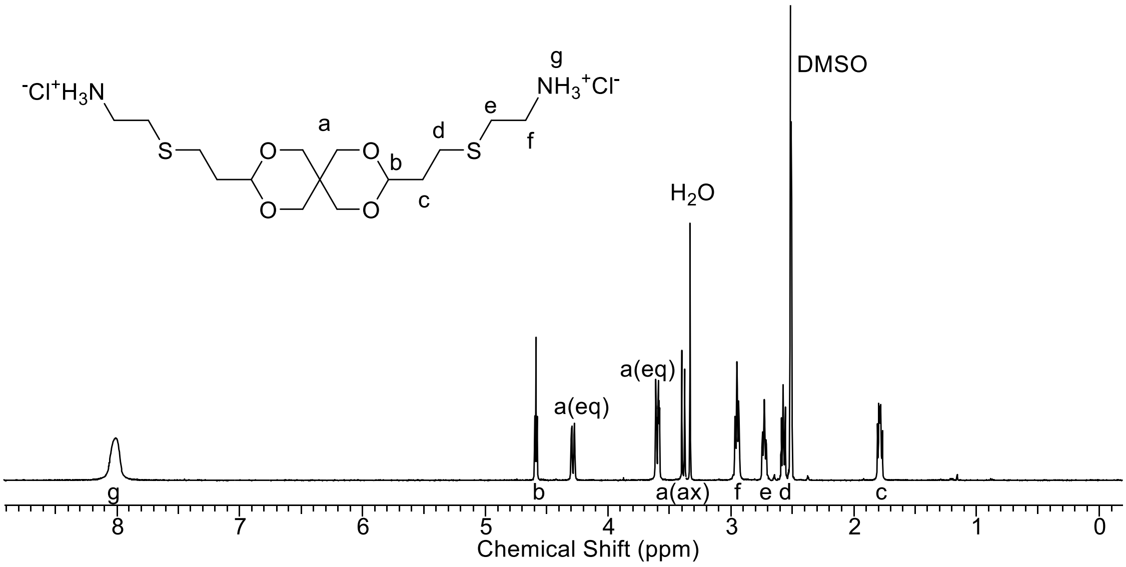
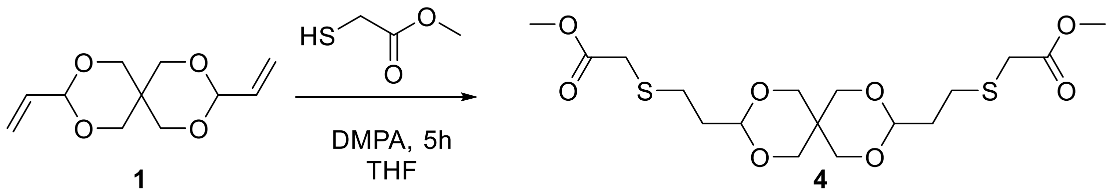


Figure 6.4. ^{1}H-NMR spectrum showing the peak assignment of the purified protected diamine (300 MHz, DMSO-d$_6$).

6.2.4 Synthesis of a diester

Parallel to the synthesis of the diol and the diamine, a diester could be synthesized from 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane and methyl thioglycolate. The photochemical reaction with DMPA as initiator was followed with TLC and was completed after approximately 5 h.

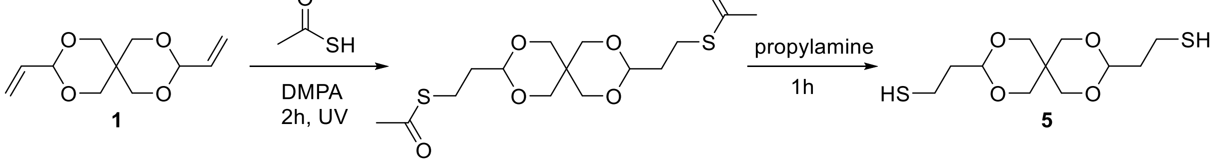


Scheme 6.5. Synthesis of the partially biobased spiroacetal diester (4), starting from 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (1) and methyl thioglycolate.

Unfortunately, the purification of the diester appeared rather challenging. After column chromatography, even when applying a gradient, impurities could still be found in the product. In an attempt to avoid impurities, a thermal reaction without initiator was also tested. The reaction of (**1**) with methyl thioglycolate showed to be much slower than the reaction with mercaptoethanol. Even after five days, full conversion was not achieved, which is ascribed to ester groups that make the thiol less reactive. At the time that these difficulties were noticed, polyurethanes and polyamides were already produced and analyzed based on the synthesized diol and diamine. Therefore, it was decided not to continue with the synthesis of diesters and thus polyesters.

6.2.5 Synthesis of a dithiol

Finally, we aimed for the synthesis of dithiols from a diene by addition of hydrogen sulfide to the diene. In view of the difficulties associated with the handling of hydrogen sulfide (smell), an indirect method was preferred.[9] The method of choice is the addition of thioacetic acid to the alkene, followed by aminolysis of the resulting thioacetate into the corresponding thiol (Scheme 6.6).[9-13] In the first step, the double bond of the diene is reacted with thioacetic acid under UV irradiation and with DMPA as initiator. In the second step, the deprotection of the thiol can be achieved by adding an amine to the dithioacetate. It was decided to only invest time in the purification of the dithiol, so no purification of the dithioacetate was performed.



Scheme 6.6. Synthesis of a dithiol from the diene (1).

After the deprotection with the amine, the reaction needs to be quenched with acid in order to obtain the thiol. Here, as acetals are present and are sensitive to hydrolysis in acidic conditions, it was decided to do the quenching with a mild acid, acetic acid, until the pH of the reaction medium was 5-6. With this mild treatment, opening of the acetals could be avoided. In order to purify the obtained dithiol (**5**), an extraction and column chromatography (hexane (60): ethyl acetate (20)) were performed. As confirmed by ^{1}H-NMR (Figure 6.5), a pure dithiol could be obtained with this described method.

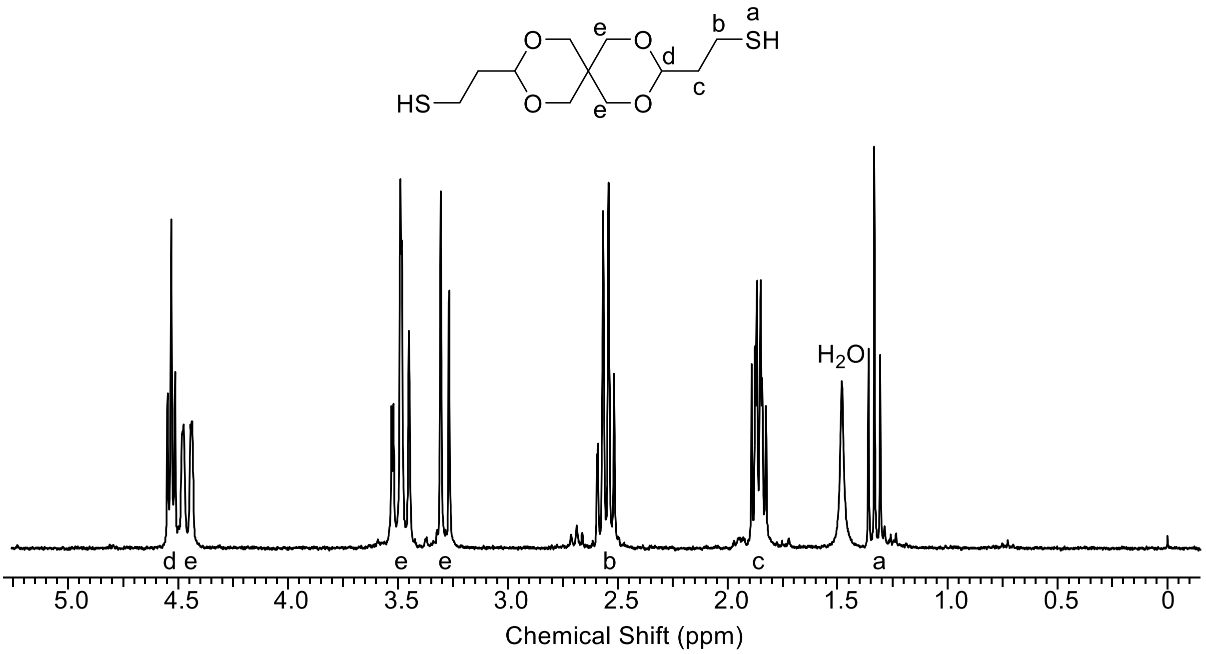


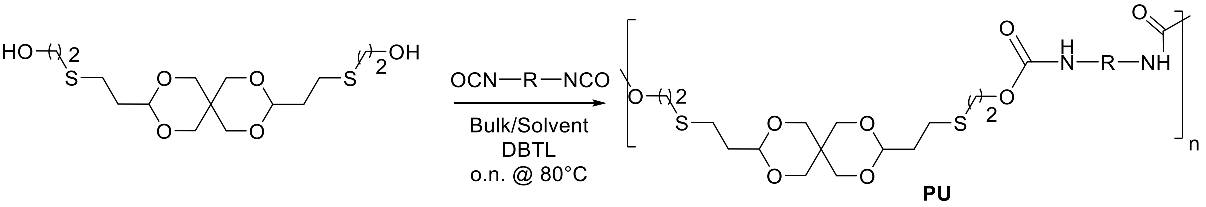
Figure 6.5. ^{1}H-NMR of the dithiol (5) synthesized from (1) (300 MHz, $CHCl_3$-d).

6.3 Polyurethanes

Polyurethanes, which constitute a large family of high-performance materials, show a wide variety of properties that are tunable by a proper control of the molecular design.[14] While polyurethanes generally decompose around 200° C, this degradation temperature can be elevated when rigid units are incorporated.[15] For example, spirocyclic units can be introduced in the main chain, which results in polymers that are more rigid and therefore have improved thermal and mechanical properties.[16-22] More specifically, polymers with unique chemical and physical properties could be synthesized by incorporation of spiroacetal units into polyurethanes, providing a new spectrum of properties.[23-24] It was shown that poor solubility and processability of the pure spiropolymers can be improved by introducing urethane groups in the polymer chain, whereas the rigidity of the polyurethanes can be enhanced by incorporating spirocyclic units. Furthermore, additional desired properties, such as transparency, can be expected as amorphous regions are introduced. To date, a small number of patents have described the properties of polyurethanes containing rigid spiroacetal diols such as spiroglycol (Scheme 6.2).[25-27] They all focused on fitting the properties of the synthesized polymers to the right application such as sheet-form articles.[25] In these reports, no studies were devoted to the specific features of these polyurethane structures. In this section, the chemical and physical properties of thermoplastic polyurethanes containing spiroacetal functionalities, which are partially obtained from renewable raw materials, are investigated. The primary goal was to overcome the common problems associated with the known spiroglycol-containing polyurethanes, such as their bad solubility in common solvents, low molecular weight and limited processability.

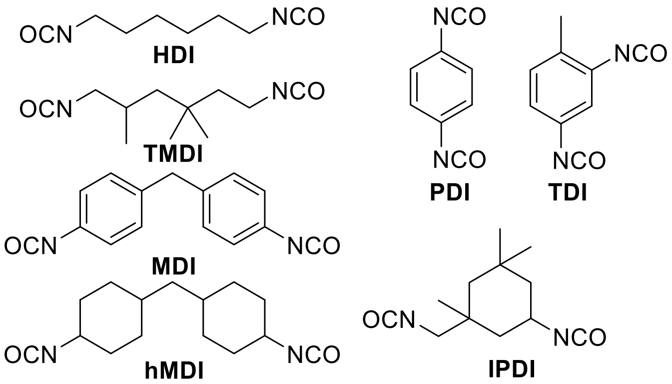
6.3.1 Synthesis and structure analysis

The spiroacetal diol was polymerized with different selected diisocyanates (Scheme 6.7) to obtain linear polyurethanes (**PU**), as shown in Scheme 6.7.



Scheme 6.7. Synthesis of polyurethanes from the synthesized spiroacetal diol (2) and a series of diisocyanates

The series of thermoplastic polyurethanes was designed with the aim to obtain polymeric structures with variable T_g, transparency and high thermal stability. Seven diisocyanates (Scheme 6.8) were used for that purpose; aliphatic linear diisocyanates (HDI and TMDI), cyclic aliphatic diisocyanates (IPDI, hMDI) and aromatic diisocyanates (PDI, TDI and MDI).



Scheme 6.8. Selected diisocyanates for the synthesis of spiroacetal-containing PUs.

The polymerizations were tested in ethyl acetate (EtOAc) and in bulk, always starting from 5 g of diol monomer (**2**) and a stoichiometric amount of isocyanate. The synthesized polyurethanes are listed in Table 6.1. The ones prepared in bulk often have lower molecular weights (3-11 kDa), determined by SEC, as mechanical stirring stopped soon in the reaction process, limiting further build-up of the polymer chain. Even using EtOAc as solvent, higher molecular weights (8-45 kDa) could only be obtained by using a mechanical stirrer. While the aliphatic polyurethanes (Table 6.1, entries 1-4) were transparent and colorless substances, the aromatic analogues (entries 5-7) were yellowish, a common feature when using aromatic diisocyanates.[28]

Table 6.1. Molar masses and dispersities (determined by SEC in DMA, with LiBr and PMMA standards) as well as thermal and mechanical properties of 7 synthesized polyurethanes. TGA measurements were performed under N_2 atmosphere and the T_d represents the temperature at 5% mass loss.

Entry	PU-X	M_n / Đ (kDa)	T_d (°C) TGA	T_g (°C) DSC	T_g (°C) DMTA	G' (GPa) DMTA	E (GPa) Tensile	Yield strength (MPa)	Tensile strength (MPa)	Strain@ Break (%)
1	PU-HDI	42.7/ 4.0	280	26	24	0.2	0.1	7.0	29.7	519
2	PU-TMDI	15.8/ 2.4	300	31	34	0.1	0.2	9.8	9.8	1590
3	PU-IPDI	21.5/ 2.4	270	76	89	1.6	1.8	51.0	51.0	15
4	PU-hMDI	45.0/ 3.5 [a]	300	85	/	/	/	/	/[c]	/[c]
5	PU-PDI	8.0/ 2.1	260	75[b]	84	0.2	/[d]	/[d]	/[d]	/[d]
6	PU-TDI	16.0/ 3.5	280	78	77	0.2	1.3	22.5	22.5	5
7	PU-MDI	27.0/ 3.0	285	85	84	1.4	1.4	36.2	40.8	117

[a] PU-hMDI was synthesized in bulk, the others in EtOAc.
[b] PU-PDI was the only polymer showing a melting temperature (T_m =166 °C).
[c] PU-hMDI could not be processed in a reproducible way.
[d] PU-PDI was too brittle to be processed and mechanically be tested.

2D-NMR-analysis of the obtained polyurethanes confirmed the anticipated backbone structure. All signals could be assigned properly, as exemplified in the HSQC spectrum (Figure 6.6) of the MDI-derived PU (Table 6.1Table 6.1, entry 7). As expected, broadening of the signals in the ^{1}H-NMR spectrum was observed after the polymerization. The hydrogens, originally next to the hydroxyl function in (**2**), shifted downfield (3.5 to 4.18 ppm), indicating the formation of a urethane bond.

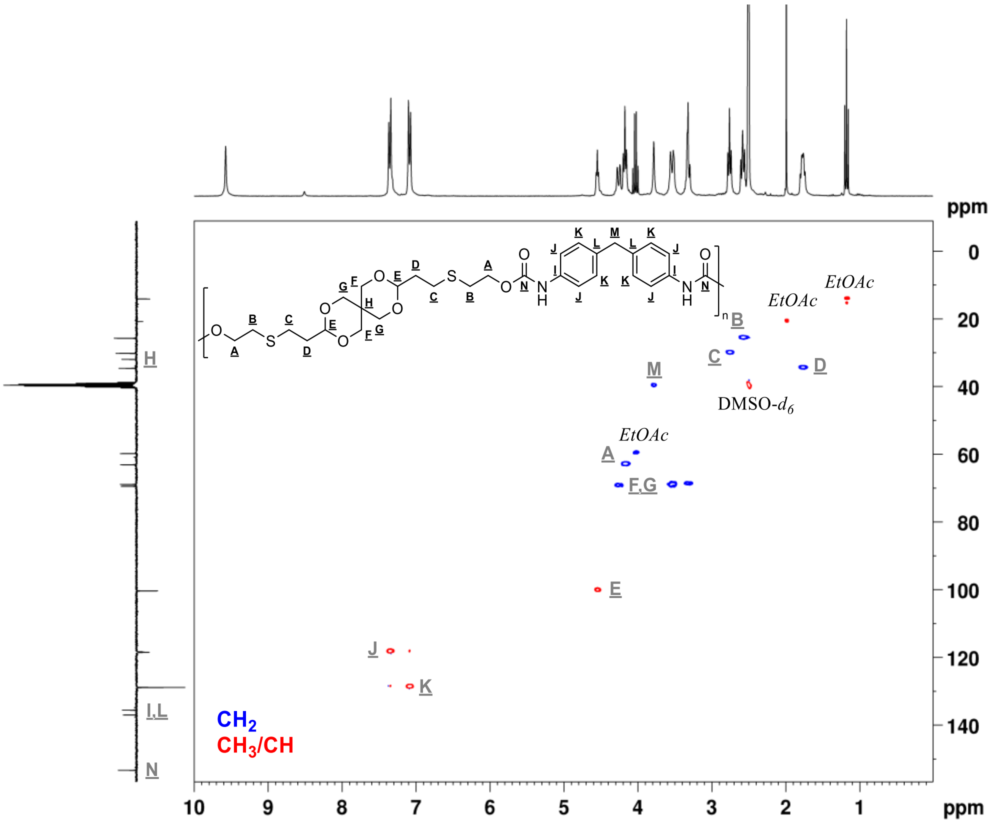


Figure 6.6. HSQC spectrum showing multiplicity editing (300 MHz, DMSO-d_6) of the MDI-derived PU (Table 6.1, entry 7) and peak assignment.

We wanted to compare the synthesis and properties of our new (**2**)-based series of polyurethanes to the ones reported with spiroglycol. As no molecular weights and thermal or mechanical properties were presented in the literature on this subject, we synthesized the corresponding spiroglycol-based polymers ourselves. The same reaction conditions were applied (Scheme 6.7), using spiroglycol in combination with the same seven different isocyanates. Unfortunately, the polymers precipitated early from the reaction mixture, so the solvent had to be replaced by a higher boiling solvent. Even then, only low molecular weight polymers could be obtained (M_n < 10 kDa) which were only soluble in HFIP. Those polymers were then analyzed by DSC measurements.

6.3.2 Thermal and mechanical properties

For the newly obtained, mostly amorphous, (**2**)-based thermoplastic polyurethanes, thermal and mechanical properties were thoroughly investigated (Table 6.1).

The thermal properties were determined by TGA, DSC and DMTA measurements. The polymers were thermally stable up to at least 260 °C, which is significantly higher than standard TPUs. Glass transition temperatures, derived from DSC (Figure 6.7) and DMTA analysis, varied from 25 to 85 °C, the latter obtained for polyurethanes synthesized from the rigid MDI or hMDI.

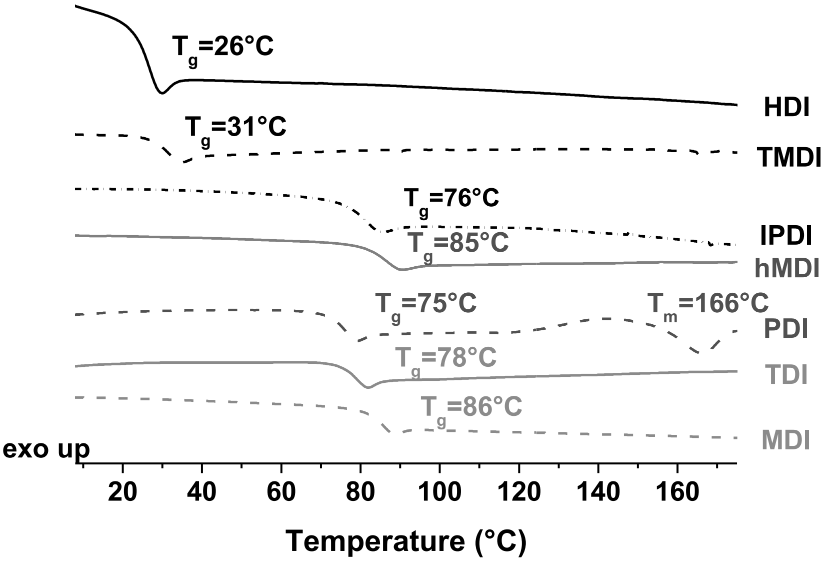


Figure 6.7. DSC analysis of the obtained PUs (second heating), revealing trends in T_g.

On Figure 6.8, the evolution of the polyurethane's T_g as a function of the chosen diisocyanate is plotted for the two series of TPUs (made from (**2**) or spiroglycol). As already mentioned in the previous section, the synthesis of the spiroglycol-based polyurethanes was hampered because of solubility problems when using the commercial diol. For example, the polymerization with MDI and PDI did not result in any polymers, explaining the lack of data.

T_g values of both the spiroglycol- and (**2**)-based polyurethanes were also estimated *via* group contribution calculation methods (by making use of a non-commercial software program), [29] which can predict properties of polymers for high molar masses.[30-31] In Figure 6.8**,** a clear trend in T_g values can be identified with increasing rigid structure of the PU. In general, the T_g values of PUs based on diol (**2**) are about 40-50 °C lower than the ones based on spiroglycol. On the other hand, for most synthesized TPUs, T_g values of around 80 °C can be observed, which is rather high compared to commercial TPUs. The T_g values were confirmed by DMTA measurements in shear (Table 6.1).

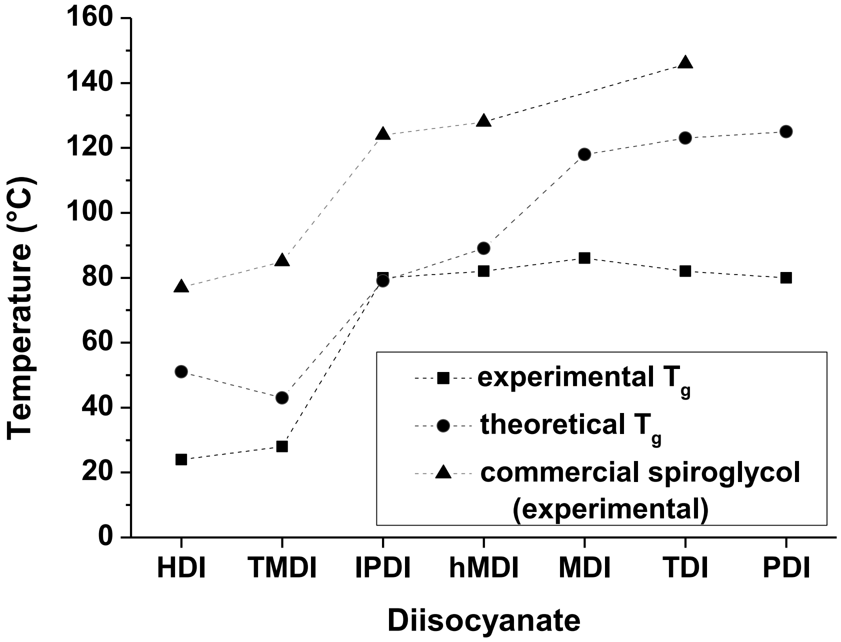


Figure 6.8. T_g values (DSC) of the PUs with (2) as diol, in comparison to the calculated T_g values (group contribution calculations). The T_g of the PUs based on commercial spiroglycol are indicated with triangles (dotted lines are a guide to the eye).

DMTA and tensile tests on compression-moulded samples were performed to assess the mechanical properties of the (**2**)-based materials. The (storage) modulus, tensile strengths and strain at break are presented in Table 6.1. The synthesized polymers show moduli comparable to known polyurethane elastomers,[32] with higher moduli, yield strength and tensile strength for the more rigid polyurethanes. Moreover, all materials showed a large ductile area, except PU-IPDI and PU-TDI that broke directly after the yield point.

6.3.3 Hydrolytic stability and renewability

In order to investigate the hydrolytic stability of the acetal containing polyurethanes, they were subjected to degradation tests. In this context, processed samples were immersed for two weeks in an aqueous solution of a specific pH at 50 °C.[33] A pH of 1, 3, 5 and 7 was tested for one aliphatic polyurethane (PU-IPDI, Table 6.1, entry 3) and one aromatic polyurethane (PU-MDI, entry 7). After the experiments, the samples were weighed and molar masses were measured by SEC to investigate whether degradation had occurred. In all cases, thus also for the experiments at low pH, no significant weight loss was observed after two weeks and more than 98% of the weight was retrieved. SEC measurements were performed to check for an eventual decrease in the molecular weight of the polymers as a result of degradation. No significant decrease in molecular weight was observed (Table 6.2), leading to the conclusion that the tested polymers remain hydrolytically stable for at least two weeks in the given conditions. It is assumed that the hydrophobicity of the polymers excludes the interaction between water and the inherently labile acetal moieties, which contributes to the stability of the material.[17]

Table 6.2. Hydrolytic degradation test: SEC data (DMA with LiBr and PMMA standards) for an aliphatic (entry 3) and an aromatic (entry 7) PU before and after treatment in aqueous solution at different pH values.

pH	**PU-MDI** **M_n / Đ (kDa)**		**PU-IPDI** **M_n / Đ (kDa)**	
	Before	*After*	*Before*	*After*
1	35.0/2.3	35.0/2.1	29.0/2.3	27.0/2.3
3	35.0/2.3	35.0/2.1	29.0/2.3	28.0/2.0
5	35.0/2.3	35.0/2.2	29.0/2.3	29.0/1.8
7	35.0/2.3	35.0/2.3	29.0/2.3	29.0/1.9

To get an idea of the renewability of the polyurethanes, the biobased carbon content was calculated taken into account that the diene can be produced from renewables. Depending on the diisocyanate, values of 36-47% biobased carbon content were obtained. These values are reasonably high compared to what is currently available.[34] On the other hand, at the moment the diene is not yet produced industrially from renewable resources.

6.4 Polyamides

Only few articles reported the synthesis of spiro-containing polyamides (PA) and when synthesized, it was mostly done from pentaerythritol-containing benzylic diamines and terephthaloyl chloride or similar aromatic derivatives *via* interfacial polymerization.[35-38] Even though interfacial polycondensation very often proves to be an efficient approach, it is not applicable for large scale synthesis and the more challenging high temperature melt polycondensation is therefore preferable. To our knowledge, only one aliphatic polyamide containing spirocenters was reported up till now.[24] A diester was synthesized from pentaerythritol and methyl 9(10) formyl stearate. In a next step, this diester was combined with diamines and diols in a polycondensation reaction, which resulted in polyamides and polyesters. The long alkane side chains (C_8-C_9) reduced the crystallinity to such a degree that the polymers were soluble in ordinary solvents like chloroform and tetrahydrofuran. Moderate molecular weights (< 12 kDa) but broad dispersities (3.9-15.5) were reported.[24] Due to the introduction of long flexible alkyl groups in the polymer chain, only low T_g values (-10 °C) could be realized. From these results and the limited number of articles on spiro-containing polyamides, one can conclude that it is challenging to obtain spiro-containing polyamides that are both soluble in ordinary solvents and exhibit good thermal properties like high T_g and T_d values. A cooperation was started with Maastricht University as they are specialized in the field of (acetal containing) polyamides.

6.4.1 Synthesis and structure analysis

The deprotected diamine (**3**) has been used for the synthesis of polyamides (PA). In Figure 6.9, a series of polymers based on the synthesized diamine and different (renewable or potentially renewable) diacids is presented. Four aliphatic diacids with varying alkyl chain length (C4-C6-C8-C10) and two aromatic diacids, terephtalic acid (TA) and isophtalic acid (IA), were used in the polymerization reactions. In part (b) of Figure 6.9, an overview of the two different polymerization routes is presented. The diamine can either be reacted with diesters (ester polymerization method), or first be transformed into a salt with a dicarboxylic acid and subsequently be polymerized in that form (salt polymerization).

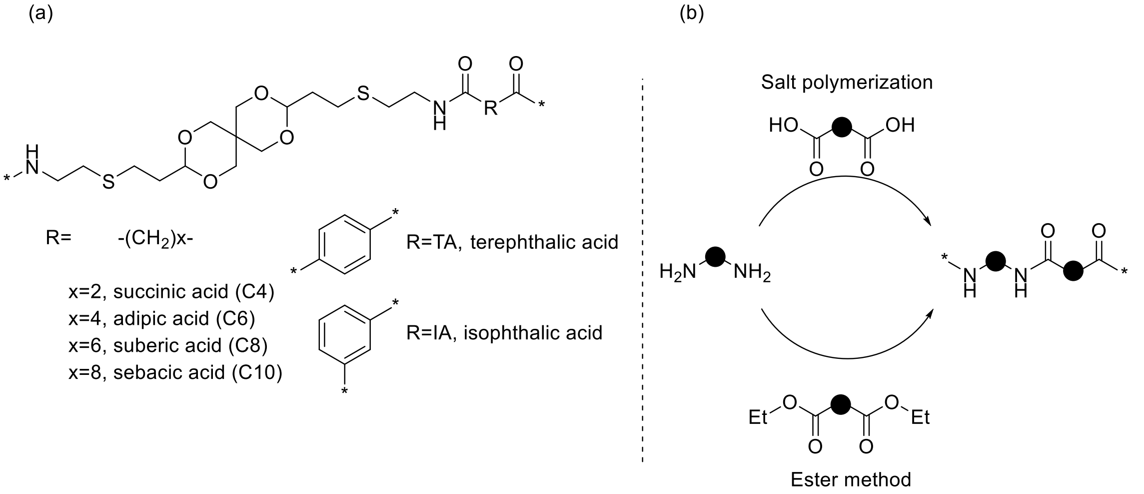


Figure 6.9. Overview of the general structure of the synthesized polymers (a) and the two different methods to obtain polyamides (b). x – number of methylene units in the aliphatic chain.

First, the aminolysis of diethyl adipate by the spirodiamine (**3**) was tested in the melt, at 220 °C. The application of this ester polymerization method resulted in an oligomer with a molecular weight of 1.3 kDa and a broad dispersity of 3.8 (Table 6.3). From literature, it is known that it is challenging to obtain high molecular weight polyamides with the ester-amide bond exchange method due to the alkylation of amine groups in the monomer by the present alkyl ester.[39] The ethylation of the diamine is a significant chain stopping mechanism (limiting high molecular weights) as secondary amines are more sterically hindered and exhibit lower reactivity than primary amines.

Table 6.3. Composition, molecular weights and thermal properties of polyamides

Method[a]	Diacid[b]	M_n (kDa)[c]	Đ	$T_{10\%}$ (°C)[d]	T_{max} (°C)[d]	m.r. salt (°C)[e]
Ester method	C6	1.3	3.8	345	360	-
Salt polymerization	C4	2.5	2.0	295	350	172-175
	C6	20.0	2.4	350	375	156-162
	C8	13.5	2.3	335	360	155-158
	C10	19.0	2.9	350	365	148-149
	TA	2.6	5.9	-	-	252-253
	IA	6.0	5.4	345	365	199-201

(a) The ester method refers to melt polycondensation of a diethylester and a diamine, salt polymerization refers to polymerization of amide salts.
(b) C4 – succinic acid unit, C6 – adipic acid unit, C8- suberic acid unit, C10 – sebacic acid unit, TA – terephthalic acid unit, IA – isophthalic acid unit.
(c) Molecular weight of polyamides determined by SEC in HFIP with RI detection.
(d) $T_{10\%}$ - temperature corresponding to 10% weight loss in TGA [°C], T_{max} – temperature corresponding to maximum peak of weight loss [°C] in first derivative curve of TGA.
(e) Melting range of the corresponding amide salts.

The structure of the obtained oligomers (from spirodiamine (**3**) and diethyl adipate by the ester polymerization method) was determined by Maldi-*ToF* (Figure 6.10 (a)). The analysis of the collected spectrum revealed the presence of three main distributions and side products formed during the melt polycondensation. The repeating unit is 476.2 g.mol^{-1}, which corresponds to the diamine-adipic acid unit. The main distribution α on the spectrum corresponds to the desired linear chains with both ester and amine end groups. Besides this, the presence of linear chains, which are terminated by the adipic ethyl ester unit are present as distribution β. Interestingly, the distribution γ on the presented graph corresponds to the linear chains terminated with adipate on one side and ethylated diamine on the other. This observation confirms that one of the limiting factors in the ester polymerization method is indeed the ethylation of amines.

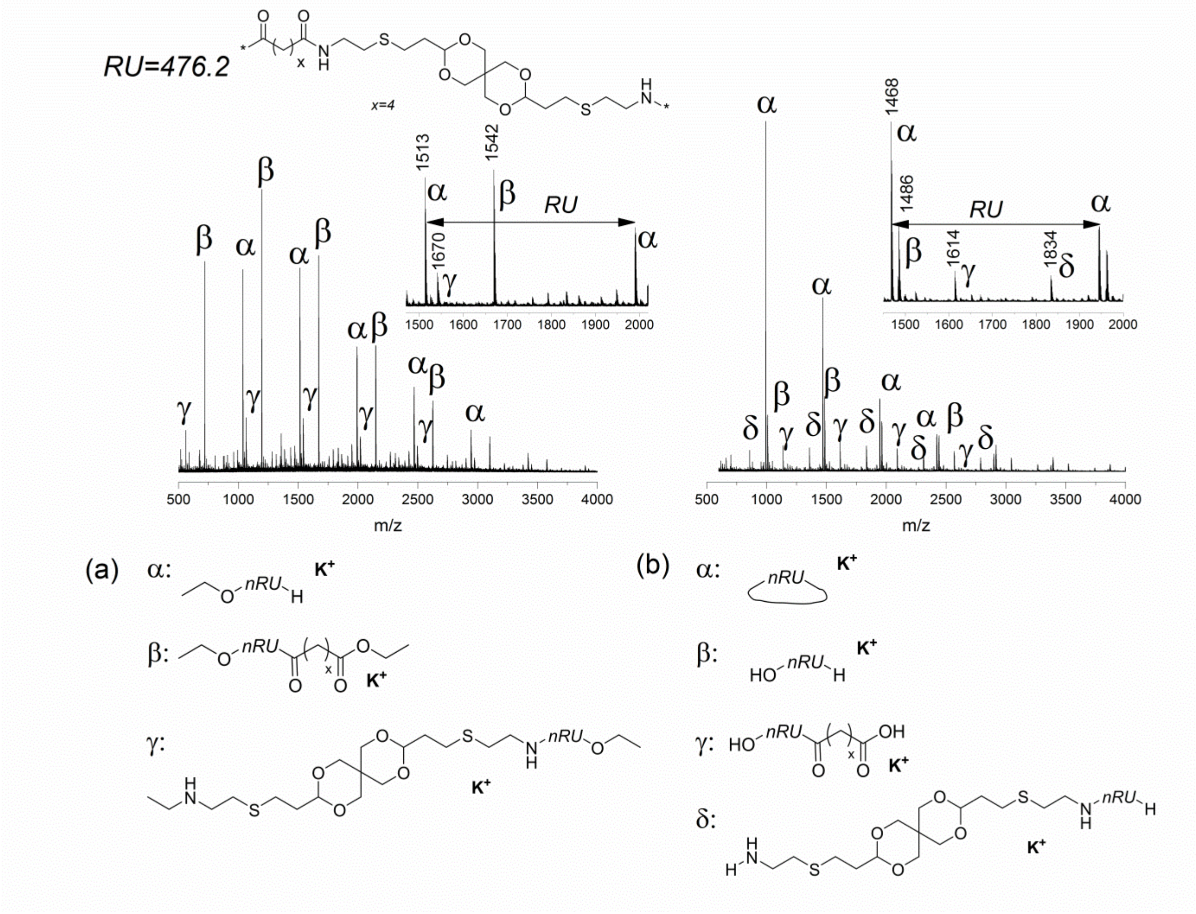


Figure 6.10. Maldi-*ToF* results for PA composed of the spirodiamine (3) and adipic acid units: (a) PA obtained *via* aminolysis of diethyl adipate (SEC: M_n=1.3 kDa, Đ=3.8), (b) PA obtained *via* salt polymerization (SEC: M_n=14.5 kDa , Đ=2.4) recorded in reflectron mode with dithranol as a matrix and KTFA as a salt.

Because the melt polymerization of the diamine with diethyl adipate only resulted in oligomers, the same polyamides were then prepared by melt polycondensation of the corresponding amide salts (salt polymerization). The polymerization can be conducted at relatively low temperatures as the salts have quite low melting temperatures (salts of spirodiamine (**3**) and aliphatic diacids melt between 140 and 180 °C). With adipic acid (PA(C6) in Table 6.3), molecular weights up to 20 kDa could be reached.

To confirm the structure of the synthesized polyamide, the Maldi-*ToF* spectrum of the obtained PA(C6) was recorded (Figure 6.10 (b)). Due to the saturation of the detector, only a part of the chains is visible in the spectrum. The analysis revealed the presence of four main distributions. The distribution α corresponds to the formation of cyclic chains. Distributions β, γ and δ correspond to linear chains terminated by acid and amine end groups, with two acid end groups and two amine end groups, respectively.

Salt polymerization proved to be the most effective method for polyamide synthesis with (**3**). Indeed, this salt polymerization method allows to sustain equimolarity during the synthesis and gives PAs with higher molecular weights than the oligomers obtained by the ester method. It was thus decided to focus on the salt polymerization and to further vary the structure of the diacid in order to map some trends in thermal and mechanical properties of the synthesized PAs and to show the versatility of the method using the synthesized diamine.

Polyamides C6, C8 and C10 were successfully synthesized and reached molecular weights of 20.0 kDa, 13.5 kDa and 19.0 kDa, respectively (Table 6.3). The polymers obtained *via* salt condensation showed high thermal stability (Table 6.3). The polyamides synthesized with aromatic diacids had lower molecular weights, i.e. 2.6 kDa for terephthalic and 6.0 kDa for isophthalic acid, and higher dispersities. The polyamide of terephthalic acid and (**3**) degraded upon application of vacuum in the last stage of the synthesis. The synthesis temperature was higher for this polyamide compared to the other polymers (250 °C instead of 220 °C). This higher temperature contributed to the formation of side products and the degradation of monomers. Moreover, it is generally known that the polymerization with terephtalic acid is challenging due to its very limited solubility in the reaction medium.[39]

In contrast to the successfully synthesized polymers with the aliphatic acids C6, C8 and C10, the polyamide containing succinic acid (C4) has a low molecular weight (2.5 kDa, Table 6.3). The Maldi-*ToF* analysis of this polymer revealed that the succinic acid is end-capping the polymer by the formation of succinimide, a phenomenon already reported in the literature.[40-41] On the spectra presented in Figure 6.11 two distributions can be distinguished. The distribution α corresponds to the cyclic chains and distribution β to the polymer with NH_2 groups that are end-capped by succinic acid.

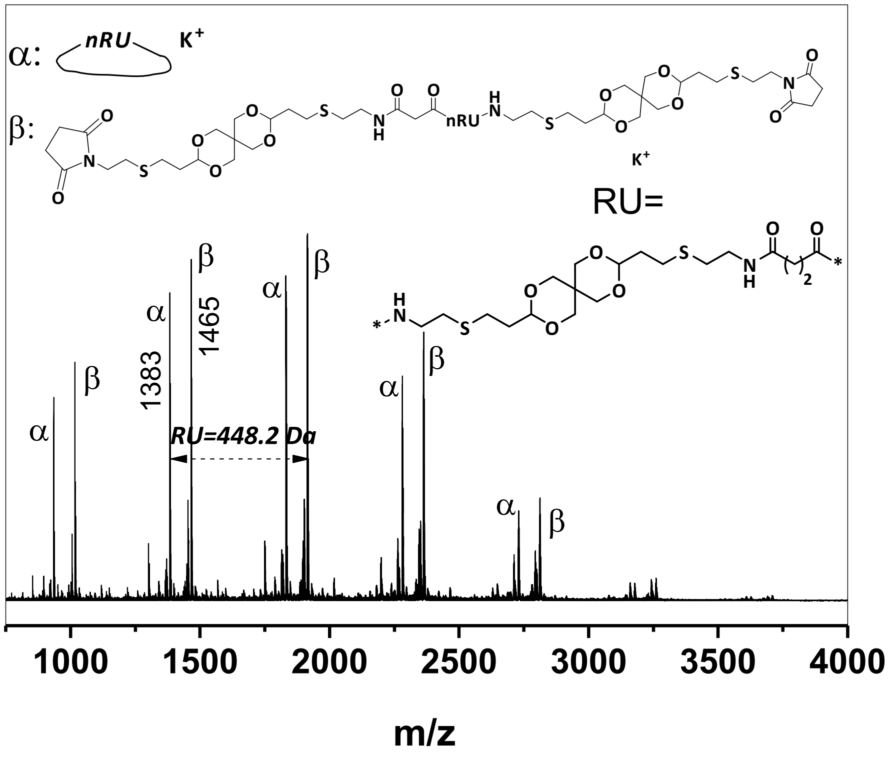


Figure 6.11. Maldi-*ToF* results for PA(C4) composed of the spirodiamine (3) and succinic acid (SEC: M_n=1.1 kDa, Đ=1.8) recorded in reflectron mode with dithranol as a matrix and KTFA as a salt.

FT-IR measurements of the PA(C4) confirmed that succinimide carbonyl groups are present in significant amount in the polymeric chains (Figure 6.12). The presence of amide protons in the FT-IR spectrum of PA(C4) at 3292 cm^{-1} (Figure 6.12, bottom) and PA(C6) at 3303 cm^{-1} (Figure 6.12, top) confirms that the polycondensation resulted in the formation of a polymeric material for both acids. For the low molecular weight PA(C4), in which more end groups should be present, a clear signal corresponding to the stretching vibration of –OH from the carboxylic acid is expected above 3000 cm^{-1}. However, this signal is not observed. Instead, a strong signal is present at 1703 cm^{-1}, corresponding to the stretching vibration of succinimide carbonyl groups, confirming the occurrence of this particular side reaction.

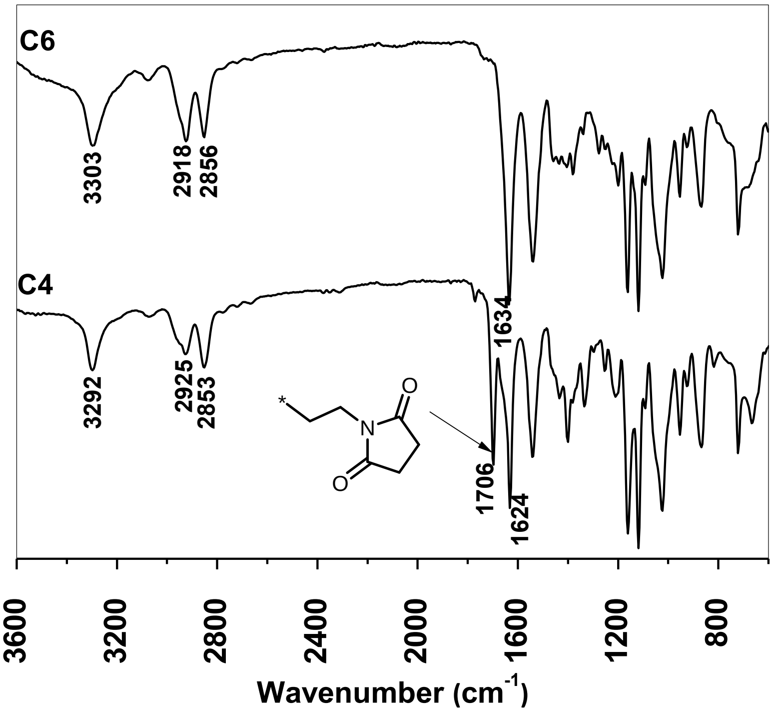


Figure 6.12. FT-IR spectrum of (top) poly(adipic acid-co-3,9-(2-ethylthio)ethanediamine-2,4,8,10-tetraoxaspiro[5.5]undecane), PA(C6) and (bottom) poly(succinic acid-co-3,9-(2-ethylthio)ethanediamine-2,4,8,10-tetraoxaspiro[5.5]undecane), PA(C4).

6.4.2 Solubility of the polyamides

A recurring problem of spiro-containing polyamides is their insolubility in common organic solvents. Therefore, the solubility of an aliphatic (PA(C10)) and aromatic polyamide (PA(IA)) was tested (Table 6.4). Both polyamides were soluble in N-methyl-2-pyrrolidone (NMP), HFIP, DMA with 5 g/L LiBr and a mixture of chloroform ($CHCl_3$) and phenol (PhOH). PA(IA), in contrast to PA(C10), is soluble in dimethylsulfoxide (DMSO). It is suspected that the lower molecular weight of PA(IA) in respect to PA(C10) as well as the amorphous character of this polyamide (Figure 6.13) contributes to the better solubility. Additionally, both polymers are unsoluble in ethanol, chloroform and tetrahydrofuran, which is often observed for polyamides.

Table 6.4. Solubility of two polyamides (PA(C10) and PA(IA)) obtained from melt condensation of the corresponding salts in different solvents/solvent mixtures.

Diacid	EtOH	$CHCl_3$	$CHCl_3$ + 25wt% PhOH	THF	DMSO	HFIP	NMP	DMA 5g/L LiBr
C10	-	-	+	-	-	+	+	+
IA	-	-	+	-	+	+	+	+

6.4.3 Thermal and mechanical analysis

Thermogravimetric analysis of this new series of polyamides showed good thermal stability ($T_{10\%}$ > 300 °C, Table 6.3). The thermal profiles of the polyamides obtained by DSC measurements showed that the aliphatic polyamides are semi-crystalline while the aromatic ones are amorphous (Figure 6.13). The long aliphatic chains can stack better than the aromatic units, which results in crystallinity. PA(C4), which was shown to be a low molecular weight polymer, end-capped with succinimide, has a T_g of 24 °C and a melting point of 125 °C, which is the lowest value among the synthesized aliphatic polyamides. These thermal analysis data is difficult to compare to the other polyamides as only low molecular weight polymers were obtained and they are end-capped with succinimide units. For polyamides with adipic acid (C6), suberic acid (C8) and sebacic acid (C10), the T_g and melting point decrease with an increase in the number of methylene units present in the aliphatic chain of the acid. The T_g values are between 36 °C and 48 °C and all melting points have values below 144 °C with rather low melting enthalpies. The amorphous aromatic polyamides only show a glass transition (T_g values around 83 °C).

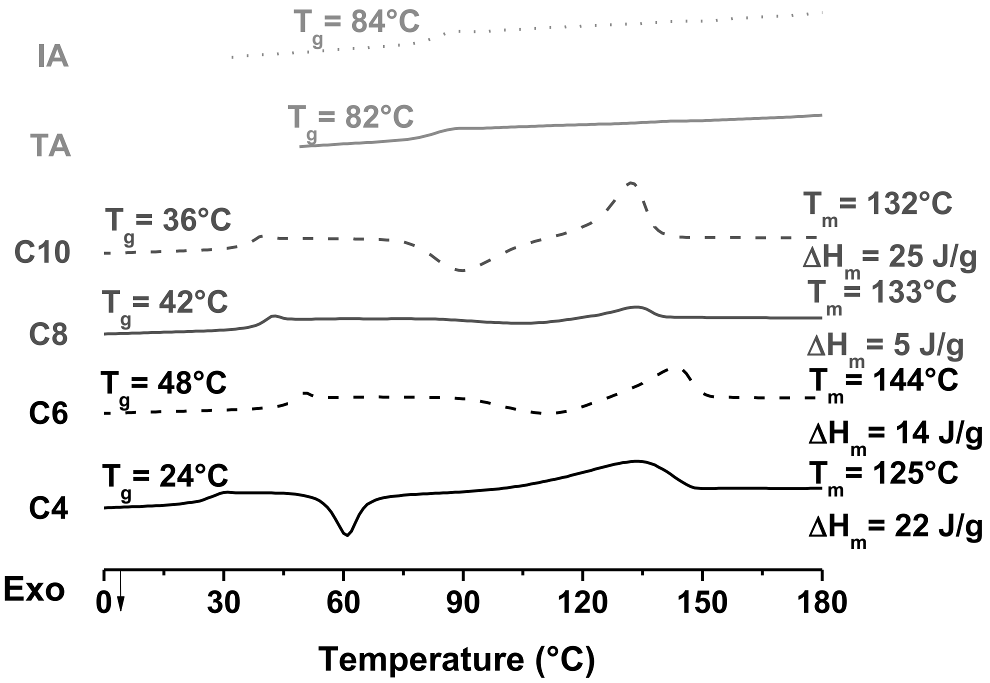


Figure 6.13. Melting profiles (DSC) of polyamides synthesized by melt polycondensation of the polyamide salts. The melting temperatures, the T_gs and the enthalpy values reported correspond to the second heating cycle.

Three of the synthesized polyamides, C6, C8 and C10, were processed *via* compression moulding and all three resulted, after fast cooling, in transparent yellowish materials. The low crystallinity of the synthesized polyamides and the fast cooling used here explain the transparency of the materials. Tensile measurements were performed on the moulded samples and the results of modulus, yield stress and strain at break can be found hereafter in Table 6.5. The shorter the chain of the diacid, the higher the value of the modulus and yield stress because of a higher rigidity of the polymer chains. The strain at break values of PA(C10) and PA(C8) were much higher than the value of PA(C6). This difference can only be explained by the longer chain of the diacid.

Table 6.5. Mechanical properties of three aliphatic polyamides.

Diacid	E (MPA)	Yield stress (MPa)	Strain@break (%)
C6	1520	31.2	43.5
C8	1130	28.8	400
C10	975	23.0	523

The results of the tensile tests are plotted in Figure 6.14. From those stress-strain curves, it is clear that the difference in strain at break is due to the highly ductile behaviour of the PAs made from the longest diacids. Both profiles of PA(C8) and PA(C10) show a yielding region followed by a long plateau region before break. High modulus, elongation at break and yield stress are typical characteristics of stiff and tough materials.[29]

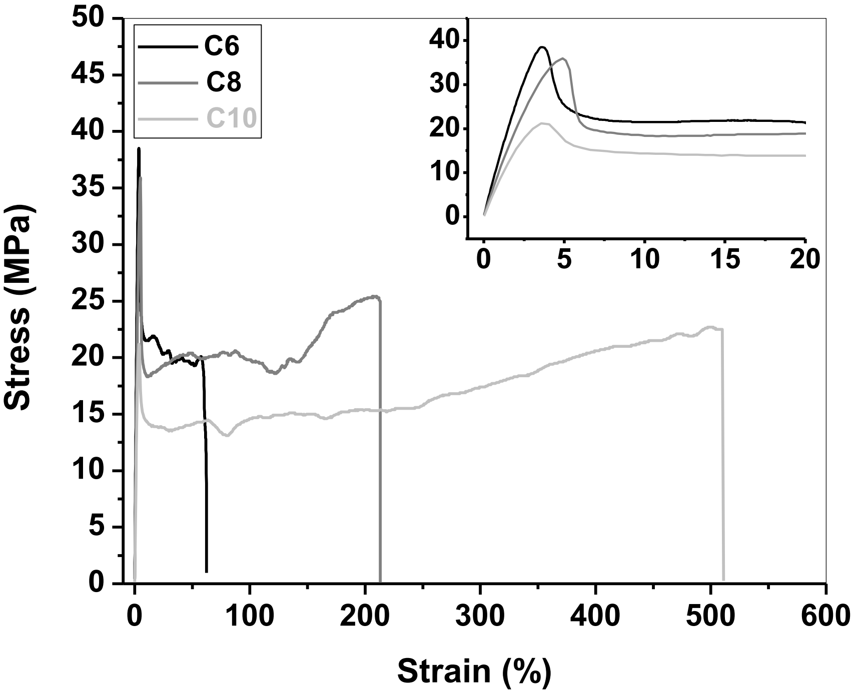


Figure 6.14. Stress-strain plot for the polyamides PA(C6), PA(C8) and PA(C10).

6.4.4 Hydrolytic stability and renewability

The hydrolytic stability of one of the processed polyamides, namely PA(C8), was tested at different pH-values. The polymer was immersed in an aqueous solution for two weeks at 50 °C, after which the samples were weighted and SEC analyses were performed to investigate if degradation took place.[33] Four different pH values were tested; pH 1, 3, 5 and 7. Already after one day, the transparent polymer changed into an opaque white material attesting that water interacts with the polymer. Upon hydration, the water molecules occupy the intermolecular space of the amorphous chains and the inter-chain hydrogen bonds are replaced by interactions with water.[42] The solutions and polymer were heated to 50 °C, which made the molecular chains realign, resulting in a cold crystallization and therefore a change from a transparent to an opaque material occured.[43] This phenomenon was already reported and is referred to as water induced crystallization.[44] After two weeks, no significant decrease in the weight of the polymer could be observed and at least 99% of the mass was retained for all samples. The SEC results in Figure 6.15 show that degradation only took place for the lowest pH-value, pH of 1.

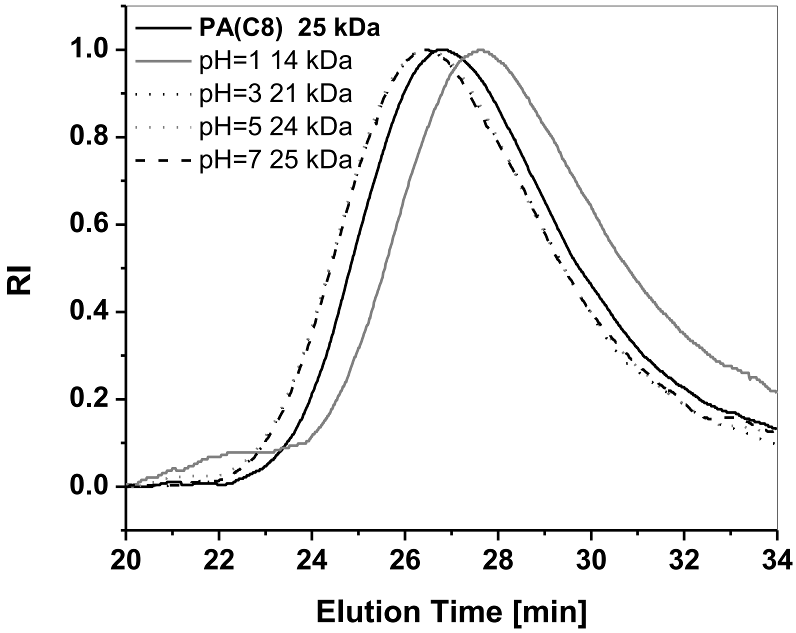
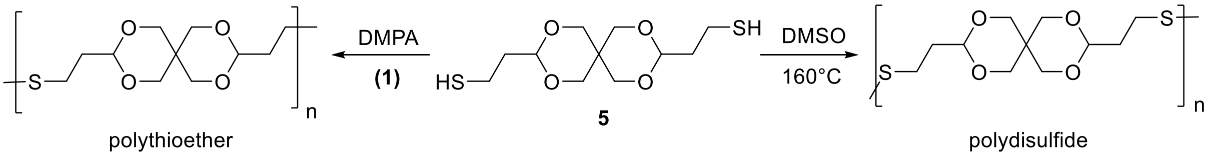


Figure 6.15. DMA SEC curves of PA(C8) measured after 2 weeks in aqueous solutions (pH 1, 3, 5 or 7) at 50 °C.

The biobased carbon content in these polyamides was calculated taking into account that the diene can be produced from renewables. When the diamine is combined with aromatic diacids, the biobased content is limited to 47%. However, when (renewable) aliphatic diacids are used, a biobased carbon content of 80-85% can be obtained.

6.5 Polythioethers and polydisulfides



Scheme 6.9. Synthesis of a polythioether and a polydisulfide from the synthesized dithiol (5).

After obtaining the dithiol, it was possible to test two polymerization routes (Scheme 6.9). On the one hand the dithiol can be reacted with a diene under UV irradiation to form a polythioether.[5] On the other hand, thiols are prone to form disulfides under oxidative conditions, this can thus be stimulated in order to obtain a polydisulfide.[45] These two different strategies were explored and will be presented separately.

6.5.1 The synthesis of polythioethers

Polythioethers can be obtained from the reaction of dithiols and dienes. This reaction can be performed under UV in the presence of a radical initiator like DMPA or can be thermally initiated.[46] UV polymerizations are generally much faster than the thermally initiated ones, so the polymerization under UV was first tested.[47] Beforehand, a kinetic study was performed by SEC analysis in order to investigate the ideal reaction time for our polymerization reaction. The first sampling was performed every hour for 6 hours. However, after two hours, the molecular weight already reached a plateau value. Therefore, a second study was performed with a sampling done every 15 min. After 45 minutes, no significant increase in molecular weight could be observed. It was thus decided to stop the thioether polymerizations after one hour of reaction time.

The solubility of the resulting polythioether was tested and good solubility was only observed in chloroform, dichloroethane (DCE) and *m*-cresol, while the polymer was also soluble in tetrahydrofuran (THF) when put in the ultrasonic bath for half an hour. The polythioether was not soluble in dichloromethane, hexane, diethyl ether, ethyl acetate, methanol, toluene, dimethyl acetamide and dimethyl formamide. With all this information, the optimal polymerization condition could be determined to obtain high molecular weight polythioethers.

EtOAc, THF and DCE were chosen as solvents. It was clear that the best results were obtained with EtOAc, however the polymer already precipitated early from the reaction mixture, which can limit the built up in molecular weight. In THF and DCE, the polymer was still in solution at the end of the polymerization reaction but lower molecular weight polymers were obtained after precipitation from methanol (Table 6.6). The obtained polymer is a white powder with a good thermal stability (T_d > 360 °C). The different polythioethers have rather high glass transition temperatures (T_g ± 63 °C) and are amorphous materials (no crystallisation/melting peaks in the DSC trace of the samples).

Table 6.6. Overview of the molecular weights, dispersities and thermal properties of the polythioethers synthesized in different solvents. TGA measurements were performed under N_2 atmosphere and the T_d represents the temperature at 5% mass loss. T_gs were measured with DSC.

solvent	M_n (kDa)	Đ	T_d (°C)	T_g (°C)
EtOAc	14	1.5	360	65
THF	6	1.5	370	61
DCE	9	1.5	360	63

As only moderate molecular weights could be obtained, it was decided to also investigate the thermally initiated synthesis of these polythioethers. Azobisisobutyronitrile (AIBN) was used as thermal initiator and the reactions were carried out in solvent, at reflux for 24 h, or in bulk, at 85 °C for 8 hours. This more time-consuming method did not seem to solve our problem as the highest obtained molecular weight was 4 kDa. With EtOAc and BuOAc as solvent, molecular weights of approximately 1.5 kDa were obtained, while with DCE no polymers were formed at all. It was eventually decided to use the polythioether of 14 kDa, obtained in EtOAc under UV, for further testing as this was our best result in terms of molecular weight.

From literature, it is known that thioether moieties present in a polymer backbone can be oxidized in order to play with the glass transition of the polymer.[48-49] The polythioether of 14 kDa was oxidized with meta-chloroperoxybenzoic acid (*m*-CPBA). As the oxidation conditions are acidic, it was important to analyze the polymer thoroughly after oxidation as the acetals in the polymer can degrade under an acidic environment. As shown by ^{1}H-NMR measurements, the oxidation proved to be successful (Figure 6.16). As expected, higher ppm values were found for the signals next to the sulfone compared to the signals in the initial polythioether. DMA SEC of the oxidized polymer showed the same molecular weight as the initial one, and the distribution was still Gaussian. Those results prove that full oxidation of the thioethers into sulfones was obtained and that no degradation took place in the oxidation process.

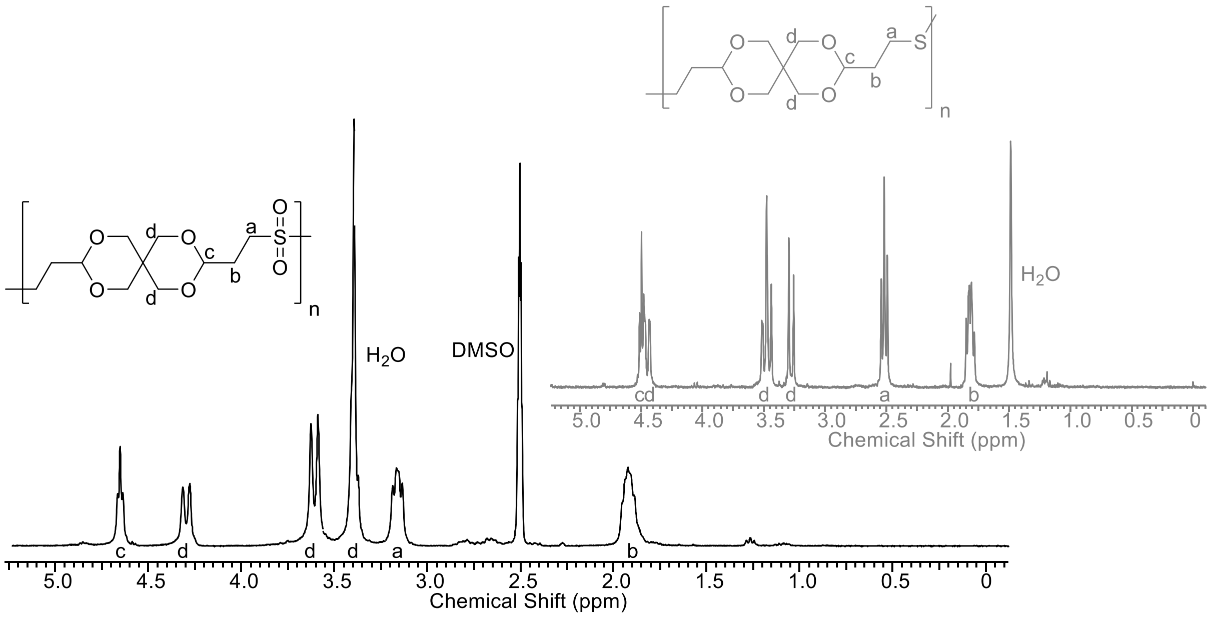


Figure 6.16. ^{1}H-NMR of the polysulfone (black) and the polythioether (grey) (300 MHz, DMSO-d$_6$ & CHCl$_3$-d)

The T$_g$ value of the resulting polysulfone was measured by DSC and showed to be higher than the one of the initial polythioether, as expected. Indeed, the T$_g$ almost doubled and a value of 124 °C was observed after DSC measurements. This increase in T$_g$ as well as the fact that no degradation of the acetal was observed during the oxidation process makes these acetal-containing polymers rather versatile; the properties of the polymers can be adjusted by a simple oxidation step.

6.5.2 The synthesis of polydisulfides

The oxidation of thiols into disulfides in the presence of oxygen is a well-known process.[50] Since the 1940's, this reaction has been applied to the synthesis of various disulfide polymers.[51] In order to achieve high molecular weights within a reasonable time, a catalyst is required, especially when air is used rather than pure dioxygen. Various catalysts and reaction conditions are described in the literature. Aiming at shorter reaction times, simplicity, and targeting high molecular weight polydisulfides, we eventually selected two possible reactions. Goethals *et al.* used dimethyl sulfoxide (DMSO) as thiol oxidizer for the polymerization of ethane dithiol, hexamethylene dithiol, and decamethylene dithiol.[52] Different polymerization times and amounts of DMSO were tested. The highest molecular weight (10.5 kDa) could be obtained with a DMSO:dithiol ratio of 2:1 and 6 hours of reaction time. Choi *et al.* polymerized large bisphenol dithiol monomers with iodide, triethylamine and oxygen.[53] When triethylamine was added, molecular weights up to 20 kDa were obtained. As the second method showed the highest molecular weight, the polymerization of dithiol was first tested with iodide and triethylamine. As shown in Table 6.7, the molecular weight of the obtained product was very low or a side reaction must have occurred, as a part of the resulting polymer was unsoluble. Next, the procedure with DMSO was tested. This second method resulted in much better results and a polymer with a molecular weight of 12.5 kDa was obtained (Table 6.7). ^{1}H-NMR analysis confirmed the chemical structure of the obtained polydisulfide (Figure 6.17). The polymer was a fluffy beige powder with a similar molecular weight as the previously synthesized polythioether (14 kDa), which is ideal for the comparison.

Table 6.7. Overview of the molecular weights, dispersities, degradation and glass transition temperatures of the polydisulfides. TGA measurements were performed under N_2 atmosphere and the T_d represents the temperature at 5% mass loss. T_gs were measured with DSC.

Procedure	M_n (kDa)	Đ	T_d (°C)	T_g (°C)
I_2/Et_3N	1.5	1.4	240	/
DMSO	12.5	1.7	315	61

6.5.3 Comparison of polythioether and polydisulfide

The structure of the polythioether and polydisulfide only differ by one atom per repeating unit, which can be seen in the NMR. As shown in Figure 6.17, the two signals from the two CH_2's next to the sulfide shift to higher ppm values for the polydisulfide compared to the polythioether. The other signals have the same chemical shift for both polymers. Next to this, the degradation temperatures show a small difference, with lower values for the polydisulfide, which is probably due to the weaker disulfide bond. However, glass transition temperatures show similar values (60-65 °C, Table 6.6 and Table 6.7).

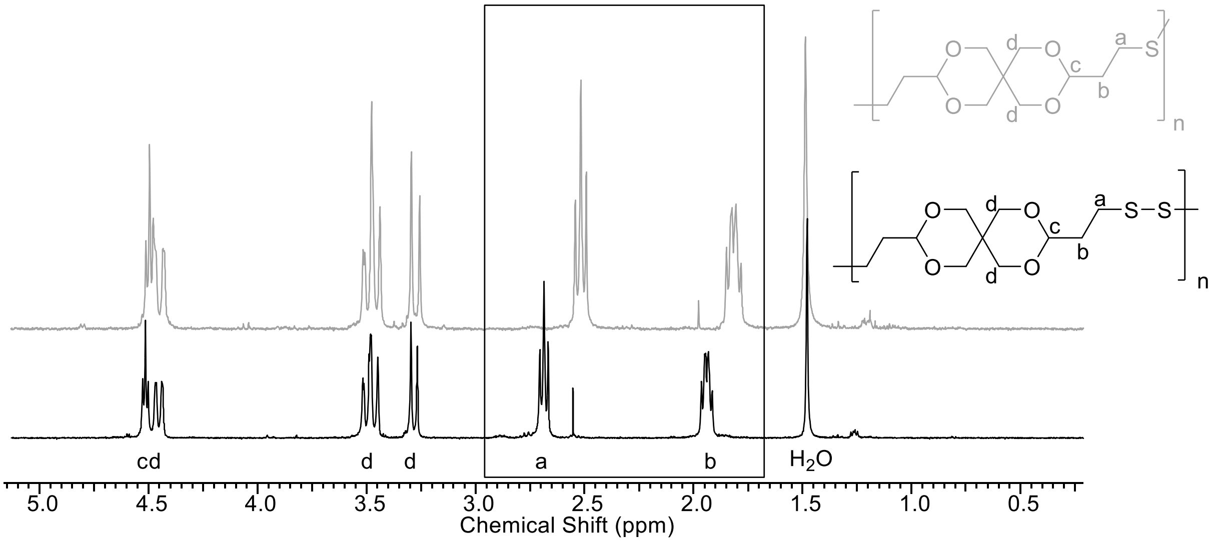


Figure 6.17. ^{1}H-NMR of the polythioether (grey) and the polydisulfide (black) (300 MHz, $CHCl_3$-d).

An interesting difference between polythioethers and polydisulfides is the reversibility of the disulfide bond.[45] From literature it is known that in reductive conditions, the disulfide bonds can open into thiols and the monomers are recovered.[54-55] Our polydisulfides are thus theoretically fully recyclable.

Next to this, the hydrolytic stability of both acetal-containing polymers was investigated with a degradation set-up described by Miller *et al.*[56] The polymers were immersed for 2 days in THF in the presence of water and sulfuric acid. After three different time intervals (3 h, 1 day and 2 days), a sample was taken and its molecular weight was determined by SEC. No degradation was observed for both the polythioether and the polydisulfide, which proves the good stability of the cyclic acetals built in our polymers.

If the diene is produced from renewables, the biobased carbon content for both polymers reaches 100%. Of course, the reactions to get the dithiol are not taken into account in these calculations.

6.6 Conclusion

Three different spiroacetal-containing monomers were successfully synthesized from 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane; a diol, a diamine and a dithiol. These three monomers could be synthesized on large scale (30 g) in the case of the diol and small scale (5 g) for the diamine and dithiol. The diol and diamine could easily be purified, except for the dithiol, which needed column chromatography. In a next step, these monomers were used in polymerization reactions to get polyurethanes, polyamides, polythioethers and polydisulfides. Molecular weight values comparable to classical polyurethanes, polyamides, polythioethers and polydisulfides could be achieved and the introduction of spiroacetal units in the polymer backbone showed to have a positive influence on the glass transition temperature; T_g values were higher than what is usually found in the literature for the same polymers without spiroacetal units. For the polythioethers the T_g value could also be easily doubled by an oxidation with meta-chloroperoxybenzoic acid.

The polyurethanes and polyamides were processed by compression moulding and transparent materials were obtained in both cases. For the polyurethanes, the processed materials were either colorless in the case of aliphatic diisocyanates or yellow when aromatic diisocyanates were used. The processed polyamides always showed a yellow color. The polyurethanes were mostly brittle as no flexible units were introduced in the polymer backbone while the polyamides showed a ductile behavior due to the long aliphatic chains of the diacids used in the synthesis.

In summary, 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane showed to be a versatile, potentially biobased, starting point to obtain different classes of polymers with varying thermal and mechanical properties that can even be tuned after polymerization.

6.7 Experimental

6.7.1 Materials

Cysteamine hydrochloride (>95.0%), dibutyltin dilaurate (>95.0%, DBTL), 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane (>98.0%), hexamethylene diisocyanate (>98.0%, HDI), iodine (>98%), isophorone diisocyanate (>99.0%, IPDI), methyl thioglycolate (>98%) propylamine (>98%), thioacetic acid (>95%) and toluene diisocyanate (>98.0%,TDI) were purchased from TCI. Decane (>99.9%), diethyl ether, 2,2-dimethoxy-2-phenylacetophenone (99%, DMPA), dithranol, ethyl acetate (dry), hexane, mercaptoethanol (≥99.0%), methanol (MeOH), 4,4′-methylenebis(cyclohexyl isocyanate) (90%, hMDI), methylene diphenyl diisocyanate (98%, MDI), 1,4-phenylene diisocyanate (≥98%, PDI), potassium trifluoroacetate (KTFA), triethylamine (99%), sodium hypophosphite monohydrate (>99%, NaHPO3·H2O) and sodium hydroxide (NaOH) were purchased from Sigma Aldrich. Adipic acid (99%), chloroform (dry, 99.9%), meta-chloroperoxybenzoic acid (70-75%), diethyl adipate (99%), dimethyl sulfoxide (99.7%, DMSO), 1,1,1,3,3,3-hexafluoro-2-propanol, isophthalic acid (99+%), N-methylpirrolidone (NMP), sebacic acid (98%), suberic acid (99%), succinic acid, terephthalic acid (99+%), were purchased from Acros Organics. Trimethyl hexamethylene diisocyanate (TMDI) was obtained from Evonik. Acetic acid (90-100%) was obtained from ChemLab. All substances were used as received without further purification.

6.7.2 Synthesis

6.7.2.1 Synthesis of 3,9-(2-ethylthio)ethanediol-2,4,8,10-tetraoxaspiro[5.5]undecane (2)

In a three-neck flask, equipped with a mechanical stirrer, 25.00 g (0.118 mol) of dialkene (**1**) and 16.94 mL (0.241 mol) of 2-mercaptoethanol were added. The oxygen was removed *via* three cycles of vacuum-nitrogen flush. The mixture was stirred at 55 °C for 48 hours after which the colourless mixture turned white. The obtained product was purified *via* two subsequent recrystallizations from hexane and diethyl ether, and dried in a vacuum oven.

Isolated yield: 80 %. **Brutoformula:** $C_{15}H_{28}O_6S_2$. **Molecular weight:** 368.50 g mol^{-1}. **^{1}H-NMR** (300 MHz, DMSO-*d*$_6$, ppm): 4.75 (*m*, 2 H), 4.56 (*app t*, 2 H), 4.26 (*app d*, 2 H), 3.62 → 3.46 (*m*, 8 H), 3.36 (*m*, 2 H), 2.56 → 2.45 (*m*, 8 H), 1.75 (m, 4 H). **^{13}C-NMR** (75 MHz, DMSO-*d*$_6$, ppm): 100.4 (CH), 69.4 (CH_2), 68.9 (CH_2), 60.8 (CH_2), 34.7 (CH_2), 33.9 (CH_2), 31.9 (C), 25.8 (CH_2).

HR-ESI-MS *calculated* m/z [M+H$^+$]: 369.1400; *experimental* m/z [M+H$^+$]: 369.1411 ; *calculated* m/z [M+H$^+$-H_2O]: 351.1294; *experimental* m/z [M+H$^+$-H_2O]: 351.1323.

6.7.2.2 Synthesis of 3,9-(2-ethylthio)ethanediamine-2,4,8,10-tetraoxaspiro[5.5]undecane (3)

In a one-neck flask of 100 mL, 5.00 g (1 equiv) of 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane and 8.00 g (3 equiv) of cysteamine hydrochloride were dissolved in 50 mL methanol. 0.30 g (0.05 equiv) of DMPA was added as catalyst. The solution was stirred under UV light for 5 hours after which the flask was put in the freezer overnight. The obtained product was filtered off and washed with MeOH. The diamine was then dried at 50 °C in vacuum overnight and an overall yield of 80% could be achieved.

Isolated yield: 80 %. **Brutoformula:** $C_{15}H_{32}Cl_2N_2O_4S_2$. **Molecular weight:** 438.12 g mol^{-1}.**LC-MS(m/z):** 367,20 [M-2HCl]. **^{1}H-NMR (300 MHz, $CDCl_3$):** δ (ppm) = 8.00 (s, 6H, $NH_3^+Cl^-$), 4.58 (t, 2H, O*CH*CH_2), 4.26 and 3.59 (2xd, 4H, C*CH*$_2$*(eq)*O), 3.36 and 3.39 (2xs, 4H, C*CH*$_2$*(ax)*O), 2.94 (t, 4H, *CH*$_2$$NH_3^+Cl^-$) 2.72 (t, 4H, S*CH*$_2$$CH_2NH_3^+Cl^-$), 2.56 (t, 4H, $CHCH_2$*CH*$_2$S), 1.78 (t, 4H, CH*CH*$_2$$CH_2$S)

In order to obtain the unprotected diamine, 10.00 g (22.8 mmol) of 3,9-(2-ethylthio)ethanediamine-2,4,8,10-tetraoxaspiro[5.5]undecane hydrochloride was dissolved in 700 mL of 0.1 M aqueous solution of NaOH. The solution was magnetically stirred for 3 hours and free diamine was extracted with 3x200 mL of chloroform. The chloroform was evaporated and the free diamine was dried overnight in the vacuum oven at 50 °C (7.90 g, 21.4 mmol, 94%).

Isolated yield: 94 %. **Brutoformula:** $C_{15}H_{30}N_2O_4S_2$. **Molecular weight:** 366.16 g mol^{-1}. **^{1}H-NMR (300 MHz, DMSO):** δ (ppm) = 4.56 (t, 2H, OC*H*CH$_2$), 4.24 and 3.59 (2xd, 4H, C*CH$_2$*(eq)O), 3.37 and 3.39 (2xs, 4H, C*CH$_2$*(ax)O), 2.64 (t, 4H, S*CH$_2$*CH$_2$NH$_2$) 2.50 (t, 4H, *CH$_2$*NH$_2$), 2.48 (t, 4H, CHCH$_2$*CH$_2$*S), 1.76 (t, 4H, CH*CH$_2$*CH$_2$S), 1.54 (s, 4H, N*H$_2$*)

6.7.2.3 Synthesis of 3,9-ethanedithiol-2,4,8,10-tetraoxaspiro[5.5]undecane (5)

In a one-neck flask of 100 mL, 5 g (1 equiv) of 3,9-divinyl-2,4,8,10-tetraoxaspiro[5.5]undecane, 3.5 mL (2.1 equiv) of thioacetate and 0.60 g (10 mol%) DMPA were dissolved in 50 mL methanol. The reaction was flushed with argon upon putting it under UV radiation for 2 h. Hereafter, an extraction with bicarb and ethyl acetate was performed. The organic layers were collected and dried over $MgSO_4$ and the solvent was evaporated. A yellowish powder was obtained, which was confirmed to be the dithioacetate.

Brutoformula: $C_{15}H_{24}O_6S_2$. **Molecular weight:** 364.10 g mol^{-1}.**LC-MS(m/z):** 365,00 [M+1]. **^{1}H-NMR (300 MHz, CDCl$_3$):** δ (ppm) = 4.48 (t, 2H, O*CH*CH$_2$), 4.44 and 3.48 (2xd, 4H, C*CH$_2$(eq)*O), 3.48 and 3.27 (2xs, 4H, C*CH$_2$(ax)*O), 2.89 (t, 4H, *CH$_2$*S), 2.25 (s, 6H, SCOC*H$_3$*) 1.83 (m, 4H, CH*CH$_2$*CH$_2$S)

In a next step 5.00 g (1 equiv) of dithioacetate was dissolved in 3.5 mL (3 equiv) of propylamine and stirred for 1 hour. After this, the reaction was quenched with acetic acid until the overall pH was 5. This was extracted with bicarb and ethyl acetate and washed with brine. The organic layers were dried on $MgSO_4$ and the solvent was evaporated at the rotary evaporator. The obtained yellowish oil was then purified by column chromatography (hexane to ethyl acetate 7: 3). A white powder was obtained with a yield of 45%. It is advised to store the dithiol in the fridge to avoid disulfide formation.

Isolated yield: 45 %. **Brutoformula:** $C_{11}H_{20}O_4S_2$. **Molecular weight:** 280.08 g mol^{-1}. **LC-MS(m/z):** 298,40 [M+18]. **^{1}H-NMR (300 MHz, CDCl$_3$):** δ (ppm) = 4.53 (t, 2H, O*CH*CH$_2$), 4.46 and 3.49 (2xd, 4H, C*CH$_2$(eq)*O), 3.49 and 3.29 (2xs, 4H, C*CH$_2$(ax)*O), 2.55 (q, 4H, *CH$_2$*SH), 1.86 (q, 4H, CH*CH$_2$*CH$_2$S) and 1.33 (t, 2H, S*H*)

6.7.2.4 Synthesis of the polyurethanes

A three-neck flask equipped with mechanical stirrer and condenser (Figure 6.18) was filled with 5.00 g (0.014 mol) of diol (**2**), 0.014 mol of the selected diisocyanate (Scheme 6.8), 1 mol% dibutyltindilaurate and 30 mL of dry ethyl acetate or no solvent in case of bulk polymerizations. An example of a possible set-up is presented in the appendix (Figure A1). The mixture was flushed with argon and was let to stir at 80 °C overnight. Finally, the polymer precipitated from the reaction mixture, the solvent (if used) was removed and the polymer was dried under vacuum. For the synthesis of PUs with commercial spiroglycol, the same procedure was followed.

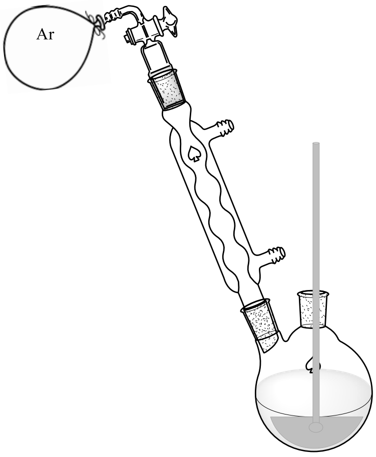


Figure 6.18. Schematical set-up for the synthesis of polyurethanes.

6.7.2.5 Melt polycondensation of the polyamides

To a 100 mL three-necked round bottom flask equipped with a vacuum tight mechanical stirrer, a vigreux column and a distillation condenser, diethyl adipate (1.66 g, 8.2 mmol), (**3**) (3.02 g, 8.2 mmol) and Irganox 1330 (0.05 g, 0.1 wt %) as an antioxidant were added. The reactants were slowly heated to 220 °C and after full release of the ethanol, vacuum was applied for 1-3 h. The crude product was a viscous material with yellowish color.

^{1}H-NMR (300 MHz, CDCl3): δ (ppm) = 6.58 (s, 2H, $\mathrm{N}\mathit{H}$), 4.72 (t, 2H, $\mathrm{O}\mathit{CH}\mathrm{CH_2}$), 4.57 (d) 3.71 (t) 3.54 (d) (8H, $\mathrm{C}\mathit{CH_2}\mathrm{O}$), 4.25 (q, 2H, $\mathrm{O}\mathit{CH_2}\mathrm{CH_3}$), 3.33 (t, 4H, $\mathit{CH_2}\mathrm{NH}$), 2.76 (t, 4H, $\mathrm{S}\mathit{CH_2}\mathrm{CH_2NH}$), 2.66 (t, 4H, $\mathrm{CHCH_2}\mathit{CH_2}\mathrm{S}$), 2.41 (s, 4H, $\mathit{CH_2}\mathrm{CONH}$), 1.98 (t, 4H, $\mathrm{CH_2}\mathit{CH_2}\mathrm{CO}$), 1.78 (s, 4H, $\mathrm{CH}\mathit{CH_2}\mathrm{CH_2S}$), 1.32 (t, 3H, $\mathrm{OCH_2}\mathit{CH_3}$)

6.7.2.6 Synthesis of the amide salts

Aliphatic diacids: To a solution of diacid (0.80 g, 5.4 mmol) in ethanol (10 mL) at 50 °C, a solution of (**3**) (2.00 g, 5.4 mmol) in ethanol (6 mL) was added. During the addition, a precipitate was formed. The mixture was stirred at 80 °C for 2 h. The crude product was filtered and recrystallized from ethanol to afford the salt as white crystals (2.40 g, 4.6 mmol, 86 %) with a melting point of 172-175 °C.

Aromatic diacids: To a solution of isophthalic/terephthalic acid (0.91 g, 5.4 mmol) in DMSO (20 mL) at 50 °C a solution of (**3**) (2.00 g, 5.4 mmol) in DMSO (6 mL) was added dropwise. During the addition, a precipitate was formed. The mixture was stirred at 80 °C for 2 h. The crude product was filtered and the salt was isolated as white crystals (2.70 g, 5.1 mmol, 97 %) with a melting point of 155-158 °C.

6.7.2.7 Polyamide salt polymerization

To a 100 mL three-necked round bottom flask equipped with a vacuum tight mechanical stirrer, a vigreux column and a distillation condenser, (**3**) and the diacid salt (3.00 g, 5.8 mmol), $NaHPO_3 \cdot H_2O$ (0.30 mg, 0,1 wt%) as a catalyst and Irganox 1330 (0.05 g, 0.1 wt%) as an antioxidant were added. The reactants were slowly heated to 220 °C and after the water was fully released, vacuum was applied. The crude product was a viscous material with a yellowish color. This procedure was applied to the melt polycondensation of all salts, except the terephthalic acid salt, which was heated to 250 °C.

6.7.2.8 Synthesis of the polythioethers

In a one-neck flask of 50 mL, 0.50 g (1 equiv) of dithiol, 0.38 g (1 equiv) of dialkene and 1 mol% of DMPA were solved in 15 mL of ethyl acetate or dichloroethane. The reaction mixture was flushed with Argon in order to remove the present oxygen. The flask was placed in a high intensity UV box for 1.5 hours after which the polymer was filtered off in the case of ethyl acetate or precipitated from methanol in the case of dichloroethane. The polymer was then dried in the vacuum oven at 40 °C overnight.

6.7.2.9 Synthesis of the polydisulfides

A raft tube was filled with 0.25 g (1 equiv) dithiol and 0.13 mL (2 equiv) DMSO. The mixture was flushed with argon after which the tube was closed and put under high vacuum. The tube was placed at 160 °C for 6 h. The mixture was cooled to room temperature and was dissolved in chloroform, hereafter the polymer was precipitated in cold methanol. After filtration, the polymer was dried in the vacuum oven at 40 °C overnight.

6.7.2.10 Oxidation of the polythioether into a polysulfone

To the polymer, dissolved in 5 mL chloroform, was added meta-chloroperoxybenzoic acid (0.49 g). After addition, the mixture warmed up because of the exothermic oxidation reaction. The resulting oxidized polymer precipitated out of solution. Next, chloroform was evaporated under reduced pressure. Purification of the polymer was done by heating in MeOH and subsequent filtration (2x).

6.7.2.11 Degradation study of the polyamides and polyurethanes

A hydrolytic stability study was performed by placing 0.10 g of polymer into test tubes, to which 10 mL of an aqueous solution of a specific pH was added. Parallel experiments were carried out at four different pH (1, 3, 5 and 7) at 50 °C. The test tubes were sealed to avoid evaporation of the water. After two weeks, the samples were rinsed with water and dried. The degradation was followed by sample weighing and SEC measurements.

6.7.2.12 Degradation studies of the polythioether and polydisulfide

Each polymer (0.25 g) was dissolved in 100 mL tetrahydrofuran. Water (0.5 mL) and sulphuric acid (0.1 ml) were added and the mixture was stirred for 48 h. Each 12 h, a sample of 5 mL is taken and run over basic alumina before evaporation of the solvent. These samples were than measured on the chloroform SEC.

6.7.3 Methods

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analyses were performed using a Mettler Toledo instrument 1/700 under nitrogen atmosphere at a heating rate of 10 °C.min^{-1} and a temperature gradient of 200 °C. The STARe software of Mettler-Toledo was used to analyze the results.

DMA-SEC

Size Exclusion Chromatography (SEC) measurements were performed on a Waters instrument, with a Waters 2414 Refractive Index detector, equipped with 3 Polymer Standards Services GPC serial columns - one GRAM Analytical 30 Å, 10 µm and two GRAM Analytical 1000 Å, 10 µm - at 35 °C. PMMA standards (690 g.mol^{-1} and 1 944 000 g.mol^{-1}) were used for calibration and N,N-dimethylacetamide (DMA) containing 0.42 g.mL^{-1}. LiBr was used as a solvent at a flow rate of 1 mL.min^{-1}. Furthermore, a Hitachi Column Oven L-7300, a Waters 600 controller and a Waters 610 Fluid Unit were used. The Molecular weight and dispersities were determined using Empower software.

$CHCl_3$-SEC

Size exclusion chromatography measurements were also performed on a Waters instrument, equipped with Waters Styragel HR3, HR4 and HR5 serial columns (5µm particle size) at 35 °C with a RI detector (2410 Waters), using PS standards for calibration, and $CHCl_3$ as an eluent at a flow rate of 1.0 mL.min^{-1}. Molecular weights and dispersities were determined using the Breeze Millennium software.

HFIP-SEC

Size Exclusion Chromatography (SEC) measurements were performed using an Agilent HPLC and a 1260 refractive index detector. The used eluent was HFIP, containing 20 mM sodium trifluoroacetate, with a flow rate of 0.3 mL.min^{-1}. Two PSS PFG 100 Å gel 5 µm mixed D columns connected in series with a similar precolumn (Agilent) were used at 35 °C. The instrument was calibrated using PMMA standards and Agilent Chemstation software was used to analyze the resulting chromatograms.

Infrared spectroscopy

Infrared spectroscopy of samples in the powder form was recorded on a Szimadzu IR affinity Single Reflection ATR.

LC-MS

An Agilent Technologies 1100 series LC/MSD system equipped with a diode array detector (DAD) and a single quad MS was used to perform LC-MS analyses. Analytical Reversed Phase HPLC-analyses were performed using a Phenomenex Lunca C18 (2) column (5µm, 250 mm x 4.6 mm) and a solvent gradient (0-100% acetonitrile in water in 15 minutes). A UV-detector (λ = 214 nm) was used to detect the eluting compounds. The electrospray mass spectra recordings were made using a single quad MS detector (VL) with electrospray ionization.

Nuclear Magnetic Resonance

Proton and carbon nuclear magnetic resonance (^{1}H and ^{13}C NMR) measurements were performed using a Bruker Avance 300 (300 MHz) and a Brucker Avance II 400 (400 MHz) instrument at room temperature. ADC/NMR Processor Academic Edition software of ACD/Labs, which is available online, was used to analyze the recorded spectra.

Maldi-ToF

Matrix-assisted laser desorption/ionization time-of-flight (Maldi-ToF) mass spectra were recorded on a Bruker UltrafleXtreme spectrometer with a 355 nm Nd:Yag laser (2 kHz repetition pulse/Smartbeam-IITM) and a grounded steel plate. All mass spectra were obtained in reflector mode. Dithranol (20 mg/mL in THF) was used as a matrix, KTFA (5 mg/mL) was used as a cationating agent, and polymer samples were dissolved in THF (1 mg/mL). The applied ratio of polymer:matrix:salt was 20:200:10. Poly(ethylene glycol) standards with Mn equal to 5000, 10000, 15000 g.mol^{-1} were used for calibration. All data were processed using the FlexAnalysis (Bruker Daltonics) software package.

Compression moulding

The used materials were processed using a metal mould, which was compressed under 7.5 ton using a manual Rubberstamp Press.

Thermogravimetric Analysis (TGA)

Thermogravimetric Analyses were performed with a Mettler-Toledo TGA/SDTA 851e instrument. The measurements were performed under nitrogen atmosphere with a heating rate of 10 K.min^{-1} from 25 °C to 800 °C on samples with sizes of 5-10 mg. Mettler-Toledo's STARe software was used to analyze the thermograms.

Tensile Testing

Tensile tests were performed on a Tinius-Olsen H10KT tensile tester, equipped with a 100 or 500 N load cell. A flat dog bone type specimen with an effective gage length of 13 mm, a width of 2 mm and a thickness of 1.3 mm was used in all the tests. A Ray-Ran dog bone cutter was used to cut out the samples. A speed of 10 mm.min^{-1} was used to perform the tensile tests and at least 3 specimens were tested for each sample.

Group contribution calculation methods

Van Krevelen *et al.* [29] described a theoretical method that allows for the estimation of polymer properties by using empirical and semi-empirical methods. This method can predict various thermodynamic and mechanical properties of both amorphous homopolymers and statistical copolymers (for molecular weight values fixed at 10^6 Da). The model uses connectivity indices as opposed to group contributions in its correlations, thus no database of group contributions is required, and properties may be predicted for most of the polymers.

Hydrolytic stability study

Hydrolytic stability study of the polyamides was performed by placing 0.1 g of polymer into test tubes, to which 10 mL of an aqueous solution of a specific pH was added. Parallel experiments were carried out with four different pH solutions, namely pH 1, 3, 5 and 7 at 50 °C. The test tubes were sealed to avoid evaporation of the solutions. After two weeks, the samples were rinsed with water and dried. The degradation of the polymers was monitored gravimetric analysis and by SEC measurements.

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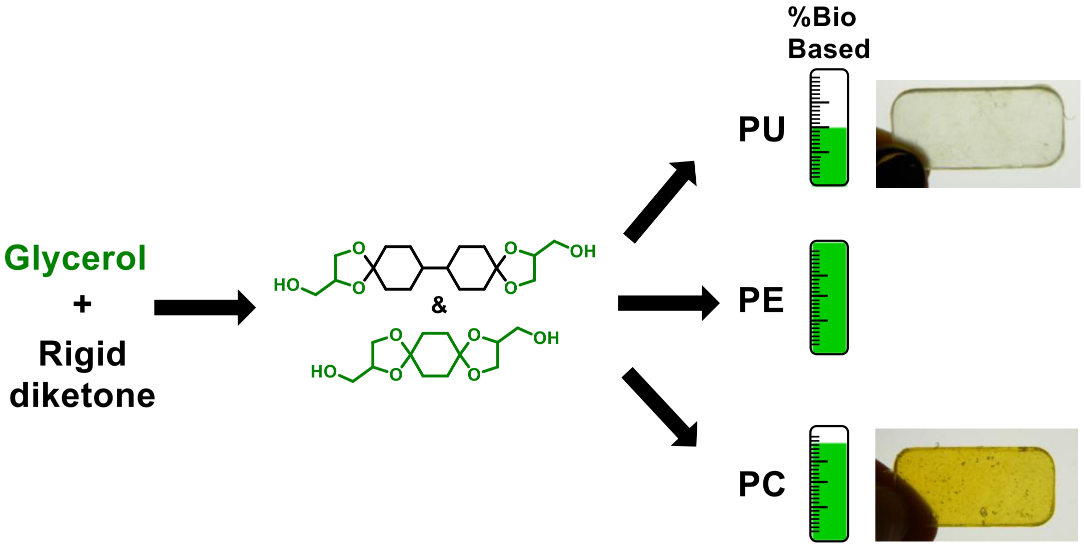


Graphical abstract in Macromolecules

(Volume 50 (14), 5346–5352 , 2017)

Abstract

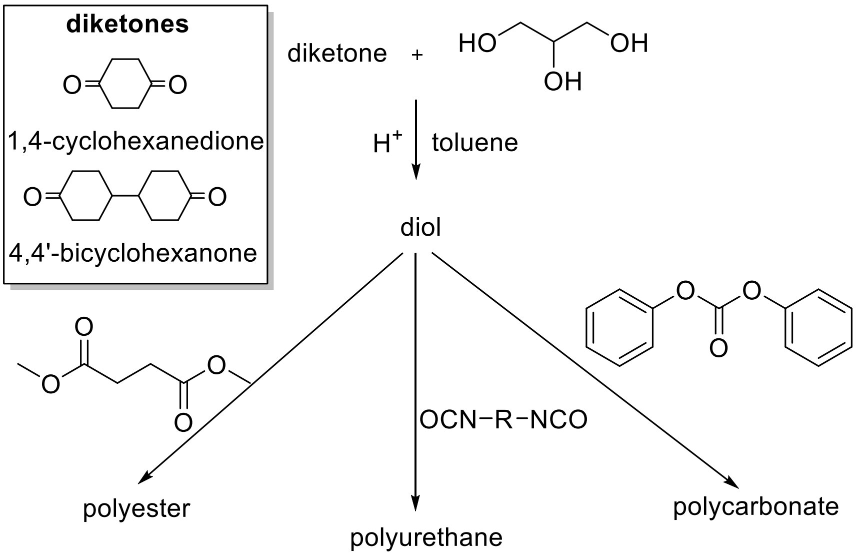
In this chapter, two biobased diols containing rigid cyclic ketal functionalities have been synthesized from diketones, 1,4-cyclohexanedione and 4,4'-bicyclohexanone, and glycerol, on a relatively large scale. The diols have then been used in step-growth reactions, resulting in polycarbonates, polyesters and polyurethanes. While molecular weights (M_n) of up to 50 kDa are obtained for the polyurethanes, they also exhibit high glass transition (T_g = 95-150 °C) and degradation temperatures (T_d =260-320 °C), are transparent and show a high mechanical strength (E= 1.10-1.35 GPa) but brittle behavior. For the polycarbonates, M_n values higher than 24 kDa and T_gs in the range of 70-100 °C have been obtained. Moreover, the polycarbonates show good mechanical properties like ductility and transparency. Finally, fully renewable polyesters have been synthesized with dimethyl succinate and dimethyl furan dicarboxylate. While moderate molecular weight values are obtained, the polyesters show T_gs of up to 96 °C as well as high T_ds (± 315 °C).

Chapter 7: Step-growth polymerization of glycerol-containing monomers

7.1 Introduction

As previously described in chapter 6, ketal or acetal containing polymers can be derived from ketal or acetal containing bifunctional monomers. From the results obtained in chapter 6, one can conclude that this method leads to more control over the polymer properties compared to direct polyketalization/acetalization, as described in chapter 5. Furthermore, the use of an acetal or ketal containing monomer opens up the possibility of producing different types of polymers such as polyesters, polycarbonates and polyurethanes, even though a synthesis step is needed. In this chapter, it was chosen to synthesize ketal-containing diols that can be made from a diketone and a triol. The most famous renewable triol is glycerol and was therefore applied in the synthesis of renewable and rigid diols. It was chosen to uniquely work with diketones, as glycerol prefers to form the 5 membered ring in ketalization reactions.

Initially, the results of the model study on the ketalization of diketones with ethylene glycol performed in chapter 5 were studied. Only the most reactive diketones were then selected to be used in the monomer synthesis. 1,4-Cyclohexanedione, 4,4’-bicyclohexanone and diacetyl were thus transformed into diols containing two cyclic ketal functionalities via an acid catalyzed ketalization reaction with glycerol. These diketones are rigid, cheap and renewable, except for 4,4’-bicyclohexanone. The synthesized diols could then be used in polycondensation and polyaddition reactions resulting in novel PEs, PCs and PUs (Scheme 7.1). By introducing a rigid moiety of two or more cycles, strong and ductile materials could be expected. As the resulting polymer materials contain ketal functionalities, acid sensitivity could be an issue. However, it was shown previously that cyclic ketal functional groups are more stable than ester groups against hydrolysis in acidic, neutral and basic media.[1-2] Moreover, the hydrolytic stability tests performed on the poly(cycloacetals) obtained in chapter 5 and 6 revealed that the polymers were rather acid stable.



Scheme 7.1. Overview of the monomer synthesis and different polymerization procedures.

7.2 Synthesis of glycerol based monomers

From the model study of ethylene glycol and diketones described in chapter 5, the conversion of the ketalization reaction in a certain reaction time could be determined by ^{1}H-NMR. It was decided to only investigate the diketones with short reaction times. Thus, diacetyl, 1,4-cyclohexanedione and 4,4'-bicyclohexanone were subsequently reacted with glycerol to form rigid and (partially) renewable diols. Only the reaction with 1,4-cyclohexanedione was previously reported as an intermediate product but no purification of the diol was performed.[3] The diols were prepared via an azeotropic distillation in toluene or petroleum ether. Depending on the diketone, different reaction times were necessary (4,4'-bicyclohexanone: 1 h, 1,4-cyclohexanedione: 4 h, diacetyl: 48 h). Hereafter, the resulting diols will be abbreviated respectively as BCD, CHD and DiAcD. BCD could easily be purified by extraction and precipitation, while CHD and DiAcD required column chromatography. As the synthesis of DiAcD took two days and resulted in low yields, this monomer was excluded from further studies.

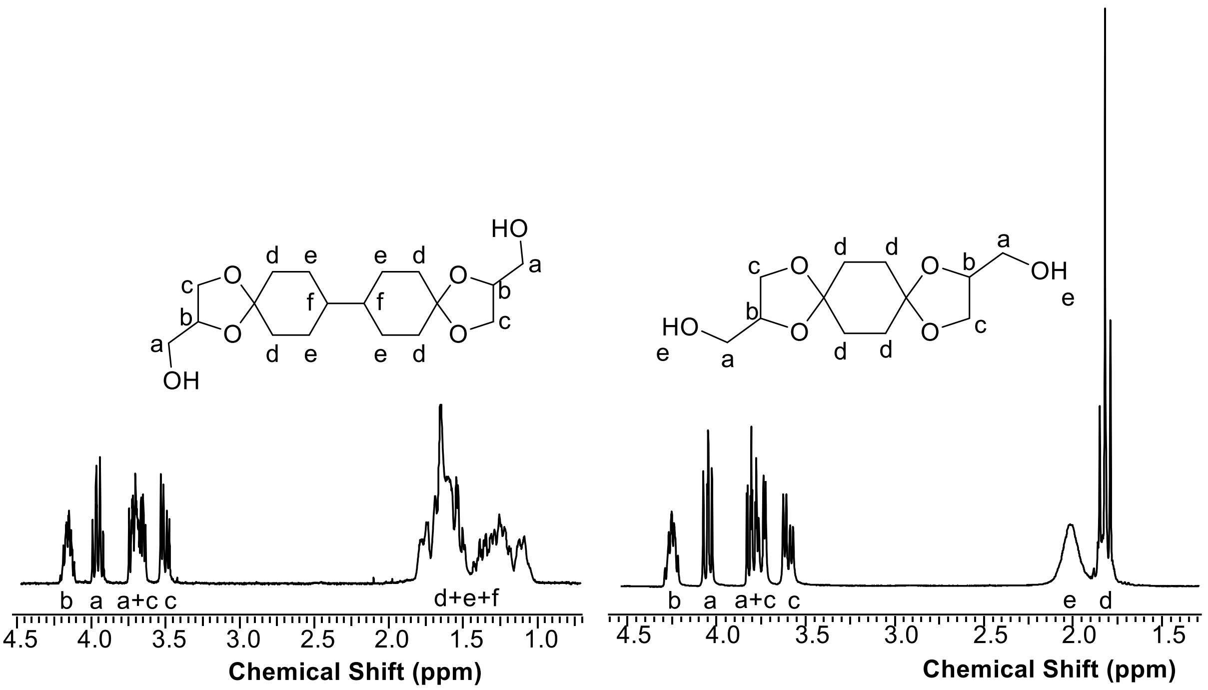


Figure 7.1. ^{1}H-NMR spectrum of the BCD (left) and CHD (right) monomer in CDCl$_3$-d .

The successful synthesis of BCD and CHD was confirmed by ^{1}H-NMR spectroscopy (Figure 7.1) and LC-MS (Table 7.1). The yields after purification were reasonable (60% for BCD and 45% for CHD). The lower yield of CHD was attributed to the long tailing when performing column chromatography as a purification method. The biobased carbon content of the diols was estimated from the theoretical amount of biobased carbon in the molecule, yielding a biobased carbon content of 100% for CHD and only 33% for BCD.

Table 7.1. Property overview of the selected diols.

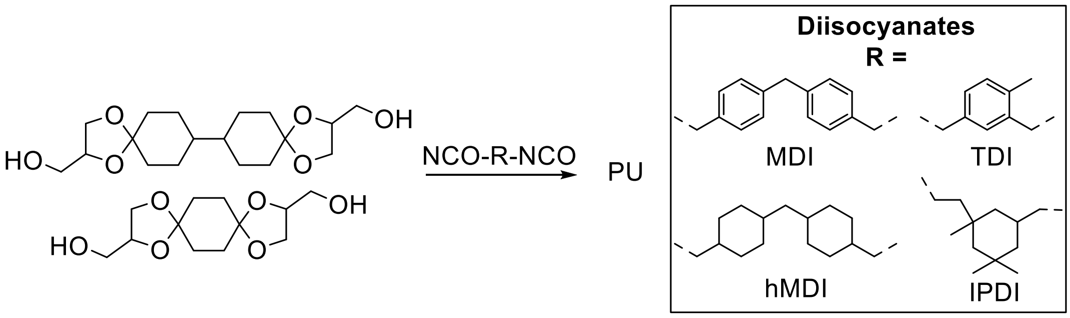
Monomer	**CHD**	**BCD**
MW (g mol^{-1})	260.29	342.43
Yield (%)	45	60
Reaction time (h)	4	1
T_m (°C)	*	130
% Biobased	100	33
[M+H]$^+$	261.20	343.20

* The product was a viscous oil at room temperature

The synthesized diols were subsequently used in polycondensation and polyaddition reactions, resulting in polyesters, polycarbonates on the one hand and polyurethanes on the other hand.

7.3 Polyurethanes

The rigid ketal containing monomers were used in the synthesis of PUs with the aim to increase the T_g of the resulting PUs.[4] Moreover, due to the polycyclic nature of the diol monomers, amorphous and, as a result, transparent materials should be obtained.



Scheme 7.2. Overview of the PU synthesis.

A set of four different rigid diisocyanates (DI) (Scheme 7.2) was utilised in the production of polyurethanes for each of the diols. The set constituted of two aromatic, methylene diphenyl diisocyanate (MDI) and toluene diisocyanate (TDI), and two aliphatic diisocyanates, hydrogenated methylene diphenyl diisocyanate (hMDI) and isophorone diisocyanate (IPDI). The diols were combined with these different DI using DBTL as a catalyst in an overnight reaction. High molecular weights were obtained (> 20 kDa, Table 7.2) for all polyurethanes, except for the IPDI based PU as a result of the lower reactivity of the secondary isocyanate group of IPDI.[5] All polymer structures were confirmed by ^{1}H-NMR; two examples are shown below in Figure 7.2 (BCD+hMDI) and Figure 7.3 (CHD+MDI).

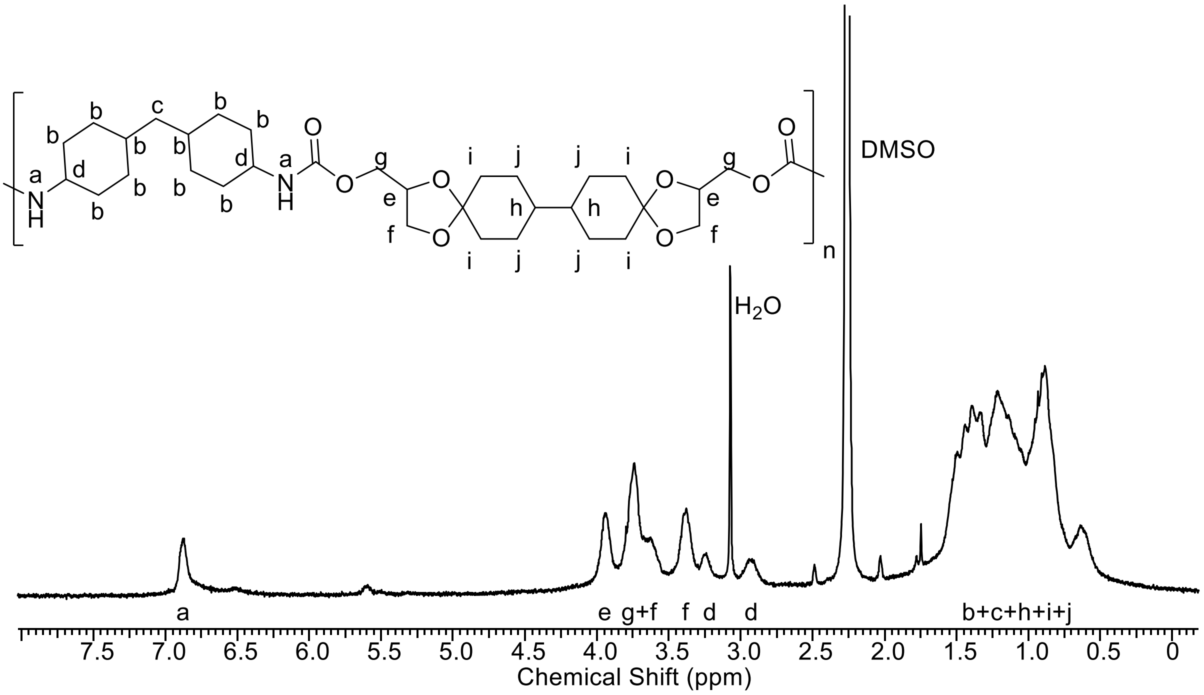


Figure 7.2. ^{1}H-NMR-spectrum of the polyurethane from BCD and hMDI in DMSO-d_6.

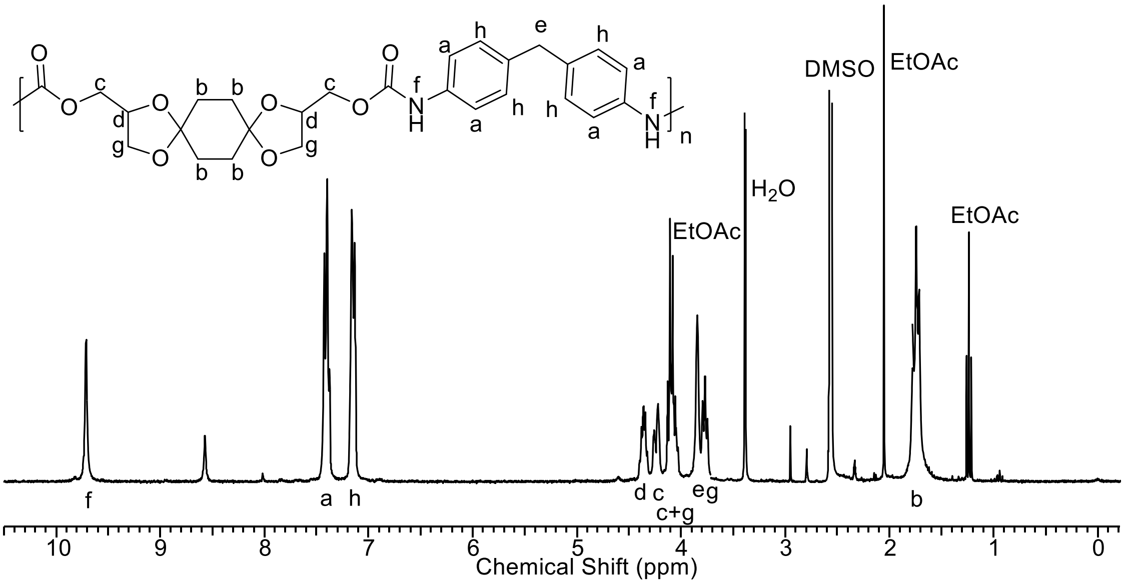


Figure 7.3. ^{1}H-NMR spectrum of the polyurethane from CHD and MDI in DMSO-d$_6$.

Subsequently, the thermal and mechanical properties of these polymers were determined and compared to each other. The degradation temperatures (T_ds), as measured by TGA analysis (5% mass loss), are around 300 °C for most of the obtained polymers, which is higher than for most known polyurethanes.[6]

Table 7.2. SEC, TGA, DSC and mechanical properties for the synthesized polyurethanes. (UTS= Ultimate Tensile Strength)

Diol	DI	M_n (kDa)	Đ	T_d (°C)	T_g (°C)	E (GPa)	UTS (MPa)
CHD	hMDI	29	2.3	310	140	1.31	75
	IPDI	18	1.8	310	130	1.42	26
	TDI	22	1.7	280	130	1.30	65
	MDI	23	1.8	300	150	1.10	20
BCD	hMDI	50	1.9	315	130	1.34	47
	IPDI	17	1.8	260	90	*	*
	TDI	26	2.0	290	105	1.26	30
	MDI	22	1.8	320	145	1.10	16

*Too brittle

Moreover, the T_g values of the PUs, measured with DSC, are shown in Table 7.2 in which high T_gs of up to 150 °C can be observed for the synthesized PUs. These high T_gs made it necessary to include an additional step in the polymer processing, i.e. heating the polymers for two hours at 170 °C under vacuum, with the aim to remove trapped solvent in order to obtain bubble-free materials.

Both the aliphatic and aromatic diisocyanate based processed PUs were transparent. However, the aromatic ones were yellow (Figure 7.4), which is a known property of aromatic diisocyanates, while the aliphatic ones were colourless.[7]

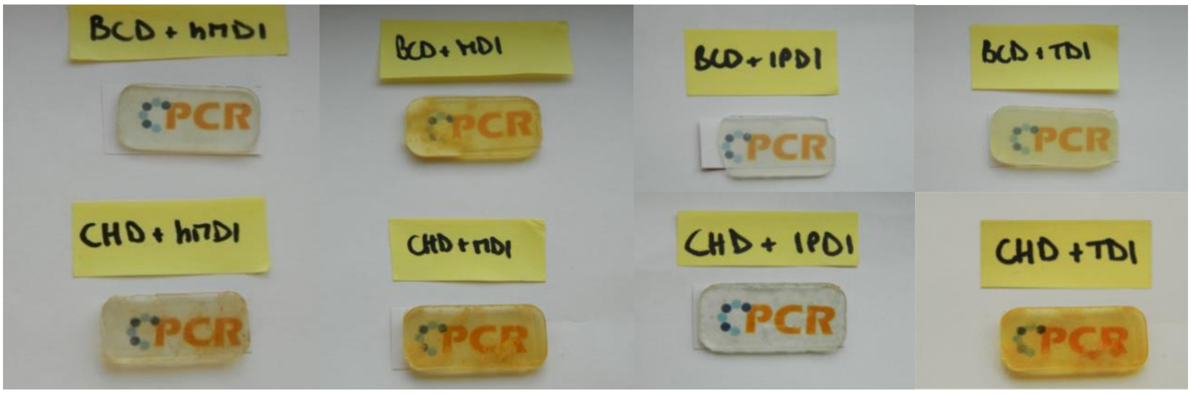


Figure 7.4. Pictures of the processed polyurethane materials.

The PU materials have high moduli in the range of 1.10-1.42 GPa (Table 2), which is much higher than commercial thermoplastic PUs (E = 0.01-1GPa).[8] All the materials were brittle and thus exhibited low elongations at break (3-13%). Full stress-strain curves can be observed in Figure 7.5 and Figure 7.6. Both hMDI based polyurethanes were mechanically strong materials as confirmed by their ultimate tensile stress (UTS = 47-75 MPa) and high moduli (E = 1.3 GPa) as compared to the aromatic MDI based polyurethanes, which showed lower values for both properties (UTS = 16-20 MPa and E = 1.1 GPa). The material based on hMDI and CHD showed the best combination of toughness and elongation at break.

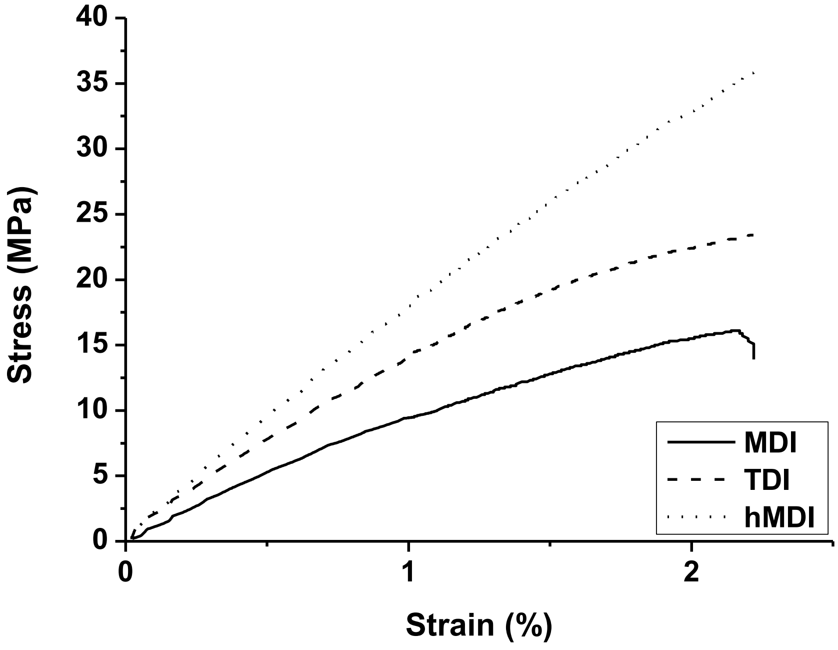


Figure 7.5. Stress-strain curves of the BCD based polyurethanes.

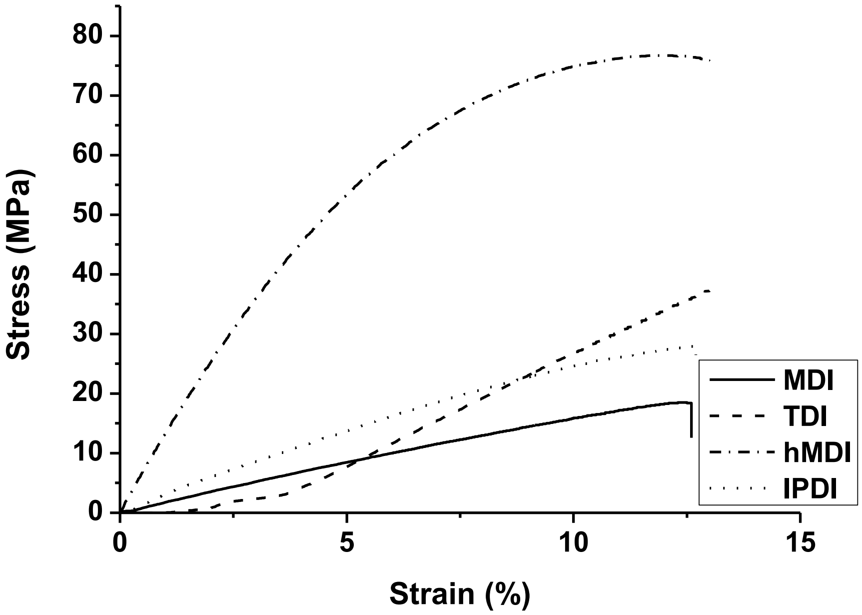
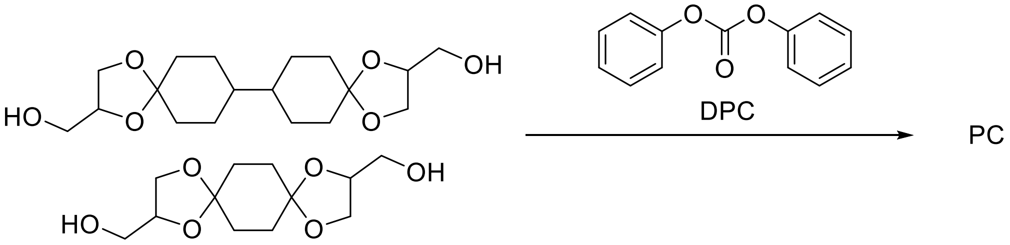


Figure 7.6. Stress-strain curves of the CHD based polyurethanes.

As the diisocyanates are not biobased, the resulting overall biobased content of these PUs is comparatively low; 48-55% for CHD based PUs and 19-24% for BCD based PUs. Note that these values are in the range of the one of the “green” bottle of Coca Cola (20%)[9], and thus represent a promising starting point.

7.4 Polycarbonates



Scheme 7.3. Overview of the poycarbonate synthesis

The synthesized diols were also used to produce polycarbonates (Scheme 7.3), since they constitute a valid alternative to bisphenol A, which is subject to scientific debate.[10-11] The applied procedure is an adaptation of the industrial production process for the production of bisphenol A based polycarbonates by Covestro.[12]

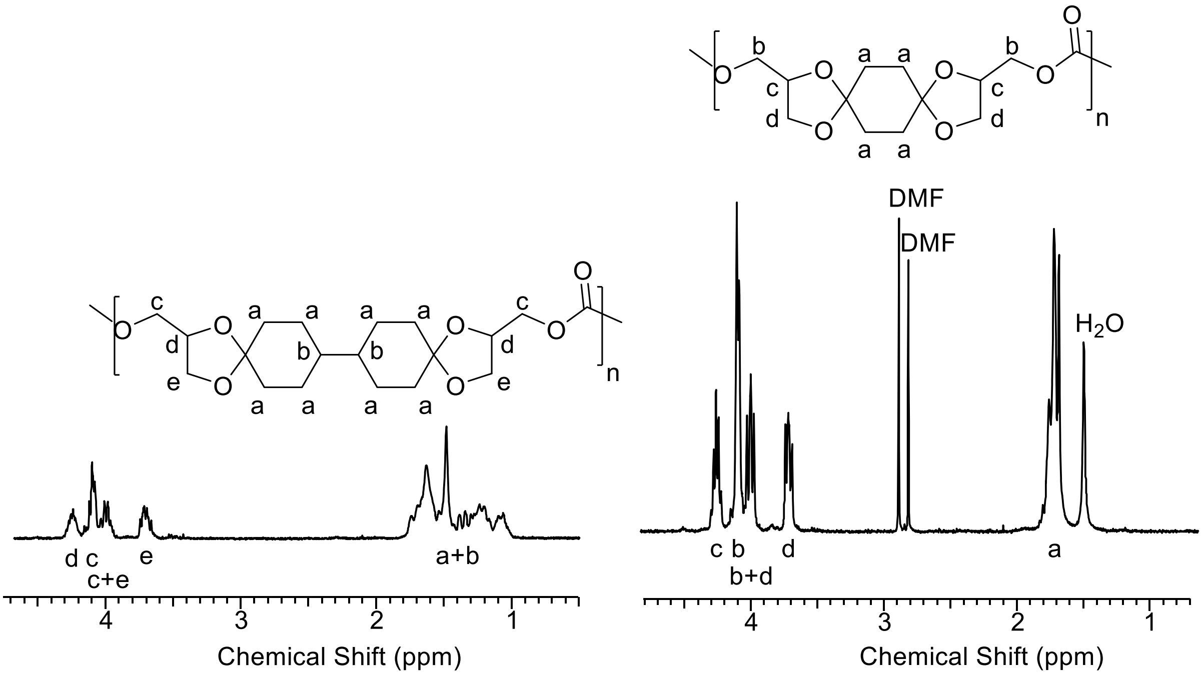


Figure 7.7. ^{1}**H-NMR spectrum of the BCD (left) and CHD (right) based polycarbonates in** $CDCl_3$**-d.**

Both the polymerizations with BCD and CHD yielded high molecular weights in a reproducible fashion (M_w > 50 kDa, Table 7.3). The structure of the polymers was confirmed by ^{1}H-NMR (Figure 7.7). Moreover, the thermal properties look promising with a T_g of 100 °C (Table 7.3) for the BCD based polycarbonate, compared to a T_g of 150 °C for bisphenol A based PC. The synthesized PCs displayed high T_ds (320 to 350 °C), as can be seen from Table 7.3.

Table 7.3. Results of molecular weight and thermal analyses for DPC polycarbonates obtained with $NaHCO_3$ **as the catalyst.**

	$CHCl_3$-SEC			*DSC*	*TGA*	
Monomer	**M_n (kDa)**	**M_w (kDa)**	**Đ**	**T_g (°C)**	**$T_{d5\%}$ (°C)**	**% biobased**
CHD	24	67	2.8	72	350	92
BCD	33	102	3.2	100	320	31

With diphenylcarbonate (DPC), a higher biobased carbon content is calculated for the BCD and CHD based polycarbonates compared to the PUs (up to 92%). However, it must be noted that the employed method of assessing the biobased carbon contents does not include the loss of non-biobased phenol.

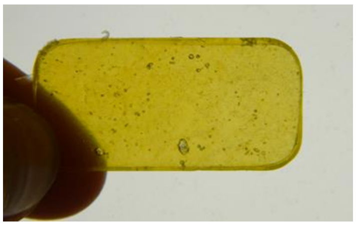


Figure 7.8. Picture of the processed polycarbonate from BCD.

After processing the polymers, yellowish transparent materials were obtained (Figure 7.8) and the mechanical properties were investigated using tensile measurements. The obtained mechanical properties are compared to the mechanical properties of a bisphenol A based polycarbonate in Table 7.4.

Table 7.4. Results of tensile measurements of polycarbonates.

Polymer	E (GPa)	σ (yield)	strain@break (%)
BCD-PC	1.2	45	28
BP-A-PC	2.4	59	40

In this comparison, the CHD based polycarbonate was not taken into account since this polymer proved to be brittle with a low modulus of 1 GPa and a low tensile stress of 9 MPa. On the other hand, for the BCD based polycarbonate, a tensile graph showing the typical behaviour of a ductile material was obtained (Figure 7.9., left) and the values for the modulus, yield stress and strain at break are summarized in Table 7.4. Compared to the known values of bisphenol A based polycarbonate (BP-A) the modulus and yield stress are lower, but the yield stress is still in the same order of magnitude. The material shows ductility, but to a lesser extent than known polycarbonates. Although the mechanical properties of the BCD-PC cannot yet compete with the mechanical properties of bisphenol A based polycarbonates, they look promising.

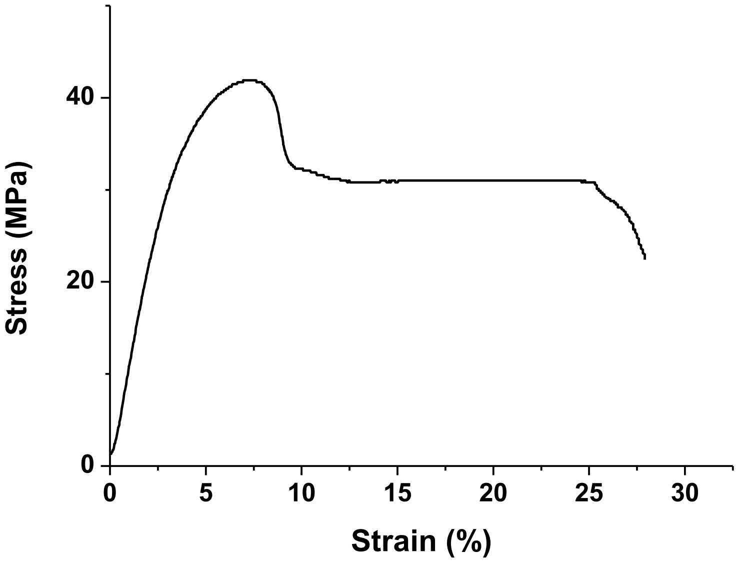
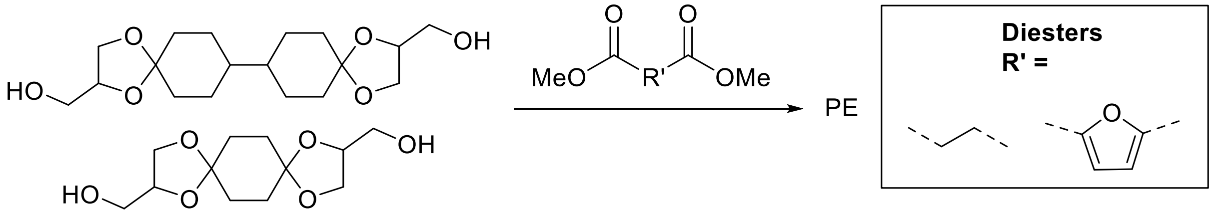


Figure 7.9. Stress-Strain curves of the BCD based polycarbonate.

7.5 Polyesters



Scheme 7.4.Overview of the polyester synthesis.

Four different polyesters were prepared from renewable dimethyl succinate (DMS) and dimethyl furandicarboxylate (DMFDC) in combination with both diols (Scheme 7.4). The synthesis of polyesters with DMS was already reported in detail in the literature, so initially this monomer was explored in combination with BCD and CHD.[13-14] At first, the polymerization process was optimized using BCD, as a result of the more facile synthesis and purification of this monomer. Several catalysts, known to be used in polyester synthesis, were investigated (Table 7.5)[13, 15-16] including both basic (TBD, DBU, K_2CO_3 and $NaHCO_3$) and acidic ones ($Ti(OBu)_4$, DBTO and Sb_2O_3).[13, 15-16] Molecular weights (12 kDa), similar to the ones described in the literature with cyclic acetal containing monomers, were only obtained when DBTO was used as the catalyst. [17-20] Therefore, all following experiments were performed using this catalyst.

Table 7.5. Catalyst screening results in the polyester synthesis with BCD (1.10 equiv) and DMS (1.00 equiv), measured on DMA-SEC.

Catalyst	M_n (kDa)	Đ
TBD*	3.0	1.2
$Ti(OBu)_4$	5.5	1.3
DBU*	2.5	1.2
DBTO	12.0	2.4
K_2CO_3	1.8	1.0
Na_2HPO_4	4.0	1.8
Sb_2O_3	2.0	1.0

* the experiments with TBD and DBU were performed at resp. 100 °C and 120 °C instead of 160 °C and 180 °C due to the thermal instability.

The catalyst screening experiments were performed using a ratio diol:diester equal to 1.1:1. The beneficial effect of using a small excess of diol in polyester synthesis was previously described in the literature.[21-22] However, the optimum monomer ratio also depends on the used monomers and temperature-pressure program. Thus, monomer ratios in the range of 1.0 to 1.2 were also investigated. The results are summarized in Table 7.6 and show that the diol:diester 1.1:1 ratio resulted in the highest molecular weight for the investigated polyester.

Table 7.6. Results of the study of the monomer ratio with BCD and DMS and DBTO as the catalyst.

Equiv BCD	Equiv DMS	M_n (kDa)	Ð
1.0	1	4.7	1.3
1.05	1	5.9	1.4
1.1	1	12.1	3.1
1.15	1	2.4	1.4
1.2	1	3.5	2.5

These optimized conditions were then used for the polymerization of CHD and DMS (Table 7.7). ^{1}H-NMR spectra of the DMS based polyesters are displayed in Figure 7.10. Despite the high rigidity of the diols, the obtained T_g values are rather low (40-50 °C) due to the flexibility of DMS. However, the T_g can be increased by the use of more rigid (renewable) diesters such as dimethyl furanoate (DMFDC) (*vide infra*).

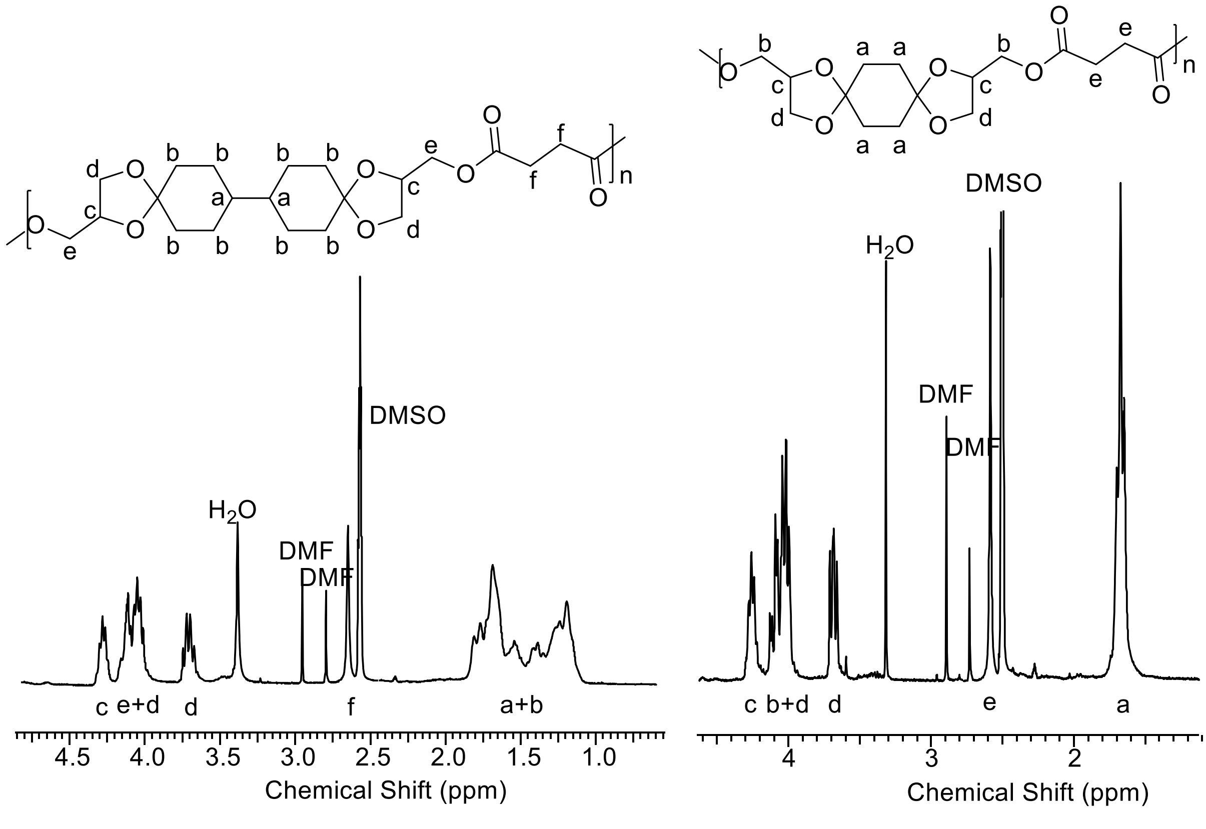


Figure 7.10. ^{1}H-NMR spectrum of the DMS based polyesters in DMSO-d6.

The T_d values (>300 °C) indicate that the polyesters are thermally stable. Furthermore, the obtained biobased carbon content has a value of 45% for BCD + DMS and 100% for CHD + DMS.

Table 7.7. Results of molecular weight and thermal analysis for the synthesized polyesters.

		$CHCl_3$-SEC		*TGA*	*DSC*	
Diester	**Diol**	**M_n (kDa)**	**Đ**	**$T_{d5\%}$ (°C)**	**T_g (°C)**	**% Biobased**
DMS	CHD	19	3.8	310	40	100
	BCD	17	2.3	320	50	45
DMFDC	CHD	8.6	2.3	320	96	100
	BCD	6.0	4.0	310	65	50

In an attempt to further increase the rigidity in the polyesters, both diols were reacted with DMFDC. The synthesis of polyesters with furandicarboxylic acid or DMFDC is a rather recent development. From literature, it was clear that it is easier to react diols with the dimethylester in order to avoid decarboxylation. The synthesis of the dimethylesters was performed based on a literature procedure.[23] Three different reported polymerization procedures were compared for the synthesis of BCD with DMFDC.[24-26] In the end, the method of Li *et al.* was selected, as that one resulted in the highest molecular weights, and because this method is very similar to the method used for the synthesis of polyesters with DMS, allowing for a straightforward comparison. The two other methods appeared to be too harsh or resulted in a loss of monomer during the first step. The only parameter that was varied in the procedure of Li *et al.* was the catalyst. DBTO, $Ti(OiPr)_4$ and $Ti(OBu)_4$ were tested but the best results were obtained with $Ti(OBu)_4$ as the catalyst. The molecular weights for DMFDC based polyesters, given in Table 7, are rather low (< 10 kDa) compared to the ones of the DMS based polyesters, but in agreement with the challenging nature of DMFDC based polyester synthesis described in literature.[22-24] The polymer structure was confirmed by ^{1}H-NMR (Figure 7.11). The T_ds (± 315 °C) were in the same range as those of the DMS based polyesters, but the T_gs (65-95 °C) were higher as was expected from the use of the more rigid DMFDC. The T_g of the CHD based polyester (96 °C) is even higher than the T_g of PET (70 °C).[27] No material properties were determined as the molecular weights of the synthesized polymers were too low to ensure sufficient chain entanglements.[28]

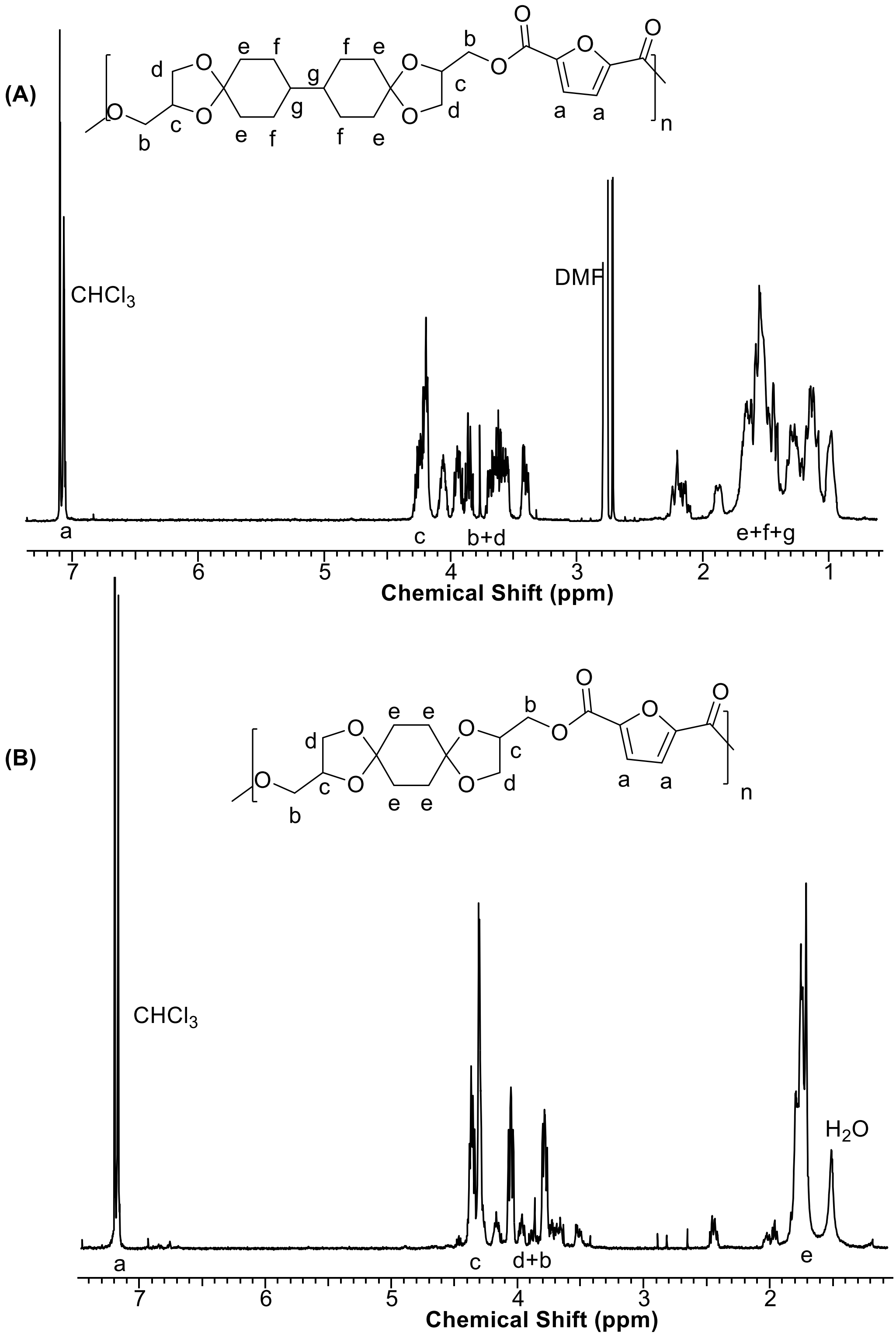


Figure 7.11. ^{1}H-NMR spectrum of the DMFDC polyesters from BCD (A) and CHD (B) in $CDCl_3$-d.

7.6 Hydrolytic stability

As all polymers contain ketal groups in their structure, it was decided to investigate the hydrolytic stability. For two weeks a polymer sample was immersed in an aqueous solution of a certain pH at 50 °C.[29] A pH of 1, 3, 5 and 7 was tested for one polyurethane (BCD + hMDI), one polycarbonate (CHD + DPC) and one polyester (CHD + DMS). After two weeks the samples were weighed and measured on the SEC to investigate whether degradation had occurred. No significant weight loss was observed after two weeks as more than 98% of the weight was retrieved. In order to confirm that no degradation had taken place, the materials were measured again on the SEC. No deviation from the original molecular weights was observed, even for polymers immersed in low pH solutions, so overall it can be concluded that the glycerol containing polymers are rather stable to acidic aqueous conditions.

7.7 Conclusion

In conclusion, two new rigid diols obtained from glycerol and two rigid diketones, i.e. 4,4’-bicyclohexanone and 1,4-cyclohexanedione, were synthesized by ketalization. The synthesis of BCD is fast, easy to scale up and the monomer can easily be purified. For CHD, longer reaction times are required and purification by column chromatography is needed, which complicates the upscaling. The two diols were used for the synthesis of three different polymer classes, being polyurethanes, polycarbonates and polyesters.

Eight different polyurethanes were synthesized and high molecular weights (M_n > 20 kDa) were obtained. The PU materials showed good thermal properties, such as high T_ds (> 300 °C) and high T_gs (100-150 °C). Moreover, the materials were transparent and showed high moduli (E = 1.10-1.35 GPa). However, the materials were brittle and exhibited low elongations at break (< 13%).

Polycarbonates were synthesized with diphenyl carbonate, which resulted in high molecular weight polymers (M_n > 24 kDa) with reasonably high T_g values (70-100 °C). The BCD based polycarbonate showed promising material properties such as ductility.

Finally, renewable polyesters were synthesized with both dimethyl succinate and dimethyl furanoate. Even after optimizing the reaction conditions, only moderate molecular weights were obtained for the polyesters. The T_ds were high (± 315 °C) and T_gs of up to 96 °C were obtained, depending on the dimethyl ester. However, no material testing could be performed on the polyesters due to too low molecular weights. Yet, the polyesters exhibit the highest biobased content (up to 100%) as compared to the polycarbonates (31-92%), and polyurethanes (20-55%). Hydrolytic stability tests in aqueous solutions of different pH’s (1-7) showed no degradation of these materials after two weeks. Diols based on rigid diketones in combination with glycerol were shown to be promising building blocks in a variety of polymer syntheses, in particular if a renewable diketone is used.

7.8 Experimental

7.8.1 Materials

N,N-Dimethylformamide (DMF, 99,8%), petroleum ether (pure), *p*-toluenesulfonic acid monohydrate (*p*-TsOH, 99%), and triethylamine (Et_3N 99%) were purchased from Acros Organics. Chloroform ($CHCl_3$, 99,8%), 1,8-diazabicycloundec-7-ene (DBU, 98%), dichloromethane (DCM, 99,8%), dimethyl succinate (DMS, 98%), diphenyl carbonate (DPC, 99%), ethylacetate (EtOAc, ≥99,7%), ethylacetate (Anhydrous) (EtOAc, 99,8%), ethylene glycol (EG, ≥99%), glycerol (99,5%), hexane (≥97%), methanol (MeOH, ≥99,9%); 4,4'-methylene diphenyl diisocyanate (MDI, 98%), 4,4'-methylenebis(cyclohexyl isocyanate) (hMDI, 90%), 1,3-propanediol (PD, 98%), toluene (99,9%), triazabicyclodecene (TBD, 98%) were purchased from Sigma-Aldrich. 4,4'-Bicyclohexanone (>98%), (±)-camphorquinone (98%), 1,4-cyclohexanedione (>98%), diacetyl (98%), dibutyltin dilaurate (DBTL, >95%), 2,5-furandicarboxylic acid (FDCA, >98%), isophorone diisocyanate (IPDI, >99%), 4-ketoisophorone (>95%), toluene diisocyanate (TDI, 98%) were purchased from TCI. Hydrochloric Acid (HCl, Chem lab, 36%), chloroform-d ($CDCl_3$, Euriso-Top, 99,8%), dimethylsulfoxide-d_6 (Euriso-Top, 99,8%), acetonitrile (Fisher Scientific, ≥99,9%), 2-butanone (Fluka Analytical, ≥99,5%), dibutyltin oxide (DBTO, Janssen Chimica, 98%), sodium bicarbonate ($NaHCO_3$, Roth, ≥99%), sodium Hydroxide (NaOH, Roth, ≥99%) and all previously mentioned substances were used as received.

7.8.2 Synthesis

7.8.2.1 1,4-Cyclohexanedione diketal glycerol

A one-neck flask was filled with 1 equivalent of 1,4-cyclohexanedione, 2.5 equivalents of glycerol and 5 mol% of *p*-TsOH as the catalyst. Toluene was added as solvent until a 0.5 M solution of 1,4-cyclohexanedione was obtained. The system was refluxed for 4 h under argon atmosphere using a Dean-Stark set-up. Hereafter, the reaction mixture was extracted with brine and the organic layer was dried with $MgSO_4$. The remaining solvent was removed *via* a rotary evaporator and the product was purified by column chromatography (toluene:methanol = 9:1, Rf = 0.1, basic aluminum oxide). A clear oil was obtained as end-product.

Isolated yield: 42%. **Molecular formula:** $C_{12}H_{20}O_6$. **Molecular weight:** 260.29 g mol^{-1}. **LC-MS (m/z):** 261.20 $[M+H]^+$. **^{1}H-NMR (300 MHz, $CHCl_3$-d):** δ (ppm) = 4.15 (p, 2H, 2xOC*H*CH_2OH), 3.96 (t, 2H, 2xOCH_2CH), 3.71 (m, 2H, 2xOCH_2CH), 3.63 (dd, 2H, 2xOCHCH_2OH), 3.52 (dd, 2H, 2xOCHCH_2OH), 2.74 (s, 2H, 2xOCHCH_2O*H*), 1.73 (t, 8H, C(CH_2CH_2)$_2$C)

7.8.2.2 4,4'-Bicyclohexanone diketal glycerol

A one-neck flask was filled with 1 equivalent of 4,4'-bicyclohexanone, 2.5 equivalents of glycerol and 5 mol% of *p*-TsOH as the catalyst. Toluene was added as solvent until a 0.5 M solution of 4,4'-bicyclohexanone was obtained. The system was refluxed for 1 h under argon atmosphere using a Dean-Stark set-up. Hereafter, the mixture was cooled and the formed precipitation was filtered off. The precipitate was then dissolved in ethylacetate, followed by an extraction with water and a washing step with a saturated bicarbonate solution. The organic layer was dried over $MgSO_4$ and the solvent was evaporated using a rotary evaporator, yielding the product as a white solid residue in the flask. The product was then dissolved in acetone and precipitated in hexane to ensure a higher purity of the product.

Isolated yield: 60%. **Molecular formula**: $C_{18}H_{30}O_6$. **Molecular weight**: 342.43 g mol^{-1}. **LC-MS (m/z):** 343.20 $[M+H]^+$. **T_m:** 130 °C. **^{1}H-NMR (300 MHz, $CHCl_3$-d):** δ (ppm) = 4.15 (m, 2H, $2\mathrm{xOC}\mathit{H}\mathrm{CH_2OH}$), 3.96 (m, 2H, $2\mathrm{xOC}\mathit{H_2}\mathrm{CH}$), 3.75-3.63 (band, m, 4H, $2\mathrm{xOC}\mathit{H_2}\mathrm{CH}$ and $2\mathrm{xOCHC}\mathit{H_2}\mathrm{OH}$), 3.51 (dd, 2H, $2\mathrm{xOCHC}\mathit{H_2}\mathrm{OH}$), 1.81-150 (band, m, 10H, $\mathrm{C(C}\mathit{H_2}\mathrm{C}\mathit{H_2}\mathrm{)_2CHCH(C}\mathit{H_2}\mathrm{C}\mathit{H_2}\mathrm{)_2C}$), 1.43-1.17 (band, m, 6H, $\mathrm{C(C}\mathit{H_2}\mathrm{C}\mathit{H_2}\mathrm{)_2CHCH(C}\mathit{H_2}\mathrm{C}\mathit{H_2}\mathrm{)_2C}$), 1.10 (m, 2H, $\mathrm{C(CH_2CH_2)_2C}\mathit{H}\mathrm{C}\mathit{H}\mathrm{(CH_2CH_2)_2C}$)

7.8.2.3 Synthesis of the polyurethanes

A dry three-neck flask equipped with a septum, a condenser and a mechanical stirrer was filled with 1 equivalent of diol, 1 equivalent of diisocyanate and 1 mol% of DBTL. Dry ethylacetate was then added as solvent. The flask was purged with argon and the reaction mixture was stirred at 70 °C overnight. The polymer precipitated from the solution, was filtered off, and washed with ethylacetate. The polymer was then dried under vacuum for 3 h at 150 °C.

7.8.2.4 Synthesis of the polyesters

Polyester synthesis (DMS). A dry Schlenk tube equipped with a mechanical stirrer was filled with 1.1 equivalents of diol, 1 equivalent of DMS and 0.6 mol% of DBTO. The tube was first purged with argon. The reaction was kept at 160 °C for 3.5 h, and the temperature was then increased to 180 °C for 30 min. Subsequently, the pressure was reduced to 200 mbar for 1 h at 180 °C. Finally, the pressure was further reduced to 5 mbar for 4 h at 180 °C. The reaction mixture was cooled down to room temperature; the polymer was then dissolved in DMF and precipitated in ice cold methanol. An example of the polyester set-up is given in the appendix (Figure A2).

Polyester synthesis (DMFDC). A dry Schlenk tube equipped with a mechanical stirrer was filled with 1.1 equivalents of diol, 1 equivalent of DMFDC and 0.1% of $Ti(OBu)_4$. The tube was first purged with argon. The following temperature program was used: 1 h @160 °C, 1 h @ 170 °C and 200 mbar, 2 h @ 180 °C and 200 mbar. Subsequently, the pressure was reduced to 1 mbar and, over a time period of 4 h, the temperature was raised from 180 °C to 230 °C. The reaction mixture was cooled down to room temperature; the polymer was then dissolved in DMF and precipitated in ice-cold methanol.

7.8.2.5 Synthesis of the polycarbonates

Polycarbonate synthesis (BCD). A dry Schlenk tube equipped with a mechanical stirrer was filled with 1 equivalent of diol, 1.1 equivalents of DPC 0.6 mol% $NaHCO_3$ as the catalyst. First, the polymerization mixture was kept at 200 °C for 1 h at atmospheric pressure, then the pressure was reduced to 200 mbar for 20 min. In the third step, the temperature was increased to 220 °C and the pressure reduced to 100 mbar for 20 minutes. For the fourth step, the pressure was further reduced to 50 mbar for 20 minutes. In step five, the temperature was increased to 240 °C and the pressure reduced to 25 mbar. Then, in the sixth step, the pressure was reduced to 4 mbar. As a seventh step, the temperature was further increased to 260 °C and the pressure reduced to 1 mbar for 20 minutes. As the final step, the temperature was raised to 280 °C and the pressure reduced to 0.5 mbar for 1 hour. The polycarbonate was then cooled down to room temperature, dissolved in DMF and precipitated in ice cold methanol. An example of the polycarbonate set-up is given in the appendix (Figure A2).

Polycarbonate synthesis (CHD). A dry Schlenk tube equipped with a mechanical stirrer was filled with 1 equivalent of diol, 1.1 equivalents of DPC and 0.6 mol% $NaHCO_3$ as the catalyst. First, the tube was kept at 160 °C for 1 h at atmospheric pressure followed by 20 min at 200 mbar. Then, the temperature was raised 10 °C every 20 min until 200 °C was reached. In the next step, the temperature was increased to 220 °C and the pressure was reduced to 100 mbar for 20 min. For the fourth step, the pressure was further reduced to 50 mbar for 20 minutes. In step five, the temperature was increased to 240 °C and the pressure reduced to 25 mbar. Then, in the sixth step, the pressure was reduced to 4 mbar. As a seventh step, the temperature was further increased to 260 °C and the pressure reduced to 1 mbar for 20 min. As the final step, the temperature was raised to 280 °C and the pressure reduced to 0.5 mbar for 1 h. The polycarbonate was then cooled down to room temperature, dissolved in DMF and precipitated in ice cold methanol.

7.8.2.6 Polymer processing

Polymer processing (PU). A fixed amount of polymer (0.65 g) was placed in a mould and the material was pre-dried for 30 min in a vacuum oven at 170 °C. Hereafter, the mould was pressed for 5 min at 0.2 metric tons. The pressure was then released, after which the mould was pressed again at 3 metric tons for 5 min.

Polymer processing (PC). First of all, the polymer material was pre-dried for 30 min. in a vacuum oven at 170 °C. Hereafter, the material was placed between two layers of teflon and pressed at 3 metric tons. This step was repeated up to three times until the material was free of bubbles.

7.8.3 Methods

^{1}H-NMR

^{1}H-NMR spectra were recorded on a Bruker Avance 300 at 300 MHz. Chemical shifts are presented in parts per million (δ) relative to either $CHCl_3$-d (7.27 ppm) or DMSO-d_6 (2.50 ppm) as internal standards.

LC-MS

LC-MS analyses were performed on an Agilent Technologies 1100 series LC/MSD system with a diode array detector (DAD) and a single quad MS.

TGA

Thermogravimetric analyses (TGA) were performed with a Mettler Toledo TGA/SDTA851e instrument under nitrogen atmosphere at a heating rate of 10 °C min^{-1} from 25 °C to 800 °C.

DMA-SEC

Size exclusion chromatography measurements were performed on a Waters instrument, equipped with 3 Polymer Standards Services GPC serial columns (1 X GRAM Analytical 30Å, 10µm and 2 x GRAM Analytical 1000Å, 10µm) at 35 °C with a RI detector (2414 Waters). PMMA standards were used for calibration and DMA containing LiBr (0.42 g mL^{-1}) was used as a solvent at a flow rate of 1mL min^{-1}. Molecular weights and dispersities were determined using Empower software.

$CHCl_3$-SEC

Size exclusion chromatography measurements were also performed on a Waters instrument, equipped with Waters Styragel HR3, HR4 and HR5 serial columns (5µm particle size) at 35 °C with a RI detector (2410 Waters), using PS standards for calibration, and $CHCl_3$ as an eluent at a flow rate of 1.0mL min^{-1}. Molecular weights and dispersities were determined using the Breeze Millennium software.

DSC

Differential scanning calorimetry (DSC) was performed with a Mettler Toledo instrument 1/700 under nitrogen atmosphere at a heating rate of 10 °C min^{-1}. For all DSC results, the information obtained from second heating was used.

Tensile testing

Tensile testing was performed on a Tinius-Olsen H10KT tensile tester, equipped with a 100 N load cell, using a flat dog bone type specimen with an effective gage length of 13 mm, a width of 2 mm, and a thickness of 1.3 mm. The samples were cut out using a RayRan dog bone cutter. The tensile rests were run at a speed of 10 mm min^{-1}.

7.9 References

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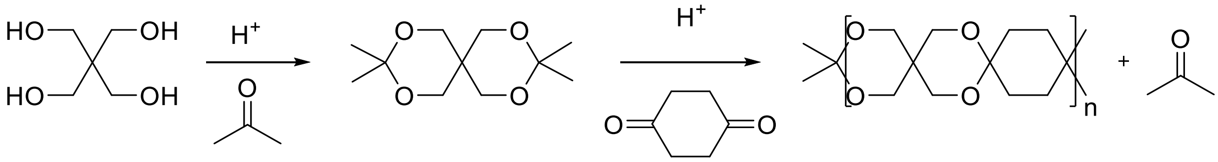
Abstract

In the three previous chapters, a compromise between renewability of the building blocks and favorable thermal and mechanical properties of the polymers was made. Therefore, the transketalization of digycerol bisacetonide, a fully renewable monomer, with renewable diketones was explored. As literature on the subject of transketalization as a polycondensation method is scarce, optimizing and defining the polymerization conditions presented a main challenge for this chapter.

Chapter 8: Transketalization

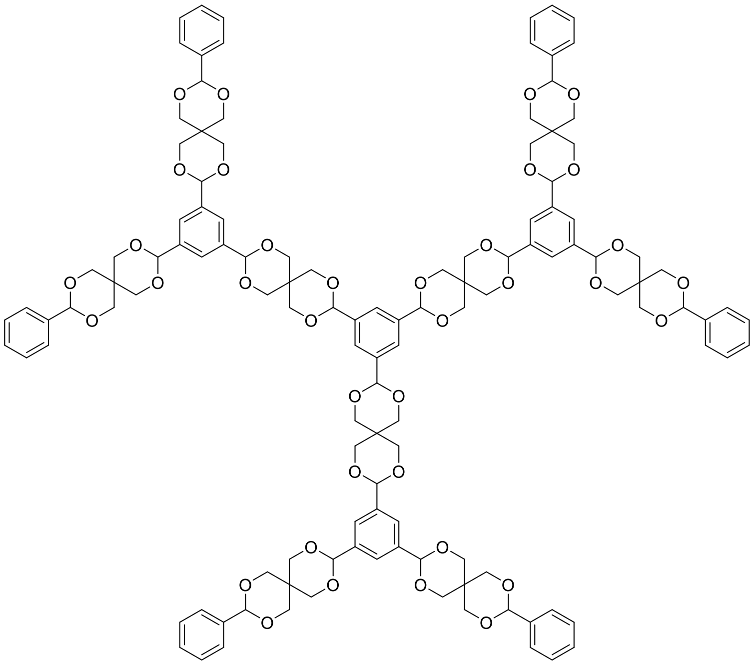
8.1 Introduction and aim

Transacetalization/ketalization as a polymerization method for poly(cycloacetal/ketals) is rarely reported in the literature (*vide infra*), but it is more frequently reported for the synthesis of linear polyacetals/ketals.[1-3] These linear polymers could be applied as acid-sensitive drug delivery vehicle, which are designed to target therapeutics to the acidic environments of tumors, inflammatory tissues and phagosomes. The transacetalization/ketalization reaction is in principle an exchange of the hydroxyl and carbonyl components of acetals or ketals. In order to illustrate the reaction, it is explained by means of an example given in Scheme 8.1. In fact, a tetraol, here pentaerythritol, is transformed into an acetal/ketal with a volatile aldehyde/ketone like acetone first. Hereafter, a dicarbonyl, which is significantly less volatile than the carbonyl component present in the acetal/ketal monomer, is used in the acid catalyzed transacetalization/ketalization reaction. The acid catalyzes the exchange of the carbonyl functionalities while the volatile carbonyl compound is removed from the system to shift the equilibrium to the poly(cycloacetal/ketal).



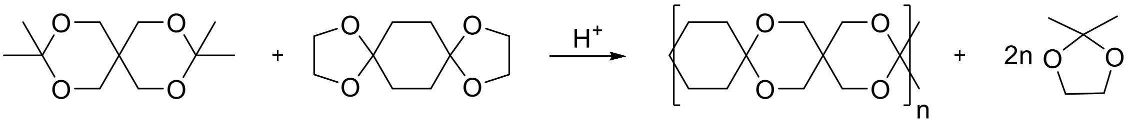
Scheme 8.1. Example of the acid catalyzed transketalization reaction with pentaerythritol acetonide and 1,4-cyclohexanedione.

To our knowledge, only two publications report on the transacetalization/ketalization reaction to synthesize poly(cycloacetal/ketals). The work of Lemcoff *et al.* is based on pentaerythritol, which is used in transacetalization reactions for the formation of dendrimers.[4] The authors used sequential transacetalization and protection-deprotection techniques to prepare macromolecular polyacetals from pentaerythritol and benzene-1,3,5-tricarboxaldehyde (Scheme 8.2). This report described the methodology and molecular modelling of these dendrimer structures, but possible applications were not included.



Scheme 8.2. Polyacetal dendrimer based on pentaerythritol and benzene-1,3,5-tricarboxaldehyde.

Another publication reports on the transketalization route as a tool to obtain spiropolymers from 1,4-cyclohexanedione and pentaerythritol.[5] Transketalization reactions between a diketal of 1,4-cyclohexanedione and a diketonide of pentaerythritol yielded a spiropolymer, which was unsoluble but which could be hydrolyzed to 1,4-cyclohexanedione and pentaerythritol (Scheme 8.3). At short reaction times, oligomers were isolated, but no polymers could be synthesized and characterized. This can be attributed to the very rigid structure of this pentaerythritol based poly(cycloketal).



Scheme 8.3. Transketalization of 1,4-cyclohexanedione bis(ethylene ketal) and pentaerythritol bisacetonide.

In summary, transketalization/acetalization was until now only explored for bisacetonides of pentaerythritol, and did not result in the synthesis of poly(cycloketal/acetals) with high molecular weights. Therefore, a new renewable tetraol with a more flexible structure was investigated as a monomer for transketalizations/acetalizations.

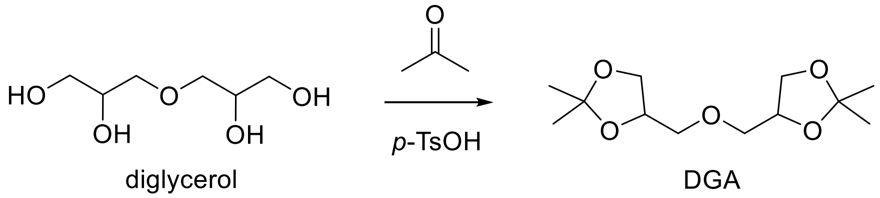
This chapter reports on the synthesis of diglycerol bisacetonide, which was polymerized in a next step with renewable dicarbonyls employing an acid catalyst. As no well established method is available for these kinds of transketalization polymerizations, identifying a good method was targeted first. In the end, the resulting polymers were extensively characterized.

8.2 Polytransketalization of diglycerol bisacetonide with diketones

Diglycerol (Scheme 8.4) is a renewable compound, which is synthesized *via* the condensation of glycerol molecules at high temperatures.[6] It is easily accessible and a cheap bulk chemical, but it is not available in a high purity. Typically, 10-15% of mono- or triglycerol are present in commercially available samples. These impurities make it impossible to directly use commercially available diglycerol as a monomer in the synthesis of thermoplastic polyacetals/ketals of high molecular weight, since branching/crosslinking and chain stopping cannot be avoided. However, it is possible to make use of the diglycerol building block in a polytransacetalization/ketalization procedure. After reacting the crude diglycerol with a small dicarbonyl like acetone, it is possible to separate the diglycerol bisacetonide from the acetals of glycerol and triglycerol by distillation and to obtain the compound in a suitably high purity.[7-8] This approach, therefore enables the use of the cheap and fully renewable diglycerol in polymerization reactions to obtain renewable poly(cycloacetal/ketals).

Commercially available diglycerol was first reacted with 1,4-cyclohexanedione and 4,4'-bicyclohexanone to investigate whether it could be directly used for polyketalization reactions. The polymerization was catalyzed with acid and vacuum was applied to remove the water. After short reaction times (1 h), low molecular weight polymers ($M_n \leq 4$ kDa, Đ = 2.0) with broad dispersities were obtained. At longer reaction times (3-8 h) an unsoluble product is obtained. From these preliminary results, it was concluded that the direct application of diglycerol in polyketalizations does not lead to the desired thermoplastic poly(cycloketal).

8.2.1 Synthesis of diglycerol bisacetonide



Scheme 8.4. The synthesis of diglycerol bisacetonide.

Diglycerol was received in 90% purity from Solvay, containing mainly monoglycerol and polyglycerol as impurities.[9] The reaction of diglycerol with acetone (Scheme 8.4) was already reported in the literature[8] but the synthesis procedure was adjusted, so that it could be performed on a larger scale in a facile manner employing straightforward purification methods. The synthesis was performed on a 100 g scale with acetone (technical grade) as the solvent at room temperature and purification was achieved by distillation. The absence of resonances corresponding to ketones and hydroxyl groups in the ^{1}H-NMR spectrum confirmed that pure diglycerol bisacetonide (DGA) was obtained (Figure 8.1).

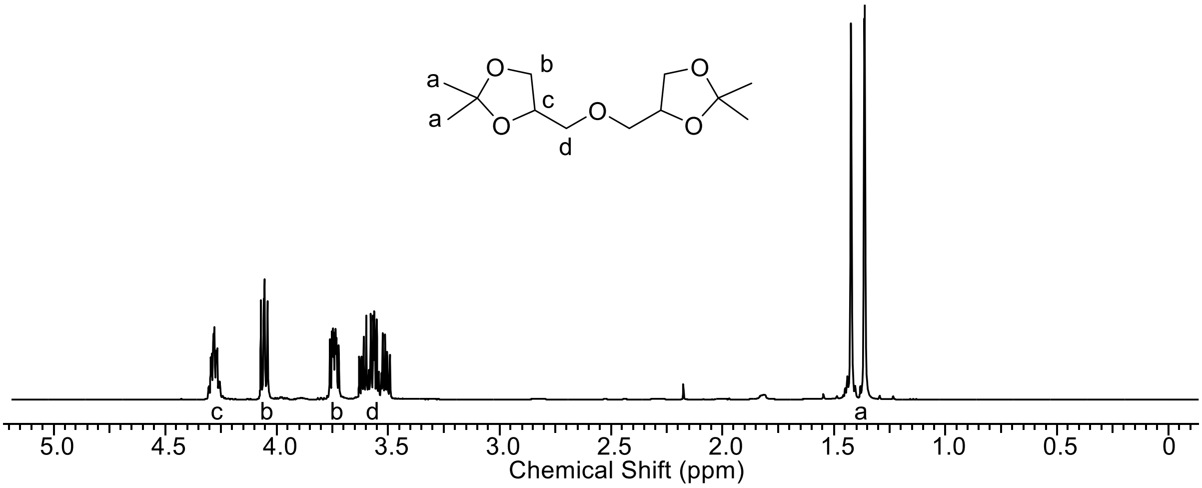


Figure 8.1. ^{1}H-NMR of the pure diglycerol bisacetonide.

As discussed in Chapter 4, the purity of the monomers is crucial in polycondensations. Therefore HPLC-MS measurements were performed to further investigate the purity of the monomer (Figure 8.2). A single major signal was observed in HPLC, and the corresponding compound exhibits the mass of DGA plus one in the mass spectrometry analysis.

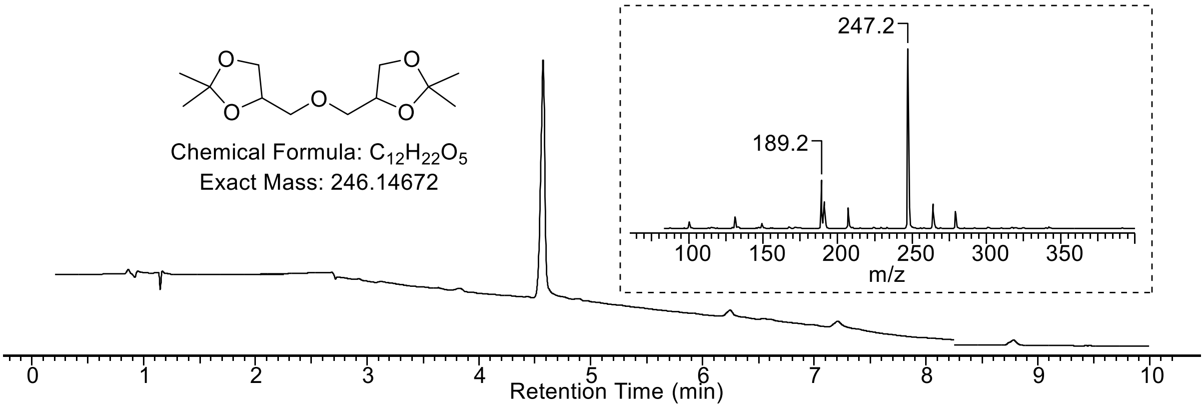
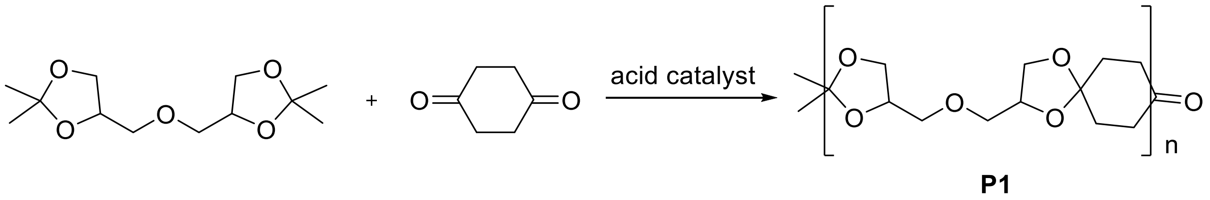


Figure 8.2. HPLC trace with MS analysis (insert, positive mode) of the purified diglycerol bisacetonide. Masses corresponding to M(diglycerol bisacetonide)+1 (247.2 Da) and M(acetone) (189.2 Da) were detected.

8.2.2 Development of the general polymerization method

A standard method needed to be developed for polymerization via transketalization to test this method for polymerizations in a reproducible manner. The condensate that is formed when using the DGA monomer, is acetone, which needs to be removed from the reaction mixture to ensure high molecular weight polymers. Furthermore, the ideal ratio of monomers and a suitable catalyst needed to be determined. All reactions for the development of the general procedure were performed with 1,4-cyclohexanedione as the dicarbonyl compound resulting in **P1** as the polymer (Scheme 8.5).



Scheme 8.5. Transketalization of DGA with 1,4-cyclohexanedione, resulting in P1.

Initially, the monomers were simply mixed with *p*-TsOH as the catalyst in bulk under vacuum, but this directly resulted in solidification of the reaction mixture at room temperature. The reaction mixture remained solid upon increasing the temperature to 150 °C. In this way, only low molecular weight polymers were obtained ($M_n < 4$ kDa). Therefore, another method was developed, in order to keep the polymer in solution or in the melt. First, a high boiling solvent (DMSO) under reduced pressure (400 mbar) was used instead of reacting the monomers in bulk. Next, different equivalent ratios of the monomers were tested. Normally, an equimolar ratio is ideal for polycondensation reactions, but it is known for example in polyester synthesis that a slight excess of the more volatile monomer can result in higher molecular weights. The results of this study are summarized in Table 8.1 and revealed that 1.05 equivalents of DGA gave the highest molecular weights.

Table 8.1. Results for the polytransketalization of varying amounts of DGA and 1.00 equiv of 1,4-cyclohexanedione.

equiv DGA	M_n	Đ
1.00	9.1	1.66
1.05	10.8	1.74
1.10	6.9	1.99
1.15	6.8	1.59

Hereafter, different acid catalysts were tested, namely Brønsted acids (*p*-TsOH & HCl) and Lewis acids (DBTO, Ti(O*i*Pr)$_4$ & Sb_2O_3). After *p*-TsOH, which was already successfully employed as a catalyst in the earlier study, DBTO was applied next. No reaction occurred, which may be due to the fact that no hydroxyl group is initially present in the reaction mixture to activate the catalyst.[10] Thermal analysis data revealed a melting point higher than 200 °C for **P1**, which suggested that high temperatures may be needed to obtain high molecular weights polymers. Therefore, the thermal stability of the Lewis acid catalysts was tested with isothermal TGA at 240 °C for 3 hours. While Sb_2O_3 showed no mass loss over this period of time, Ti(O*i*Pr)$_4$ showed mass loss of about 50% already after 10 min and DBTO showed a mass loss of 10% after 80 min. Taking these results into account, it was decided not to investigate Lewis acid catalysis for polytransketalizations further. Finally, HCl was tested as catalyst, which resulted in a dark coloration of the reaction mixture. Moreover, the conversions were much lower in the same reaction time as for *p*-TsOH, so it was chosen to keep working with *p*-TsOH as the acid catalyst.

Although the transketalization proceeded well with DMSO as a solvent, toluene was investigated as a solvent as well, since DMSO is a comparatively expensive solvent and prone to decomposition and side reactions at elevated temperatures, resulting in an undesirable pungent odor. Since toluene exhibits a significantly lower boiling point (110 °C) than DMSO, a two-step procedure was investigated. In the first step, toluene was used as a solvent and the dimerization was followed by ^{1}H-NMR. After completion (2 h), the solvent was evaporated and the polymerization was continued in bulk at gradually increasing temperatures and gradually decreasing pressure. This second step proved to be difficult since it typically resulted in fast solidification and consequently crosslinked polymer. Eventually, improved results (no solidification or crosslinking) were obtained by maintaining the reaction mixture in the second step at a temperature of 250 °C under a nitrogen flow. Although this temperature is higher than the melting temperature of ±210 °C of **P1**, the reaction mixture remained in the solid state. However, employing a nitrogen flow instead of high vacuum resulted in much slower solidification and thus in higher molecular weights. The reaction temperature was not increased further to avoid degradation (see below).

Nevertheless, this two-step procedure did not result in higher molecular weights than the previous polytransketalization in solution in DMSO. Thus, finally, a two-step procedure comprising a first step in solution in DMSO, followed by a second step in bulk at 250 °C under nitrogen flow, was established as the procedure yielding the polymers with the highest molecular weights (M_n > 20 kDa). The best results obtained with the different methods are displayed in Table 8.2. Yet, polytransketalization did occur to some extent in toluene, and since different solubilities and thermal properties are expected for different dicarbonyl monomers, both toluene and DMSO will be considered as solvents in the next paragraph.

Table 8.2. Overview of the SEC and thermal analysis results of the polymers from DGA and 1,4-cyclohexanedione via three different methods.

Method	M_n (kDa)	Đ	T_g (°C)	T_m (°C)	ΔH (J/g)	T_d (°C)
Bulk	4	2.3	47	-	-	180
DMSO 2 step	24	2.1	48	210	44.3	315
Toluene 2 step	12	1.8	46	203	45.6	310

8.2.3 Polytransketalization of different diketone monomers with DGA

Four different diketones were considered for the polytransketalization with DGA, based on the results from the model study in chapter 5. Acetonylacetone, camphorquinone and 1,4-cyclohexanedione are renewable diketones, while 4,4'-bicyclohexanone is an interesting diketone beacuse of its rigid structure, but it is not biobased. The reactions with camphorquinone did not result in any polymer, which is probably due to the steric hindrance resulting from the structure of this diketone. It is known from the literature that reaction times are long for camphorquinone as a monomer.[11] The chemical structures of the polymers obtained from DGA and 1,4-cyclohexanedione (**P1**), 4,4'-bicyclohexanone (**P2**) and acetonylacetone (**P3**) were confirmed by ^{1}H-NMR spectroscopy (Figure 8.3). The SEC and thermal analysis results of the poly(cycloketals) obtained via polytransketalization are summarized in Table 8.3 for both polymerization procedures in toluene and DMSO as the solvents, respectively.

Table 8.3. Overview of the SEC ($CHCl_3$) and thermal analysis results of the poly(cycloketals) synthesized via polytransketalization.

Polymer	Method	M_n (kDa)	Đ	T_g (°C)	T_m (°C)	ΔH (J/g)	T_d (°C)
P1	DMSO 2 step	24	2.1	48	210	44.3	315
	Toluene 2 step	12	1.8	46	203	45.6	310
P2	DMSO 2 step	27	3.8	78	241	33.0	360
	Toluene 2 step	8.2	2.9	87	-	-	310
P3	DMSO 2 step	-	-	-	-	-	-
	toluene 2 step	3.3	1.83	-23	-	-	140

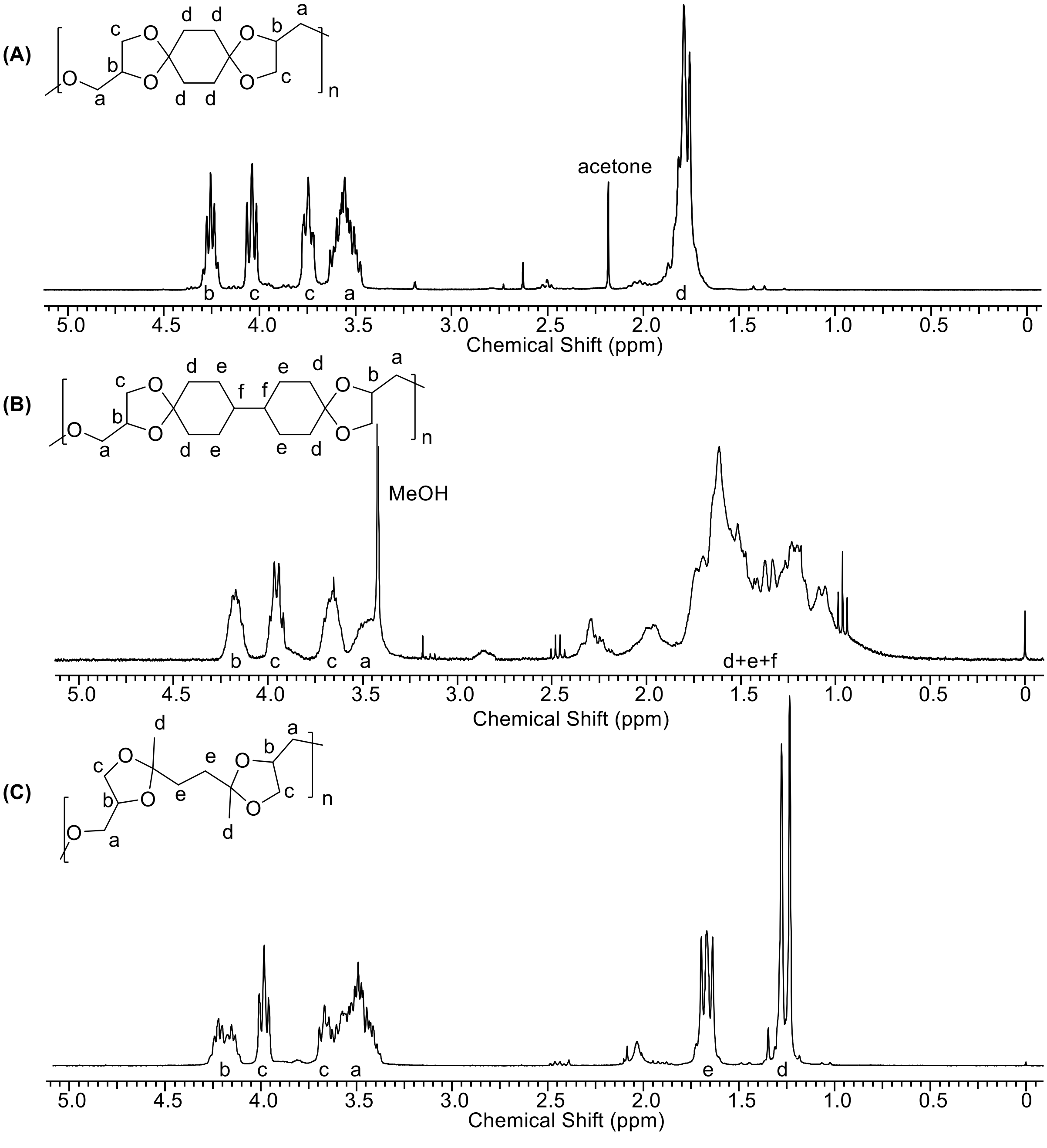


Figure 8.3. ^{1}H-NMR of the poly(cycloketals) P1 (A), P2 (B) and P3 (C)

The polymerization of 4,4'-bicyclohexanone (**P2**) resulted in higher molecular weight polymers when the procedure in DMSO was used. **P2** showed to have a higher T_g (= 87 °C) than **P1** and also had a high melting point of 240 °C. On the other hand, the polymerization of acetonylacetone with DGA was rather challenging. When using DMSO as a solvent, a black unsoluble precipitate was realized, whereas, using toluene as a solvent, a brown and sticky material was obtained. However, only low molecular weight polymers with a maximum M_n of 3.3 kDa were obtained. Moreover, because of the high flexibility of acetonylacetone, the T_g of this polymer is low (T_g = -23 °C).

P1 and **P2** were thermally stable above 300°C while **P3** showed a low degradation temperature. This phenomenon was also observed previously (paragraph 5.1.3.3), when acetonylacetone was polymerized with di-TMP.

Initially, **P1** was processed to investigate its mechanical properties as it showed a high enough molecular weight. For processing of the polymer by hot pressing, temperatures of 240 °C or higher are required because of the melting point of 210 °C. Yet, the combination of the pressure and this high temperature resulted in degradation of the polymer. Visually, the polymer changed from a light brown color to a dark brown color and SEC measurements revealed a significant decrease in molecular weight, from M_n = 24 kDa to M_n = 5.5 kDa. It is not unusual for semi-crystalline polymers with acetal units having a high oxygen content (e.g. cellulose), to degrade rather than undergo a melting transition. [12-13]

Due to lack of time, no processing of **P2** was performed. Nonetheless, **P2** had a high molecular weight but displayed a higher melting temperature than **P1**, which would most probably also result in problems during compression moulding.

To circumvent the high temperatures during processing of **P1,** we considered lowering the crystallinity and reduction of the melting temperature by copolymerization.

8.2.4 Co-polytransketalization

The polymerization of 1,4-cyclohexanedione with DGA resulted in high molecular weight poly(cycloketals), which were semi-crystalline. Due to the high melting point, hot pressing required high temperatures and resulted in degradation of the polymer. In order to facilitate processing of the polymers, 1,4-cyclohexanedione was copolymerized with DGA and varying amounts of di-TMP. The latter tetraol was already investigated in combination with 1,4-cyclohexanedione (section 5.1.3.3), yielding amorphous polymers with a high T_g of 106 °C. Therefore, incorporating di-TMP as a comonomer is expected to reduce the crystallinity and the melting point compared to **P1** and at the same time increase the T_g (T_g(**P1**) = 48 °C) as a highly favorable side effect.

The copolymers were synthesized in the same way as **P1** and NMR analysis revealed that di-TMP is incorporated in accordance with the feed ratio of the two tetraols. As can be seen from Table 8.4, an increase in T_g is observed when di-TMP is used as comonomer. Moreover, di-TMP reduces the crystallinity and a fully amorphous polymer was obtained when 25% of di-TMP or more was incorporated in the polymer. When di-TMP is used, the biobased carbon content in the resulting polymer diminishes, but nevertheless rather high values were realized.

First attempts were made to process (compression moulding) the synthesized copolymers and transparent brownish materials were obtained. SEC measurements of the processed materials confirmed that no degradation took place during processing. Unfortunatly, air bubbles were still present in the materials, which made mechanical analysis not yet possible. The copolymerization approach looks very promising but the processing procedure must be further optimized.

Table 8.4. Overview of the SEC ($CHCl_3$), DSC and TGA results of the copolymers from DGA, di-TMP and 1,4-cyclohexanedione.

% DGA	% di-TMP	M_n (kDa)	Đ	T_g (°C)	T_m (°C)	ΔH (J/g)	T_d (°C)	% biobased
0	100	25	1.8	106	-	-	315	33
50	50	13.1	3.6	72	-	-	320	60
75	25	13.2	2.4	63	-	-	320	78
90	10	12.2	2.6	55	157	9.86	330	90
100	0	24	2.1	48	210	44.31	315	100

In the future, copolymers where the diketone, 1,4-cyclohexanedione, is partially replaced by other diketones can be considered as well to obtain amorphous materials that are more easily processable.

8.3 Conclusion

A bisketal from diglycerol was synthesized on a large scale *via* an easy process from crude diglycerol and technical acetone. This bisketal could be used in the transketalization reaction with diketones in order to obtain fully renewable poly(cycloketals). First, a general procedure was developed to use transketalization as a polymerization reaction as this is rarely reported in literature. Different catalysts, monomer ratios and temperature-pressure programs were investigated. The best results were observed with *p*-TsOH as the catalyst and the use of a 1.00 (diketone) to 1.05 (DGA) ratio. The DMSO 2-step procedure yielded the highest molecular weight polymers. With 1,4-cyclohexanedione and 4,4'-bicyclohexanone, high molecular weight polymers could be obtained and the polymers were semi-crystalline with a high melting temperature (resp. T_m = 210 °C & T_m = 241 °C). Because of this high melting temperatures, the polymer based on 1,4-cyclohexanedione degraded when processed *via* compression moulding. Therefore, copolymers were synthesized with di-TMP as comonomer. When at least 25% of di-TMP is incorporated, a fully amorphous poly(cycloketal) was obtained. Moreover, the T_g values increased when more di-TMP was used but no degradation was observed when these polymers were processed. Mechanical analysis must still be performed and alternative comonomers can be explored.

8.4 Experimental section

8.4.1 Materials

N,N-Dimethylformamide (DMF, 99,8%), *p*-toluenesulfonic acid monohydrate (*p*-TsOH, 99%), and triethylamine (Et_3N 99%) were purchased from Acros Organics. 4,4'-Bicyclohexanone (>98%), (±)-camphorquinone (98%), (±)-10-camphorsulfonic acid (>98.0%), 1,4-cyclohexanedione (>98%) and titanium(IV) isopropoxide were purchased from TCI. Aluminium oxide (basic Bruckmann I), antimony (III) oxide (99.9%), chloroform ($CHCl_3$, 99.8%), di-trimethylolpropane (di-TMP, 97%), ethyl acetate, hexane, methanol (MeOH), toluene (99.9%) and triethylamine (99%) were purchased from Sigma Aldrich. Diglycerol (90%) was received from Solvay. Acetone (technical grade, UNIVAR), chloroform-d ($CDCl_3$, Euriso-Top, 99.8%), dibutyltin oxide (DBTO, Janssen Chimica, 98%), dimethylsulfoxide-d6 (Euriso-Top, 99.8%), hydrochloric Acid (HCl, Chem lab, 36%), and all previously mentioned substances were used as received.

8.4.2 Synthesis

8.4.2.1 Synthesis of diglycerol bisacetonide

To diglycerol in a round bottom flask equipped with a mechanical stirrer (100.00 g, 1.00 equiv, 0.6 mol, Solvay sample) acetone is added as a solvent and reactant (2 L, technical grade). Upon addition of *p*-TsOH (5.70 g, 5 mol%, 30 mmol) the digylcerol slowly starts to solubilize. The reaction mixture is stirred overnight at ambient conditions (open to air).

Two different work-up procedures are possible to purify the monomer and are given below.

OPTION A

The reaction mixture was neutralized with Et_3N and subsequently concentrated under reduced pressure. The residue is filtered over silicagel (and eluted with nHex/EtOAc: 1/1 + 5 vol % Et3N. The collected fractions were concentrated and a vacuum distillation (Claisen piece, ca. 1 mbar, 88 °C) was performed.

OPTION B

The reaction mixture was filtered over alumina (Al_2O_3, basic, Brockmann I) to remove *p*-TsOH and the filtrate was concentrated under reduced pressure. Next, a vacuum distillation (Vigreux, Claisen piece, ca. 1 mbar, 88 °C) was performed to obtain pure product.

Note: yield of purified diglycerol bisacetonide (colorless liquid): 60 - 65%, regardless of the work-up. Both options are effective for removing the acid catalyst. Option A results in a straightforward distillation (one fraction, and residue). Option B avoids the filtration over silica but an additional major fraction is collected during the distillation (solketal: bp ca. 30 °C, 1 mbar, ca. 6 g) and a residue remains as well.

Isolated yield: 60-65%. **Molecular formula:** $C_{12}H_{25}O_5$. **Molecular weight:** 246.30 g mol^{-1}. **^{1}H-NMR (400 MHz, $CHCl_3$-d):** δ (ppm) = 4.29 (m, 2H, C*H*CH_2OCH_2), 4.06 (dd, 2H, CO*CH*$_2$CH), 3.74 (m, 2H, CO*CH*$_2$CH), 3.57 (m, 4H, CH*CH*$_2$$OCH_2$), 1.46 and 1.39 (s, 12H, C*H*$_3$C).-**^{13}C NMR (125 MHz, $CHCl_3$-d):** δ (ppm) = 109.38 (Cq), 74.57 (CH), 72.56 (CH_2), 66.63 (CH_2), 26.70 (CH_3), 25.35 (CH_3).

8.4.2.2 Optimization of the ratio DGA/1,4-cyclohexanedione

DGA and 1,4-cyclohexanedione (1.00 g, 1.00 equiv, 8.92 mmol) were added in a Schlenk-flask equipped with a mechanical stirrer and heated to 120 °C until complete dissolution. Subsequently, 0.03 g *p*-TsOH monohydrate (0.02 equiv, 0.18 mmol) were added in 1.50 mL DMSO and the pressure was reduced to 400 mbar for 80 min maintaining a temperature of 120 °C. The temperature was raised to 140 °C at 400 mbar and the reaction mixture was kept overnight under these conditions. Approximately 1 mL of triethylamine was added to quench the reaction, and after dissolution in chloroform the polymer was precipitated in methanol containing 10% v/v triethylamine, filtrated, and dried *in vacuo* at 40 °C overnight.

8.4.2.3 Polytransketalization in DMSO *via* a two-step procedure

The diketone (1.00 equiv) and DGA (1.05 equiv) were heated in a round bottom flask equipped with a mechanical stirrer to 110 °C until complete dissolution. *p*-TsOH monohydrate (2 mol%) was added in DMSO (1.50 mL/1.00 g diketone) and the temperature was raised to 150 °C at 400 mbar. After 6 h the pressure was reduced to approx. 10 mbar to remove the DMSO. At the same time, the temperature was increased to 250 °C. After the removal of the DMSO the reaction mixture was kept at 250 °C under a flow of nitrogen for 1 h. The reaction mixture was cooled to ambient temperature and chloroform, containing 10% v/v, was added for dissolution. The polymer solution was passed over a short column of basic alumina to remove unsoluble gel-like particles and catalyst residues, precipitated in methanol containing 10% v/v triethylamine, and the precipitate was dried *in vacuo* overnight at 40 °C.

8.4.2.4 Polytransketalization in toluene *via* a two-step procedure

1,4-Cyclohexanedione

1,4-Cyclohexanedione (1.00 g, 1.00 equiv, 8.92 mmol), DGA (2.30 g, 1.05 equiv, 9.34 mmol)and *p*-TsOH (0.03 g, 2 mol%, 0.17 mmol) are dissolved in 10 mL toluene in a round bottom flask equipped with a mechanical stirrer and a Liebig condenser. Toluene is slowly distilled off at a bath temperature of 125 °C for 2.5 h. Subsequently, the temperature is raised to 150 °C and after almost all the toluene (80%) is removed, the temperature is raised to 220 °C. After 15 min a gentle flow of nitrogen is applied and the reaction mixture is kept at 220-240 °C under a gentle flow of nitrogen until the reaction mixture solidifies and cannot be agitated anymore (max 1 h). Triethylamine (2 mL) is added to quench the polymerization when cooled down. After dissolution in chloroform, the polymer was precipitated in methanol and dried *in vacuo* at 40 °C overnight.

4.4'-Bicyclohexanone

4,4'-bicyclohexanone (1.00 g, 1.00 equiv, 5.15 mmol), DGA (1.33 g, 1.05 equiv,5.40 mmol) and *p*-TsOH (0.02 g, 2 mol%, 0.10 mmol) are dissolved in 10 mL toluene in a round bottom flask equipped with a mechanical stirrer and a Liebig condenser. Toluene is slowly distilled off at a bath temperature of 125 °C for 3 h. Subsequently, the temperature is raised to 150 °C and after 2 h under a gentle flow of nitrogen, the pressure was lowered to 1 mbar for half an hour. Triethylamine is added to quench the polymerization after cooling to ambient temperature. After dissolution in chloroform, the polymer was precipitated in methanol and dried in vacuo at 40 °C overnight.

Acetonylacetone

Acetonylacetone (2.00 g, 1.00 equiv, 13.9 mmol), DGA (3.59 g, 1.05 equiv, 14.6 mmol) and 2 tips of a spatula of camphorsulfonic acid are dissolved in 20 mL toluene in a round bottom flask equipped with a mechanical stirrer and a Liebig condenser. Toluene is slowly distilled off at a bath temperature of 125 °C for 2.3 h. Subsequently the temperature is raised to 130 °C and after 1 h to 140 °C. After 45 min a gentle flow of nitrogen is applied and the reaction mixture is kept at 140 °C under a gentle flow of nitrogen overnight. Triethylamine is added to quench the polymerization. After dissolution in chloroform, the polymer was precipitated in methanol containing 10% v/v triethylamine and dried *in vacuo* at 40 °C overnight.

8.4.2.5 Co-Transketalization

The diketone 1,4-cyclohexanedione (1.00 equiv), DGA and di-TMP (1.05 equiv in total) were heated in a round bottom flask equipped with a mechanical stirrer to 110 °C until complete dissolution. *p*-TsOH monohydrate (2 mol%) was added in DMSO (1.50 mL/1.00 g diketone) and the temperature was raised to 150 °C at 400 mbar. After 6 h the pressure was reduced to approx. 10 mbar to remove the DMSO. At the same time, the temperature was increased to 175 °C. After the removal of the DMSO the reaction mixture was kept at 175 °C under a flow of nitrogen for 1 h. The reaction mixture was cooled to ambient temperature and chloroform, containing 10% v/v, was added for dissolution. The polymer solution was passed over a short column of basic alumina to remove unsoluble gel-like particles and catalyst residues, precipitated in methanol containing 10% v/v triethylamine, and the precipitate was dried *in vacuo* overnight at 40 °C.

8.4.3 Methods

^{1}H-NMR

^{1}H-NMR spectra were recorded on a Bruker Avance 300 at 300 MHz. Chemical shifts are presented in parts per million (δ) relative to either $CHCl_3$-d (7.27 ppm) or DMSO-d_6 (2.50 ppm) as internal standards.

LC-MS

An Agilent Technologies 1100 series LC/MSD system equipped with a diode array detector (DAD) and a single quad MS was used to perform LC-MS analyses. Analytical Reversed Phase HPLC-analyses were performed using a Phenomenex Lunca C18 (2) column (5µm, 250 mm x 4.6 mm) and a solvent gradient (0-100% acetonitrile in water in 15 minutes). A UV-detector (λ = 214 nm) was used to detect the eluting compounds. The electrospray mass spectra recordings were made using a single quad MS detector (VL) with electrospray ionization.

DMA-SEC

Size exclusion chromatography measurements were performed on a Waters instrument, equipped with 3 Polymer Standards Services GPC serial columns (1 X GRAM Analytical 30Å, 10µm and 2 x GRAM Analytical 1000Å, 10µm) at 35 °C with a RI detector (2414 Waters). PMMA standards were used for calibration and DMA containing LiBr (0.42 g mL^{-1}) was used as a solvent at a flow rate of 1 mL min^{-1}. Molecular weights and dispersities were determined using the Empower software.

$CHCl_3$-SEC

Size exclusion chromatography measurements were also performed on a Waters instrument, equipped with Waters Styragel HR3, HR4 and HR5 serial columns (5µm particle size) at 35 °C with a RI detector (2410 Waters), using PS standards for calibration, and $CHCl_3$ with 5% trimethylamine as an eluent at a flow rate of 1.0 mL min^{-1}. Molecular weights and dispersities were determined using the Breeze Millennium software.

TGA

Thermogravimetric analysis (TGA) were performed on a Mettler Toledo TGA/SDTA851e instrument under nitrogen atmosphere at a heating rate of 10 °C min^{-1} from 25 °C to 800 °C.

DSC

Differential scanning calorimetry (DSC) was performed with a Mettler Toledo instrument 1/700 under nitrogen atmosphere at a heating rate of 10 °C min^{-1}. For all DSC results, the information obtained from second heating was used.

Press

The used materials were processed using a custom-made metal mould, which was compressed under 7.5 ton at a temperature 20-30 °C above T_m or T_g of the polymer. The dog bones were cut out using a manual Rubberstamp Press.

Tensile testing

Tensile testing was performed on a Tinius-Olsen H10KT tensile tester, equipped with a 100 N load cell, using a flat dog bone type specimen with an effective gage length of 13 mm, a width of 2 mm, and a thickness of 1.3 mm. The samples were cut out using a RayRan dog bone cutter. The tensile rests were run at a speed of 10 mm min^{-1}.

8.5 References

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Abstract

To prove that the class of poly(cycloacetal/ketals) can be even more versatile, an attempt was made to introduce functionalities onto the polymer backbone. Therefore, a poly(cycloacetal) containing pending double bonds was synthesized, which could subsequently be applied in post-polymerization reactions. These double bonds can react with thiols via thiol-ene chemistry and as such, different functional groups could be built in depending on the thiol selected. Moreover, the polymer could be crosslinked, after which it could be potentially degradable in acid conditions.

Chapter 9: Post-modification of tartrate based poly(cycloacetals)

9.1 Introduction

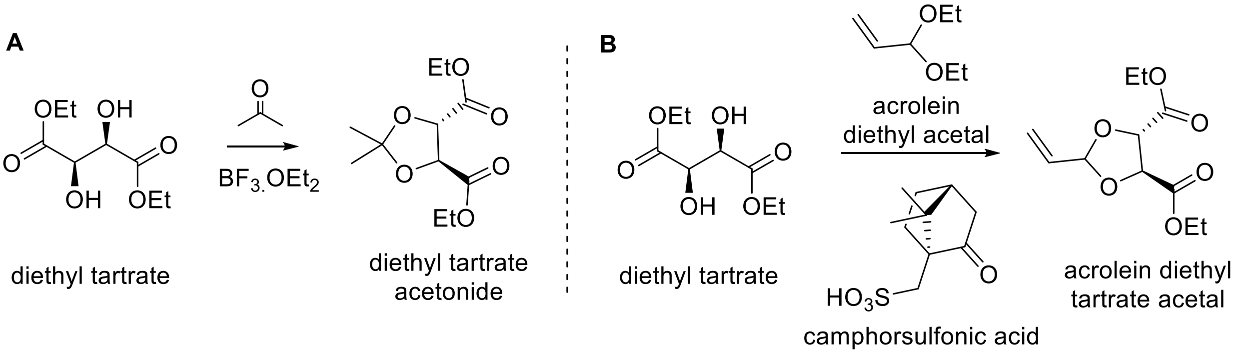
2,3-Dihydroxybutanedioic acid, better known as tartaric acid, is a principal by-product of the conversion of grape stock to wine by fermentation.[1-3] In 2015, the EU was responsible for 60.1% of the total global production of wine, thus demonstrating Europe's large potential to produce tartaric acid in bulk, relatively inexpensive.[4] This naturally occurring compound is already frequently used for the production of a wide array of products; for example within flame retardants. [1, 5] Moreover, tartaric acid is a useful monomer for the synthesis of renewable polymers. In order to synthesize renewable polyesters, tartaric acid can be easily converted to the corresponding diethyl ester monomer. [6-7]

Recently, the use of cyclic sugar derivatives in polycondensation reactions have attracted a lot of interest. Muñoz-Guerra and co-workers have extensively reported polyesters made from cyclic acetalized carbohydrate monomers of D-galactose[8-10], D-glucose[11], D-mannose[12-13] and L-tartaric acid[14-15]. All acetals were synthesized with formaldehyde in order to obtain cyclic methylene acetals. These synthesized polyesters have been considered as PET alternatives. Jacob *et al.* on the other hand, reported the ketalization of tartrate with acetone to obtain 2,3-*O*-isopropylidene tartrate.[16] The synthesized polyesters were then treated with acid to gain a hydroxyl containing polyester.

To our knowledge, it was never attempted to incorporate specific functionality on the cyclic acetal, which could be altered in a post-modification reaction with the aim to obtain other polymer properties. Moreover, desired compounds could be incorporated onto the polymer chain and when introduced to an acidic medium these compounds can be subsequently released.

In this work, two cyclic acetal containing diesters from tartaric acid were synthesized on 100 gram scale. In the first case, diethyl tartrate was combined with acetone to form diethyl tartrate acetonide, while on the other hand diethyl tartrate was combined with acrolein, yielding a diester with a pending double bond. For the polymer synthesis, a collaboration was set-up with the group of professor Sebastián Muñoz-Guerra of the Universitat Politècnica de Catalunya, in Barcelona. These renewable monomers were combined with 1,4-butanediol in order to obtain on the one hand a 'dummy' polyester without functional groups along the polymer backbone as a control, and on the other hand polyesters with pending double bonds. After polymerization, the functionalization of the double bond by thiol-ene was investigated using different functionalities including hydroxyl, fluoro and benzylic groups were added on the polymer backbone. Hereafter, the release of these compounds was tested with acid hydrolysis. It must be emphasized that these polyesters are fully renewable as the tartrates on which they are based are also renewable, as well as 1,4-butanediol.[17]

9.2 Synthesis of tartrate based acetals



Scheme 9.1. (A) Reaction of diethyl tartrate with acetone and boron trifluoride diethyl etherate as a catalyst, (B) Reaction of diethyl tartrate with acrolein diethyl acetal and camphorsulfonic acid as a catalyst.

The hydroxyl groups of diethyl tartrate were reacted with two different carbonyl-containing compounds, after which a cyclic acetal was formed. First, diethyl tartrate was reacted with acetone and boron trifluoride diethyl etherate as a catalyst (Scheme 9.1 (A)).[18] After 3 hours reaction time and an easy purification, an extraction and distillation, pure diethyl tartrate acetonide could be obtained (Figure 9.1, top). Moreover, this reaction could easily be upscaled to a 100 gram scale.

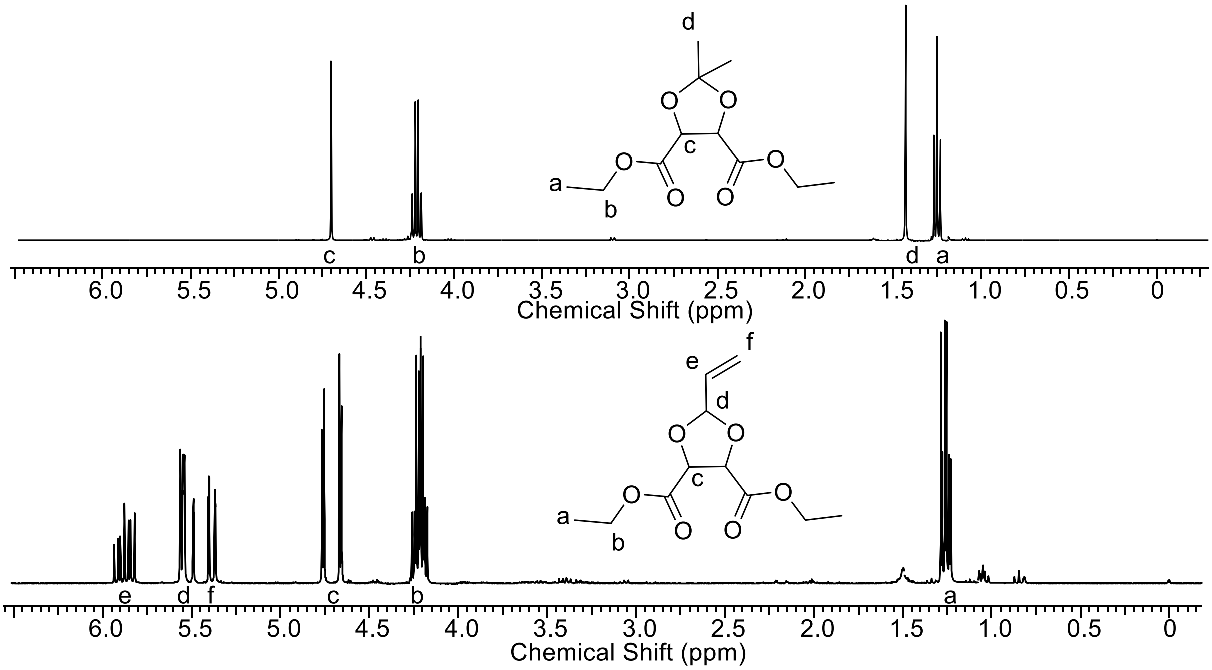


Figure 9.1. ^{1}H-NMR of diethyl tartrate acetonide (top) and acrolein diethyl tartrate acetal (bottom) ($CHCl_3$-d, 300 MHz).

Secondly, diethyl tartrate was reacted with the diethyl acetal of acrolein and camphorsulfonic acid as the catalyst (Scheme 9.1 (B)).[19] However, the reaction of this acetonide was more complex as ethanol was released instead of water and this released amount needed to be followed in order to know when the reaction was complete. As ethanol and toluene are miscible, it was not possible to quantify the amount of ethanol removed using a standard Dean-Stark set-up. Thus, the reaction conversion was followed by ^{1}H-NMR. The Dean-Stark apparatus was emptied completely at time intervals (no extra toluene was added to the reaction mixture, so the mixture became more concentrated) and the distillate was weighed. Next, the ethanol content could be determined by ^{1}H-NMR (relative integrations of toluene (2.3 ppm, 3H) and ethanol (3.6 ppm, 2H)). After 30 h, almost no ethanol was released anymore, thus suggesting that full conversion of the acetalization reaction was achieved. It must be noted that after 24 hours, catalyst was added again to the reaction in order to ensure that the reaction went to completion (Figure 9.2).

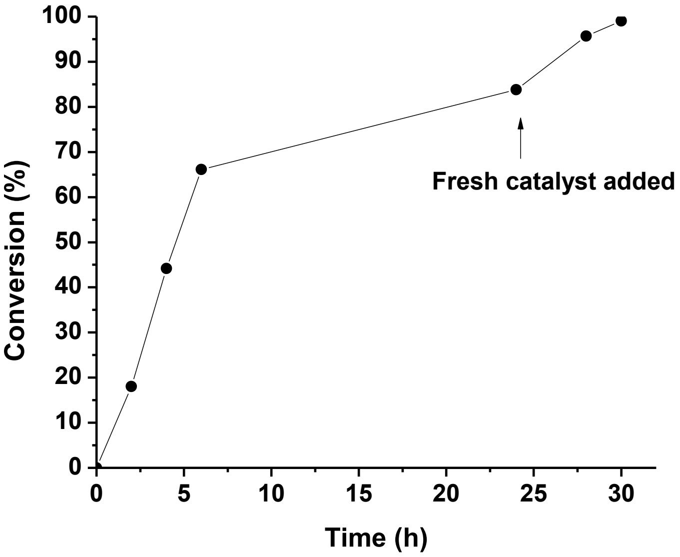


Figure 9.2. Conversion of the acetalization of diethyl tartrate with the diethyl acetal of acrolein displayed over time. Full conversion was reached after 30 h after adding a second amount of catalyst.

Compared to the facile purification of diethyl tartrate acetonide, column chromatography and distillation was needed in order to obtain pure acrolein diethyl tartrate acetal (Figure 9.1, bottom).

From ^{1}H-NMR measurements in chloroform, it was already noticed that the acetal could open due to the HCl present in this solvent, thus the stability of the monomer was tested. The aim was to perform the transesterification at 100 °C, so the monomer was heated to 100 °C and samples were taken at regular intervals. In one vial, a drop of water was added as this is normally necessary to open the acetal. After 6 h, no degradation was noticed but after 24 hours the monomer with the water drop opened and a small amount of opening was noticed in the vial with just monomer. In order to further clarify the stability of this monomer, isothermal TGA measurements were performed at four different temperatures for 2 hours. As can be seen in Figure 9.3, temperature does have an influence on the stability of our monomer. At 90 °C, only a small mass loss of 5% was noticed, while at 100 and 120 °C a larger mass loss was observed and at 140 °C this was even more severe. When analyzing the residual product by ^{1}H-NMR, it was clear that at 100 and 120 °C the acetal opens, while at 140 °C a polymer resulted, probably due to the reactivity of the double bonds present in acrolein diethyl tartrate acetal at such high temperatures.

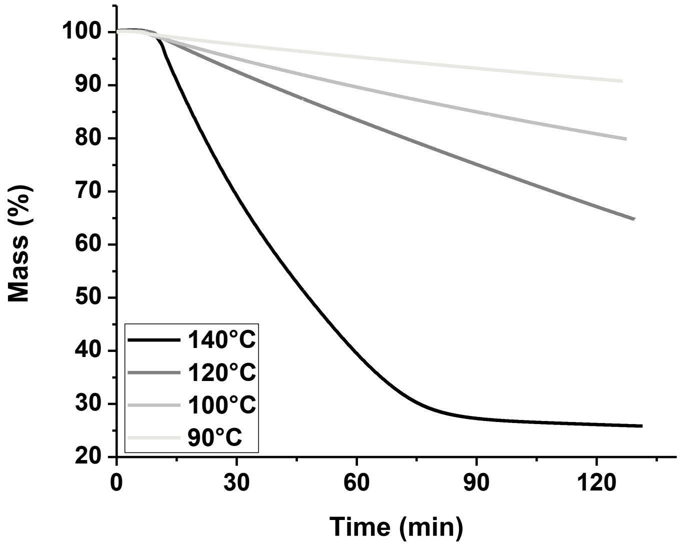


Figure 9.3. Isothermal TGA curves of acrolein diethyl tartrate.

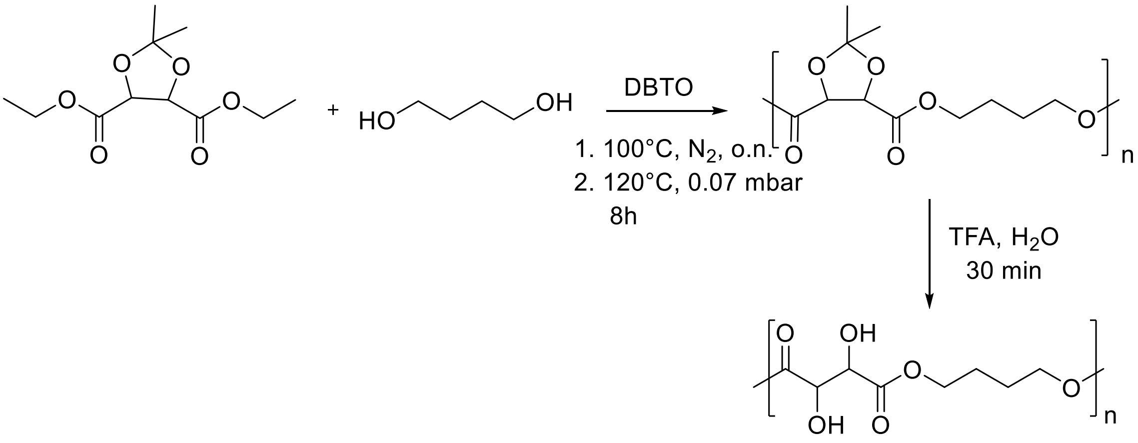
Originally, also cyclic acetal diesters were synthesized from citronellal and diethyl tartrate. Citronellal contains a substituted double bond that could react with functionalized 1,2,4-triazoline3,5-dione (TAD), which would allow to apply another area of expertise from our research group.[20] Unfortunately, the synthesis with citronellal resulted in a mixture of compounds, which could not be separated.

9.3 Polymerization

The synthesized diesters could then be applied in polyester synthesis in order to obtain cyclic acetal containing polyesters, using 1,4-butanediol. As polyesters are made with an acid catalyst it is important to polymerize at relatively low temperatures to prevent opening of the acetal, which would result in crosslinking of the reactants. Furthermore, Billiet *et al.* reported that a radical inhibitor is required in the synthesis of polyesters with pending alkene or alkyne bonds.[21] So, when acrolein diethyl tartrate acetal was used, hydroquinone (10 mol% relative to the alkene-containing diester) was added to the reaction mixture to avoid crosslinking via radical reaction of the double bonds.

9.3.1 Diethyl tartrate acetonide polyester

The synthesis of polyesters from diethyl tartrate acetonide was already reported by Jacob *et al.*[16] They varied the diol from 1,4-butanediol to longer diols such as decane diol, however the reported molecular weight for 1,4-butanediol was rather low (3.8 kDa). We were able to use this reported work as a benchmark for the polymers described in this chapter. First, the synthesis was repeated and adjusted by changing the temperature and catalyst, in order to obtain higher molecular weight polymers. It was important to keep the temperature below 130 °C as opening of the acetal could then be avoided while long reaction times were necessary to obtain high molecular weight polymers. The transesterification step required overnight reaction and the polycondensation was performed over 8 hours. Eventually, higher molecular weights could be achieved with values up to 16 kDa. The cyclic ketals in this polyester can be opened by a short reaction with trifluoroacetic acid (TFA), which results in a hydroxyl containing polyester (Scheme 9.2).



Scheme 9.2. Overview of the synthesis of poly(butylene 2,3-*O*-isopropylidene tartrate) and the deprotection step to obtain poly(butylene tartrate).

The two polymer structures were confirmed by ^{1}H-NMR as can be seen from Figure 9.4.The CH_3-signals at 1.5 ppm from the acetonide disappear after the deprotection with TFA.

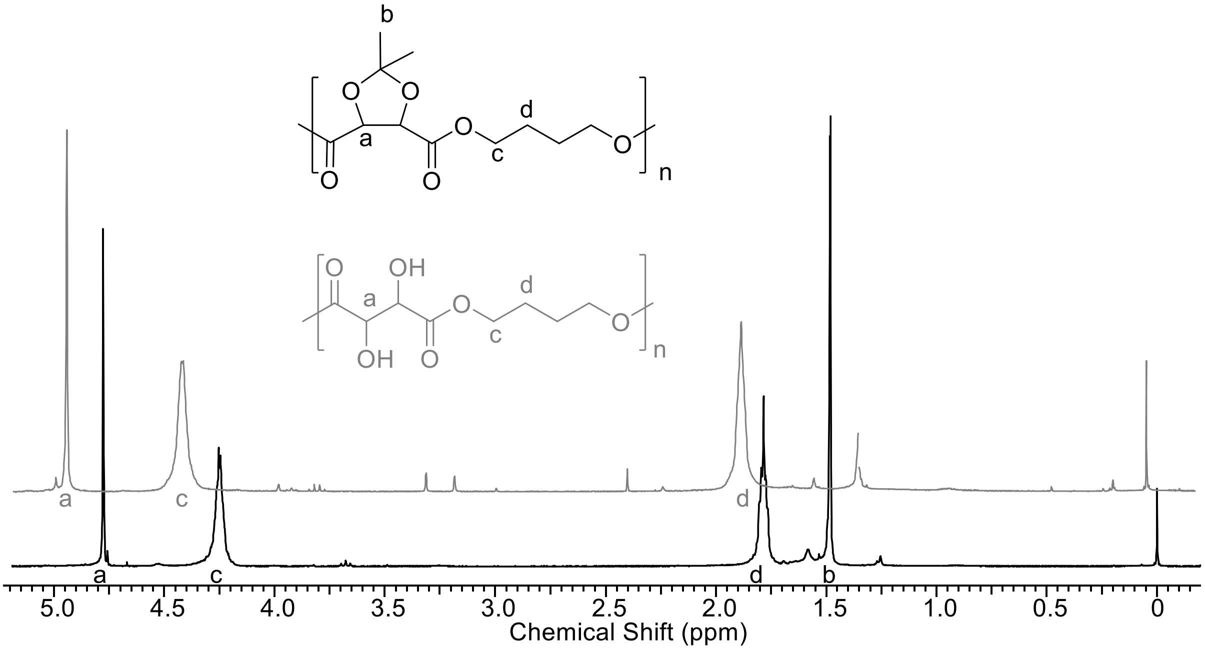


Figure 9.4. ^{1}H-NMR of poly(butylene 2,3-*O*-isopropylidene tartrate)) (black, $CHCl_3$-d, 300 MHz) and poly(butylene tartrate) (grey, TFA-d, 300 MHz).

Both polymers have a very similar chemical structure but differ in certain properties like T_g and crystallinity. As can be seen from Table 9.1 a decrease in molecular weight was observed after deprotection, as expected. Poly(butylene 2,3-*O*-isopropylidene tartrate) is a fully amorphous polymer with a T_g of -4 °C. When hydrolyzed, a crystalline polymer with a higher T_g is obtained. The formation of hydrogen bonds and better stacking of the polymer chains give rise to these properties. The degradation temperature of poly(butylene tartrate) is lower than the one of poly(butylene 2,3-*O*-isopropylidene tartrate), which was also observed by Jacob *et al.*[16]

Table 9.1. SEC ($CHCl_3$) and thermal analysis results of poly(butylene 2,3-*O*-isopropylidene tartrate and poly(butylene tartrate).

polymer	M_n (kDa)	Đ	T_g (°C)	T_m (°C)	T_d (°C)
Poly(butylene 2,3-*O*-isopropylidene tartrate)	16	1.9	-4	-	300
Poly(butylene tartrate)	9.5	1.9	30	146	260

This way of obtaining functionalization along the backbone of polyesters is successful but limited to hydroxyl groups. Therefore, we investigated the synthesis of functionalized acetal containing polyesters, which could be post-modified with a variety of chemical groups after polymerization.

9.3.2 Acrolein diethyl tartrate acetal polyester

Polyesters from acrolein diethyl tartrate acetal contain pending double bonds along the polymer backbone, which can be further functionalized in a next step *via* radical thiol-ene chemistry. We concluded from the stability tests performed on the monomer that it would be the best to perform the transesterification step at 90 °C. The transesterification was followed by ^{1}H-NMR in order to know when the monomer is no longer present. After 6 h the transesterification was nearly completed and the polycondensation could be started. First, the polycondensation was also performed at 90°C, but after 1 hour a white precipitate (oligomers) was formed. Nevertheless, after 12 h of polycondensation a low molecular weight polymer was obtained. By DSC-analysis a melting range (106-115 °C) was observed, so it was necessary to perform the polycondensation above the melting point. Therefore, the polycondensation was done at 130 °C and before applying high vacuum, the mixture was stirred at 200 mbar to be sure not to lose residual monomer.

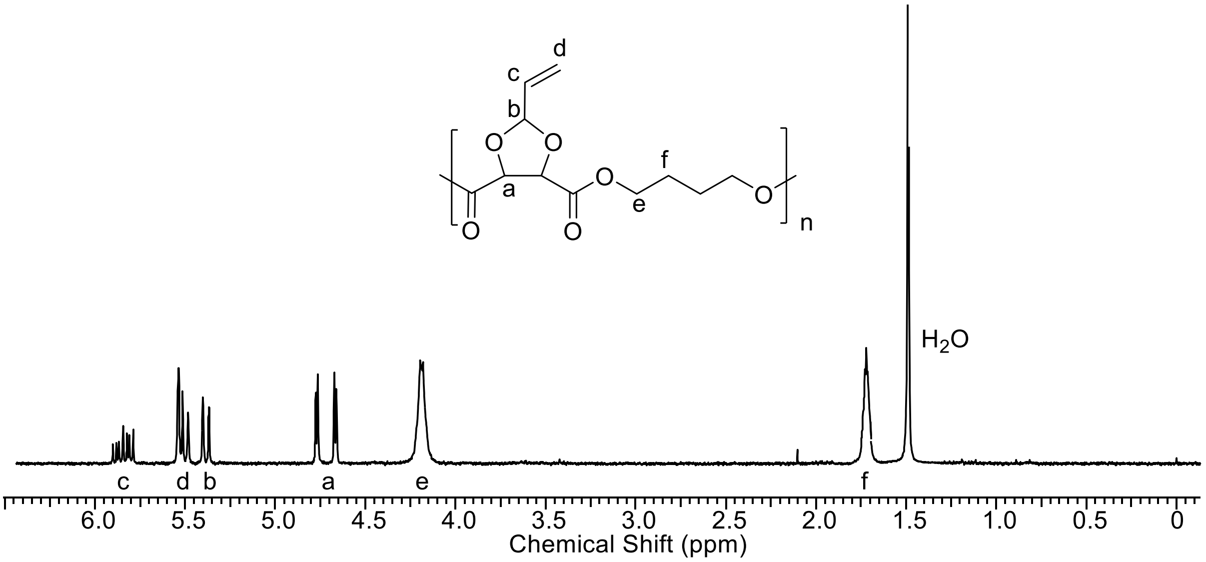


Figure 9.5. ^{1}H-NMR of the polyester from acrolein diethyl tartrate acetal and 1,4-butanediol ($CDCl_3$-d, 300 MHz).

The structure of the polymer was confirmed by ^{1}H-NMR measurements (Figure 9.5) while the SEC and thermal analysis data can be found in Table 9.2. The first entry represents a low molecular weight polymer and no T_g could be observed in the DSC. The second entry, which has a higher molecular weight shows a T_g of 2 °C and has a higher melting enthalpy and degradation temperature compared to entry 1.

Table 9.2. $CHCl_3$-SEC and thermal results of two polymers from acrolein diethyl tartrate acetal and 1,4-butanediol

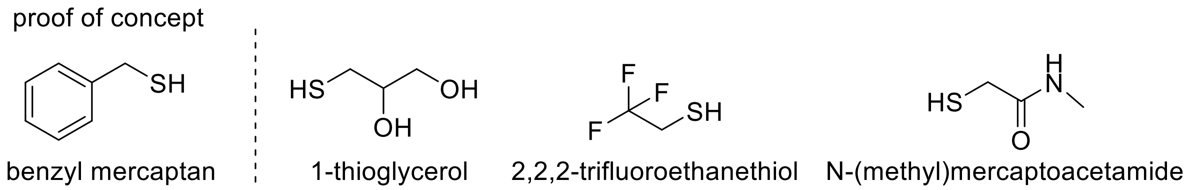
Entry	M_n (kDa)	Đ	T_g (°C)	T_m (°C)	ΔH (J/g)	T_d (°C)
P3a	5.8	2.2	-	106 & 115	37	290
P3b	16	1.8	2	106 & 115	42	310

The polymerization of acrolein diethyl tartrate acetal and 1,4-butanediol was also tested with enzymes as catalyst. The enzymes applied here were Candida Antarctica lipase, immobilized on macroporous acrylic resin (CALB), which needed to be activated first by putting them at 40 °C at low vacuum for 24 h. The polymerization temperature was limited to 80 °C as too high temperatures denature the enzymes. Unfortunately, the reaction of the enzymes resulted in opening of the acetal and thus an appearance of a clear signal at 4.5 ppm from the CH next to the resulting hydroxyl group. When lower temperatures and longer reaction times were applied

(40 °C, 2 days & 60 °C, 24 h), no polymer or 5% conversion of the transesterification was noticed. It was clear that for the synthesis of polymers from acrolein diethyl tartrate acetal, DBTO is the most suitable catalyst.

9.4 Functionalization of poly(cycloacetal-esters) containing pending double bonds

These poly(cycloacetal-esters) containing pending double bonds can be functionalized in a post-modification reaction with thiol-ene chemistry. First, this polycondensation was tested with benzyl mercaptan as a proof of concept. Hereafter, an attempt was made to functionalize the double bonds with thiol compounds that also contain hydrophilic and hydrophobic groups (Scheme 9.3). Important to note is that the thiol-ene reactions were done under high intensity UV light (365 nm, 3 x 3W).



Scheme 9.3. Overview of the thiol containing compounds for the post-modification reaction.

The conversion of the different functionalizations was followed by ^{1}H-NMR and every 30 min a sample was taken. All structures were confirmed with ^{1}H-NMR (Figure 9.6 and Figure 9.7) and the reaction time at 100% conversion is showed in Table 9.3, as well as the SEC and thermal analysis results.

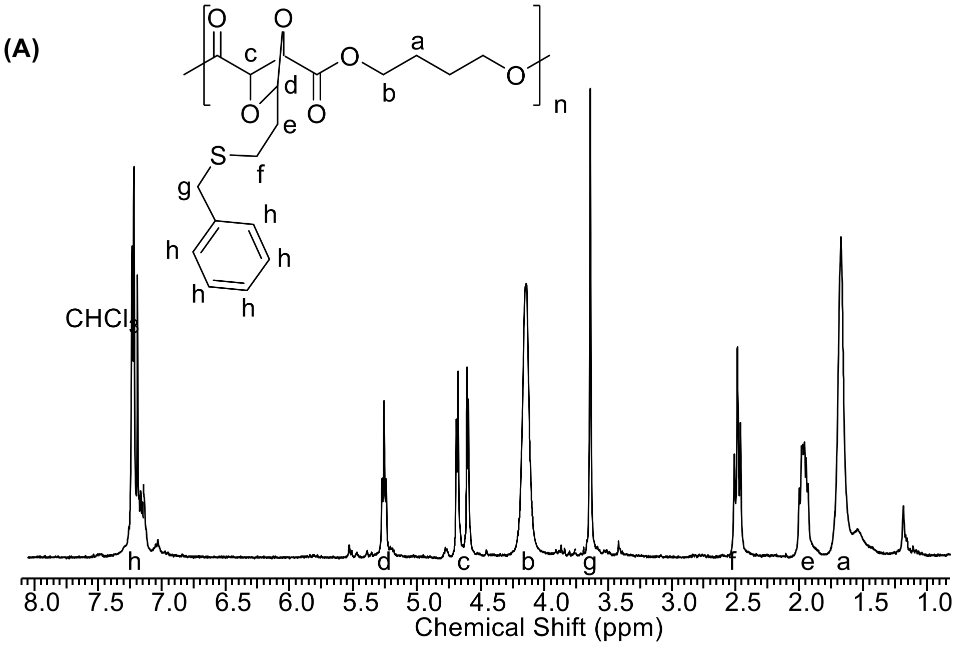


Figure 9.6. ^{1}H-NMR of the functionalized polymer of P3b with benzyl mercaptan (A), measured in $CDCl_3$-d.

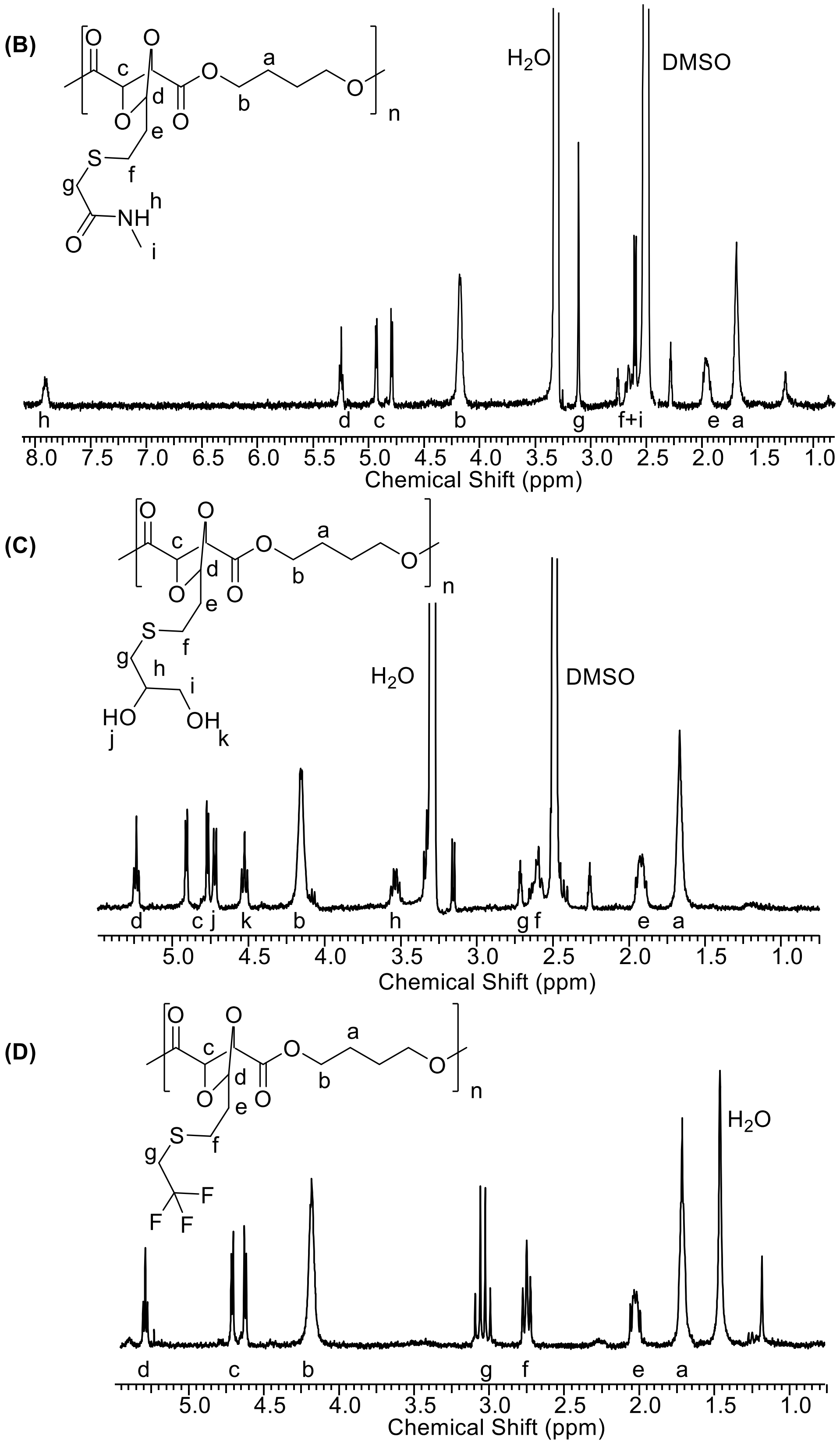


Figure 9.7. ^{1}H-NMR of the functionalized polymers of P3b with 1-thioglycerol (B), N-(methyl)mercaptoacetamide (C) and 2,2,2-trifluroethanethiol (D). D was measured in $CDCl_3$-d, while B and C were measured in DMSO-d_6, at 300 MHz.

The molecular weights are higher after the functionalization procedure, however it is difficult to compare the polymers as P3a and P3b are not soluble in DMA, while all the functionalized polymers were not soluble in chloroform and only in DMA.

Table 9.3. SEC and thermal results of the post-modification reactions via thiol-ene as well as the reaction temperature.

	M_n (kDa)	Đ	T_g (°C)	$T_m/\Delta H$ (°C)/J.g^{-1}	T_d (°C)	Reaction time
P3a	*5.8**	*2.2*	-	*106 & 115/37*	*290*	-
P3a + benzyl mercaptan	8.2	1.8	-5	-	310	1,5h
P3a + 1- thioglycerol	21.0	1.3	-2	-	280	2h
P3a + N-(methyl)mercaptoacetamide	7.1[a]	1.3	-24	-	150	3h
P3a + 2,2,2-trifluoroethanethiol	8.3	1.5	-12	-	320	4h
P3b	*16.0**	*1.8*	*2*	*106 & 115/42*	*310*	-
P3b + benzyl mercaptan	32. 0	3	-1	-	320	2h
P3b + 1-thioglycerol	34.0	1.7	-15	-	290	2,5h
P3b + N-(methyl)mercaptoacetamide	6.0	1.6	12	-	310	3h
P3b + 2,2,2-trifluoroethanethiol	35.0	1.8	-9	-	360	4h

[a] Multiple SEC signals

* Measured on $CHCl_3$-SEC, all other molecular weights were measured on a DMA-SEC

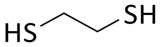
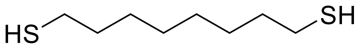
A clear trend in T_g cannot be seen from the low molecular weight polymers, but it was clear from the DSC measurements that all functionalized polymers changed from a semi-crystalline to a completely amorphous state. When looking for a trend in T_g for the high molecular weight polymers, an increase in T_g was observed for the functionalization with N-(methyl)mercaptoacetamide while in all other cases a lower T_g was obtained. The introduction of amide groups can result in the formation of hydrogen bridges and therefore a higher T_g material.[22] When the other thiol compounds are reacted with the double bond, the good stacking of the semi-crystalline polymer is disturbed, which results in a lower T_g than the original material. The functionalization with N-(methyl)mercaptoacetamide led to side reactions as multiple peaks were visible in the SEC-curve and the degradation temperature was low. On the other hand, introducing fluoro groups on the polymer increases the degradation temperature, which is a known feature of fluoro-containing polymers. As mentioned before, the conversion was followed with ^{1}H-NMR. For the functionalization of the high molecular weight polyesters, longer reaction times were necessary as expected.

P3b and P3b functionalized with benzyl mercaptan were subjected to a hydrolytic stability testing. The reaction with TFA and water that was performed on poly(butylene 2,3-*O*-isopropylidene tartrate) resulted in deprotection of the acetal. From ^{1}H-NMR it was clear that the alkene containing polyester released acrolein and resulted in the hydroxyl containing polyester, while the acetal signals in the benzyl containing polyester were still present. It seems that when the poly(cycloacetal-ester) is functionalized, degradation is slowed down, which was also confirmed by SEC analysis. For both polymers, a decrease in molecular weight was observed. A possible application of these polymers could be in the area of controlled release in acid environment.[23-24]

9.5 Crosslinking of poly(acetal-esters)

The polyesters bearing alkene functionalities could also be crosslinked with a dithiol, which should lead to acid-degradable networks. Two crosslinkers were chosen, i.e. the short 1,2-ethanedithiol and the longer 1,8-octanedithiol, which were added in 10 mol%. Due to solubility issues, only the low molecular weight polyester was used for further crosslinking. After mixing polymer, dithiol and a radical initiator in a suitable solvent, the solution is put between two glass plates and irradiated with 370-380 nm UV light for 2 hours. Next, the swelling and soluble fraction were determined by performing a soxhlet extraction in chloroform (85 °C, 48 h). HR-MAS measurements were performed on both networks and the chemical structure was confirmed. Finally, the thermal properties of the dried networks were determined using advanced thermal analysis measurements. (Table 9.4).

Table 9.4. The thermal properties, degree of swelling and soluble fraction for the networks from the alkene containing poly(cycloacetal-ester)

Entry	Crosslinker	T_g (°C)	T_d (°C)	Swelling (%)	Soluble fraction (%)
1		5	310	420	13.4
2		10	320	278	3.2

The network made from 1,2-ethanedithiol (**1**) has a larger soluble fraction compared to the network from 1,8-octanedithiol (**2**), which was expected. Indeed, the shorter the crosslinker, the harder dangling thiols, coming from reaction of one of the two thiol functionalities with an alkene side chain, can find another alkene due to sterical hindrance. This lower amount of crosslinking could also be observed from the higher swelling ratio of the network comprising 1,2-ethanedithiol. The combination of higher soluble fraction and high swelling makes us believe that the network **1** has a low(er) crosslink density, which also explains why the T_g-increase (polymer vs network) is still rather low (only an increase of 10 °C was noticed). With 1,8-octanedithiol, we expected a higher crosslink density, which is confirmed by a low soluble fraction of this network and less swelling. Both networks were transparent but network **2** showed to have a yellow colour as can be seen from Figure 9.8. The synthesis of these networks should be considered as another proof of concept of post-modification of the alkene-containing poly(cycloacetal-ester).

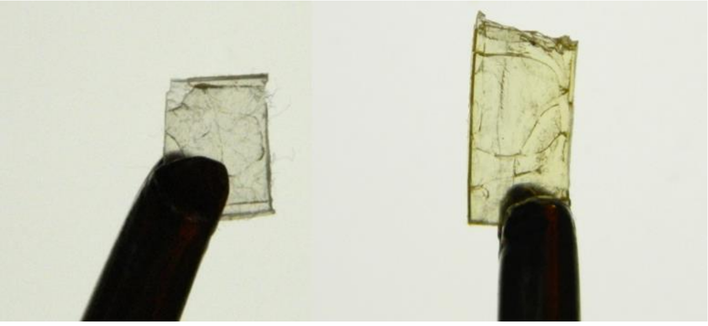


Figure 9.8. Picture of the network (after soxhlet) with 1,2-ethanethiol (left), and 1,8-octanedithiol (right).

Finally, both networks were treated with TFA to check their degradability. First, the networks were swollen in a little amount of chloroform. Next, TFA and water were added and the resulting mixture was stirred for 24 h. After 10 minutes, network **1** with 1,2-ethanedithiol was solubilized, while network **2** with 1,8-octanedithiol maintained its network integrity. The degraded network from 1,2-ethanedithiol was analysed with ^{1}H-NMR which revealed the presence of degradation products, like poly(butylene tartrate). The network from 1,8-octanedithiol did not dissolve, from which we conclude that only little degradation could have taken place.

9.6 Conclusion

Two acetalized tartrate monomers were successfully synthesized on a large scale with acetone and acrolein. The latter, containing a pending double bond, could be functionalized after incorporation of the monomer in a polyester. First, polyesters were synthesized with diethyl tartrate acetonide and 1,4-butanediol to test the experimental conditions of the synthesis of these kind of polymers. Higher molecular weights could be obtained than previously reported and when treated with acid a hydroxyl containing polyester was obtained.[16] Both polymers differed in thermal properties as the protected one is fully amorphous with a T_g of -4 °C while the deprotected one is semi-crystalline with a much higher T_g of 30 °C and a melting point of 146 °C. When polymerizing acrolein diethyl tartrate acetal with 1,4-butanediol, it is important to heat the reaction mixture above the melting point of the polymer (106 and 115 °C). Molecular weights up to 16 kDa could be obtained and the polymers displayed a T_g value of 2 °C. Hereafter, this poly(cycloacetal-ester) containing double bonds was functionalized with four different thiol compounds and as such the thermal properties could be altered. After functionalization, the polymers were all amorphous and displayed different T_g values. This alkene containing polymer could also be crosslinked with two different dithiols. With the longer dithiol, overall better properties were obtained, the T_g increased with 15 °C and it was less brittle than the one derived from 1,2-ethanedithiol. The network from 1,2-ethanedithiol degraded completely after a treatment with TFA, while the network of 1,8-octanedithiol kept its shape.

From this work it could be conducted that poly(cycloacetals) are versatile polymers that can be applied in post-modification reactions and network formation.

9.7 Experimental

9.7.1 Materials

Acetone, acrolein diethyl acetal (96%), benzyl mercaptan (99%), 1,4-butanediol (BD, 97%), Candida Antarctica lipase immobilized on macroporous acrylic resin (CALB), chloroform, dibutyl tin oxide catalyst (DBTO, 98%), dichloromethane, diethyl ether, dimethyl formamide, 1,2-ethanedithiol, ethanol, ethyl acetate, hexane, hydroquinone (≥99%), methanol, N-(methyl)mercaptoacetamide (≥97.0%), sodium carbonate (≥99,5%), thioglycerol (≥97.0%), toluene, triethylamine and 2,2,2-trifluoroethanethiol (95%) were purchased from Sigma-Aldrich. Boron trifluoride - ethyl ether complex (>98%), (±)-10-camphorsulfonic acid (>98%), diethyl L-(+)-tartrate (>98%) and thioacetic acid (>95%) were purchased from TCI. Anhydrous magnesium sulfate (97%), Azobisisobutyronitrile (AIBN, 98%), 2,2-dimethoxy-2-phenylacetophenone (99%), potassium carbonate (≥98%) were purchased from Acros. Chloroform-d (Euriso-Top, 99,8%), dimethylsulfoxide-d_6 (Euriso-Top, 99,8%), sodium bicarbonate ($NaHCO_3$, Roth, ≥99%), trifluoroacetic acid (TFA, Iris Biotech) and all previously mentioned substances were used as received.

Note that all NMR’s measured of monomers were measured with $CDCl_3$ on K_2CO_3 to avoid opening of the acetal in the NMR tube due to the acidic nature of $CDCl_3$.

9.7.2 Synthesis

9.7.2.1 Synthesis of diethyl tartrate acetonide

Under an inert atmosphere, a 2-L, two-necked, round-bottomed flask, equipped with a magnetic stirring bar and a pressure-equalized addition funnel, was charged with (+)-diethyl L-tartrate (103.00 g, 0.5 mol) dissolved in acetone (HPLC, 900 mL). To the clear solution was added, at room temperature, boron trifluoride diethyl etherate (82.5 mL 48% solution, 0.31 mol) over 30–40 min. The resulting yellow solution was stirred for an additional 3 h during which time the color of the solution became red-brown. For workup, the reaction mixture was poured into an aqueous saturated sodium bicarbonate solution (4 L). The turbid mixture was divided into two parts, and each part was extracted three times with ethyl acetate (3 × 500 mL). The combined organic layers were washed twice with water (2 × 1 L) and dried over anhydrous magnesium sulfate. After filtration the solvent was removed by rotary evaporation. The yellow oil that was obtained was purified (twice) by fractional distillation (1 mbar, bp ca. 100 °C).

Isolated yield: 82%. **Molecular formula:** $C_{11}H_{18}O_6$. **Molecular weight:** 246.11 g mol^{-1}. **^{1}H-NMR (400 MHz, $CHCl_3$-d):** δ (ppm) = 4.70 (s, 2H, $OCHC$), 4.21 (q, 4H, CH_3CH_2O), 1.43 (s, 6H, CH_3C), 1.25 (t, 6H, CH_3CH_2O)

9.7.2.2 Synthesis of acrolein diethyl tartrate acetal

In a 500 mL boiling flask equipped with a Dean-Stark apparatus, a solution containing diethyl tartrate (64.83 g, 0.3144 mol), acrolein diethyl acetal (50.00 g, 0.384 mol) and the acid catalyst, camphor sulfonic acid (1.00 g, 4.3 mmol) in toluene (1.2 L, HPLC) was refluxed. The course of the reaction was monitored by ^{1}H-NMR of the Dean-Stark distillate (*vide infra*). After 24 h, further 1 g of the catalyst was added and refluxed for a further 12 h. Et_3N (100 mL) was added and the solvents were removed. The crude product was purified by a silica gel column (20% AcOEt, 80% n-hexane + 5 vol% Et_3N) and vacuum distillation (1 mbar, bp 115 °C).

Isolated Yield: 68%. **Molecular formula:** $C_{11}H_{16}O_6$. **Molecular weight:** 244.09 g mol^{-1}. **^{1}H-NMR (400 MHz, $CHCl_3$-d):** δ (ppm) = 5.88 (ddt, 1H, $CH_2C\mathit{H}CH$), 5.56 (s, 1H, $CH_2CHC\mathit{H}$), 5.45 (dq, 2H, $C\mathit{H_2}CHCH$), 4.70 (dd, 2H, $OC\mathit{H}C$), 4.21 (qd, 4H, $CH_3C\mathit{H_2}O$), 1.25 (td, 6H, $C\mathit{H_3}C$)

9.7.2.3 Synthesis of octane-1,8-dithiol

A 2-neck flask was filled with 1,7-octadiene (16.70 g, 0.15 mol), thioacetic acid (43 mL, 0.61 mol) and AIBN (0.25 g, 1.5 mmol), and was heated to 80 °C for 4 h. Next, the mixture was diluted with Et_2O (200 mL), and was washed with water (5 x 150 mL) and brine (100 mL). Finally, the organic phase was dried with $MgSO_4$ and evaporated *in vacuo* to yield octane-1,8-dithioacetate as a white/yellowish solid. This product was used in a next step without purification. To a cooled solution of octane-1,8-dithioacetate in MeOH (150 mL), potassium carbonate (104.00 g, 0.75 mol) was added. The resulting mixture was stirred at room temperature for 4 hours. Next, the solvent was partially evaporated after which potassium carbonate was quenched with a saturated ammonium chloride solution, and the desired product was extracted with Et_2O (3 x 150 mL). The combined organic layers were washed with water (100 mL), dried with $MgSO_4$ and evaporated in vacuo. The obtained product was purified by vacuum distillation (115 °C at 9 mmbar).).

Isolated Yield: 65%. **Molecular formula:** $C_8H_{18}S_2$. **Molecular weight:** 178.35 g mol^{-1}. **^{1}H-NMR (400 MHz, $CHCl_3$-d):** 2.53 (q, *J = 7.4 Hz*, 4H), 1.62 (quin, *J = 7.4 Hz*, 4H), 1.35 (m, 8H).

9.7.2.4 Polymerization of diethyl tartrate acetonide with 1,4-butanediol

In a 3-neck flask 1 equiv of diethyl tartrate acetonide, 1.1 equiv of 1,4-butanediol and 0.5 mol% of dibutytinoxide were added. The transesterification step was performed at 100 °C, under a N_2 flow overnight. Hereafter, the temperature was raised to 120 °C and vacuum (0.07 mbar) was applied for 8 h. The reaction was cooled down and the sticky product was dissolved in a minimum volume of chloroform where after the polymer was precipitated in cold methanol. The methanol was decanted and the polymer was dried overnight in the vacuum oven at 40 °C.

9.7.2.5 Polymerization of acrolein diethyl tartrate acetal with 1,4-butanediol

In a 3-neck flask 1 equiv of diethyl tartrate acetonide, 1.1 equiv of 1,4-butanediol, 10 mol% hydroquinone (with respect to the double bonds) and 0.5 mol% of dibutytinoxide were added. The transesterification step was performed at 90 °C, under a N_2 for 6 h. Hereafter, the temperature was raised to 130 °C and low vacuum (200 mbar) was applied for 1 h. Next, the vacuum was increased to 1 mbar and the reaction was at this condition for 12 h.The reaction was cooled down and the product was dissolved in a minimum volume of chloroform where after the polymer was precipitated in cold methanol. The precipitate was filtered off and the polymer was dried overnight in the vacuum oven at 40 °C.

9.7.2.6 Functionalization of poly(butyl-acrolein tartrate)

The polyester (0.25 g, 1 equiv double bonds) was dissolved in 5 mL dichloromethane. Two equivalents of the thiol and 5 mg/mL DMPA were added to the mixture. The solution was flushed with nitrogen in order to remove the present oxygen. The flask was irradiated under UV light (LED lamp of 365 nm, 3x3W) whilst stirring. The conversion was followed by ^{1}H-NMR with samples taken every hour.

9.7.2.7 Crosslinking poly(butyl-acrolein tartrate)

The polyester (0.20 g) was dissolved in 0.5 mL dichloromethane. The dithiol crosslinker (10 mol%) and 2 vol% DMPA was added. The solution was inserted in a spacer between two glass plates and placed under UV light (Hg lamp of 365 nm). After 2 h the network was removed from the glass plates and was dried under vacuum. Next, a soxhlet extraction with chloroform was performed for 48 h to remove the soluble fraction. Herafter, the materials were dried for 2 days in the vacuum oven at 40 °C.

9.7.2.8 Controlled acid degradation

The polyester (0.20 g) was dissolved in a 2 mL of a TFA/H_2O mixture (80/20). When the polymer was completely dissolved, the mixture was stirred for 30 min at room temperature. Next, the water was evaporated and the product was precipitated in diethylether. The polymer was dried overnight in the vacuum oven at 40 °C.

9.7.3 Methods

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analyses were performed using a Mettler Toledo instrument 1/700 under nitrogen atmosphere at a heating rate of 10 °C min^{-1} and a temperature gradient of 200 °C The STARe software of Mettler-Toledo was used to analyze the results.

LC-MS

An Agilent Technologies 1100 series LC/MSD system equipped with a diode array detector (DAD) and a single quad MS was utilized to perform LC-MS analyses. Analytical Reversed Phase HPLC-analyses were performed using a Phenomenex Lunca C18 (2) column (5µm, 250 mm x 4.6 mm) and a solvent gradient (0-100% acetonitrile in water in 15 minutes). A UV-detector (λ = 214 nm) was used to detect the eluting compounds. The electrospray mass spectra recordings were made using a single quad MS detector (VL) with electrospray ionisation.

Nuclear Magnetic Resonance

Proton and carbon nuclear magnetic resonance (^{1}H and ^{13}C NMR) measurements were performed using a Bruker Avance 300 (300 MHz) and a Brucker Avance II 400 (400Mhz) instrument at room temperature. ADC/NMR Processor Academic Edition software of ACD/Labs, which is online available, was used to analyse the recorded spectra.

HR-MAS analyses were recorded in $CDCl_3$-d and were performed on a Bruker Avance II 700 spectrometer (700 MHz) using a HR-MAS probe equipped with a ^{1}H, ^{13}C, ^{119}Sn and gradient channel. Samples were spun at a rate of 6 kHz. All spectra were measured with an acquisition time of 1.136 s in which 32 768 fid points were obtained, leading to a spectral width of 20.6 ppm.

DMA-SEC

Size exclusion chromatography measurements were performed on a Waters instrument, equipped with 3 Polymer Standards Services GPC serial columns (1 X GRAM Analytical 30Å, 10µm and 2 x GRAM Analytical 1000Å, 10µm) at 35 °C with a RI detector (2414 Waters). PMMA standards were used for calibration and DMA containing LiBr (0.42 g mL^{-1}) was used as a solvent at a flow rate of 1mL min^{-1}. Molecular weights and dispersities were determined using Empower software.

$CHCl_3$-SEC

Size exclusion chromatography measurements were also performed on a Waters instrument, equipped with Waters Styragel HR3, HR4 and HR5 serial columns (5µm particle size) at 35 °C with a RI detector (2410 Waters), using PS standards for calibration, and $CHCl_3$ as an eluent at a flow rate of 1.0mL min^{-1}. Molecular weights and dispersities were determined using the Breeze Millennium software.

Thermogravimetric Analysis (TGA)

Thermogravimetric Analyses were performed with a Mettler-Toledo TGA/SDTA 851e instrument. The measurements were performed under nitrogen atmosphere with a heating rate of 10 K min^{-1} from 25 °C to 800 °C on samples with sizes of 5-10 mg. Mettler-Toledo's STARe software was used to analyse the thermograms.

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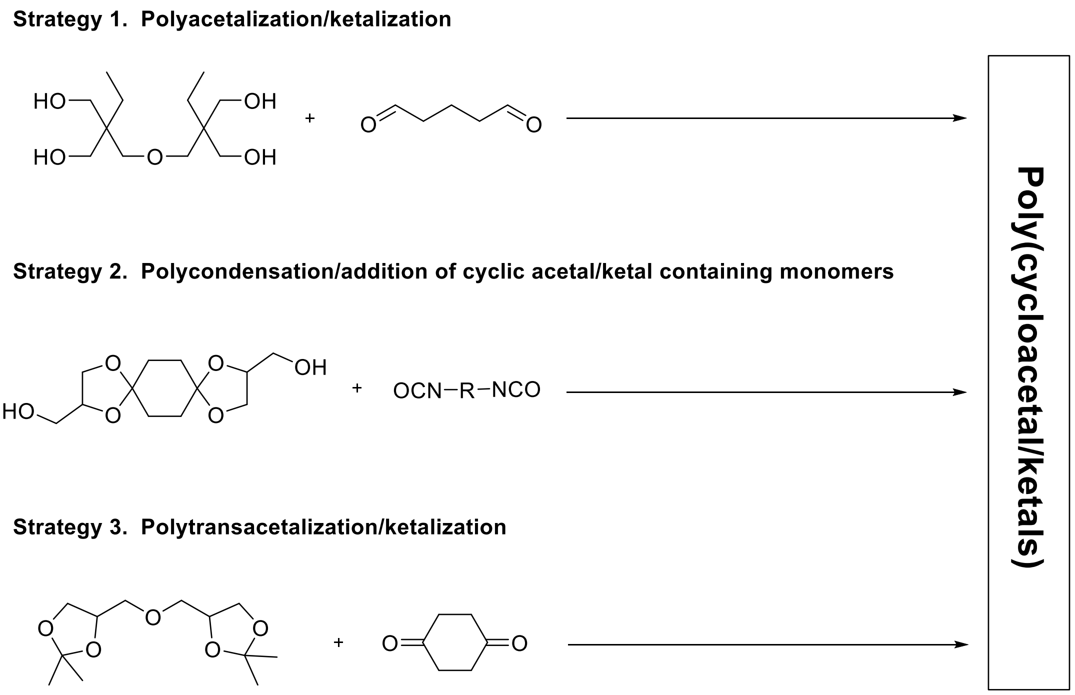
Chapter 10: Conclusions and perspectives

10.1 Aim of the work

The aim of this PhD research was to synthesize poly(cycloacetal/ketals) from renewable resources. With these poly(cycloacetal/ketals), we originally aimed at transparent materials with high glass transition temperatures (T_g > 100 °C) and degradation temperatures (T_d > 300 °C). Moreover, the materials were mechanically tested in order to estimate the chance of possible implementation in high-end applications. At the moment, biobased polymers are mostly applied in packaging applications because of limited thermal and mechanical properties. Economically, biobased polymers should seek to compete in higher value and higher performance application areas like thermoplastic elastomers and engineering plastics. Thus, one of the clear challenges in biobased polymers is the search for rigid polymer structures with resulting good thermal and mechanical properties. A possible solution for the above-mentioned challenges in biobased polymers are poly(cycloacetal/ketals) as these polymers are rigid.[1] Moreover, by the introduction of multiple aliphatic cycles in the polymer chain, amorphous and therefore transparent polymers should be realized.

Fully and partially renewable poly(cycloacetal/ketals) can be synthesized via three different pathways (Scheme 10.1). When tetraols and dicarbonyls are combined in a direct fashion, poly(cycloacetal/ketals) can be obtained as such. A second pathway consists of the synthesis of cyclic acetal/ketal containing bifunctional monomers from renewable feedstock, followed by a polycondensation or polyaddition reaction. On the one hand, linear poly(cycloacetal/ketals) can be synthesized in this way, while on the other hand polymers, which can be functionalized in a post-polymerization reaction, could be obtained. Lastly, poly(cycloacetal/ketals) were synthesized via a polytransacetalization/ketalization reaction.



Scheme 10.1. Overview of the three different strategies to synthesize poly(cycloacetal/ketals), illustrated by an example.

10.2 Overview of the results

Research into renewable poly(cycloacetal/ketals) was started with a model study to investigate the reactivity of commercially available dialdehydes and diketones. Only the most reactive dicarbonyls were considered for the following part of this thesis. The results of this model study can be found in **Chapter 5**. Hereafter, the first strategy to make poly(cycloacetal/ketals) was explored. The direct polyacetalization and polyketalization of the selected dicarbonyls was performed with pentaerythritol and di-trimethylolpropane (di-TMP) as tetraols. The polymerization with pentaerythritol only led to low molecular weight polymers (M_n < 5 kDa), which was also reported in literature.[1-9] These low molecular weights were the result of the too rigid structure of the polymers and the associated problems of keeping everything in the melt or solution. With di-TMP, high molecular weight poly(cycloacetal/ketals) could be synthesized with glutaraldehyde, *o* and *m*-phthalaldehyde and 1,4-cyclohexanedione (M_n > 20 kDa). The poly(cycloacetals) from glutaraldehyde and di-TMP could be processed with compression moulding into transparent colorless materials. Due to the flexible nature of glutaraldehyde, low T_g materials (T_g = 38 °C) with a low young modulus (E = 0.5 GPa) were obtained, but a large ductile area could be observed (strain at break = 70%).[10] The other poly(cycloacetal/ketals) were more rigid as the used dicarbonyls were cyclic, which also resulted in higher T_g values varying from 90-110 °C. When these more rigid poly(cycloacetal/ketals) were processed, only brittle materials could be realized and therefore no mechanical tests could be performed.

Only a limited amount of renewable and rigid dicarbonyls is commercially available, so we decided to synthesize renewable dialdehydes from hydroxyaldehydes like 5-hydroxymethylfurfural (5-HMF) and hydroxypivaldehyde (HPA). When 5-HMF was combined with different diisocyanates, we could synthesize six different dialdehydes. HPA is present as a dimer at room temperature, which makes the synthesis of dialdehydes from HPA more challenging. In the end, it was not possible to achieve 100% purity for the HPA dialdehydes, thus only polyacetalizations of the 5-HMF based dialdehydes with di-TMP were successful. The resulting poly(cycloacetals) have medium high molecular weights (M_n < 15 kDa) and high T_gs (T_g = 70-110 °C) when rigid diisocyanates were used in the monomer synthesis. The processing of these polymers was rather challenging due to the low degradation temperatures (T_d < 250 °C) as a result of the unstable furan moiety in the polymer backbone. The poly(cycloacetals) that could be processed were brown, opaque and brittle, so no mechanical testing could be done. The poly(cycloacetal/ketals) synthesized in this chapter were only partially renewable, with a biobased carbon content lower than 35%, as di-TMP is not yet renewable.

The results from the direct polyacetalization/ketalization of dicarbonyls with di-TMP did not fully meet our needs. Therefore it was chosen to explore the second strategy of making poly(cycloacetal/ketals). Cyclic acetal/ketal moieties can also be built in the polymer backbone by starting from a bifunctional molecule that already contains this functionality, and by polymerizing it with a polycondensation or polyaddition reaction. In **Chapter 6**, a diol, a diamine and a dithiol were synthesized from a diene with thiol-ene chemistry. The diene is commercially available and contains cyclic acetal moieties from the reaction of pentaerythritol and acrolein. In **Chapter 7**, two diols were synthesized from rigid diketones and glycerol. After optimization of the synthesis routes, the diols could be applied in the synthesis of polyurethanes, polycarbonates and polyesters.

From the three synthesized bifunctional molecules based on pentaerythritol, polyurethanes, polyamides and polythioethers could be synthesized, with the results given in **Chapter 6**. Seven different polyurethanes were obtained with high molecular weights.[11] The T_g values varied from 26-85 °C depending on the used diisocyanate used and all processed polymers showed to be transparent. The polyurethanes with IPDI and MDI had high moduli (E = ±1.5 GPa) while the polymers made with HDI, TMDI and MDI were ductile. The synthesized polyurethanes only had a biobased carbon content of 36-47% as petroleum-based diisocyanates were used. After the study of the polyurethanes, the synthesized diamine was combined with diacids in order to obtain polyamides.[12] Our combination of monomers required salt polymerization as a technique to synthesize polyamides with high molecular weights. The T_gs of the polymers varied from 24-85 °C, depending on the diacid used and the aliphatic polyamides were semi-crystalline. Three aliphatic polyamides were processed *via* compression moulding and transparent materials were obtained when fast cooling was applied. Some of the diacids used in the polyamide synthesis were renewable and as such a higher biobased carbon content (50-80%) could be calculated for these polymers. Finally, a dithiol could be synthesized *via* a two-step procedure. On the one hand, the dithiol was reacted with the starting diene to form polythioethers, while on the other hand it was stimulated to react with itself by the formation of disulfides. The synthesized polythioethers and polydisulfides had medium high molecular weights (M_n < 15 kDa) and T_g values around 60 °C. When the polythioether was oxidized into a polysulfone, the T_g was increased to 124 °C, which proves that these polymers are versatile.

Moreover, the calculated biobased carbon content for these polymers was 100%, which is the highest value obtained until now.

In **Chapter 7**, the synthesized diols from glycerol were used to synthesize polyurethanes, polycarbonates and polyesters.[13] The synthesized polyurethanes had extremely high T_gs (90-150 °C) and were all transparent. The moduli of the processed polyurethanes had values between 1.0 and 1.5 GPa, but these tough materials did not contain a ductile area. These polyurethanes exhibited extraordinary thermal and mechanical properties but their biobased carbon content was rather low (20-40%) due to the use of petroleum-based diisocyanates. Next, the diols were used in the polycarbonate synthesis as an alternative to bisphenol A. High molecular weight polymers with T_gs of 70 or 100 °C could be obtained. After processing, a transparent material could be mechanically tested and a modulus of 1.2 GPa and strain at break of 28% was measured. When we compare those novel polycarbonates to the bisphenol A based one, it is clear that our materials cannot yet substitute these polycarbonates but the first results were positive and the biobased carbon content can go up to 92%. Subsequently, the diols were reacted with renewable diesters (dimethyl succinate and dimethyl furanoate) to create polyesters. Unfortunately, the molecular weights obtained were not so high and depending on the used diester the T_g was low (dimethyl succinate, T_g = 40-50 °C) or higher (dimethyl furanoate, T_g = 65-95 °C). The polyesters were not processed, as the molecular weights were too low to ensure good chain entanglements. The calculated carbon content for these polyesters could be 50 or 100% depending on the used diketone in the monomer synthesis.

In the previous chapters, a compromise had to be made between the renewability and good thermal and mechanical properties. In order to avoid this compromise, a renewable bisketal from diglycerol was synthesized and the third synthesis route towards poly(cycloacetals/ketals), namely transacetalization/ketalization, was tested and reported in **Chapter 8**. Polytransketalization is rarely reported, thus a complete procedure needed to be developed.[14-15] The equivalent ratio, catalyst and temperature/pressure program were investigated and finally two programs were used with a 1 to 1.05 ratio and *p*-toluenesulfonic acid as the catalyst. Only high molecular weight polymers could be obtained with 1,4-cyclohexanedione and 4,4'-bicyclohexanone as diketones in the transketalization reaction. The poly(cycloketal) of 1,4-cyclohexanedione had a biobased carbon content of 100%, as required. We noticed degradation of the polymer material when processed, because of the high processing temperatures as a consequence of the high melting point (T_m = 210 °C). When this poly(cycloketal) was copolymerized with di-TMP, the crystallinity was decreased and the processing temperatures could be reduced.

In **Chapter 9**, the versatility of poly(cycloacetal/ketals) was investigated more thoroughly. For this, the diethyl ester of tartaric acid was reacted with acrolein, which resulted in an alkene containing diester that could be built in polyesters. The pending double bonds could then be reacted with a thiol *via* thiol-ene chemistry in a post-modification reaction. Five different functionalities were successfully attached onto the polymer backbone, which altered the thermal and hydrophilic properties. Then again, the alkene containing poly(cycloacetal-esters) could be crosslinked with a dithiol to form a network that could be degraded in acid environment.

All synthesized polymer materials were subjected to hydrolytic stability tests in acid environments. Almost all poly(cycloacetal/ketals) were stable in an aqueous solution of pH 1 for two weeks. Only the described polyamides in chapter 6 and the polyesters from tartaric acid (chapter 9) degraded at these low pH values. It was concluded that cyclic acetal/ketal containing polymers are much more stable towards acids than linear polyacetal/ketals.[16-17]

10.3 Perspectives

In this project, poly(cycloacetal/ketals) were synthesized from renewable resources and we aimed for high T_gs, transparency and good mechanical properties. In this thesis three strategies were explored to synthesize poly(cycloacetal/ketals), namely polyacetalization/ketalization, polycondensation/polyaddition of cyclic acetal/ketal containing bifunctional monomers and polytransacetalization/transketalization. The second strategy had the highest potential as a whole range of different polymers with varying properties could be obtained in this way. Only a few monomers, based on pentaerythritol and glycerol, were explored in this thesis. These monomers were used to make polyurethanes, polyamides, polyesters, polycarbonates and polythioethers. Depending on the monomer used, high T_gs (up to 150 °C) could be realized. When processed, these polymers were almost always amorphous and transparent, which was also one of our demands at the start of the project. The materials could be brittle, tough and even ductile, which shows us that poly(cycloacetal/ketals) are a versatile class of polymers. We only started from pentaerythritol and glycerol for the synthesis of our cyclic acetal/ketal containing monomers but this could be broadened, and many more possibilities could be examined. In addition to this, copolymerization could help to fine-tune the properties for a certain application. Of course, the challenge remains to find an equilibrium between the biobased carbon content, price, high T_g and desired mechanical properties.

Finally, other parts of this doctoral thesis could be the subject of further improvements. Polytransacetalization/ketalization is a polymerization technique that can certainly be explored more in detail. We only synthesized one bisketal for the polymerization reaction but many more bisketals/acetals could be made, for example from solketal (glycerol acetonide). These bisacetals and bisketals could then be polymerized with different dialdehydes and diketones. Moreover, copolymerization with commercially available tetraols could be the key to gaining extraordinary polymer materials. In addition to thermoplastic poly(cycloacetal/ketals), cyclic acetal/ketals could be used as a reversible chemistry for the synthesis of covalent adaptable networks. This kind of networks, that consist of covalently crosslinked material, are capable of being (re)processed as well as mended and recycled. When a hydroxyl-containing polymer is reacted with a dicarbonyl and cyclic acetal/ketal moieties are formed, the reversible chemistry of acetalization/ketalization allows us to recycle these networks. Thus, it is clear that still many routes can be explored for cyclic acetal/ketal containing polymers!

10.4 References

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Chapter 11: Nederlandstalige samenvatting

11.1 Inleiding

Kunststoffen zijn niet meer weg te denken uit onze moderne maatschappij. Je kunt ze overal vinden in het dagelijks leven, met toepassingen in verpakking, constructiematerialen en elektrische apparaten. Verder hebben polymeren ook voor grote doorbraken gezorgd in bijvoorbeeld de medische wereld. Echter, als gevolg van de toekomstige uitputting van de fossiele brandstoffen, wordt de verdere, geplande uitbreiding van de polymeerindustrie, met een verwachte jaarlijkse productie van meer dan 1 miljard ton tegen 2050, een uitdaging.[1-2] Bovendien neemt de bewustwording van de overheden, industrieën en de openbare opinie toe als het gaat om duurzaamheid van producten.[3] Als gevolg hiervan neemt de belangstelling voor de ontwikkeling van "groene" kunststoffen uit hernieuwbare bronnen toe. Hernieuwbare alternatieven voor fossiele brandstof gebaseerde producten worden onderzocht, evenals producten met nieuwe functionaliteiten.[1] De hernieuwbare bouwstenen die in de polymeerindustrie kunnen aangewend worden, variëren van vetzuren tot suikers, vezels, proteïnen en CO_2.[4-5] Vooral vetzuren en suikers kregen tot nu toe veel aandacht omwille van hun abundantie, lage kostprijs en de aanwezigheid van modificeerbare functionele groepen.

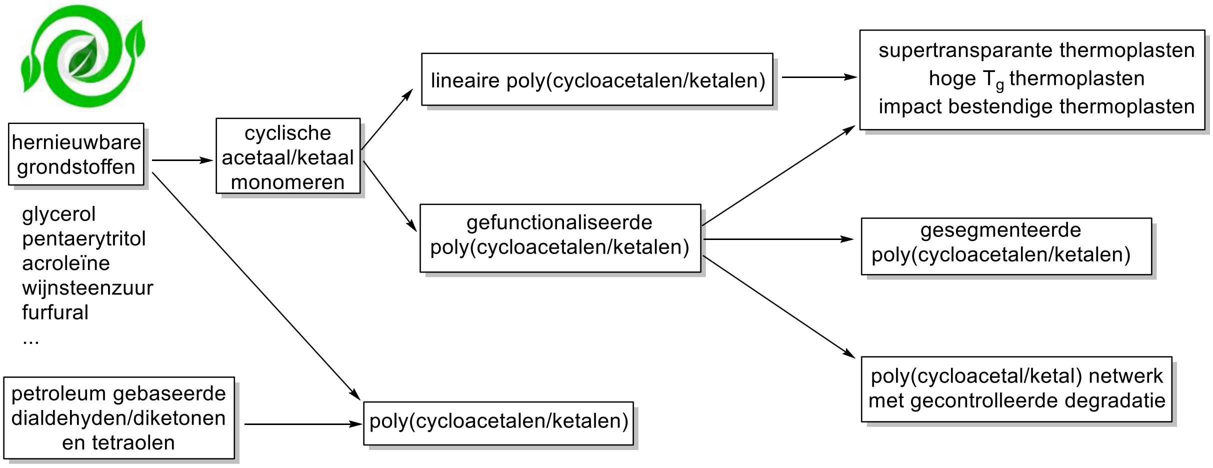
Biogebaseerde materialen hebben reeds hun weg naar de markt gevonden. Bekende voorbeelden zijn bio-afbreekbare draagtassen in de supermarkt[6] en plastic bekers[7]. Een groeiende reeks multinationals zoals Coca-Cola, Mitsubishi, Toyota, DSM en vele andere, dragen “biogebaseerd” en “duurzame processen” hoog in het vaandel. Zo heeft Coca-Cola al 20% van het polyethyleentereftalaat (PET) in hun plastic flessen “groen” gemaakt door gebruik te maken van hernieuwbaar ethyleenglycol.[8-9] Het uiteindelijke doel van Coca-Cola is 100% biogebaseerde flessen te produceren, via biogebaseerd tereftaalzuur of met polyethyleenfuranoaat (PEF) als duurzaam alternatief voor PET. Tegenwoordig zijn er dus al een beperkt aantal commerciële successen voor biopolymeren, maar met een volume dat goed is voor minder dan 1% bezetten ze nog maar een fractie van de wereldwijde markt.[10]

De uitdagingen om de groeiende marktvraag naar biogebaseerde producten te beantwoorden, zijn divers. De huidige generatie biogebaseerde polymeren situeert zich in de typische wegwerptoepassingen omdat hun verhouding kost/functionaliteit onvoldoende toelaat zich te kwalificeren voor duurzame producten (auto-industrie, elektronica, gebruiksgoederen etc.). Hierdoor blijven vele potentiële applicaties momenteel onbeantwoord. Om deze marktvraag in te vullen, bestaat de keuze tussen “drop-in” oplossingen (bestaande plastics vergroenen) en “nieuwe” plastics (vervangende of zelfs overtreffende functionaliteit ten opzichte van bestaande plastics). Het huidig financiële klimaat bewerkstelligt een uitgesproken voorkeur voor drop-in oplossingen omdat het businessplan en de waardeketen al bestaan. Echter, een indrukwekkende reeks nieuwe biogebaseerde bouwstenen kan eenvoudig gesynthetiseerd worden uit hernieuwbare grondstoffen en deze zijn tot op heden nooit getest in materialen. Materialen gemaakt uit nieuwe bouwstenen, vertonen echter nieuwe (combinaties van) eigenschappen.

Voor heel wat toepassingen voldoen de fysische en mechanische eigenschappen van de huidige generatie hernieuwbare polymeren niet.[11] Een gekende tekortkoming voor heel wat applicaties is het gebrek aan rigiditeit van deze polymeren met daarbij horend een lage glastransitietemperatuur (T_g) en dus een lage vormstabiliteit bij gebruik. Anderzijds wil de industrie biogebaseerde polymeermaterialen met supertransparantie en goede mechanische eigenschappen zoals ductiliteit. Een mogelijk materiaal dat aan deze voorwaarden voldoet en dat het uitgangspunt vormde van dit doctoraatsonderzoek zijn poly(cycloacetalen/ketalen) uitgaande van rigide, cyclische monomeren.[12]

11.2 Doelstelling

Het doel van dit doctoraatsonderzoek is de synthese van nieuwe poly(cycloacetalen/ketalen) uit hernieuwbare grondstoffen uitgaande van cyclische acetaal/ketaalmonomeren, waarbij de volgende materiaaleigenschappen van de verkregen polymeren worden beoogd: een hoge T_g (>100° C), supertransparantie, lage kristalliniteit en een hoge ductiliteit. Afhankelijk van welke eigenschappen het materiaal bezit, kan het aangewend worden als thermoplast, additief, gecontroleerd degradeerbaar polymeernetwerk e.a. (Figuur 11.1).



Figuur 11.1. Overzicht van de verschillende strategieën die gevolgd worden in deze thesis, vetrekkende van zowel hernieuwbare als petroleum gebaseerde bouwstenen.

Allereerst zullen poly(cycloacetalen/ketalen) gesynthetiseerd worden uit commercieel beschikbare dialdehyden/diketonen en tetraolen via polyacetalisatie/ketalisatie. Hierbij worden sommige gerapporteerde procedures herhaald om de technieken onder de knie te krijgen. Vervolgens zullen acetaal- en ketaalmonomeren gesynthetiseerd worden uit hernieuwbare grondstoffen, in eerste instantie vooral vanuit suikerafgeleiden of afvalstroomproducten.[13-21] Onder andere glycerol, pentaërytritol, acroleïne, wijnsteenzuur en furfural zijn bouwstenen die hier zeker aangewend zullen worden. Vetzuren en afgeleiden bezitten, wegens hun hoge ketenflexibiliteit, niet de juiste eigenschappen om de vooropgestelde doelstellingen te halen. De acetaal/ketaalmonomeren zullen na optimalisatie van hun syntheseroutes en de nodige opschaling vervolgens gepolymeriseerd worden via polycondensatie- of polyadditiereacties. Indien de polymeerstructuur dit toelaat zullen ook nog post-modificatie reacties zoals thiol-een chemie en vernetting uitgevoerd worden.

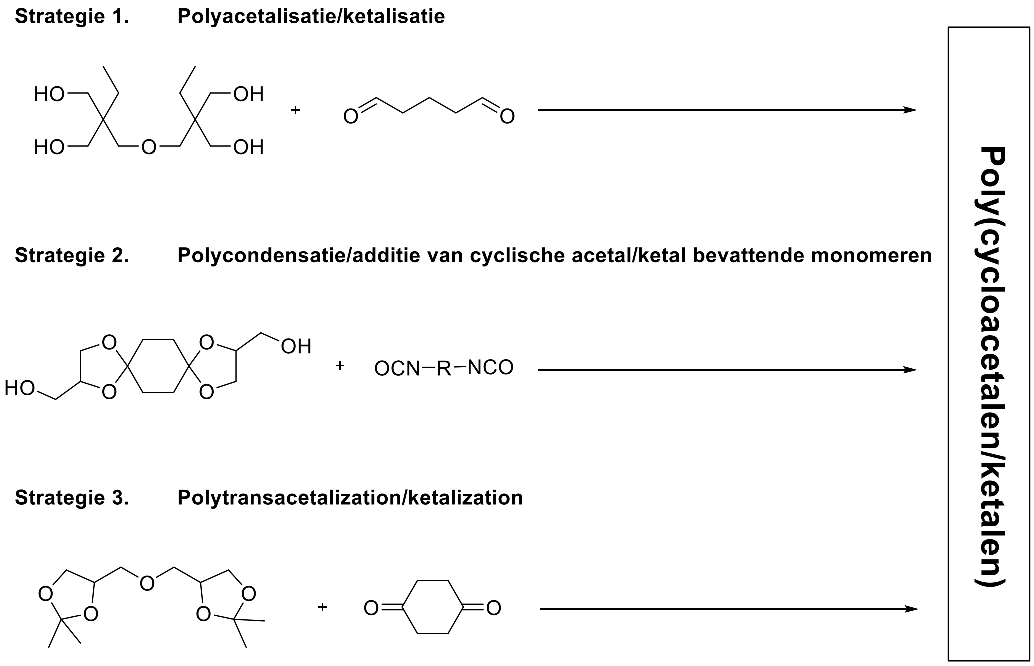
Van de gesynthetiseerde poly(cycloacetalen/ketalen) zullen vervolgens de materiaaleigenschappen bepaald worden, met in de eerste plaats T_g, de transparantie en mechanische eigenschappen zoals ductiliteit. Daarnaast zal ook de zuurgevoeligheid van deze polymeren grondig onderzocht worden. Afhankelijk van welke resultaten hiermee verkregen worden, kunnen ze in specifieke gevallen aangewend worden als materialen met gecontroleerde degradatie.

In dit doctoraatsonderzoek zullen zowel de synthese van de monomeren, de polymerisatie als de bepaling van de materiaaleigenschappen uitgevoerd worden. Deze vormen een O&O waardeketen voor één bepaalde klasse van verbindingen. Door deze drie elementen te combineren in één onderzoek, kunnen naast nieuwe polymeren ook “structuur-eigenschap” relaties onthuld worden met zowel wetenschappelijke als industrieel indicatieve waarde.

11.3 Overzicht van de resultaten

Het onderzoek naar hernieuwbare poly(cycloacetalen/ketalen) werd gestart met een modelstudie om de reactiviteit van verschillende commerciële dialdehyden en diketonen te testen. De resultaten van deze studie staan beschreven in **Hoofdstuk 5**. Hierna werden de meest reactieve dialdehyden en diketonen gepolymeriseerd met commercieel beschikbare tetraolen zoals pentaërytritol en di-trimethylolpropaan (di-TMP). De polyacetalisatie/ketalisatie van pentaërythritol met commerciële dialdehyden en diketonen stond al beschreven in de literatuur maar enkel laag moleculair gewicht polymeren werden gerapporteerd door de te hoge rigiditeit van de polymeren, wat ook zelf waargenomen werd. Met di-TMP, een iets flexibeler tetraol, konden hoge moleculaire gewicht polymeren ($M_n > 20$ kDa) gesynthetiseerd worden met glutaraldehyde, *o* en *m*-ftaalaldehyde en 1,4-cyclohexaandion. De poly(cycloacetalen) van glutaraldehyde en di-TMP konden verwerkt worden door warm te persen en transparante materialen werden verkregen. Door de flexibele structuur van glutaraldehyde was de T_g van deze materialen laag ($T_g = 38$ °C), net zoals de Young modulus ($E = 0.5$ GPa), maar het materiaal had wel een ductiel gebied (strain at break = 70%).[22] De andere poly(cycloacetalen/ketalen) waren veel rigider omdat er gestart werd van cyclische dialdehyden/diketonen wat dus ook leidde tot T_g waarden van 90-110 °C. Helaas, bij de verwerking van deze polymeren werden enkel brosse materialen verkregen en konden geen mechanische testen uitgevoerd worden. Aangezien er maar een beperkt aantal hernieuwbare, rigide dialdehyden en diketonen beschikbaar is, werden ook dialdehyden gesynthetiseerd uit hernieuwbare hydroxyaldehyden zoals 5-methylhydroxyfurfural (5-HMF) en hydroxypivaldehyde (HPA). Zes nieuwe dialdehyden werden gesynthetiseerd uit 5-HMF en zes verschillende diisocyanaten, waarbij het mogelijk was de synthese op te schalen. HPA komt op kamertemperatuur in zijn dimeervorm voor, dus de synthese van dialdehyden uit HPA vormde een uitdaging. Helaas konden met HPA geen 100% zuivere dialdehyden gemaakt worden, dus werden enkel de dialdehyden uit 5-HMF gepolymeriseerd met di-TMP. De moleculaire gewichten waren middelmatig en de polymeren bezaten hoge T_g's wanneer rigide diisocyanaten werden gebruikt (T_g = 70-110 °C). De thermische degradatietemperaturen voor deze polymeren waren laag ($T_d < 250$ °C) wat de verwerking van de materialen bemoeilijkte. De polymeren die dan toch verwerkt konden worden waren bruin, opaak en bros en konden dus niet mechanisch getest worden. De gesynthetiseerde poly(cycloacetalen/ketalen) in dit hoofdstuk waren partieel biogebaseerd (<35%) aangezien di-TMP nog niet hernieuwbaar geproduceerd wordt.

De resultaten via de rechtstreekse polyacetalisatie/ketalisatie van dialdehyden/diketonen met tetraolen bleken niet 100% te voldoen aan onze vooropgestelde eisen, dus werd er geopteerd voor een andere strategie (Figuur 11.2). Cyclische acetalen/ketalen kunnen ook ingebouwd worden in polymeren door te starten van een bifunctioneel monomeer die deze eenheid al bevat en ze daarna te polymeriseren via polycondensatie of polyadditie. In **Hoofdstuk 6** werd een diol, diamine en dithiol gesynthetiseerd uit een dialkeen via thiol-een chemie. Het commercieel dialkeen waaruit gestart werd bevat cyclische acetaaleenheden die gevormd werden door pentaërythritol en acroleïne. In **Hoofdstuk 7** werden twee diolen gesynthetiseerd uit rigide diketonen en glycerol. Na optimalisatie van de verschillende syntheses werden deze monomeren gebruikt in polycondensatie en polyadditie reacties.



Figuur 11.2. overzicht van de verschillende strategieën om poly(cycloacetalen/ketalen te maken, geïllustreerd met een voorbeeld.

In **Hoofdstuk 6** werden polyurethanen, polyamides en polythioëthers verkregen uit de gesynthetiseerde bifunctionele moleculen gebaseerd op pentaërythritol. Zeven verschillende polyurethanen konden gesynthetiseerd worden met hoge moleculaire gewichten.[23] De T_g's varieerden van 26 tot 85 °C afhankelijk van het gebruikte diisocyanaat en alle verwerkte polyurethanen waren transparant. De polymeren uit IPDI en MDI hadden hoge moduli (E = ±1.5 GPa) en de polymeren met HDI, TMDI en MDI vertoonden een lang ductiel gebied.

Aangezien diisocyanaten tot nu toe nog volledig petroleum gebaseerd zijn, is de hernieuwbaarheid van deze polymeren maar 36-47%. Hierna werd het gesynthetiseerde diamine gecombineerd met zes verschillende dizuren tot polyamides.[24] Voor onze combinatie van monomeren bleek polymerisatie van het zout de beste resultaten te geven. Afhankelijk van het gebruikte dizuur varieerden de T_g's van 24-85 °C en de alifatische polyamides waren semi-kristallijn. Drie alifatische polyamides werden verwerkt tot transparante materialen door ze warm te persen. Hoe langer de keten van het dizuur, hoe lager de modulus en hoe langer het ductiel gebied en de strain at break. Het percentage biogebaseerdheid van de polyamides was hoger dan die voor de polyurethanen omdat sommige dizuren hernieuwbaar zijn, en afhankelijk van het dizuur kon dit 50 tot 80% zijn. Uiteindelijk werd ook nog een cyclisch acetal bevattend dithiol gemaakt via een tweestaps procedure en werd dit gereageerd met ons start-dieen enerzijds of werd het gestimuleerd om disulfides te vormen met zichzelf. De gevormde polythioëthers en polydisulfides hadden medium hoge moleculaire gewichten (M_n < 15 kDa) en een medium hoge T_g rond de 60 °C. Beide polymeren konden tot 100% biogebaseerde koolstoffen bevatten. De polythioëthers konden ook geoxideerd worden tot polysulfonen waarbij de T_g 65 °C hoger werd (T_g = 125 °C).

De gesynthetiseerde diolen in **Hoofdstuk 7** werden toegepast in de polyurethaan, polycarbonaat en polyester synthese.[25] De polyurethanen uit deze diolen hadden zeer hoge T_g waarden (90-150 °C) en waren allen transparant. De moduli varieerden van 1.0-1.5 GPa en deze sterke materialen vertoonden geen ductiliteit. Deze polyurethanen bezitten uitzonderlijke thermische en mechanische eigenschappen maar hun biogebaseerdheid was eerder laag (20-40%) door het gebruik van petroleum gebaseerde diisocyanaten. Vervolgens werden de diolen gebruikt in de polycarbonaatsynthese als alternatief voor bisfenol-A en de behaalde resultaten waren zeker positief. Hoge moleculaire gewichten konden verkregen worden en de T_g varieerde van 70 tot 100 °C. Na verwerking werd een transparant materiaal verkregen dat mechanisch getest werd en een modulus had van 1.2 GPa en een strain at break van 28%. Wanneer we deze nieuwe polycarbonaten vergelijken met de bisfenol- A gebaseerde polycarbonaten (T_g = 150 °C, E = 2.4 GPa, strain at break = 40%) kunnen onze materialen nog niet als vervanging dienen maar zijn we wel goed op weg. Daarbij komt nog dat onze polycarbonaten tot 92% biogebaseerde koolstoffen bevatten. Tot slot werden deze diolen gereageerd met hernieuwbare diësters (dimethyl succinaat en dimethyl furanoaat). Jammer genoeg konden enkel middelmatig hoge moleculaire gewichtspolymeren gesynthetiseerd worden en afhankelijk van het diëster was de T_g eerder laag (dimethyl succinaat, T_g = 40-50 °C) of hoog (dimethyl furanoaat, T_g = 65-95 °C). De polyesters werden niet verwerkt omdat de moleculaire gewichten te laag waren om goede ketenverstrengeling te verzekeren en dus zouden enkel brosse materialen verkregen worden.

In de vorige hoofdstukken werd altijd een compromis gesloten tussen hernieuwbaar en goede mechanische en thermische eigenschappen. Om dit te vermijden werd in **Hoofdstuk 8** een volledig hernieuwbaar bissketal gesynthetiseerd uit diglycerol dat kon gepolymeriseerd worden door middel van transketalisatie reacties. Polytransketalisatie is zelden gerapporteerd en het uitwerken van een procedure kreeg dan ook de nodige aandacht.[26-28] De equivalentenratio, katalysator, temperatuur-en drukprogramma werden onderzocht en uiteindelijk werden twee procedures goedgekeurd, waarbij werd gewerkt met een 1.0 tot 1.05 verhouding en *p*-

tolueensulfonzuur werd gebruikt als katalysator. Acetonylaceton, 1,4-cyclohexaandion en 4,4’-bicyclohexanon waren de diketonen die getest werden in deze polymerisatie reactie, waarbij 1,4-cyclohexaandion en 4,4’-bicyclohexanon konden ingebouwd worden in hoog moleculaire gewichtspolymeren (M_n > 20 kDa). Bij de verwerking van deze poly(cycloketalen) werd degradatie waargenomen doordat het polymeer een hoog smeltpunt (T_m = ±210 °C) heeft en dus zeer hoge verwerkingstemperaturen gebruikt moeten worden. Door deze poly(cycloketalen) te copolymeriseren met di-TMP kon de kristalliniteit verlaagd worden en kon de verwerking doorgaan bij lagere temperaturen.

In **Hoofdstuk 9** werd de veelzijdigheid van poly(cycloacetalen/ketalen) onderzocht. Het diëthylester van wijnsteenzuur werd gereageerd met acroleïne, wat resulteerde in een biogebaseerd diëster dat een cyclisch acetal bevat met daaraan een dubbele binding. Wanneer deze diësters ingebouwd worden in polyesters werden polymeren verkregen met meerdere vrije dubbele bindingen langs de keten. Deze dubbele bindingen kunnen in een post-modificatie reactie gereageerd worden met thiol bevattende componenten via een thiol-een reactie. De functionaliteiten van vijf verschillende thiol componenten ingebouwd in de polymeerketen werden onderzocht. Via deze post-modificatiereactie konden de thermische eigenschappen en hydrofiliciteit van deze poly(cycloacetal-esters) gevarieerd worden. Anderzijds werden ook netwerken verkregen van deze alkeen bevattende polymeren met twee verschillende dithiolen. Afhankelijk van het gebruikte dithiol kon het netwerk gecontroleerd gedegradeerd worden in zuur milieu.

Van alle gesynthetiseerde polymeermaterialen werd getest of ze stabiel zijn in waterig zuur milieu. Bijna alle poly(cycloacetal/ketalen) waren stabiel voor twee weken in waterig milieu tot pH 1 bij 50 °C. Enkel de polyamides uit hoofdstuk 6 en de wijnsteenzuur-gebaseerde polyesters uit hoofdstuk 9 vertoonden degradatie bij die lage pH. Uit deze resultaten kon ook besloten worden dat cyclische acetaal/ketaal bevattende polymeren veel stabieler zijn tegen zuren dan lineaire acetaal bevattende polymeren.[29-30]

11.4 Vooruitzichten

In dit project werden poly(cycloacetalen/ketalen) gesynthetiseerd uit hernieuwbare grondstoffen waarna de thermische en mechanische eigenschappen onderzocht werden. Vooral transparantie, hoge T_g en goede mechanische eigenschappen zoals ductiliteit werden vooropgesteld.

Er werden in deze thesis drie verschillende strategieën verkend om poly(cycloacetalen/ketalen) te verkrijgen, namelijk polyacetalisatie/polyketalisatie, polycondensatie of polyadditie van cyclische acetaal/ketaal bevattende monomeren en polytransketalisatie (Figuur 11.2). De tweede strategie blijkt het hoogste potentieel te bezitten aangezien veel verschillende soorten polymeren met daarbij horende eigenschappen kunnen gemaakt worden. In deze thesis werden slechts enkele opties verkend met pentaërythritol en glycerol gebaseerde monomeren. Deze konden ingebouwd worden in polyurethanen, polyamiden, polyesters, polycarbonaten en polythioëthers. Afhankelijk van de monomeren konden zeer hoge T_g waarden ($T_g \leq 150$ °C) verkregen worden. Na verwerking waren deze poly(cycloacetalen/ketalen) bijna altijd amorf en transparant, wat ook een van de eisen was. Zowel brosse, taaie als ductiele materialen konden gesynthetiseerd worden. Deze resultaten geven aan dat poly(cycloacetalen/ketalen) een zeer veelzijdige klasse van polymeren is en dat er natuurlijk nog veel mogelijkheden zijn. Andere cyclische acetaal/ketaal bevattende bifunctionele monomeren kunnen gesynthetiseerd worden en ingebouwd worden in tal van polymeren. Daarnaast kan copolymerisatie helpen voor het aanscherpen van de juiste eigenschappen voor een bepaalde toepassing. Vooral een evenwicht vinden tussen biogebaseerdheid, kost, hoge T_g, transparantie en goede mechanische eigenschappen blijft de uitdaging vormen.

Tot slot zijn nog andere delen van dit doctoraatswerk vatbaar voor verbetering en mogelijk interessant om verder onderzocht te worden. Zo kan transacetalisatie/ketalisatie als polymerisatietechniek nog uitgebreid verkend worden. Wij beperkten ons tot de synthese van één bisketal maar meerdere bisketalen en bisacetalen kunnen gemaakt worden uit glycerol of andere hernieuwbare componenten, die op hun beurt gepolymeriseerd kunnen worden met diketonen of dialdehyden. Ook hier kan copolymerisatie met commerciële tetraolen leiden tot interessante polymeermaterialen. Anderzijds kunnen cyclische acetalen bijvoorbeeld ook gebruikt worden voor de synthese van covalent adaptieve netwerken. Dergelijke netwerken kunnen verwerkt en gerecycleerd worden omdat ze gebaseerd zijn op een reversibele chemie. Het vormen van acetalen en ketalen gebeurt via een reversibele chemie, dus wanneer een hydroxyl-bevattend polymeer met een dicarbonyl wordt gereageerd kan een covalent adaptief netwerk verkregen worden. Er zijn dus nog vele mogelijkheden voor deze cyclische acetaal/ketaal bevattende polymeren!

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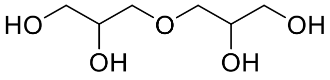
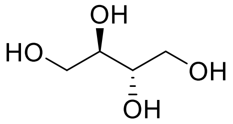
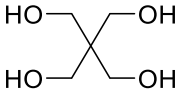
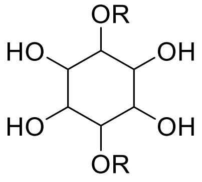
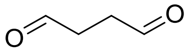
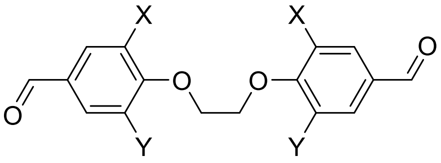
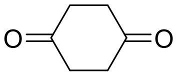
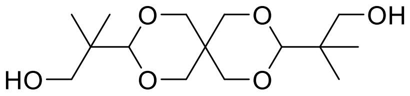
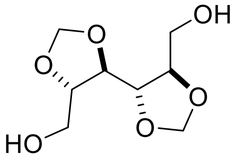
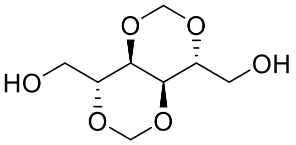
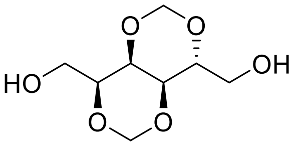
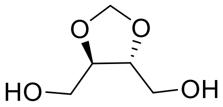
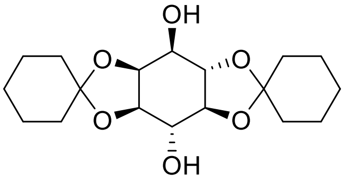
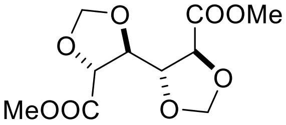
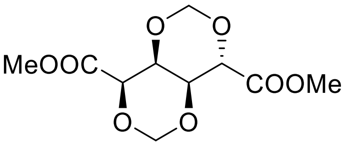
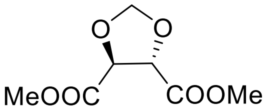
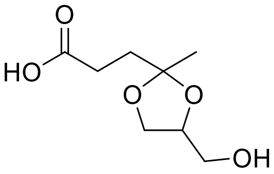
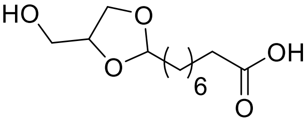
Appendix

Table A1. Renewable building blocks for poly(cycloacetal/ketals) that are aready reported.

Name	Structure	Commercially available?	Reference
Tetraols			
Diglycerol		Yes (80% pure)	1
Erythritol		Yes	2
Pentaerythritol		Yes	3
Myo-inositol tetraol	 R= Me, Allyl, benzyl	No	4
Dialdehydes			
Succinic dialdehyde		Yes	5
Hydroxybenzaldehyde ethers	 X=H, OMe, OEt Y=H, OMe	No	6
Diketones			
1,4-cyclohexanedione		Yes	7
Diols			
Spiroglycol		Yes	8
2,3:4,5-di-O-methylene-galactitol		No	9

2,4:3,5-Di-O-methylene-D-mannitol		No	9
2,4:3,5-Di-O-methylene-D-glucitol		No	10
2,3-O-methylene-L-threitol		No	11
Diol from *myo*-inositol		No	12
Diesters			
Dimethyl 2,3:4,5-di-O-methylene-galactarate		No	9
Dimethyl 2,4:3,5-di-O-methylene-glucarate		No	9
Dimethyl 2,3-O-methylene-L-tartrate		No	11
AB-type monomers			
Levulinic acid + glycerol		No	13
glycerol monoazelaaldehydate		No	14

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