Green Polymers:

Part 1: Polylactide Growth on Various Oxides: Towards New Materials

Part 2: Poly(epoxides-co-anhydrides) from porphyrin catalysts

Dissertation

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Abstract

Biodegradable polymers made from renewable resources ("green" polymers) are a very interesting alternative to recycling in a world more and more turned towards environmentally-friendly solutions.

Poly(lactide) is a biodegradable, biocompatible material coming from renewable resources. Such properties, added to a more and more competitive cost makes it a very interesting material for current industries. Coupled with other materials, properties can be fine tuned for different fields, ranging from construction materials to biomedical applications.

Poly(lactide) was grown on the surface of various oxide particles through ring-opening polymerization of lactide, using lactic acid as surface modifier. The aim was to determine what materials were compatible with this method to make cost-efficient materials with new properties. To this end, a simple, one-pot reaction under very mild conditions was developed and tested with various materials.

Particles containing about 40% polymer were successfully obtained from silica gel particles. Poly(lactide) growth was confirmed through Fourier-transform infrared and solid state $^{13}$C nuclear magnetic resonance analyses. Scanning electron microscopy showed a polymer growth on the particles, although it was shown part of the growth comes from the surface initiator polymerizing on its own. It was also shown that polymer did not smoothly coat the particles but rather grew in random pattern.
White quartz, basic alumina, titanium oxide and montmorillonite clay all successfully grew poly(lactide), while iron oxide, cobalt oxide, barium titanate and starch did not within the chosen reaction conditions. It is also possible to vary the monomer being used or the surface modifier, as was shown by growing poly(caprolactone) or by using glycolic acid on silica gel particles.

Poly(propylene oxide) is widely used in polymer industry, in particular in the process of making polyurethanes, which can be found in many aspects of our daily lives. It is made from propylene oxide, a petroleum-based molecule, and it is not biodegradable. However, it can be copolymerized with CO₂ or natural succinic anhydride to make biodegradable polyesters.

Propylene oxide was copolymerized with succinic anhydride in a reaction catalyzed by aluminum porphyrins. Molecular weights of around 4000 Da were obtained, with polydispersity indexes as low as 1.03. The turnover frequency was found to be almost twice as high as that of the homopolymerization of propylene oxide, and a high regioselectivity was observed, although stereoselectivity could not be determined. Kinetic studies showed that the reaction is first order in propylene oxide and in metal center.

Variations of this reaction were investigated. Chromium was found to be faster than aluminum, while cobalt reacted at about the same speed. Changing the electron-donating ability of the porphyrin was shown to influence the rate of the reaction. And it was shown that the copolymerization can be done with substituted or unsaturated
anhydrides, allowing to tune the properties of the final polymer. Finally, chain extension of the polymer was investigated to increase the molecular weight, although unsuccessfully.

Overall, it was shown that "green" polymers can be tuned and modified in various ways. This shows there is a future for environmentally-friendly polymers, that they can replace petroleum-based polymers, if the right combination of materials can be found to make them competitive.
Dedication

Dedicated to those of you who have been waiting for me to finish up and come back (thank you for your patience), and to those of you who've kept me going here (thank you for your help).
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I would like to express my gratitude to Dr Malcolm Chisholm for supporting and advising me.

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Vita

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Fields Of Study

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Introduction
Green Polymers

1. History of Polymers

Polymers have been in use since the sixteenth century, when the Mayas made balls for their children from the local rubber trees. Only in 1839 did Charles Goodyear discover the process of vulcanization, improving natural rubber's durability and making it usable for car tires.

The first synthetic polymer was made by Leo Baekeland, from formaldehyde and phenol. The patent for the method used to make this polymer, called Bakelite, was filed in 1907. In 1920, H. Staudinger published a paper proposing that polymers are made of long chains of short molecules linked together by covalent bonds. This was the development of modern polymer theory and he was rewarded with a Nobel prize in 1953. Staudinger also founded the first polymer chemistry journal, “Die Makromolekulare Chemie”, in 1947.

In 1927, large-scale production of polyvinyl chloride (PVC) began. PVC is still nowadays the third most widely produced plastic, being used for a great part in construction. In 1930, polystyrene was produced, still used today for packaging, amongst other applications. In 1938, W. Carothers, at Dupont, produced Nylon, a polymer that was a big commercial success. By 1944, polyethylene was produced in large scale. Polyethylene is still the most widely produced polymer, and is used mainly in packaging.
In 1976, the polymer industry outstripped steel as the most widely used material per unit volume in the US. Polymers are used in every aspect of our lives, from packaging to construction, from the automobile industry to the textile industry, from electronics to stuffed animals.

2. Renewable resources

The polymer industry therefore knew a massive development at the end of the 19th century and the beginning of the 20th century. At that time, coal-based chemistry, and later petrochemicals were also developing very fast. Therefore, most modern polymers originate from such fossil-fuels-based chemicals.

This is beginning to cause several problems:8

– Natural reserves of fossil resources such as oil and natural gas are dwindling, and a significant shortage will likely be seen within one or two generations.

– The price of oil has been ever increasing recently, and there is no indication it would drop significantly in the future.

– Governments and industry are starting to become aware of the need for sustainability.

However, before the rise of oil-based polymers, most macromolecular materials in use were of renewable origins: wood, paper, leather, rubber, gelatin, starch, cotton, cellulose...
There are several ways to develop renewable resources-based polymers.\(^8\) It is possible to take existing, natural polymers, and modify them. Polysaccharides (starch, cellulose, chitin) can be used in medicine or nutrition. They can also be chemically modified, blended or coupled with non-renewable polymers (or other renewable polymers) to increase their physical properties. Natural macromonomers, such as vegetable oils or tannins, can also be polymerized. Smaller natural molecules can also be polymerized, such as furan and lactic acid derivatives. Finally, the production of biodiesel gives out many byproducts that can be used for polymerization reactions (diols, diacids, oxiranes, acrylic acids...). It is even technically possible to make current fossil-fuels-based polymers, such as polyethylene terephthalate entirely from renewable resources.\(^9\)

3. Biodegradability

According to the US Environmental Protection Agency website,\(^{10}\) plastic waste accounted for 31 millions tons (12.4% of the total municipal solid waste) in 2010. In the USA, the most common method of municipal solid waste disposal is landfill (54%), followed by recycling (34%, and only 7.6% of the total plastic waste is actually recycled) and combustion (12%). However, landfilling results in the generation of greenhouse gases and takes up and may contaminate land that could be used otherwise.

The ideal approach to reducing this waste would be to develop plastics that would degrade rapidly into compost to replace all currently used plastics. However, the quality of a degradable plastic is often inferior to that of traditional plastics, especially in the long
Introduction

The realistic solution is to develop degradable plastics for short-lived applications, such as packaging materials, disposable nonwovens, consumer goods (disposable products, toys, etc.) and agricultural tools (mulch films or planters).

3.1. Rate of degradation

In general, polymer degradation takes place through scission of the chain. Such scission can occur through chemical (hydrolysis) or biological (enzymatic) mechanisms.

Many factors influence the rate of degradation of polymers. On one hand, the conditions under which the polymer is degraded (moisture, acidity, temperature, aerobic or anaerobic conditions or enzyme specificity\(^\text{[11]}\)) play an important role. This means plastics should be disposed of in specific infrastructures optimized for degradation and not in dry landfills that retard biodegradation.\(^\text{[12]}\) This is however beyond the scope of this dissertation and will not be discussed extensively.

On the other hand, the polymer’s properties also play a role on degradation:\(^\text{[11]}\) A flexible polymer will give easier access to water molecules for hydrolysis, and fit more easily into the active sites of enzymes. Crystalline polymers will degrade more slowly, both because water can not diffuse through crystalline regions and because amorphous regions are more flexible. Molecules with molecular weights greater than 20,000 Da are usually too large to allow their entrance into microorganisms’ cells. Some natural polymers can be degraded outside the microorganisms when those microorganisms can produce enzymes to cleave the polymer's backbone. In general though, the longer the backbone, the slower the degradation. The size and the shape of the polymer will also play a role: polymers with a higher surface area will offer more contact with moisture and
microorganisms and therefore degrade faster. Finally, the introduction of comonomer into a backbone can change most of the points mentioned above and will therefore also impact degradation.

3.2. Biodegradable polymers

One way to make biodegradable polymers is to use naturally biodegradable polymers such as starch and cellulose and couple them with other monomers to improve their physical properties:\cite{12} Thermoplastic starch can be blended or even grafted with polymers such as polycaprolactone to improve flexibility and moisture resistance. Blends with more than 85% starch are used for foaming and injection molding, in particular as loose fills for packaging. Cellulose acetate is used in many common applications, including toothbrush handles and adhesive tape backing.

Some synthetic polymers can also be degraded: Polyesters\cite{12} have been known to degrade since 1973. Polylactide degrades primarily by hydrolysis and not by microbial attack, but it is currently used in packaging and for making fibers. Polycaprolactone, blended with starch, is used to make trash bags. Blended with cellulose, it is used to make fibers. Poly(alkene succinates) have properties that mimic those of traditional plastics but are also degradable, and are used in fibers, films, bottles and cutlery.

Biodegradable polymers are in full development, and begin to enter the plastics market, due to both more competitive production costs and increasing ability to improve those polymers and give them physical properties that are closer to traditional polymers'.
4. Recycling

The best alternative for disposal of plastics is of course recycling. It eliminates both waste and crude oil needs. However, recycling polymers is not easy. There are four ways of recycling polymers.[13]

- Primary recycling: Used polymer-based products are mixed with either other used polymer-based products or virgin material, and melted into new polymeric products. This is the most popular method, but it produces poor quality materials, that can only be used for certain applications, and the number of cycles a plastic can go through is limited.

- Mechanical recycling: Similar to primary recycling, it involves sorting of polymeric materials before melting into pure polymeric granules that can be used for similar applications. It requires more work than primary recycling, and here again, the number of cycles a polymer can go through is limited, as the process reduces the polymer's molecular weight.

- Chemical recycling: Polymeric materials go through a process of depolymerization, either through solvolysis or pyrolysis, yielding back its starting material or short polymeric chains. These can then in turn be used to produce some more polymer, after having been purified.
– Energy Recovery: When the other methods are not desirable, polymers can be burned for heat and energy production. This method releases CO\textsubscript{2}, and it is hard to prevent production of toxic or polluting gases from any additive present in the polymers.

The main issue with polymer recycling is the fact that many polymers are different and require sorting before being recycled. Many small common plastic commodities do not have any indication of what materials they are made from. In addition, different products made with the same polymer will have different additives in them. Products never used in the food industry might have toxic additive, and care should be taken not to mix those with food industry plastics, for example. So recycling also involves purifying. Finally, the actual recycling process can be costly in terms of energy, and requires specific facilities.

Chemical recycling is the most desirable process, because it simplifies purification, and makes it possible to produce items of a comparable quality to those that are being recycled.

Although recycling is the best alternative for the environment, the ability to make biodegradable polymers from renewable resources is a very good alternative, perhaps less costly and easier to implement.
Part 1: Polylactide Growth on Various Oxides: Towards New Materials
Introduction

1. Polylactide in industry

Polylactide, also called poly(lactic acid) and often abbreviated as PLA, is a polyester that has been known since 1780 when it was first isolated from sour milk by Sheele. It was first produced industrially in 1881,[14] but had only recently become of great interest, because its biodegradability, its renewable resources origins and improvements in manufacturing processes are starting to lower its production cost as compared to fossil fuel derived polymers.

First patented in 1954 by DuPont,[15] work on PLA was discontinued because of the susceptibility to hydrolytic degradation. In 1972, Ethicon reinstated interest in PLA through high-strength, biocompatible fibers made from poly(glycolic-co-lactic) acid and usable as resorbable medical sutures. The cost of making those polymers kept them from being used in other applications until the late 1980s, where new, more cost-efficient methods for producing lactic acid were discovered.[16]

In 2007, the demand for polylactide in the US was of 90 millions pounds, representing 26% of the biodegradable plastics, and was expected to increase 25% annually through 2012. The main PLA producer is NatureWorks LLC (joint venture of Cargill and Teijin), and other companies involved in its production include Toyota and PURAC.
PLA is used for a broad range of applications. Because of its biodegradability,\textsuperscript{[11]} it has been used in packaging films, rigid thermoformed containers and coated papers. It also has created a lot of interest for biomedical applications, from drug delivery\textsuperscript{[17,18,19,20]} to biocompatible material used in helping tissue regeneration.\textsuperscript{[21,22,23]}

2. Chemistry of polylactide

2.1. Living Polymerization and Ring Opening Polymerization

The term "living polymerization" is applied to ionic polymerizations in which the capacity to terminate has been removed.\textsuperscript{[24]} This in theory makes it possible for the polymer chains to grow as long as some monomer is present, including if some monomer is added afterwards, be it the same or another one.\textsuperscript{[25]} In practice, though, a small amount of terminating agent is always present, and increase in viscosity and insolubility will slow down the reaction at some point. Living polymerizations are of interest because they yield high molecular weight polymers with narrow polydispersity indexes, allow good end-group control and provide access to block polymers.

Ring opening polymerization (ROP) is an example of living polymerization. The principle is that an initiator will open a cyclic molecule, giving a new charged moiety at the end of the opened cycle, which will in turn open a new cycle\textsuperscript{[24]} (See figure 1). One advantage of ROP is that, in contrast to condensation reactions, there is no elimination of small molecules which have to be removed or left as impurities. ROP is used to make polylactide, poly(propylene oxide), poly(caprolactone), and many other polyesters, as well as some polyethers.
2.2. Polylactide synthesis

There are two different synthesis routes for making high molecular weight PLA, as shown in figure 2. In both routes, a condensation polymerization of lactic acid leads to a low molecular weight, brittle, glassy polymer. Then, in one route, the polymer is enhanced by adding coupling agents that lengthen the chains. This is not ideal because the low concentration of reactive end-groups leave low concentration of water or other impurities in the polymer. The other route consists of obtaining lactide rings by depolymerization of the obtained polymer, purification and ring-opening polymerization of those lactide units to yield high molecular weight PLA. The ROP of lactide method
was the only way of making pure, high-molecular-weight PLA until recent development by Mitsui Toatsu Chemicals, in which lactic acid and catalyst are azeotropically dehydrated in an aprotic solvent under reduced pressures.\cite{27,28,29,30} We will here focus on the ROP of lactide, as it is still more widely used for preparation of PLA, and was for this reason used in our experiments.

The polymerization of lactides can follow different mechanisms, depending on the type of initiators used.\cite{31} These mechanisms are:

- enzymatic polymerizations
- cationic polymerizations
- anionic polymerizations
- coordination-insertion polymerizations

Enzymatic polymerizations are interesting in the medical field, because enzymes are biocompatible. It has been shown that enzymatic polymerization can produce polylactide with molecular weights of up to 126,000 Da.\cite{32}

The mechanism for the cationic polymerization is shown in figure 3. It consists of a protonation or alkylation of one of the carbonyl oxygen atoms which results in the electrophilic activation of the O-CH bond. This bond will cleave by nucleophilic attack of another lactide ring, and the reaction will propagate following this process, until a monofunctional nucleophile causes termination. It has been shown\cite{31} that only extremely strong acids or carbenium ion donors will initiate this process. It is also a rather slow reaction below 50°C, and it yields low to moderate molecular weights.
Figure 4 shows the mechanism for the anionic polymerization of lactide. In this case, the chain growth occurs through nucleophilic attack on the carbonyl group of the lactide, followed by cleavage of the CO-O bond. Termination occurs by protonation of...
Part 1: Polylactide Growth on Various Oxides: Towards New Materials

the alkoxide. This process involves the possibility of chain transfer and transesterification mechanisms, resulting in low to moderate molecular weights and the possible presence of macrocycles.

Finally, the coordination-insertion mechanism is based on coordinating a lactide monomer onto a metal center (figure 5), enhancing electrophilicity of the CO-group and nucleophilicity of OR groups, resulting in an insertion of the monomer onto the growing chain. This process allows for less side reactions, making it possible to reach higher molecular weights (higher than 200,000 Da[33]) and keep a better control on the reaction.

2.3. Stereochemistry

Lactide exists under three forms, shown in figure 6. Those three isomers have different properties on their own: D-lactide and L-lactide melt at 97°C, meso-lactide melts at 52°C. The most common isomers found are L-lactide and rac-lactide, which is a racemic mixture of D- and L-lactide. In turn, the polymers will have different physical
properties: pure poly-D-lactide (PDLA) and pure poly-L-lactide (PLLA) have equilibrium crystalline melting points of 207°C\textsuperscript{[34]} while poly-rac-lactide (rac-PLA) melts at 126-127°C.\textsuperscript{[14,16]} Reeve et al.\textsuperscript{[35]} showed the ratio of D- to L- lactide in PLA influences the enzymatic degradability of the polymer, with optimal degradability occurring for a ratio of 92% L- to D- isomer. Wanamaker et al.\textsuperscript{[36]} showed the physical properties of triblock copolymers with PLA at both end of the chain were very different depending on the stereoisomer used for PLA.

![Lactide stereoisomers: a) D-lactide b) L-lactide c) meso-lactide](image)

Stereochemistry for PLA goes farther than a simple differentiation between polymers made from the different lactide stereoisomers. To study the stereoselectivity of a catalyst, it is indeed important to know the exact stereosequence of the polymer. To that end, it is common in PLA literature to designate assignments by pair, as isotactic ("i") for -RR- and -SS- pairs, and syndiotactic ("s") for -RS- and -SR- pairs. From there, it is common to study tetrads (a combination of four stereocenters). All possible tetrads are given in table 1.
Table 1: Possible stereosequence tetrads in PLA

The polymerization mechanism will determine the stereochemistry of the polymer. It has been shown that cationic polymerization of L-lactide only yields optically pure PLLA under 50°C and induces racemization above that temperature. Anionic polymerization always leads to racemization, because of the planarity of the delocalized anion. In the case of coordination-insertion mechanism, the catalyst will determine if racemization will occur, and to what extent. This method therefore allows good control on the stereochemistry of the final polymer by fine-tuning of the catalyst.

2.4. Polylactide properties

Mechanical properties and crystallization behavior of PLA are very dependent on the molecular weight and stereochemistry of the backbone. Since both those variables can be controlled quite easily, the overall properties of the polymer can be tuned to different applications.

C. Perego et al. studied the effect of molecular weight of PLLA and rac-PLA on physical properties of the polymer. Their results, summarized in table 2, show how control on molecular weight and stereochemistry allow control on a wide range of physical properties. In this table, viscosity was measured in chloroform at 25°C at a concentration of 0.20 g/dL, and was used to determine the molecular weights.
Infrared peak band assignments for PLA have been reported in the literature and are given in Table 3.

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</tr>
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<td>-C=O carbonyl stretch</td>
<td>1759</td>
</tr>
<tr>
<td>-CH- deformation</td>
<td>1382, 1362, 1453</td>
</tr>
<tr>
<td>-C-O- stretch</td>
<td>1194, 1130, 1093, 1047, 1268</td>
</tr>
<tr>
<td>-C-C stretch</td>
<td>868</td>
</tr>
</tbody>
</table>

Table 3: Peak Band Assignments for PLA Infrared Spectra

A very useful tool to analyze PLA and its stereochemistry is nuclear magnetic resonance (NMR). Indeed, in the NMR spectrum of a given polymer, the observed resonances can be assigned to stereosequence combinations in the polymer, although the exact reason why the different chemical shifts arise is still unknown. Many articles are available in the literature discussing the assignment of peaks with
Part 1: Polylactide Growth on Various Oxides: Towards New Materials

stereochemistry\cite{40,41,42,43,44} using either $^1$H NMR, $^{13}$C NMR or both, and not all agree on said assignment, so we will not expand upon this here. Table 4 gives a general assignment for PLA peaks in chloroform.

<table>
<thead>
<tr>
<th>Chemical Shift (ppm)</th>
<th>Multiplicity</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H NMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>doublet</td>
<td>methyl</td>
</tr>
<tr>
<td>5.1-5.2</td>
<td>quartet</td>
<td>methyne</td>
</tr>
<tr>
<td>$^{13}$C NMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>169-170</td>
<td>-</td>
<td>C=O</td>
</tr>
<tr>
<td>69-70</td>
<td>-</td>
<td>methyne</td>
</tr>
<tr>
<td>16-17</td>
<td>-</td>
<td>methyl</td>
</tr>
</tbody>
</table>

Table 4: Chemical shifts for PLA NMR in chloroform-D

Research has shown\cite{45} tin and lead oxide are very effective catalyst for ring-opening lactide. Tin, antimony and bismuth octanoate catalysts are also very efficient as far as yield and viscosity are concerned. Finally, tin and bismuth octanoate are both very good at preventing racemization for reaction times under 12h, while still giving >95% conversion. Tin is widely used because of its low toxicity, making it compatible with biomedical applications.

2.5. Environmental considerations

PLA is a very likely candidates for many green polymer applications.
PLA is biodegradable, and its degradation has been intensively studied\(^\text{[46,47,48]}\) and it has been showed that it is highly dependent on crystallinity and does vary with stereochemistry. R.T. McDonald et al. showed that, with regard to proteinase-K-mediated degradation, highly crystalline samples degrade much slower than low-crystallinity samples and PDLA degrades faster than PLLA\(^\text{[47]}\).

It is also quite easy to chemically recycle PLA. In fact, part of the L-lactide used for our experiments was obtained by sublimation of orange juice bottles in the presence of ZnO, yielding pure L-lactide in very good yield.

Polylactide is also of great interest because it is biocompatible: It can be introduced in the body, will degrade slowly, and the products of the degradation are non-toxic.

Finally, PLA has been found to have physical properties that are very similar to many traditional polymers currently used on the market. It is still more expensive to produce than other polymers like poly(ethylene terephthalate), but costs are dropping, and are expected to become more competitive as the price of crude oil increases.

3. Polylactide hybrids

PLA is an interesting polymer on its own, but there are a lot of applications that could use hybrids. Used in copolymers, blends, or attached to non-polymeric materials, it gains new properties, it can be used for different applications.

Starch is a natural product both renewable and degradable. It is easily extracted from a variety of botanic sources, and it has some polymeric properties. It however has limited mechanical performance. Combining it with PLA would improve its mechanical
properties while improving PLA's biodegradability. Several ways of combining starch and PLA have been explored, including starch acetylation,[49] PLA functionalization with acrylic acid,[50] or maleic anhydride,[51] inclusion of diisocyanates,[52] or plain simple grafts.[53] E. Schwach et al. studied the benefits of several methods of compatibilization of Starch and PLA,[54] and showed that peroxide reticulation and addition of copolymer compatibilizer (PLA-grafted amylose) best improved tensile mechanical and thermal properties of the blend.

Similarly, PLA properties have been modified using clays,[55,56] sugars,[57,58] or natural fillers.[59]

Another way to modify the polymer's properties is by adding another monomer to the polymerization, producing copolymers with properties usually somewhere in between the properties of the polymers produced from each type of monomer. Examples of co-monomer that have been used include ε-caprolactone,[60] glycolide,[61,62] trimethylene carbonate,[63] and dioxepanone[64] each inducing changes in the properties of the polymer.[65]

4. Polylactide and nanoparticles

Nanoparticles have applications in many important fields of research: catalysis,[66,67,68] solar cells,[69,70] biochemistry,[71] biomedicine,[72,73] etc. Very often, nanoparticles are either made of polymer or coupled with polymers to improve on their physical properties. Polylactide is often used in such applications, especially where biochemistry is concerned.
A. Pfister et al. used a blend of polylactide and difluoroboron dibenzoylemthane to make nanoparticles with fluorescent and phosphorescent properties, as well as biocompatibility and the ability to be processed into fibers and films. Interestingly, this material also gains temperature-sensitive delayed fluorescence and green oxygen-sensitive room-temperature phosphorescence that are not properties of either of the starting materials. Such a material could be very useful for imaging or optical sensing.\(^{[74]}\)

Another useful application of nanoparticles including polylactide is in drug delivery. By using magnetic materials, usually iron oxide, it would be possible to direct drugs embedded in polylactide to certain area of the body by using magnetic fields. This would make it possible to reduce the quantity of drugs injected, since the concentration in the targeted area could be higher than in the rest of the body, and to reduce any toxicity issues such as those seen in chemotherapy treatment against cancer. There are here several approaches to making such nanoparticles. A magnetic material is needed to give magnetic properties, and polylactide helps holding the nanoparticles together and opens possibilities as to attaching drugs to the particles, but research has been done both on making nanoparticles out of a blend of those materials,\(^{[75]}\) or on coating magnetic nanoparticles with polylactide.\(^{[75,76]}\)

The biodegradable and biocompatible properties of PLA have been found to be of great interest in drug delivery systems.\(^{[77]}\) The possibility to trap a drug in polylactide copolymers (or a polylactide composite) and to have it be released upon degradation of the polymer has been thoroughly investigated.\(^{[20,78]}\)
5. Goals

Seeing as how PLA is of so much interest, we tried to explore the possibility to develop new types of materials by coating PLA around nanoparticles and powder particles. One goal was to explore how feasible that was with a variety of materials that could be used in different applications. To fulfill that goal, a wide range materials were investigated, from iron oxide to sand.

One major problem nowadays with everything that touches renewable "green" resources is their cost. Customers are in majority ready to pay a little extra for environment-friendly materials if those materials compare with what they are used to, but being able to make those materials as cost-efficient as possible would be a great improvement. That is why our secondary goal was to develop a cost-efficient, if possible easy way of coating our materials with PLA. To fulfill this goal, we have used a simple synthesis, and stuck with it – with slight variations if needed – for the whole study.
Surface Growth Of PLA

1. Particles coating

Several ways of preparing nanoparticles involving PLA can be found in the literature. One way is through the evaporation and solvent emulsification method. It consists of making nanoparticles out of a homogeneous blend of PLA and nanoparticles of interest.\(^{[20,79]}\) The advantages of this method are that it gives a good control on the particle sizes, and it starts from polylactide, rather than lactide, allowing for a good control on the polymerization, since it can be done under whatever conditions desired. However, it is rather tedious and asks for accurate settings in order to obtain satisfying results. It will also be a blend, not an inorganic core in a polymeric shell.

Another way is through surface-grafting of polymer on nanoparticles.\(^{[80]}\) It consists of attaching polylactide to the surface of the particles. It allows for a good control of the polymerization here again, since the polymer is also prepared separately and it results in a core-shell structure. However, it requires separate steps for the polymerization and the functionalization of the particles.

The last method is the surface growth method.\(^{[76]}\) In this method, polylactide is grown from lactide directly on the surface of the nanoparticles. For this to happen, there needs to be active hydroxide groups on the surface of the particle to ring-open lactide and initiate chain growth. Most metal oxide particles will have those hydroxides on their
Part 1: Polylactide Growth on Various Oxides: Towards New Materials

surface, but they are not active enough to ring-open lactide. That’s why the metal oxide starting particles have to be pretreated with some surface agent that will both attach easily to the surface hydroxides and provide an active alkoxide, such as titanium isopropoxide, glycolic acid[^76] or lactic acid[^80]. Although there is not as much control on the particles size and the polymerization, this method is much simpler, since it consists only of blending reagents together in a one-pot preparation. It will also produce particles with a core/shell structure instead of the blend structure.

Because of its simplicity, which results in better cost efficiency, the surface-growth method was selected to be used for this study. When surface modifiers would be needed, research had already been done on using glycolic acid on magnetic nanoparticles.[^76] Lactic acid is very similar in structure to glycolic acid, but using it as surface modifier makes it easier to manage toxicity and bioproperties of the particles, because it will be indistinguishable from the grown PLA chains (as shown in figure 7).

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[^76]: Reference 76
[^80]: Reference 80

Figure 7: Glycolic acid (a) and lactic acid (b) as surface modifier

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25
2. Initial test

As an initial test, to get an initial feeling of how the reaction behaved, TiO$_2$ nanoparticles were coated with PLA, using titanium isopropoxide as surface modifier, following a mechanism indicated in figure 8. This gave quite satisfactory results, with particles on which a melting point could clearly be observed around 130°C, and with a solid state $^{13}$C NMR giving sharp peaks at 170, 74 and 16 ppm, characteristic of PLA (data not shown). A FT-IR spectrum also gave a very sharp peak at 1750 cm$^{-1}$ (figure 9), confirming presence of PLA on the particles' surface. Weight determination shows 66% of the particles is actually polymer. This very high polymer content was very encouraging, being much higher than what can be found in the literature with other methods.

![Figure 8: Mechanism of titanium isopropoxide induced ROP of PLA on TiO$_2$](image)

![Figure 9: FT-IR spectrum of PLA-coated TiO$_2$ nanoparticles](image)
This was however somewhat outside the goals that were chosen for this study, since using titanium isopropoxide involves working under closely controlled atmosphere, which is not exactly easy or cost-efficient.

3. Methods

From the initial test with titanium oxide, a method was developed to be used with every test from here on. Unless stated otherwise, this method was followed for every experiment described later on.

3.1. Surface functionalization

Surface functionalization was not always implemented. However, when it was, it was done in accordance with the following method:

Nanoparticles were suspended in tetrahydrofuran by ultrasounds or vigorous stirring, depending on the size of the particles. A large excess of the surface modifier was then added slowly while stirring the nanoparticles in the solvent. The reaction was left stirring overnight, and the nanoparticles were then washed repeatedly with tetrahydrofuran and dried.

The solvent and nanoparticles were kept away from air during most of the reaction, to prevent too large input of water that could offset lactide ring-opening in the next step.

3.2. Polymerization

Polymerization was done in accordance to the following method:
Nanoparticles were dried for 8h under vacuum at 80°C. If a surface modifier was needed, the particles were dried before functionalization and kept under nitrogen most of the time to avoid moisture input.

The nanoparticles, with or without surface modifier, were then suspended in toluene by ultrasound (or vigorous stirring for bigger particles). The monomer was then added, usually with a 3:1 weight ratio, and left to dissolve at 60°C for a couple of hours. The catalyst was then added, and the reaction left to reflux for 8 hours. The final particles were then washed twice with toluene and twice with chloroform to wash away any free polymeric chain, then dried under vacuum.

3.3. Analysis

Analysis of the final product was done with several methods:

Fourier-Transform InfraRed spectroscopy (IR) was used in most cases to determine whether PLA was present, characterized by a peak at 1750 cm\(^{-1}\). Those were run on a Perkin-Elmer Spectrum GX instrument.

An experiment was devised to determine the quantity of polymer that grew on the particles. It consisted in weighing the particles before and after burning them in an Coorstek high-density alumina crucible over a Bunsen burner. Any weight-loss would be due to polymer decomposition, leaving only the inorganic particles.

Solid state \(^{13}\)C nuclear magnetic resonance (\(^{13}\)C NMR) was run on select samples with a Bruker DSX 300 MHz instrument, using magic angle spinning.

A Jeol JSM-5500 scanning electron microscope (SEM) was used for imaging of the particles.
4. Silica and derivatives

The possibility of coating silica or sand with polymer can have interesting applications in areas such as construction work, because it would make a very cost-effective materials that would have the handling properties of a powder with the physical properties of the polymer.

4.1. Silica

Reacting lactide directly with silica gel having proved unsuccessful, the surface modification of lactide with lactic acid was then experimented with.

Figure 10: FT-IR spectra of SiO2-PLA compounds made from different catalysts
Part 1: Polylactide Growth on Various Oxides: Towards New Materials

Lactic acid was reacted onto silica gel, and the resulting particles were then reacted with lactide, using different catalysts known to promote ring-opening polymerization, namely 4-dimethylaminopyridine (DMAP), tin octanoate (Sn(oct)$_2$) and zinc oxide (ZnO). Figure 10 shows FT-IR spectra for, from bottom to top, silica gel, silica gel reacted with lactic acid, and PLA-coated silica gel made using DMAP, Sn(oct)$_2$ and ZnO as catalyst. A peak at 1750 cm$^{-1}$ is clearly visible for each catalyst used, confirming their efficiency for this reaction. Results also showed at least 30% weight content of polymer on the final particles, as shown in table 5. Finally, a solid state $^{13}$C NMR spectrum of the reaction using Sn(oct)$_2$ as catalyst confirms presence of PLA (figure 11). This showed that for

![Figure 11: Solid state 13C NMR spectrum of PLA-coated silica gel particles](image)
coating silica gel with PLA, either of the three catalysts tested worked fine, although DMAP gave a lower conversion. It should be noted that the reaction with DMAP produced more free polymer than either of the other catalysts. Whether this was due to DMAP ring-opening lactide on its own or to a better catalysis of ring-opening with water has not been determined.

<table>
<thead>
<tr>
<th>Surface Modifier</th>
<th>Monomer</th>
<th>Catalyst</th>
<th>Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactic acid</td>
<td>Lactide</td>
<td>DMAP</td>
<td>30%</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>Lactide</td>
<td>Sn(oct)$_2$</td>
<td>38%</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>Lactide</td>
<td>ZnO</td>
<td>39%</td>
</tr>
<tr>
<td>Glycolic acid</td>
<td>Lactide</td>
<td>Sn(oct)$_2$</td>
<td>16%</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>$\varepsilon$-caprolactone</td>
<td>Sn(oct)$_2$</td>
<td>18%</td>
</tr>
</tbody>
</table>

Table 5: Relative weight of polymer on silica gel, using different surface modifier, monomer or catalyst

An optical image of the particles was obtained through scanning electron microscopy (see figure 12). Each steps shows a difference in the aspect of the particles.

Two observation should be noted: First, coating with lactic acid is quite important, and
probably involves some degree of polymerization of lactic acid. Secondly, the so-called "coating" doesn't coat the particles uniformly. Rather, polylactide seems to grow at certain spots, giving a very heterogeneous surface. This is further discussed in the Discussion section.

Although lactic acid as the surface modifier and lactide as the monomer worked very well and were to be benchmarks for all other experiments, variations were tested on silica. Using glycolic acid as surface modifier gave 16% weight polymer, which is in the range of the 13.3% obtained on iron oxide nanoparticles in the literature.[76] Similarly, using ε-caprolactone as the monomer yielded 18% polymer on the particles. (FT-IR spectra for those two experiments are given in Appendix A).

Sand is composed mostly of silica, and would provide for an even more cost-effective material than silica gel. Experiments showed however than using any sand would not work. Initial experiments involved plain beach sand, and no polymerization at all was observed using Sn(oct)$_2$ as catalyst, with and without surface modifier. Trying to wash the sand with a base to activate the surface hydroxides didn't improve the reaction. It is assumed too many impurities were present in the sand, and that surface hydroxides were too few to provide with any initiator for the reaction.

Figure 13: SEM picture of PLA growth on white quartz

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White quartz was then bought from Aldrich. This material induced polymerization, although an infrared spectrum could not be obtained. 20.2% of the particles were polymer. PLA growth on the sand surface was however confirmed by SEM (figure 13).

4.2. Metal oxides

Following the procedure used for silica, an attempt at coating iron oxide was made. Starting from nanoparticles bought from Sigma-Aldrich, using either lactic acid or glycolic acid did not give any results: FT-IR did not show any PLA peaks, and weight determination were always below 5%.

An attempt to reproduce results from F. Chen et al.\textsuperscript{76} did not lead to better results. For this, nanoparticles were synthesized in the lab: Iron (II) and iron (III) were mixed in a 1:2 ratio in water and nanoparticles were formed by adding ammonia under vigorous stirring. The particles were washed and dried, then reacted immediately with glycolic acid. The rest of the procedure was done according to previous experiments. FT-IR again did not show any PLA, and SEM confirmed no polymer growth had happened. Other particles were experimented upon without more success. BaTiO$_3$ and Co$_3$O$_4$ never grew polylactide.
Basic alumina, however, successfully grew PLA up to 11% of the oxide's weight, without any surface modifier. Both FT-IR and NMR confirm presence of PLA, as shown on figure 14. The idea to try basic alumina came from the fact that some surfaces seemed to be better than other for ring-opening lactide. This shows that basic character of the surface hydroxide is needed to achieve polymerization without using surface modifiers.

Finally, TiO₂ was tested with lactic acid and lactide. This gave 12% weight polymer on the nanoparticles. FT-IR confirmed presence of PLA with a peak at 1750 cm⁻¹, as shown in appendix A.
## Part 1: Polylactide Growth on Various Oxides: Towards New Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_2$O$_3$</td>
<td>No polymerization</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>11% polymer</td>
</tr>
<tr>
<td>Co$_3$O$_4$</td>
<td>No polymerization</td>
</tr>
<tr>
<td>BaTiO$_3$</td>
<td>No polymerization</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>12% polymer</td>
</tr>
</tbody>
</table>

*Table 6: Summary of results for metal oxide particles*

### 4.3. Other materials

Following the same basic idea of using surface hydroxide to ring-open lactide or react with some surface modifier, other materials were tried.

Starch has a lot of properties that would make it interesting when combined with PLA, as has been mentioned before. Using either DMAP or Sn(oct)$_2$ as catalyst did not lead to any polymerization, as confirmed by NMR. It was deemed that using a surface modifier would not be useful, since starch structure does contain a large amount of hydroxides bound to organic molecules. Therefore, adding an organic molecule to starch should not improve the properties of available hydroxides in any way. In fact, when that didn't work and the experiment using lactic acid as an initiator was run, it was found it didn't work either.

Seeing how starch would be a very good candidate for a polylactide blend, we tried a more "violent" approach, using first titanium isopropoxide, then as that did not work, MeLi as the catalyst. This gave a very small PLA peak on the NMR, as well as on the IR, but it was deemed insufficient to conclude PLA had grown on starch. Mass
determination could of course not be used on starch samples. The reason why polylactide would not react when using MeLi is still undetermined, but we assume the hydroxide groups on starch might have undergone a rapid exchange with MeLi, effectively quenching the reaction.

Clays also have free hydroxides in their structure. Combining clay and PLA could also lead to interesting properties. Montmorillonite was selected as it had been used for PLA-grafting before,\(^\text{[81]}\) although the polymer was not grown on the clay. Surface treatment by lactic acid followed by ring-opening polymerization of lactide gave 17% polymer on the final product. Presence of PLA was confirmed both by FT-IR and NMR, as shown in figure 15.

Montmorillonite, as most clays, has a layered structure. It was deemed possible that polymer chains would grow between layers, altering the structure of the clay. This was proven wrong, however. X-ray diffraction pattern (shown in Appendix B) proved exactly the same for the clay with or without PLA. This shows that PLA will grow on the outside hydroxides, lactide molecules being sterically prevented from getting between layers.
Figure 15: FT-IR and NMR spectra for montmorillonite coated in PLA
Discussion And Conclusion

A method for growing polylactide on nanoparticles was developed. The principle is that hydroxide groups on the material surface will ring-open lactide and induce polymerization.

Experimentation showed that not every material will ring-open lactide. Surface hydroxide groups have to be both readily accessible and active enough to ring-open lactide. Some will not induce reaction with lactide, probably because of a too great electronegativity character of the atom they are bound to.

In some cases, it is possible to use a surface modifier to provide with reactive hydroxide groups. Those surface modifiers will bind with surface hydroxides and provide a reactive hydroxide group to ring-open lactide. Glycolic acid or lactic acid act very well as such, since they can undergo esterification at the particle's surface and provide with a reactive hydroxide. They also are very close in structure to lactide, and do not interfere with the polymer biodegradability or toxicity. One observation that has been made is that lactic acid seems to polymerize to some degree on the surface of the particles. Mass measurements actually showed that around 40% of the final polymer weigh comes from lactic acid polymerizing. Since lactic acid and lactide polymers will have the same monomer, this will not influence the polymer backbone, but it will likely prevent any
stereoselectivity in the polymer. Quantities of lactic acid used are large enough to assume that polymer grown from lactic acid only would not grow longer than what has been observed, and shows that reacting additional lactide allows elongation of the backbone.

During most experiments, a weight ratio of 3:1 lactide to particles was used. This was to prevent formation of free polylactide chains that made separation of the particles difficult. However, the possibility of using higher quantities of polymer was tested. A 3:1 weight ratio of lactide to silica particles leads to 23% polymer weight on the particles, while a 20:1 ratio leads to 38% polymer on the particles. Within experimental error, an increase can be seen, but it is not very significant. This seems to show there is a ceiling to the length of the polymer backbone.

Although some sort of coating of the particles was expected, what was actually observed was actually more random growth on the surface of the particles. That is most probably due to a larger particle size than what has been used in the literature. It is particularly visible on sand, which consists of bigger particles than other materials (see figure 13). This would be due to a preference for any incoming monomer to react with the end-alkoxide from the growing chain rather that with a new surface hydroxide.

In summary, polylactide can be grown from the surface of different particular materials, theoretically giving them properties from the polymer while retaining properties from the material and the particular shape. Silica-based materials reacts readily, and other usable materials have been listed. Using lactic acid as an initiator, it is possible to get up to 40% polymer on the particles, and that number goes up to 66% if using titanium isopropoxide.
Part 2: Poly(epoxides-co-anhydrides) From Porphyrin Catalysts
Introduction

1. Poly(propylene oxide) in industry

High molecular weight polymers made from epoxides were first reported in 1933 by Staudinger.[82] It was made from ethylene oxide. In 1955, Pruitt and Baggett of the Dow Chemical Company developed an iron-based catalyst to polymerize propylene oxide.[83]

Shell has been producing poly(propylene oxide) (PPO), also known as polypropylene glycol (PPG) since 1959. In 2003, about 4 million tons of PPO were produced,[84] accounting for around 60% of the total consumption of propylene oxide. The greatest share of PPO is used as polyol for the production of polyurethanes, which are in turn used in many diverse applications, from construction materials to flexible or rigid foams to coatings and paints. Other uses include flocculants, elastomers such as Spandex and Lycra and specialty biocompatible polymers.

2. Chemistry of Poly(propylene oxide)

2.1. Synthesis of PPO

PPO is produced from PO following a ring-opening living polymerization (see Part 1, section 2.1, page 11). Contrary to lactide, however, PO is not a symmetrical molecule. Attack can occur at the methine or at the methylene carbons, resulting in different isomers (see below).
2.2. Isomerism

Stereochemistry plays an important part with PPO. Indeed, tacticity of the polymer will have an influence on the final material properties: Similar to lactide, PO has a chiral center. It can be found either as R-PO or S-PO. Commonly, rac-PO is used (the racemic mixture of both isomers). Therefore, the chiral centers will be found all along the polymer chain, and the tacticity of the polymer will influence its final properties.

As shown in figure 16, a polymer can be isotactic, when all chiral centers have the same configuration, heterotactic when they alternate regularly, and atactic when they are in a random order. This differs from polylactide in that each chiral center comes from a different monomer, whereas polylactide's chiral centers come in sets of two.

![Figure 16: Tacticity of a generic polymer](image)

The tacticity of the polymer will depend on several factors:

- The stereochemistry of the starting monomer
- The ability of the catalyst to promote polymerization of one enantiomer over the other, in case both are present
- The possibility of the catalyst to promote a chiral inversion on the methine center
This shows the importance of the choice of catalyst depending what stereochemistry is desired for the polymer.

The tacticity of poly(propylene oxide) can be determined by $^{13}$C NMR to the diad, triad or even tetrad level quite accurately,$^{[85]}$ with different peaks for the methine and the methylene carbons depending on whether they are in an isotactic or a heterotactic environment.

There's another isomerism type to take into account with PO: regiochemistry. Depending on whether each individual propylene oxide is opened at the methine or at the methylene carbon (figure 17), different polymers will be obtained.

![Figure 17: Regioselectivity of the attack of the nucleophile onto PO](image)

If the attack occurs consistently at the same carbon, the final polymer will be a succession of head-to-tail (HT) or tail-to-head (TH) junctions. HT and TH being structurally equivalent, we will refer to them both as HT. If, however, the carbon attacked varies, head-to-head (HH) and tail-to-tail (TT) junctions will appear. Figure 18 shows these regioisomers' structures.
PPO regioisomers can be distinguished by $^1$H or $^{13}$C NMR. The difficulty is, as mentioned above, NMR spectra will become more complicated depending on the polymer's tacticity. This can be simplified by starting from an enantiomerically pure propylene oxide and using a stereoselective catalyst.

In a regioregular (HT) and in a regioirregular (TT and HH) junction, the methine and methylene's nuclei will have different NMR shifts, because they will be in a different environment: The distance between two methine carbons in a HT junction is 3 bonds, whereas it is only 2 bonds in a HH junction and 4 in a TT junction. Statistically, there must be as many HH junctions as there are TT junctions. This means it is possible, by integrating the appropriate peaks in the NMR, to determine the degree of regioregularity of PPO and its derivatives. Studies have for example determined the exact NMR shifts for regioregular and regioirregular poly(propylene carbonate)$^{[86]}$ and poly(propylene succinate)$^{[87]}$. 

\[\text{Figure 18: Regioisomers of poly(propylene oxide)}\]
2.3. NMR of PPO

A common way of analyzing PPO is using $^1$H and $^{13}$C NMR. Table 7 gives the chemical shifts for PO.

<table>
<thead>
<tr>
<th>Chemical shift (ppm)</th>
<th>Multiplicity</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H NMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Sextet</td>
<td>Methine</td>
</tr>
<tr>
<td>3.1</td>
<td>Doublet</td>
<td>Methylene</td>
</tr>
<tr>
<td>0.9</td>
<td>Doublet</td>
<td>Methyl</td>
</tr>
<tr>
<td>$^{13}$C NMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>-</td>
<td>Methine</td>
</tr>
<tr>
<td>73</td>
<td>-</td>
<td>Methylene</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>Methyl</td>
</tr>
</tbody>
</table>

*Table 7: Chemical shifts for PPO NMR in chloroform-D*

2.4. Environmental Considerations

By itself, PPO can not be considered a "green" polymer. It is not biodegradable. Currently, it is also industrially made from petrochemicals (PO is produced through oxidation of propylene), although ways to make epoxides from renewable resources have been studied.$^{[88,89]}$

Considering the broad use of PO in industry, it is important to find ways to make it more environmentally acceptable. One such way is to ensure it is biodegradable by turning PPO into a polycarbonate or a polyester, using copolymerization with carbon
dioxide or anhydrides, for example. Succinic anhydride, in particular, is of great interest since succinic acid is now produced from renewable resources by companies such as Myriant Technologies.

3. Copolymers of Poly(propylene oxide)

3.1. Poly(propylene carbonate)

\[
\text{PO} + \text{CO}_2 \xrightarrow{\text{catalyst}} \text{Poly(propylene carbonate)} + \text{Propylene carbonate}
\]

*Figure 19: Alternating copolymerization of PO and CO}_2*

Inoue discovered that a mixture of ZnEt\textsubscript{2} and H\textsubscript{2}O would copolymerize PO and CO\textsubscript{2} in 1969\textsuperscript{[90]} (see figure 19). Only a few metals (including Al, Co, Cr, Mg, Li, Zn, Cu and Cd) being active for this reaction, research afterwards would focus on modification of ligands to improve the catalysts,\textsuperscript{[91]} with both porphyrin- and salen-derivatives showing promising results. Indeed, catalysts not only dictate the rate of the reaction, they also influence stereo- and regioselectivity, the amount of cyclics versus polymer formed as well as the ratio of ether-rich junctions in the polymer.

Poly(propylene carbonate) is of much interest because it can be used for ceramics, adhesives, propellants, resins, packaging materials and production of polyurethanes. It also uses CO\textsubscript{2}, which is nontoxic, nonflammable and a naturally abundant C1 feedstock. Finally, it is biodegradable.
3.2. Poly(propylene oxide) and anhydrides

Aliphatic biodegradable polyesters are typically prepared either by ring-opening polymerization of cyclic esters or by polycondensation of dicarboxylic acids with diols. Fujimaki et al. synthesized a high-molecular-weight polyester from succinic acid and 1,4-butandiol in 1993.\textsuperscript{92} Although it’s been shown high-molecular-weight polymers can be obtained by condensation reactions, such reactions require removal of water as the reaction proceeds. Living ring-opening polymerization are preferable.

As early as 1954, Fisch and Hoffman studied uncatalyzed reaction between epoxides and anhydrides, showing some degree of homopolymerization of the epoxides did occur, giving copolymers with 50 to 85% polyether.\textsuperscript{93} In 1960, Fischer made perfectly alternating copolymers by catalyzing the reaction with a tertiary amine.\textsuperscript{94} In 1969, Inoue et al. studied the copolymerization of phthalic anhydride and propylene oxide catalyzed by a metal catalyst, dialkylzinc.\textsuperscript{95} They showed that propylene oxide coordinates to the metal center first, then ring-open the anhydride, which in turn will ring-open another propylene oxide, to form the copolymer.

Y. Maeda et al. studied the properties and the biodegradability of copoly(succinic anhydride/ethylene oxide) with magnesium catalysts,\textsuperscript{96} getting molecular weights from 1600 to 20,000 Da, with polydispersities around 2.0. They also studied how to improve molecular weights while keeping good biodegradability by chain extension of this polymer with itself\textsuperscript{96} or with polyethers such as PPO,\textsuperscript{97} finding copolyesterethers kept good degradability and physical properties while increasing the molecular weight of the polymers.
More recently, Suh et al. studied the copolymerization of succinic anhydride, phthalic anhydride or maleic anhydride with propylene oxide using a Zn-Co double metal cyanide catalyst. They obtained alternating polymers with molecular weights ranging from 2300 to 10,000 Da, with narrow polydispersity index (1.02 to 1.49). Finally, Coates showed a variety of epoxides and anhydrides could copolymerize to produce high molecular weight, narrowly dispersed polymers with highly active β-diiiminate zinc or chromium (III) salen complexes.

4. Goals

Work had been done in our lab on the copolymerization of propylene oxide with carbon dioxide, using aluminum, cobalt or chromium porphyrins as catalysts. In view of the interest in copolymerizing cyclic ethers and cyclic anhydrides, we investigated the copolymerization of propylene oxide with succinic anhydride (see figure 20), using tetraphenylporphyrin aluminum chloride as a catalyst (see figure 21 for mechanism). Using NMR and mass spectrometry, we investigated activity of the catalyst as well as control on the polymerization, including molecular weight distributions and stereochemistry.

\[
\text{Figure 20: Reaction of propylene oxide and succinic anhydride}
\]
To investigate the possibility to tune the catalyst to different needs, we investigated the same properties using chromium or cobalt as the metal center, as well as using octaethylporphyrin and tetra(pentafluorophenyl)porphyrin with the aluminum center.

Finally, to study the possibility of tuning the polymer, we investigated the copolymerization of PO with substituted anhydrides, such as methylsuccinic anhydride and phenylsuccinic anhydride, as well as unsaturated anhydrides such as maleic anhydride. The possibility of chain-extending the short molecular weight copolymers obtained was also investigated.

Other work done in our lab that will be mentioned in this thesis include substituting propylene oxide with styrene oxide and looking at similar experiments, as well as copolymerizing propylene oxide, succinic anhydride and carbon dioxide.
Figure 21: Mechanism of copolymerization of propylene oxide and succinic anhydride with a metal catalyst.
Poly(propylene Succinate)

1. Methods

1.1. Catalysts preparation

1.1.1. Aluminum catalysts

Aluminum porphyrins were all prepared the same way, regardless of the porphyrin used: The porphyrin was dried for at least 5h under vacuum at 60°C, then dissolved in benzene. An excess of diethylaluminum chloride was added, and the mixture was stirred overnight at 40°C. Solvent was removed under vacuum for about one hour, then the catalyst was dried (ensuring removal of excess diethylaluminum chloride) at 70°C under vacuum for at least 5h. The catalyst was then stored in a glove box.

![Figure 22: Synthesis of TPPAlCl](image)

*Figure 22: Synthesis of TPPAlCl*
1.1.2. Chromium/Cobalt catalysts

Chromium and cobalt porphyrins were prepared the same way, regardless of the porphyrin used: The porphyrin was added to the metal dichloride, then dissolved in dimethylformamide (DMF). The reaction mixture was refluxed for at least 3h. A couple drops of acidic methanol (10% HCl in MeOH) were added to the mixture and it was left to oxidize in air overnight. The precipitate was then filtered, dried, washed with water to remove excess metal dichloride, then with hexanes to remove leftover porphyrin. It was then dried under vacuum at 70°C for at least 5h, then stored in a glove box.

1.1.3. Anhydrides

Anyhrides used were obtained from commercial sources. Subliming succinic anhydride to dry it did not make any visible improvement in the reaction, so most of the other anhydrides were used as received.

1.2. Solvent polymerization reactions

Solvent polymerizations were run according to the following procedure: In a glove box, 0.02 mmol of catalyst were mixed with 0.02 mmol of cocatalyst (PPNCl) and dissolved in about 1mL chloroform-D. The anhydride (1.1 equivalents to propylene oxide) was dissolved in acetonitrile, then added to the catalyst solution. Propylene oxide was then added to this solution, with a micro stir bar, and the polymerization was allowed to proceed at room temperature.
When studying turnover frequencies, the polymerization was done in vials, sealed with parafilm and kept in a glove box to allow sequential aliquot-taking. When only the final polymer was of interest, the polymerization was done in a sealed elemental analysis ampoule, according to the procedure described in the next section.

1.3. Melt polymerization reactions

Melt polymerization were prepared according to the following procedure: In a glove box, 0.02 mmol of catalyst, 0.02 mmol of cocatalyst (PPNCl) and anhydride (1.1 equivalents to propylene oxide) were added to an elemental analysis ampoule. Propylene oxide was added, then the ampoule was closed, taken out of the glove box, frozen in liquid nitrogen and sealed. If heating was required, it was done in a sand bath. It is important to note that no stirring was done with melt polymerizations.

1.4. Analysis

Polymerizations were rarely quenched, the reason being that when interested in the final polymer, quenching wasn't really useful, and trace amounts of water in solvents used for analysis were enough to separate the polymer chains from the porphyrin catalysts. When doing activity studies, the dilution of the polymer into the analysis solvent would slow the reaction enough to not change reaction completion significantly in the 20 minutes required to take a NMR spectrum. If required, polymerizations were quenched using acidic methanol.

Final polymers were dried under vacuum for several hours to get rid of solvents and propylene oxide.
NMR spectra (\(^1\)H and \(^{13}\)C) were taken on Bruker DPX 400MHz and 250MHz spectrometers, using chloroform-D as solvent. Molecular weights and polydispersity indexes were determined by gel permeation chromatography (GPC), done on a Waters instrument, with two Styrage 7.8x300mm columns, using THF as a solvent, and polystyrene standards for calibration. ESI mass spectrometry (MS) was done on a Bruker MicrOTOF instrument.

2. Tetraphenylporphyrin aluminum chloride

From previous work done in our lab,\(^{[101]}\) we knew that aluminum porphyrin tended to react slower and give better control over PO polymerization than chromium or cobalt porphyrins. We decided to therefore use aluminum tetraphenylporphyrin (TPP) as our reference for the copolymerization of propylene oxide and succinic anhydride.

2.1. Solvent polymerization

Succinic anhydride being a solid at room temperature, the initial reaction was done using a mixture of chloroform-D (for NMR), that would dissolve the final polymer as well as the catalyst system, and acetonitrile, that would dissolve the anhydride.

This reaction proceeds quite slowly, with a turnover frequency (t.o.f.) of 1.1 h\(^{-1}\). The molecular weight obtained was 3894 Da, with a polydispersity index (PDI) of 1.4. The polydispersity can be reduced by using a polyethylene vial to run the reaction in instead of a glass vial. In that way, the resulting molecular weight was 4009 Da, while the PDI was 1.03. We assume surface hydroxides on the glass' surface account for some chain transfer, increasing the polydispersity index.
2.2. Melt polymerization

The reaction in solvent being very slow, we investigated the turnover frequency in the melt. This provides useful information, especially since the influence of the catalyst is much more preeminent without solvent. One problem we faced in the melt is that succinic anhydride does not dissolve in PO (the reason why we were using solvent), and does not melt until 120°C, which would make the reaction very fast. To keep the reaction homogeneous, we actually used methyl-succinic anhydride (MeSA) in the melt. MeSA melts at 35°C. We could heat MeSA to 35°C, add it to the reaction and the mixture would stay homogeneous at room temperature. All turnover frequencies were therefore measured in the melt with MeSA. TPPAlCl had a t.o.f. of 18.9 h⁻¹. As a reference, the polymerization of propylene oxide (on its own) with the same catalyst, in the same experimental conditions, gave a t.o.f. of 10.4 h⁻¹. This indicates that the anhydride coordinates to the metal center and ring-opens very rapidly, then promotes ring-opening of PO.
2.3. NMR

$^1$H NMR data of the resulting polymer is given in appendix 3, although notable resonances are shown in figure 23. The multiplet at 5.1 ppm is attributed to the methine proton (1), the resonance at 4.1 ppm represents the signal due to an ABX spin system and is attributed to the methylene protons (3). This spin system was simulated to verify chemical shifts and integration (see Appendix 4). Both these resonances are shifted down-field significantly (by about 2 ppm) from PPO by the proximity of the ester groups. The resonance at 2.6 ppm is attributed to the anhydride's backbone methylene protons (5 and 7), and the doublet at 1.2 ppm is attributed to the methyl hydrogens (2), only slightly shifted down-field compared to PPO. Multiplicity and integration of those resonances are as expected. A small resonance present at 2.0 ppm correspond to leftover acetonitrile that

![Figure 23: 1H NMR spectrum of polypropylene succinate initiated by TPPAICl (details), taken in CDCl$_3$](image-url)
was not removed under vacuum, and the resonance at 7.24 ppm is CDCl$_3$. Small resonances above 7.24 ppm are attributed to the porphyrin hydrogen nuclei and PPNCl, while other small resonances are attributed to end-groups.

**Figure 24:** $^{13}$C NMR spectrum of polypropylene succinate initiated by TPPAlCl (details), taken in CDCl$_3$

* shows minor regioisomer resonances

$^{13}$C NMR spectra for this polymer are given in appendix 3, with notable resonances shown in figure 24. The two resonances around 170 ppm are attributed to the carbonyl carbons (4 and 8). The resonance at 67 ppm is attributed to the methine carbon (1), the resonance at 64 ppm to the methylene carbon (3), and the resonance at 14 ppm to the methyl carbon (2). The resonances at 27 ppm correspond to the methylene
carbons on the succinate backbone (5 and 7). These last resonances are interesting because a small resonance can be distinguished on each side of the bigger ones. These are due to regioselectivity. Takasu et al. made model compounds[^87^] that allow us to exactly assign those resonances, from the lower field to the higher field, to carbons 3, 1, 2 and 4 (see figure 25 for this numbering scheme, only used here). Integrating these peaks gives a regioselectivity of 85.8% HT junction for this reaction.

Normally, it is also possible to observe stereosequences in PPO or poly(propylene carbonate) by $^{13}$C NMR[^85^]. Figure 26, showing a comparison of all poly(propylene succinate) resonances made from either R-PO or rac-PO shows that stereochemistry of the polymer is not visible in this case. This is attributed to the greater distance between successive chiral centers.
Figure 26: $^{13}$C NMR of the poly(propylene succinate) with R-PO or rac-PO in CDCl$_3$
2.4. Mass spectrometry

ESI mass spectrometry does not give very good spectra of high molecular weight polymers. However, it is enough to be able to detect the low molecular weight chains to gather information about our polymers. Figure 27 shows a spectrum of the copolymerization of PO and SA with TPPAlCl. This polymer was intentionally prepared with only 10 equivalents of PO and 11 equivalents of SA to make analysis easier. Only the peaks easily identifiable have been labeled.

The difference between peaks of the major series is 158 Da, corresponding to one monomer of propylene oxide and one monomer of succinate. Further, the peak at 591.2 Da corresponds exactly to 3 succinate monomers, 4 propylene oxide monomers, one sodium ion (coming from the ESI procedure), one hydroxide end-group (gained by cleaving the aluminum porphyrin with trace amounts of water present in solvents), and one chloride end-group that initiated the first ring-opening. This suggests that chloride on the aluminum porphyrin ring-opens PO, which in turn will ring-open succinic anhydride. The presence of peaks at 491.1 Da and 649.2 Da suggests in this experiment, a slight excess of PO was present (due to experimental error with dealing with such low amounts), and one ether-rich (PO to PO) junction is present in the polymer. Other spectra suggest some polymers are ring-opened by trace amount of water present in the solvents, as they show hydroxide end-groups on both ends.
2.5. Kinetic studies

Kinetics were studied in solution, with the conversion of monomer to polymer measured over time for different concentrations of catalyst. The overall rate of the reaction, assuming succinic anhydride reacts very fast with the metal center, is as follow:

\[
\frac{d[PO]}{dt} = k [M]^a [PO]^b
\]

with [M] the concentration of the metal center.
Considering the concentration of catalyst stays constant over the course of the reaction, the previous equation can be reduced to:

\[
\frac{d[PO]}{dt} = k_{app}[PO]^b
\]

(where \(k_{app}\) is the apparent rate constant), which integrates to

\[
\ln\left(\frac{[PO]_0}{[PO]_t}\right) = k_{app}t
\]

if the reaction is first order in PO. Figure 28 shows a plot of \(\ln\left(\frac{[PO]_0}{[PO]_t}\right)\) versus time, verifying that the reaction is indeed first order in PO (straight lines), and obtaining \(k_{app}\) for different catalyst concentrations (in this case, shown as equivalents of catalyst for 100 equivalents of PO).

![TPPA\text{Cl} kinetics](image)

*Figure 28: First-order graph for PO with different equivalents of catalyst ([M])*
From there, we have $k_{app} = k[M]^a$. Taking the natural log of the previous equation gives $\ln k_{app} = \ln k + a \ln [M]$. A plot of $\ln k_{app}$ versus $\ln [M]$ will therefore have the catalyst's order for a slope, showing the copolymerization is first order in catalyst (see figure 29: The slope is 0.94, which can be approximated to 1, considering experimental errors).

Figure 29: Determination of kinetic order of metal center in copolymerization of PO and SA by TPPAlCl
3. Catalyst variations

3.1. Metal variations

Our group had been working on aluminum-, chromium- and cobalt-based porphyrins to polymerize PO. We therefore studied the polymerization of PO and SA with chromium and cobalt coordinated by tetraphenylporphyrin.

Initial reactions were done in the melt at 50°C, with 200 equivalent of monomer to catalyst. Molecular weight obtained that way were comparable to molecular weights obtained for aluminum in a similar experiment (see table 8). Aluminum and cobalt gave almost exactly the same molecular weights and polydispersity, and cobalt was slightly faster than aluminum. Considering TPPCoCl is more difficult to prepare than TPPAlCl, and 1H NMR spectra of cobalt-containing compounds are complicated by the paramagnetic metal center, we decided to leave cobalt and concentrate on chromium. As expected, we showed the chromium catalyst reacts much faster than aluminum (almost three times as fast in the melt with MeSA, as shown in table 8).

<table>
<thead>
<tr>
<th></th>
<th>MW (Da)</th>
<th>PDI</th>
<th>t.o.f. (h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>7527</td>
<td>1.40</td>
<td>18.9</td>
</tr>
<tr>
<td>Cr</td>
<td>5483</td>
<td>1.16</td>
<td>51.5</td>
</tr>
<tr>
<td>Co</td>
<td>7577</td>
<td>1.46</td>
<td>25.1</td>
</tr>
</tbody>
</table>

*Table 8: Results summary for copolymerization of PO and SA with different metal centers.*

Carbon NMR spectra of chromium-initiated copolymerizations showed similar features to that of aluminum (see figure 30), although the paramagnetism of chromium makes it impossible to distinguish regioselectivity. It is however expected to be less
Part 2: Poly(epoxides-co-anhydrides) from porphyrin catalysts

regioselective if any different, since it is much faster. Attempts to separate the chromium metal from the polymer were not successful and prevented the attainment of satisfactory $^{13}$C NMR spectra.

Overall, the difference in copolymerization of propylene oxide and succinic anhydride with different metals is much as we expected compared to previous work we did with those metals: Aluminum gives better control while chromium is much faster.

Figure 30: $^{13}$C NMR of poly(propylene succinate) catalyzed by TPPCrCl
3.2. Porphyrin variations

Similarly, our group had been working on different porphyrins. We tried our copolymerization with octaethylporphyrin (OEP) and tetra(pentafluorophenyl)porphyrin (TFPP) on aluminum and studied how those compared to the reaction with TPP (see figure 31). In theory, TFPP would be more electron-withdrawing than TPP, and OEP would be more electron-donating. This should in turn influence the strength of the metal-alkoxide bond and therefore influence reactivity of the catalyst towards ring-opening polymerization: On one hand, the more electron-donating ligand will weaken the metal bond with the initiator or the growing chain, making it easier to break that bond to insert a new monomer, but on the other hand, it will make the metal less electrophilic, and therefore less likely to activate PO toward ring-opening.

The influence of the porphyrin on the polymerization will be different for each metal center. Table 9 shows the turnover frequency for each metal center with the three different porphyrins. It shows that TPP is best for aluminum and cobalt, striking a balance between electron-withdrawing and electron-donating for best results. Chromium is not
much influenced by electron-withdrawing ability, but the electron-donating OEP reduces its efficiency by half. It also shows it is possible to influence the activity of the catalyst quite heavily by changing the substituents on the porphyrin.

<table>
<thead>
<tr>
<th>t.o.f. (h⁻¹)</th>
<th>Al</th>
<th>Cr</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFPP</td>
<td>7.9</td>
<td>49.7</td>
<td>17.1</td>
</tr>
<tr>
<td>TPP</td>
<td>18.9</td>
<td>51.5</td>
<td>25.1</td>
</tr>
<tr>
<td>OEP</td>
<td>8.5</td>
<td>28.5</td>
<td>19.1</td>
</tr>
</tbody>
</table>

*Table 9: Turnover frequency for the copolymerization of PO and SA for three different porphyrins for Al, Cr and Co metal centers.*

*Figure 32: 13C NMR spectra for the copolymerization of PO and SA. From top to bottom: TFPPAlCl, OEPAlCl and TPPAlCl.*
Part 2: Poly(epoxides-co-anhydrides) from porphyrin catalysts

Molecular weights and polydispersity were very similar for each aluminum porphyrin, and NMR spectra showed similar regioselectivity (85.8%, 83.5% and 77.2% for TPP, TFPP and OEP respectively). Figure 32 shows the NMR spectra of the final copolymer for each of those three porphyrins, while figure 33 shows specifically the succinate's methylene carbons region, where regioselectivity can be seen.

4. Anhydride variations

To investigate the possibility of tuning the polymer to different applications, we investigated whether it was possible to copolymerize propylene oxide with derivatives of succinic anhydride.
Figure 34 shows the different anhydrides we experimented with: SA is the basic succinic anhydride that can be obtained from renewable resources. Methylsuccinic anhydride (MeSA) and phenylsuccinic anhydride (PhSA) are two variants of SA we investigated to see whether adding a side-arm to SA would impede the reaction. Maleic anhydride would make a more rigid polymer, due to the presence of the double bond in its backbone, as would phthalic anhydride (PA). PA has also been used often in such polymerizations, and has been shown to give higher molecular weights than other anhydrides.

Table 10 gives the molecular weights and polydispersity indexes for polymerization of each of those anhydrides with PO, initiated by TPPAlCl.
**Part 2: Poly(epoxides-co-anhydrides) from porphyrin catalysts**

<table>
<thead>
<tr>
<th>Anhydride</th>
<th>M_n (Da)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>3290</td>
<td>1.33</td>
</tr>
<tr>
<td>MeSA</td>
<td>1127</td>
<td>1.19</td>
</tr>
<tr>
<td>PhSA</td>
<td>753</td>
<td>1.16</td>
</tr>
<tr>
<td>MA</td>
<td>1112+</td>
<td>1.02</td>
</tr>
<tr>
<td>PA*</td>
<td>12830/5073</td>
<td>1.02/1.13</td>
</tr>
</tbody>
</table>

*Table 10: GPC analysis for copolymerization of PO with different anhydrides, initiated by TPPAlCl.*

* Maleic anhydride did not dissolve well in GPC solvents. It is likely the actual molecular weight was higher than that.

* PA gave two peaks in the GPC. Both are indicated in the table.

From the table above, it is first clear that copolymerization happened for all of the anhydrides. Adding a side-arm (MeSA and PhSA) reduces the molecular-weight, although it is not clear exactly why. One possibility is that those contain a higher amount of the corresponding acid, that could be responsible for chain-transfer. Maleic anhydride gives a very narrow PDI, and from the fact it is harder to dissolve in common solvent, it is likely that the chains are indeed less flexible. Finally, it is not clear why PA gave two different peaks in the GPC. It is possible initiation occurred by two different initiators with different reactivity. However, it is clear the molecular weight is indeed much higher than any of the others. That has been observed before, but there is once again no clear explanation as to why that is, although it could be as simple as that anhydride being easier to dry and less inclined to hydrolyze back to the diacid.
It could be interesting to investigate the regiochemistry of poly(propylene methylsuccinate). However, as shown in figure 35, the NMR is very complicated. Indeed, not only will regiochemistry influence the NMR, but so will stereochemistry. Figure 35 was taken on a polymer made using R-PO to try to simplify the influence of stereochemistry, but methylsuccinic anhydride was a racemic mixture. Even though all peak clusters can be identified (with the help of a HMQC experiment, showed in appendix 5), it is hard to get enough information to discuss regio- or stereoselectivity accurately, other than to say the reaction is not stereoselective.

Figure 35: $^{13}$C NMR for poly(R-propylene methylsuccinate)
5. Chain extension

In view of the low molecular weights obtained in the copolymerization reactions, we decided to investigate chain extension of poly(propylene succinate).

From the nature of the reaction, either of the two monomers can be found at the end of each chain. That means we would have to deal with either a carboxylic acid end-group or an hydroxide end-group. (From our MS experiments, we showed that the amount of chloride end-groups is limited and decided to concentrate on hydroxides instead.) Seeing how PO is always the first monomer to be ring-opened, it means at least half our end-groups will be hydroxides. In theory, since the polymerization was done with an excess of SA, the other half should be solely carboxylic acid end-groups. Our MS experiments show it is not quite the case. So we expect to have more than half our end-groups being hydroxides, and the rest being carboxylic acids.

One of the major industrial uses for PPO is as a polyol for polyurethanes production. It seemed logical to use the urethane reaction to chain-extend our hydroxides end-groups (figure 36).

![Figure 36: Urethane formation](image)
A similar reaction allows formation of amides from carboxylic acids and amines. The use of a diamine could chain-extend our carboxylic acid end-groups. This reaction works best by going through an acyl chloride, and reacting it with the amine (figure 37).

Both these reactions are advantageous: They either do not form any side product, or the side products are gases that will bubble out of the reaction, driving it forward. Another advantage is that they can both be catalyzed by a tertiary amine, which means it will limit the amount of reactants needed for the chain extension. Furthermore, the isocyanate group will react with amines to give urea, and with other isocyanate to form a trimer. Although these reactions should occur slower than the formation of polyurethane when catalyzed by a tertiary amine, they should ensure a substantial increase of molecular weight of our polymers, even if the chain extenders are not added stoichiometrically (which is likely to happen since it is hard to quantify the polyesters' end-groups).

For this reaction, poly(propylene succinate) was prepared with TPPAlCl. A MALDI mass spectrum made sure the end-groups were mostly hydroxides and carboxylic acids (as opposed to chloride end-groups). The chain extenders were chosen to be ethylene diamine, and 4,4'-methylenediphenyldiisocyanate (MDI). MDI was chosen
because it is commonly used to make elastomers in industry, and because it is the less hazardous of the commonly available isocyanates. The catalyst was chosen to be pyridine.

Poly(propylene succinate) with $M_n = 3894$ Da (as determined by GPC) was reacted with 1 equivalent of SOCl$_2$, then with 0.5 equivalent of ethylene diamine, and finally with 0.75 equivalent of MDI dissolved in hexanes. The whole reaction was done in about 1mL of chloroform, using about 0.1 equivalent of pyridine as the catalyst. Each reactant was added after about 2 hours of stirring with previous ones, and the final mixture was left to react overnight. A GPC analysis did not show any significant improvement in molecular weight.

In order to investigate the reason why molecular weight did not increase, a number of model reactions were done. To investigate the formation of the amide bonds, octanoic acid was converted to octanoyl chloride by reaction with thionyl chloride, catalyzed by pyridine. $^1$H NMR shows this reaction gave a 100% yield (Appendix 6.1). Ethylene diamine was then added to the reaction vessel. $^1$H NMR of the product was not entirely assigned, but it was clear ethylene diamine was not present anymore (Appendix 6.2). An ESI-MS spectrum could once again not be assigned entirely (Figure 38), but the two most preeminent peaks (at 313 and 335 Da) can be assigned to the expected product having two octanoic acids joined by ethylene diamine. The two peaks come from the molecule having either a proton or a sodium ion added on by the ESI procedure. Another
observation that can be made is that even though there are unassigned peaks at higher molecular weight, there are clearly none where either octanoyl chloride or ethylene diamine would be, indicating the molecular weight should increase.

An experiment was done reacting succinic acid with thionyl chloride, then with ethylene diamine. Here again, MS did not give any easy results to analyze, but they clearly did not show any leftover succinic acyl chloride or ethylene diamine, only higher molecular weights.

Figure 38: ESI-MS spectrum of the products of the reaction of octanoyl chloride with ethylene diamine in the presence of pyridine
The formation of the urethane junction was investigated by first reacting 4,4'-MDI with isobutanol, in the presence of pyridine. Here again, an ESI-MS spectrum could not be completely assigned (Appendix 6.3), but peaks at 399 and 421 Da showed the presence of the expected product of two isobutanol linked by one MDI molecule. In this case, a small amount of leftover MDI was found, and several peaks between 700 and 800 Da could not be assigned. Once again, however, they should indicate an increase of molecular weight. There was no peak indicating any leftover isobutanol. To investigate the polymerization reaction, 4,4'-MDI was reacted with 1,3-propanediol in the presence of pyridine. Figure 39 shows the ESI-MS spectrum of the products of this reaction. Here again, some MDI remains unreacted (peak at 249 Da). The peak at 321 Da could be assigned to the product of the reaction of propanediol with MDI, where one isocyanate moiety on MDI was changed into an amine by reaction with water and could not therefore react with another propanediol. The peak at 365 Da can be assigned to the reaction of MDI with one propanediol, the peaks at 425 and 441 Da to the reaction of MDI with two propanediol (with different cations added on), and the peak at 691 Da can be assigned to the reaction of 2 MDI with 2 propanediol. This clearly shows that, even if the polymerization is not extensive, polymers' molecular weights should at least double from reaction with 4,4'-MDI.
Overall though, the reason why chain extension could not be observed on our polyesters was not determined. One reason could be the low solubility of the resulting polymer, or the very small amounts of reactants used (under 5 \( \mu \)L) which makes evaporation or presence of water more important.

6. Other work

Dr Nicole Harrold has been working on similar reactions using styrene oxide instead of propylene oxide, catalyzed by TPPCrCl. In particular, she found that she gets higher molecular weight when using exactly a 1:1 ratio of styrene oxide to succinic anhydride. Excess of either comonomers decreases the polymer’s molecular weight. This
could be due to both trace presence of acid in the anhydride and the poor reactivity of the homopolymerization of styrene oxide. She gets identical results using phthalic anhydride, although molecular weights are higher in general. She also found that some amount of styrene oxide will turn into phenylacetaldehyde, although the effects of this reaction have not been investigated yet. Dr Harrold finally investigated the regiochemistry of poly(styrene succinate), making model compounds of the head-head junction and comparing carbon NMR to assign chemical shift of different types of junctions.

Chandrani Chatterjee has been working on the influence of the amount of cocatalyst on the rate of the reaction. She observed in particular that using 0.5 equivalent of cocatalyst to catalyst increases the amount of ether-rich junctions in poly(propylene succinate), while at least 1 equivalent is required to get purely alternating copolymer. As she investigated the same parameter for the formation of poly(propylene carbonate), she observed the reaction is faster with 0.5 equivalent of cocatalyst, in addition to the increase in ether-rich junction. This hasn't been investigated for poly(propylene succinate) yet but it is likely similar.

She also investigated the possibility of making poly(propylene succinate carbonate), by polymerizing propylene oxide, carbon dioxide and succinic anhydride together, using TPPCrCl as catalyst. This reaction does form the terpolymer, probably as a block polymer, although this has not yet been proven. She did show however that if propylene oxide is present in limited amount, poly(propylene succinate) will be the major product of the reaction, which tend to indicate succinic anhydride reacts faster with the activated metal alkoxide than CO₂ does.
7. Conclusions

The copolymerization of propylene oxide and succinic anhydride catalyzed by metal porphyrins was thoroughly investigated. It was found the metal center can be changed to tune the reactivity, with chromium being much faster than cobalt and aluminum. Substituents on the porphyrin will also influence the reactivity. It was found tetraphenylporphyrin strikes a good balance, being faster than both the more electron-donating octaethylporphyrin and the more electron-withdrawing tetra(pentafluorophenyl)porphyrin. Interestingly, using succinic anhydride as a comonomer makes the polymerization faster than the homopolymerization of propylene oxide.

It was found that adding substituents on the anhydride is possible. Both using a more rigid anhydride (phthalic or maleic anhydride) and a substituted anhydride (methyl or phenyl anhydride) were shown to be possible, although fine-tuning of reaction parameters would be required to obtain molecular weights comparable to those obtained with succinic anhydride. This should however make it possible to prepare polymers with different physical properties for different applications.

Finally, the possibility of increasing the copolymer's molecular weight was investigated through chain extension of the low-molecular weights obtained. Although this should work in theory, and worked to some extent on model compounds, it did not give significant results and would require a more thorough investigation.
Overall, we showed it is possible to copolymerize propylene oxide with cyclic anhydrides to produce a biodegradable polymer in similar ways that propylene oxide is homopolymerized or copolymerized with carbon dioxide. Succinic anhydride in particular being now available from renewable resources, this could be a big step towards making poly(propylene oxide) a more environment-friendly polymer.
Conclusion
Although quite different in scope and methods, both projects described above tend to show that green chemistry is the future of polymers. There is still a lot of work to do to make green polymers both economically and physically competitive with oil-based polymers, but we've shown it is possible to make a wide array of materials, from cost-effective biorenewable and biodegradable coating for nanoparticles to biodegradable derivatives of the widely used poly(propylene oxide).

Currently, green polymers are both more expensive and with poorer physical properties than their widely-used oil-based equivalents. As Dr. James C. Stevens recently put it: "What's the most important property for a new polymer? Its price." Of course, that's assuming physical properties are at least equal to what is currently in use. The general public will not accept a poorer material, even if it's cheaper. But it will also not accept to pay more for a barely improved material. Research should then focus both on investigating ways to make those polymers cheaper to produce and to improve their physical properties. Inserting comonomers is one way of improving the properties, and so is investigating secondary materials that could be mixed to the polymers to improve their resistance (such as nanoparticles).

For these reasons, there is still a lot of work to be done before renewable, biodegradable polymers take over the plastics market, but polylactide is used in packaging already, and with the growing general interest in environmentally-friendly solutions, including the many articles that can be found investigating ways to make current materials from renewable resources, and the steady increase in oil prices, we should be seeing more and more of those green polymers into our daily lives.
References

15. C.E. Lowe, US Patent 2,668,162 (to DuPont), 1954
23. Thomas et al., *SPLINE* (2008), **33**, 734


87. A. Takasu, T. Bando, Y. Morimoto, Y. Shibata and T. Hirabayashi, *Biomacromolecules* (2005), 6, 1707


89. Z. Yu, L. Xu, Y. Wei, Y. Wang, Y. He, Q. Xia, X. Zhang and Z. Liu, *Chem. Commun.* (2009), , 3934


Appendix
Additional Materials

1. FT-IR Spectra

1.1. Glycolic acid surface-treated silica gel reacted with lactide
1.2. Lactic acid surface-treated silica gel reacted with ε-caprolactone
1.3. Lactic acid surface-treated titanium oxide reacted with lactide

![Image of XRD Spectrum of Montmorillonite coated in PLA]

2. XRD Spectrum of Montmorillonite coated in PLA
3. NMR spectra of PO + SA initiated by TPPAlCl, taken in CDCl$_3$
Appendix

\[ {}^{1}H\text{ NMR} \]

\[ {}^{13}C\text{ NMR} \]
4. $^1$H NMR simulation of poly(propylene succinate)

The figure above shows a simulation (top), done with TOPSIN, compared to the actual spectrum (bottom) of poly(propylene succinate)'s resonances for the propylene backbone's methylene (4.10 ppm) and methine (5.11 ppm) protons. On the right are the parameters used for the simulation. The two protons on the methylene group have different environments due to the chirality of the methine group, giving this ABX pattern.

Chemical shift (ppm):

- proton a: 4.139
- proton b: 4.652
- proton c: 5.107
- proton d: 1.214
- proton e: 1.214
- proton f: 1.214

Spin coupling (Hz):

- couple a b: 11.97
- couple a c: 3.68
- couple b c: 6.54
- couple c d: 6.34
- couple c e: 6.34
- couple c f: 6.34
5. HMQC experiment on poly(R-propylene methylsuccinate) in CDCl$_3$
6. Chain extension model reactions

6.1. $^1$H NMR of octanoyl chloride in CDCl$_3$

The absence of a peak at 12 ppm shows there is definitively no octanoic acid left at this point.
6.2. $^1$H NMR of the products of the reaction of octanoyl chloride with ethylenediamine in the presence of pyridine, taken in CDCl$_3$
6.3. ESI-MS spectrum of the products of the reaction of 4,4'-MDI with isobutanol in the presence of pyridine