A Study of the Manufacturing and Product Possibilities of a Cork/Polyactic Acid Compound

by

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B.S., Mathematics, University of Colorado, Boulder (2003)

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

A study of the manufacturing and product capabilities of a cork/polylactic acid compound was conducted. Fine granulated cork, 1mm in diameter, was compounded with Natureworks’ Ingeo™3051D PLA and extruded into pellets. The PLA was compounded with cork in two concentrations: 5% by weight and 10% by weight. The material was then pressed in the flat sheets in a hot press and subject to rheological and mechanical testing. A simulation of the injection molding process was conducted using Autodesk’s MoldFlow™ software. Material property data was gathered and approximated and then fit into a model which was used to run the simulation. Finally, a dinner plate was thermoformed from flat sheets of each of the concentrations. From the mechanical testing it was found that while the cork weakened the PLA slightly the elastic moduli for both formulations were close enough to that of other common plastics to be acceptable for product use. The injection molding simulation showed the material to be injection moldable, although further study of the injection molding parameters will be needed to ensure the molded part is high quality throughout.

Thesis Supervisor: David Wallace
Title: Professor of Mechanical Engineering
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Chapter 1

Introduction

1.1 Motivation

Excessive solid waste production is a common environmental hazard of our culture today. In 2008 Americans produced about 250 million tons of trash. They recycled and composted, however, 83 million tons of this trash—a 33.2% recycling rate. This rate has been steadily growing for the past three decades. More specifically a 34% increase in composting rates was achieved, raising the total composted 22.1 million tons [3].

The increase in recycling and composting rates can be attributed to a growing awareness and concern for environmental issues by both consumers and governments. Consumers who identify themselves as having "lifestyles of health and sustainability" now make up 20% of the shopping market. [26] Sales of products marketed as environmentally friendly have seen dramatic growth in the recent past. In 2008 there were 458 "eco-products" launched, double the number launched the year before. Natural food stores saw a 10.9% increase in sales in 2008. In Europe, government regulation of products' recyclability has increased. The EU now requires its member states to have legislation in place that mandates at least a 50% recycling rate for packaging. It has also mandated that member states reduce the amount of biodegradable waste they landfill by 35% of 1995 levels by 2016. [12]

Biodegradable products tap directly into this growing market for environmentally
friendly products. Cork is a natural material harvested from the bark of the Quercus Suber (Cork Oak) tree. The bark can be harvested every 9-10 years until the tree is about 200 years old without killing the tree. [19] This makes it a renewable resource. The influx of alternative bottle stoppers has prompted cork producers to look for new ways in which to apply their product. [20] The biodegradable products industry, including disposable tableware, cutlery and packaging, is one in which cork has yet to explore, but which could hold a large market.

Granulated cork can be made into products via two main avenues. It can be self-agglomerated, in which the cork is pressed at high temperatures without any binders, also known as insulation cork board, or it can be mixed with a binder and then pressed or cast into a mold, which is known as composition cork. In this project a biodegradable resin was chosen as the binder for making composition cork. Biodegradable resins, such as Polylactic Acid (PLA), are made from starch based agricultural products. Crops such as corn and sugar cane can be processed to make polymers similar to fossil fuel based polymers, but without the environmental consequences the fossil fuel based polymers bring. As cork is a renewable material, it is fitting to compound it with another renewable material like a biodegradable resin. A product made from cork and biodegradable resin has the opportunity to enhance the environment at the end of its life cycle instead of harming it.

Using biodegradable materials for packaging as well as disposable and short-life cycle products serves to reduce landfill growth and fossil fuel use.

1.2 Objective

The purpose of this research was to determine the manufacturing viability of a cork/biodegradable polymer compound. The questions I sought to answer were:

- Can granulated cork be compounded with a biodegradable polymer at an acceptable cork to polymer ratio?
- What are the rheological and mechanical properties of the resulting compound?
- Can the compound be injection molded using conventional injection molding machines?
- Can the compound be thermoformed with pleasing results?
Chapter 2

Background

2.1 Cork

Cork is a natural material harvested from the bark of the Quercus Suber (Cork Oak) tree. The bark can be harvested every 9-10 years until the tree is about 200 years old [19]. After being stripped from the tree the cork is visually inspected, graded, boiled and then dried flat. Cork is well known for its open, honeycomb-like cell structure with cells about 50 micrometers in diameter. Thin sections of cork reveal a cell structure resembling a brick wall [29].

Fifty two percent of the cork produced in the world is produced in Portugal. The cork oak tree is very sensitive to changes in microclimate and therefore can only be grown in certain parts of the world (mostly the Western Mediterranean region). Only 25% of the cork grown in Portugal is used for bottle stoppers, and as the alternative bottle stopper market grows, there has become less demand for the cork bottle stopper. [17] Portugal, therefore, has been looking for alternative uses for its remaining granulated cork. This project was instigated by the University of Portugal as they search for new uses for their cork derivatives.

Cork is made into a wide range of products today. The highest grade cork, graded mostly for its uniform appearance, is punched directly from the raw, dried bark, and then the rest is ground into a variety of grain sizes and then made into other products [29]. Composition cork is, for the most part, produced by mixing cork granules
with a binder in a compounding machine and then curing in a mold, often at high temperatures. Composition cork has many beneficial properties including: excellent thermal, vibrational and acoustical insulation and high compressive strength. Today composition cork is made into products ranging from shoe insoles to space shuttle heat shields. Another large market for composition cork is floor and wall covering [17]. The binding material used in composition cork ranges from synthetic materials such as epoxies and polyurethanes to thermoplastics and natural rubbers. The properties of the resulting composition cork depend on the properties of the binding material [17].

There does not exist literature on a cork/PLA composite, but as PLA is a thermoplastic it is worth a review of the literature on existing studies of cork/thermoplastic composites. In 1993 Luis Silva conducted a study of cork powder/thermoplastic (polyethylene and polypropylene) composites [16]. The composite was tested for properties such as density and moisture content and then cork boards, some with wood veneer outer laminations were made from the composite. The intended application
for these boards was mainly architectural: flooring, walls, ceilings. Boards made in this way are advantages from a manufacturing standpoint because, as opposed to traditional laminated boards which require multiple gluing steps, these boards were pressed in one step (once the cork had been combined with the thermoplastic). Although the resulting boards from the two different types of thermoplastic had slightly differing properties, in general the boards were found to have less moisture swelling than wood fiber boards and similar tensile strength and lower densities than fiber boards [16].

Other studies have been conducted on cork/polypropylene blends [14, 13]. It has been found the the hydrophilic nature of the cork and the hydrophobic nature of the polymer lead to poor surface adhesion between the matrix and the fiber. This poor adhesion can lead to lower tensile moduli than that of the matrix. Solutions to this have been studied such as boiling the cork before compounding, or applying a surface treatment of silane [14, 13]. For the purpose of this study, since tensile modulus is not necessarily a property to be maximized, these treatments have not been followed.

2.2 Biodegradable Polymers

The biodegradable polymer industry grows larger every year. As the price of oil rises biodegradable polymers have become more competitive. Global production has risen from 25,000 Tonnes in 1995 to 600,000 Tonnes in 2008. This has been driven by a number of factors: the cost of raw materials has dropped due to new research into alternative sources, the processing of those raw materials has evolved to be cheaper and more efficient, and finally there has been a ground swell of popular demand for more environmentally friendly products. [28]

Biodegradable polymers come in three main classes [28]:

- Naturally Biodegradable Polymers– These are naturally occurring polymers and the most common for commercial uses are polysacharids (starch).
- Synthetic Biodegradable Polymers– These are polymers produced by mankind, but which biodegrade in by the same mechanisms as the naturally occurring poly-
mers. The most common are aliphatic polyesters with a hydrolysable linkage along the polymer chain such as polylactic acid (PLA).

- Modified Naturally Biodegradable Polymers—These are essentially combinations of the above two and are not a commercially prevalent as the others.

### 2.2.1 Polylactic Acid

For this study Polylactic Acid, specifically Cargill’s Natureworks PLA was chosen. PLA was chosen for its many favorable characteristics as well as its easy availability on the commercial market. PLA is clear or light in color which, for our purposes, is preferable for highlighting the natural look of the cork. PLA also shares many of the same properties of PET, out of which packaging and disposable dinnerware are often made. PLA is resistant to moisture and grease and is a good flavor and odor barrier. PLA also has similar tensile strength and modulus of elasticity to PET [28]. PLA is made from naturally occurring starches, usually corn or sugar cane, which is milled to separate the starch from the raw material. The starch is then bacterially fermented and chemically processed to produce the final product.

Cargill’s Natureworks, originally a joint venture with Dow Chemical Company, was first produced in 2001. The Natureworks PLA, under the trade name of Ingeo, is made in 21 different resin formulations. It can be made into fibers, films, extrusions, injection molded and thermoformed. It is marketed towards industries now using polyester, polyolefins, polystyrene and cellulosics [23]. The resin used in this study was the 3051D, recommended by the manufacturer and stocked by the compounding facility.

PLA can be disposed of either by composting in a municipal composting facility or by being broken down back into monomers and then reconstituted into polymers. Once fully composted no sign of the original polymer remains [28]. On the other hand, under dry conditions, pure PLA can last more than 10 years [10].
2.2.2 Biodegradation Process

Polymer biodegradation is generally considered to be the process of degradation via biological activity. It is often accompanied by, or preceded by other forms of degradation such as hydrolysis and photodegradation. Biological degradation proceeds in two possible ways: [28]

- Enzymes or other by products secreted by microorganisms breakdown the polymer via depolymerization (chain cleavage) and mineralization.
- Microorganisms ingest the polymer and degrade it via its own digestive system.

Products that are marketed as "Fully Biodegradable" are generally considered to be able to be completely converted by microorganisms in an industrial composting facility into carbon dioxide, water and humus. For anaerobic biodegradation the degradation results in carbon dioxide, methane and humus [11]. The products envisioned for the material studied in this thesis (packaging, disposable dinnerware, etc.) would fit into the category of products intended to be disposed of in a municipal composting facility. Such a biodegradation environment is characterized as a high solids, aerobic environment. Proper biodegradation is very much subject to the biodegradation environment.

2.2.3 Biodegradation Norms and Standards

There has been considerable controversy surrounding the methods by which products are deemed "biodegradable." As yet, there is no global consensus on one method to determine if a product is biodegradable. This is partly due to the variety of environments a product may or may not biodegrade in. For example, a polymer may be fully biodegradable in an industrial compost facility, but only minimally biodegradable in a traditional landfill or an aquatic environment (river, ocean, etc.).

In 1992 an international conference was convened to discuss the matter. The following four points were agreed upon at the conference:

- For all practical purposes of applying a definition, material manufactured to be
biodegradable must relate to a specific disposal pathway such as composting, sewage treatment, denitrification, or anaerobic sludge treatment.

- The rate of degradation of a material manufactured to be biodegradable has to be consistent with the disposal method and other components of the pathway into which it is introduced, such that accumulation is controlled.
- The ultimate end products of aerobic biodegradation of a material manufactured to be biodegradable are carbon dioxide, water and minerals and that the intermediate products include biomass and humic materials. (Anaerobic biodegradation was discussed in less detail by the participants).
- Materials must biodegrade safely and not negatively impact on the disposal process or the use of the end product of the disposal [10].

This conference then led to the establishment of a variety of standards applying to biodegradability. Standardization bodies such as the American ASTM, European CIN, DEN and OCED, Japanese JIS, and international ISO have all established norms and standards for both testing of biodegradability of a product and declaring a product biodegradable. For biodegradability within a municipal composting environment, under which the product studied here falls, all of the organizations listed earlier have declared testing procedures.

### 2.2.4 Compost Biodegradation Tests

- ISO 14855 Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide.

In this test the product is mixed with mature compost at optimum moisture and temperature conditions. The rate of carbon dioxide production is then measured. The tests lasts between 45 and 60 days. The percentage of biodegradation is determined by the net amount of carbon from the product that is converted into carbon dioxide [10].
This test method is designed to determine the biodegradability of plastic materials in a municipal composting facility under laboratory conditions. Test samples are exposed to a sample of microorganisms from a composting facility and then kept in a temperature, humidity and aeration controlled environment. The conversion of carbon to CO2 is monitored to determine biodegradation rate.

### 2.3 Strengths and Weaknesses of the Materials

#### 2.3.1 Cork

In the area of disposable consumer products, including packaging and disposable dinnerware, cork has many advantages. In so much as it can be re-harvested for 200 years it is a renewable resource. It is also very light— a benefit to shipping costs. Cork, when compounded with PLA, may also increase the thermal insulation properties of the matrix, thereby allowing the compound to be used for hot liquid containers. \(^1\) This, however, is not studied in this thesis. From an aesthetic point of view the cork adds a "natural" look to the compound, which may appeal to the growing market for

---

\(^1\)Currently PLA cannot be used for hot liquid containers due to deformation of the plastic when exposed to heat.
environmentally friendly products. For disposable dinnerware, specifically, it could provide added value to the PLA by distinguishing it from more plain looking products. Products such as disposable plates made from Bamboo, which are also compostable, have already made strides in this market. Furthermore, cork is about the same price, by weight, as PLA therefore dinnerware made from a cork/PLA compound could be made at nearly the same cost as dinnerware made from only PLA (although the compounding would increase the cost slightly).

Cork as raw material, however, is much less abundant than the common agricultural products PLA is made from (corn, sugar cane, etc.) There would be a limit to the ubiquity with which cork could be used in mass market products. Also, if the products are to be made outside of Portugal or the other cork producing countries, the cork will have to be shipped long distances, thereby increasing its overall carbon footprint.

2.3.2 Polylactic Acid

Since PLA is made from common agricultural products it is a renewable resource. According to Natureworks, the company that makes Ingeo, the PLA used in this study, manufacturing this PLA uses less energy and produces fewer CO₂ emissions than the manufacturing of other comparable plastics [24].

![Graphs](image)

(a) Comparing Greenhouse Gas Emissions

(b) Comparing Non-Renewable Energy Use

Figure 2-3: Comparisons of Natureworks Ingeo™PLA to other common plastics.

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2Quotes for each material were given as the following: Cork: $2.59/kg [?], PLA: $2.22/kg [1]
PLA is the second largest class of biodegradable polymers sold in the world today. It is second to the broader class of Starch-based materials.

PLA, on its own, is suitable for a broad range of manufacturing processes, including injection molding, blow molding and thermoforming. NatureWorks PLA polymers are well designed for food packaging in that they have good permeability to water vapor so that moisture can pass through flexible and rigid film thus minimizing condensation. They are comparable to glass and PET as a flavor and aroma barrier. They also have good grease resistance to most oils and fats and stiffness which allows for down-gauging [28]. The high permeability of the material, however, does limit it to packaging for short-shelf life, dry or refrigerated products. PLA is comparable in strength to other thermoplastics commonly used for packaging.
### Table 2.1: Mechanical Properties of Common Packaging and Food Service Plastics [7]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/cm³)</th>
<th>Young's Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Fracture Toughness (MPa.m⁴/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>900</td>
<td>.816</td>
<td>29</td>
<td>34.5</td>
<td>3.75</td>
</tr>
<tr>
<td>PE</td>
<td>950</td>
<td>.74</td>
<td>22.5</td>
<td>29</td>
<td>1.55</td>
</tr>
<tr>
<td>PET</td>
<td>1345</td>
<td>3.45</td>
<td>59.4</td>
<td>60.4</td>
<td>5</td>
</tr>
<tr>
<td>PS</td>
<td>1045</td>
<td>1.4</td>
<td>47.5</td>
<td>46.2</td>
<td>.9</td>
</tr>
<tr>
<td>PLA</td>
<td>1230</td>
<td>3.64</td>
<td>54</td>
<td>54</td>
<td>.9</td>
</tr>
<tr>
<td>PHA*</td>
<td>1240</td>
<td>2.4</td>
<td>37.5</td>
<td>37.5</td>
<td>1</td>
</tr>
</tbody>
</table>

*PHA is another common biodegradable polymer.

PLA, however, does continue to be generally more expensive than other thermoplastics [7, 28]. The environmental benefits of the material, therefore, must be considered as added value. As the market for PLA grows larger, cheaper manufacturing methods are being discovered. This could potentially bring the cost of PLA down to equivalent with PET [28].

### 2.4 Overview of the Biodegradable Products Market Today

In 2009 a market strategy consulting firm, Cone LLC, conducted a survey of consumer interest in environmental products. Despite the economic downturn they found that interest in products marketed as environmentally friendly continued to grow [21]. More specifically they found that:

- 35 percent of Americans have higher interest in the environment today than they did one year ago
- 35 percent of Americans have higher expectations for companies to make and sell

22
environmentally responsible products and services during the economic down-
turn; and,

- 70 percent of Americans indicate that they are paying attention to what com-
panies are doing with regard to the environment today, even if they cannot buy
until the future [21]

As the market for biodegradable products grows more companies are jumping in. Currently the main manufacturers are Cargill’s Natureworks LLC, BASF, Novamont, and Rodenburg Biopolymers[28]. In 2007 BASF predicted a 20% growth per year in the market as a whole and used the prediction to announce new biodegradable poly-
mer formulations [5]. The growth is largely driven by new European recycling and composting regulation. Global production has risen from 25,000 Tonnes in 1995 to 600,000 Tonnes in 2008 [28]. The market for disposable packaging and dinnerware has grown as consumers’ eating habits have changed. Increasingly, especially in North America, meals are eaten away from the house and often in a "to-go" setting. Ac-

According to a survey of the global foodservice packaging industry by the Foodservice Packaging Institute in 2010, 53% of Foodservice Operators surveyed expected their sales to rise this year and expected a growth in take- away or "to-go" food service. Almost all also expected to offer either recycling or composting in either the front or back of the house within five years. They also listed recyclability within the top three factors in choosing foodservice packaging [18].

The biodegradable products industry is small enough that there are not yet good statistics on the size of the industry as a whole. A search on Google for Biodegradable Dinnerware will turn up hundreds of suppliers of biodegradable dinnerware made from both fiber materials (paper-like materials) and plastics. In price these range from $.072 per plate for plates made from Bagasse, a sugarcane or sorgum fiber, to $.57 per plate for plates made from bamboo veneer.
2.5 Overview of Composting Facilities and Trends

Municipal composting facilities are more common in the EU than in the USA. As of 2005, in some EU countries, like Germany and The Netherlands, more than 60% and 90% of households had access to industrial composting plants[28]. Facing land shortages, the EU has passed extensive legislation directing waste away from landfills. In December 1994 passed the European Parliament and Council Directive 94/62/EC. The following were some of the directives imposed: [27]

- By no later than 31 December 2008, at least 60% by weight of packaging waste to be recovered or incinerated at waste incineration plants with energy recovery.
- By no later than 31 December 2008, between 55 and 80% by weight of packaging waste to be recycled.
- By no later than 31 December 2008 the following targets for materials contained in packaging waste must be attained:
  - 60% for glass, paper and board
  - 50% for metals
  - 22.5% for plastics and
  - 15% for wood
- States must ensure that packaging placed on the market complies with the essential requirements of Annex II:
  - to limit the weight and volume of packaging to a minimum in order meet the required level of safety, hygiene and acceptability for consumers
  - to reduce the content of hazardous substances and materials in the packaging material and its components
  - to design reusable or recoverable packaging

As a result of these directives the EU posted a recycling or composting rate of 40% in 2008. This includes a 17% composting rate [30].

Americans, in 2008 produced about 250 million tons of trash. They recycled and composted, however, 83 million tons of this trash. [4] That equates to a 33.2% recycling rate— a rate which has been steadily growing for the past three decades. More
specifically 22.1 million tons of this waste was composted (9%). Compared to 16.5 million tons in 2000, that equates to a 34% increase in composting rates. [3] Personal environmental concerns drive the American increase in composting more than governmental regulation. Consumers who identify themselves as having "lifestyles of health and sustainability" now make up 20% of the shopping market. [26]

### 2.6 Functional Requirements of Biodegradable Dinnerware

Overall Biodegradable Products must function at least as well, if not better, than their non-biodegradable peers. It is often assumed in eco-product design that inferior functionality can be covered up by superior environmental credentials. It is the opinion of this researcher that this is not the case. There are no industry technical standards for disposable dinnerware. For the sake of this research, however, it is expected that disposable dinnerware (plates and bowls) meet the following requirements:

- Plates hold up to 1lb of food without significantly warping.
- Plates are heat and water resistant enough to hold hot and soggy food without warping.
- Bowls are completely waterproof and do not leak liquid or get soggy.
- All dinnerware is attractive.

It is the expectation of this research that other products could be made from the cork/PLA compound. The functional requirements of other products would have to be compared with the functional abilities of the compound when designing those products.

### 2.7 Possible Manufacturing Processes

PLA is designed to be suitable for injection molding, thermoforming, extrusion and blow molding. It is expected that the cork/PLA compound could be formulated as
well to fit any of these processes. Blow molding would be the most difficult, but it’s possible that if very fine cork particles were used the properties of the PLA would not be changed enough as to significantly alter them, leaving the compound available for blow molding. Using both injection molding and thermoforming, the cork/PLA compound could be made into a wide variety of products ranging from durable household items, to disposable packaging and dinnerware. This research presents a theoretical investigation into the possibility of injection molding and thermoforming the compound.
Chapter 3

Experimentation

3.1 Compounding

The compounding of the cork and the PLA was done by Royce Colors of E. Rutherford, NJ on a twin screw compounding machine. The cork was compounded with the Natureworks@3051D PLA Polymer in two weight percentages: 5% and 10%. A 20% by weight compound was attempted by the company but they were unable to strand the material due to excessive brittleness and gassing. Furthermore they reported that the material no longer had the visual look of cork. [2] The extruder used was a 34 mm co-rotating twin screw machine with a high dispersion screw configuration. [8] The residence time of the material was less than 20 seconds and the max temperature the material was exposed to was 300 F. The material was extruded at a rate of 360 lbs per hour. [9]

3.2 Rheological Testing

3.2.1 Sample Making

The samples for testing were made in the following manner:

1. Resin pellets were dried in a vacuum oven for 17 hours at 80 C according to the manufacturer’s recommendations.[22]
2. Dried resin pellets were placed in a clean Teflon mold and pressed in a hot press in the following manner:
   - Mold was heated for 40 min at 175 C under 0 pressure.
   - Mold was pressed at 725 psi for 5 minutes. At this time the material relaxed, causing the pressure to drop to 507 psi.
   - Pressure was raised back to 725 psi for 5 min.
   - Pressure was released and machine and mold were allowed to cool before removing.

3. Samples were cut into approximately 12.7mm diameter cylinders from the pressed material in a laser cutter.

![Sample Images](image1.png)  
(a) 10% Cork Compound  
(b) 5% Cork Compound

Figure 3-1: Pressed Cork Compound Samples

![Press Image](image2.png)

Figure 3-2: Hot press used to press all samples.
3.2.2 Rheological Testing

The Rheological testing was conducted on a Rheometric Scientific Ares machine. Johannes Soulares, a post doctorate in the lab advised in use of the machine. Samples were baked at 80°C for at least 12 hours before being tested. An average density was calculated for each type of sample (10% cork, 5% cork, and raw PLA) by calculating the density of two cylinders of each and averaging the two. The following average densities were calculated: Table 3.1: Densities of Samples

<table>
<thead>
<tr>
<th>Cork % by Mass</th>
<th>Average Density (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.998</td>
</tr>
<tr>
<td>5</td>
<td>1.04</td>
</tr>
<tr>
<td>0</td>
<td>1.07</td>
</tr>
</tbody>
</table>

**Rheological Data for 10% Cork Sample**

After conducting an amplitude sweep, a strain of 1% was selected for subsequent dynamic testing. Below is the $G'$ and $G''$ data collected by the Rheometer. The dynamic data was collected at a $T_{ref}$ of 175°C.

![Figure 3-3: Dynamic Data for 10% Cork Compound at 175 °C](image-url)
This data indicates a relaxation time of 4.4 ms. The Zero Shear Rate viscosity, \( \eta_0 \), was found to be 4006 Pascals as indicated in figure 3-4.

The temperature dependency was found using \( T_{ref} = 175^\circ C \). \( A_T \) was found using the following formula:

\[
a_T = \exp \left[ \frac{E_A}{R} \times \left( \frac{1}{T} - \frac{1}{T_{ref}} \right) \right]
\]

where \( R \) is the ideal gas constant and \( T \) is in Kelvin. Then \( \eta_0(T) \) can be found using:

\[
a_T = \frac{\eta_0(T)}{\eta_0(T_{ref})}
\]
Rheological Data for 5% Cork Sample

After conducting an amplitude sweep, a strain of 1% was selected for subsequent dynamic testing. Below is the $G'$ and $G''$ data collected by the Rheometer. The dynamic data was collected at a $T_{ref}$ of 175 °C.

Figure 3-5: Temperature Dependence for 10% Cork Compound

Figure 3-6: Dynamic Data for 5% Cork Compound at 175 °C

This data indicates a relaxation time of 4.6 ms. The Zero Shear Rate viscosity, $\eta_0$
was found to be 2476 Pascals as indicted in figure 3-7.

![Figure 3-7: Shear Data for 5% Cork Compound at 175 °C](image)

![Figure 3-8: Temperature Dependence for 5% Cork Compound with $T_{ref} = 175^\circ$C (Formulas for $A_T$ and $\eta_0(T)$ are the same as for 10% Cork)](image)

**Rheological Data for Raw PLA (0% cork)**

After conducting an amplitude sweep, a strain of 1% was selected for subsequent dynamic testing. Below is the $G'$ and $G''$ data collected by the Rheometer. The
dynamic data was collected at a $T_{ref}$ of 175°C.

$T_{ref}=175^\circ$C (strain of 1%)

$G'$ (Pa) $\star$ $G''$ (Pa) $\star$

A relaxation time was not found at this temperature. The test would need to be redone at a lower temperature to find a crossover point (relaxation time). The Zero Shear Rate viscosity, $\eta_0$ was found to be 526 Pascals as indicted in figure 3-10.

Figure 3-9: Dynamic Data for Raw PLA at 175 °C

Figure 3-10: Shear Data for Raw PLA at 175 °C
Summary of Rheological Data

The viscosity of a material is a function of the temperature, pressure and shear rate. Because of this the rheological data can be viewed in a number of ways. At low shear rates the viscosity of the compound increases with cork percentage as can be seen by the rising zero-shear rate Eta values in Table 3.2.

Table 3.2: Zero Shear Rate Eta Values Compared

<table>
<thead>
<tr>
<th>Cork % by Mass</th>
<th>Viscosity, $\eta_0$, at 175°C [Pas]</th>
<th>Relaxation Time, $\lambda$ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4006</td>
<td>4.4</td>
</tr>
<tr>
<td>5</td>
<td>2476</td>
<td>4.6</td>
</tr>
<tr>
<td>0</td>
<td>526</td>
<td>NA</td>
</tr>
</tbody>
</table>

Injection Molding, however, involves high shear rates so the zero-shear rate viscosity is not at useful. Figure 3-12 shows the viscosity of the material as a function of shear rate and temperature, which is more appropriate for injection molding. At high shear rates the viscosity of the three materials grow closer together. The 5% cork
stands out as slightly less viscous than the other two at each of the three temperatures, although not by much.

![Viscosity graph](image)

Figure 3-12: Viscosity as a function of shear rate and temperature.

### 3.3 Mechanical Testing

All samples for the bending and tensile tests were made in the following manner:

1. Resin pellets were dried in a convection oven for at least 24 hours at 80°C according to the manufacturer’s recommendations.[22]
2. Dried resin pellets were placed in a clean Teflon mold and pressed in a hot press in the following manner:
   - Mold was heated for 40 min at 175°C under 0 pressure.
   - Mold was pressed at 50 bars for 2 minutes (a shorter pressing time was needed in this case to protect the machine from excessive overflowing of the mold).
   - Pressure was released, but mold was kept flat between the plates and allowed to fully cool before removing.
3. Samples were cut to the appropriate size according the ASTM standard from the pressed material in a laser cutter.
3.3.1 Bending Test

The ASTM standard followed for the bending testing was ASTM D790-07: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. The specimen dimension designation for Molding Materials was followed. The specimens were cut to 12.7mm by 3.2mm. Procedure A was followed in the actual testing of the material. A support span of 51mm was used.

10% Cork

A crosshead rate of 1.19 \( mm/min \) was used for the 10\% cork compound. An average flexural strength of 36.33 MPa (s.d. = 4.71 MPa) and Modulus of Elasticity of 1.733 GPa (s.d. = 0.7052 GPa) was observed.

![10% Cork Bending Data](image)

Figure 3-13: 10\% Cork Compound Bending Test Results

5\% Cork

A crosshead rate of 1.22 \( mm/min \) was used for the 5\% cork compound. An average flexural strength of 48.27 MPa (s.d. = 6.75 MPa) and Modulus of Elasticity of 2.086 GPa (s.d. = 0.2589 GPa) was observed.
PLA Only (0% Cork)

A crosshead rate of 1.22 mm/min was used for the PLA only samples. An average flexural strength of 94.83 MPa (s.d. = 7.62 MPa) and Modulus of Elasticity of 3.217 GPa (s.d. = .342 GPa) was observed. Six samples were tested but the last two samples produced significantly different results and were therefore discarded. The average Modulus of the first four samples is in line with the published Modulus of the material from the manufacturer (3.828 GPa).
Table 3.3: Summary of Bending Data

<table>
<thead>
<tr>
<th>Cork % by Mass</th>
<th>Flexural Strength (MPa)</th>
<th>Flexural Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>36.33</td>
<td>1.733</td>
</tr>
<tr>
<td>5</td>
<td>48.27</td>
<td>2.086</td>
</tr>
<tr>
<td>0</td>
<td>94.83</td>
<td>3.217</td>
</tr>
</tbody>
</table>

3.3.2 Tensile Test

The samples for the tensile test were made in the same manner as the bending test. The ASTM standard followed was ASTM D638-08 Standard Test Method for Tensile Properties of Plastics. Specimen geometry IV was used to cut the specimens to size. All specimens were tested at 50mm/min.

10% Cork

The 10% cork compound was found to have an average Modulus of Elasticity of 0.146 GPa (s.d. = 0.008 GPa) and an average Tensile Strength of 19.6 MPa (s.d. = 3.88 MPa).

Figure 3-16: 10% Cork Tensile Test Results
5% Cork

The 5% cork compound was found to have an average Modulus of Elasticity of 0.161 GPa (s.d. = 0.016 GPa) and an average Tensile Strength of 29.1 MPa (s.d. = 1.19 MPa).

![5% Cork Tensile Data](image)

Figure 3-17: 5% Cork Tensile Test Results

PLA Only

The PLA was found to have an average Modulus of Elasticity of 0.227 GPa (s.d. = 0.025 GPa) and an average Tensile Strength of 55.8 MPa (s.d. = 4.87 MPa).

![Raw PLA Tensile Data](image)

Figure 3-18: Raw PLA Tensile Test Results
Below is a summary of the tensile results:

Table 3.4: Summary of Tensile Data

<table>
<thead>
<tr>
<th>Cork % by Mass</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>19.6</td>
<td>0.146</td>
</tr>
<tr>
<td>5</td>
<td>29.1</td>
<td>0.161</td>
</tr>
<tr>
<td>0</td>
<td>55.8</td>
<td>0.227</td>
</tr>
</tbody>
</table>

The tensile modulus for the composite is significantly lower than that of the PLA (3.5 GPa). The cork itself has a relatively low tensile modulus (20 MPa), but by the basic mixture rules the modulus of the PLA should dominate, giving a modulus a factor of 10 higher. Earlier studies of cork/polypropylene blends have shown that the hydrophilic nature of the cork and the hydrophobic nature of the polymer can lead to poor fiber-matrix adhesion [14, 13]. PLA, however, tends to be hydrophilic in nature so poor fiber-matrix adhesion for the aforementioned reasons is not likely the cause of the low tensile modulus. Bubbles or other defects in the samples are a possible cause. When making the flat sheets, out of which the "dog bones" were cut, bubbles were a constant problem and one which was never fully overcome.

3.4 Injection Molding Simulation

A simulation of the injection molding process was conducted using Autodesk's MoldFlow software. Since the cork/PLA compound did not already exist within MoldFlow's material database a new material file was produced for each of the formulations. In order to get a rough estimate of the compounds' ability to be injected a number of property values were approximated. Within MoldFlow's material database already was Natureworks' 3251D PLA. This PLA is very similar to the 3051D (the one compounded with the cork) and differs only in that it is a higher viscosity grade. In populating the material dataset for the compound the measured viscoelastic properties were used, but a number of other properties were approximated using the data from the 3251D material.
3.4.1 Theory of Volume Averaging of Properties

The ability to average material properties based on the volume fraction of the constituent materials comes from the idea of load sharing. Consider an idealized isotropic composite cylinder with cylindrical, aligned fibers as the filler. Subject to an external stress, the strain on the composite will be equal to the strain on filler and the strain on the matrix.

\[ \epsilon_c = \frac{\sigma_c}{E_c} = \epsilon_m = \frac{\sigma_m}{E_m} = \epsilon_f = \frac{\sigma_f}{E_f} \]

Considering, then, that the total load on the composite is the sum of the loads carried by each constituent material and that a load is a stress times area we arrive at:

\[ \sigma_c * A_c = \sigma_m * A_m = \sigma_f * A_f \]

By combining the two previous equations and then dividing through by \( \epsilon \) we arrive at:

\[ E_c = E_m \frac{A_m}{A_c} + E_f \frac{A_f}{A_c} \]

Then, since the composite and the filler were assumed cylindrical the area fraction is equal to the volume fraction.

\[ E_c = E_m * \nu_m + E_f * \nu_f \]

The previous formula is for the elastic modulus of the material but can be used for a number of other properties including the specific heat and thermal conductivity by replacing \( E_x \) with the desired property value.

The following properties of cork were used to make the material datasets:
Table 3.5: Cork properties used in injection molding simulation

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>120 (kg/m³) [29]</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>350 (J/kg°C) [29]</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.045 (W/m°C) [29]</td>
</tr>
<tr>
<td>Elastic Modulus (radial)</td>
<td>38 (MPa) [29]</td>
</tr>
<tr>
<td>Elastic Modulus (axial/tangential)</td>
<td>25 (MPa) [29]</td>
</tr>
<tr>
<td>Poisson’s Ratio (v12)</td>
<td>0.05 [29]</td>
</tr>
<tr>
<td>Poisson’s Ratio (v23)</td>
<td>0.5 [29]</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>130 (10⁻⁶/°C) [6]</td>
</tr>
<tr>
<td>Tensile Strength (axial/tangential)</td>
<td>1.0 (MPa) [29]</td>
</tr>
<tr>
<td>Tensile Strength (radial)</td>
<td>1.1 (MPa) [29]</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>1</td>
</tr>
</tbody>
</table>

Please see Appendix A for the full list of material properties used in the simulations.

3.4.2 Simulation Results

A simulation of the injection molding process was run using a simple dinner plate solid model.

Figure 3-19: Solid Model of a Dinner Plate

The simulation was run for all three formulations: 0% Cork, 5% Cork and 10% Cork. For each formulation the simulation was run at two different melt temperatures.
The melt temperature recommended by the software was 200 °C so a simulation for each formulation was run at this temperature. Due to the cork's tendency to char at high temperatures, however, a simulation was run at 175 °C as well.

Fill Time

![Figure 3-20: Fill Time Results with 200°C Melt Temperature](image)

(a) 10% Cork Compound  
(b) 5% Cork Compound  
(c) PLA Only

Table 3.6: Fill Time Results in Seconds

<table>
<thead>
<tr>
<th>Melt Temperature Setting</th>
<th>10% Cork</th>
<th>5% Cork</th>
<th>PLA Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>1.205</td>
<td>1.219</td>
<td>1.229</td>
</tr>
<tr>
<td>175°C</td>
<td>1.088</td>
<td>1.208</td>
<td>1.224</td>
</tr>
</tbody>
</table>

Interestingly, the fill time is lower for the 175°C melt temperature. The reason for this is unknown. This is further seen in the overall cycle times in Table 3.9.

Pressure Drop

The pressure drop refers to the drop in pressure at any area of the part compared to the maximum pressure used during the shot. High pressure drops, generally over 80% of the maximum pressure allowed can lead to poor part quality.[25] In this case a max pressure was set at 180 MPa. The slightly lower viscosity of the 5% can be seen in the slightly lower max pressure values for that compound.
Figure 3-21: Pressure Drop with 200°C Melt Temperature

Figure 3-22: Pressure Drop with 175°C Melt Temperature

Table 3.7: Maximum Pressure Drop (MPa)

<table>
<thead>
<tr>
<th>Melt Temperature Setting</th>
<th>10% Cork</th>
<th>5% Cork</th>
<th>PLA Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>59.26</td>
<td>55.21</td>
<td>62.77</td>
</tr>
<tr>
<td>175°C</td>
<td>70.48</td>
<td>68.61</td>
<td>79.67</td>
</tr>
</tbody>
</table>

Average Temperature

Figure 3-23: Average Temperature with 200°C Melt Temperature
Possible causes of "medium" part quality include: high pressure needed to push material through, melt temperature too low for the material, part thickness is too
thin. Further investigation of these possible causes is needed to ensure a good part quality throughout the part. As the 5% cork compound is the most viscous it tends to have the best part quality and the higher melt temperature also produced the best quality.

Cycle Times

The following are the expected cycle times:

<table>
<thead>
<tr>
<th>Melt Temperature Setting</th>
<th>10% Cork</th>
<th>5% Cork</th>
<th>PLA Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>9.13</td>
<td>9.40</td>
<td>9.41</td>
</tr>
<tr>
<td>175°C</td>
<td>8.91</td>
<td>9.14</td>
<td>9.41</td>
</tr>
</tbody>
</table>

### 3.5 Thermoforming

A test of the thermoforming process was conducted using a dinner plate mold machined in high density polyurethane foam. Flat sheets were made for the thermoforming using the same method as for the earlier mechanical and rheological testing. The sheets were made to be approximately 1/16” thick. The sheets were heated in the thermoforming machine for 45 seconds at which point they began to sag and were vacuumed into the mold. The pieces, then, took longer to cool than was expected and could not be safely removed for 4-5 minutes. The final results are strong, nice looking plates. The outer surface (not in contact with the mold) is slightly rough where the cork grains were pushed from the compound and the user can actually feel cork grains. On the inside the plate is as smooth as the mold.
3.6 Other Testing

Before the PLA and cork were compounded a simple bake test was performed to determine the temperature at which the cork began to darken in color. This test was performed in order to determine if the cork would discolor at the temperatures needed to compound the material. The cork was found to discolor slightly at 175°F and significantly at temperatures above 200°F. This is probably why the compounded cork appears darker than the raw cork granules.

Figure 3-27: 10% Cork Thermoformed Plate

Figure 3-28: Baked Raw Cork Granules
Chapter 4

Conclusions

4.1 Overview

An initial study of the ability to compound granulated cork with polylactic acid was conducted. Further, a study of the mechanical and rheological properties, a simulation of the injection molding process, and a test thermoforming were also conducted.

4.2 Material Testing

As expected, the inclusion of the cork within the raw PLA weakened the material slightly and increased the viscosity. The observed results, however, are comparable to other plastics and are, therefore, found to be acceptable for further investigation into product use.
The measured Young's moduli are lower than expected by about a factor of 10. This could be due to bubbles or other defects in the samples that were tested and would explain why the raw PLA tensile modulus also measured lower than expected. When making the flat sheets, out of which the "dog bones" were cut, bubbles were a constant problem and one which was never fully overcome. The discrepency could also be due to residual strain in the material from the pressing process. Further work into a better way of making flat sheets of the material will need to be conducted to eliminate the bubbles.
4.3 Injection Molding Simulations

The injection molding simulations showed that the material should be relatively successful to injection mold. Although quality is improved at the higher melt temperature, cycle times are longer and care will have to be taken to avoid charring the material. Further investigation, probably on an actual injection molding machine will need to be conducted to test all the necessary parameters and ensure good part quality.

4.4 Product Viability

Visually, the compound is very appealing, which is promising for its future use in consumer goods. The natural look and smooth finish will allow the compound to be made into a variety of products and marketed to a high-end market interested in environmentally friendly products. The success of the thermoforming is further promising for the future of the material. The plates that were formed are strong, feel nice in the hand and look "organic."

4.5 Future Work

As this is the first investigation into this new material there is quite a bit of work still to be done on it. Future investigations could include:

- Further experimentation of the compounding process with the intention of increasing the percentage of cork and seeing if the color of the compound can be lightened.
- Injection molding of the material.
- Investigation of the possibility of extruding flat sheets of the material for thermoforming.
- Further experimentation of the thermoforming process.
  - Thermoforming of thinner sheets.
- Thermoforming of other mold shapes and textures.

- Experimentation with various other biodegradable polymers to be used as the matrix in place of the PLA.

- A thorough cost analysis to determine if products made from this compound would be competitive in the market.

- A more thorough material characterization of the compound.
Appendix A

Material Properties Used in MoldFlow Analysis

The following is a list of the material property values used in the simulations. The individual property values were compiled or calculated by the author and then fit to the model by Edwin Klopen at MoldFlow.
### Material Data Summary

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture Name</td>
<td>NatureWorks</td>
</tr>
<tr>
<td>Trade Name</td>
<td>NatureWorks 3051D</td>
</tr>
<tr>
<td>Material ID</td>
<td>1</td>
</tr>
<tr>
<td>Family Abbreviation</td>
<td>PLA</td>
</tr>
<tr>
<td>Filler</td>
<td>Other</td>
</tr>
<tr>
<td>Percent Filler</td>
<td>29-Sep-10</td>
</tr>
<tr>
<td>Data Status</td>
<td>Confidential</td>
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<td>Default Shrinkage Model</td>
<td>Uncorrected</td>
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<td>Mold Temperature (C)</td>
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<td>Mold Temperature Range Minimum (C)</td>
<td>4</td>
</tr>
<tr>
<td>Mold Temperature Range Maximum (C)</td>
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<td>Ejection Temperature (C)</td>
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</tr>
<tr>
<td>Transition Temperature (C)</td>
<td>105</td>
</tr>
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<td>Cross WLF Viscosity Model</td>
<td>MIT</td>
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<tr>
<td>$n$</td>
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<td>Tau (Pa)</td>
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<td>$D_1$ (Pa.s)</td>
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<td>$D_3$ (K/Pa)</td>
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</tr>
<tr>
<td>$A_2$ (K)</td>
<td>51.6</td>
</tr>
<tr>
<td>Junction loss coefficients</td>
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</tr>
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<td>C1</td>
<td>0</td>
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<tr>
<td>C2</td>
<td>0</td>
</tr>
<tr>
<td>Measured MFR</td>
<td>0</td>
</tr>
<tr>
<td>Specific heat (J/kg.K)</td>
<td>1180</td>
</tr>
<tr>
<td>Thermal conductivity (W/m.K)</td>
<td>0.16</td>
</tr>
<tr>
<td>Melt density (kg/m3)</td>
<td>1050.1</td>
</tr>
<tr>
<td>Solid density (kg/m3)</td>
<td>1195.5</td>
</tr>
<tr>
<td>Tait PVT model coefficients</td>
<td></td>
</tr>
<tr>
<td>$b_5$ (K)</td>
<td>388.15</td>
</tr>
<tr>
<td>$b_6$ (K/Pa)</td>
<td>0.00000005</td>
</tr>
<tr>
<td>$b_{1m}$ (m3/kg)</td>
<td>0.0008936</td>
</tr>
<tr>
<td>$b_{2m}$ (m3/kg.K)</td>
<td>7.831E-07</td>
</tr>
<tr>
<td>$b_{3m}$ (Pa)</td>
<td>126800000</td>
</tr>
<tr>
<td>$b_{4m}$ (1/K)</td>
<td>0.005315</td>
</tr>
<tr>
<td>$b_{5m}$ (m3/kg.K)</td>
<td>7.8E-07</td>
</tr>
<tr>
<td>$b_{6m}$ (Pa)</td>
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</tr>
<tr>
<td>$b_{7m}$ (1/K)</td>
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</tr>
<tr>
<td>$b_{8m}$ (m3/kg)</td>
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</tr>
<tr>
<td>$b_{9m}$ (1/Pa)</td>
<td>9.922E-09</td>
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<tr>
<td>Mechanical properties data</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus $E_1$ (Pa)</td>
<td>3500000000</td>
</tr>
<tr>
<td>Elastic modulus $E_2$ (Pa)</td>
<td>3500000000</td>
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<tr>
<td>Poissons ratio $v_{12}$</td>
<td>0.36</td>
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<tr>
<td>Poissons ratio $v_{23}$</td>
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<tr>
<td>Shear modulus $G_{12}$ (Pa)</td>
<td>128700000</td>
</tr>
<tr>
<td>Transversely isotropic CTE data</td>
<td></td>
</tr>
<tr>
<td>Alpha1 (1/C)</td>
<td>0.000085</td>
</tr>
<tr>
<td>Alpha2 (1/C)</td>
<td>0.000085</td>
</tr>
</tbody>
</table>

### Cross-WLF Viscosity Model

![Cross-WLF viscosity model](image)

### 2-domain Tait pvT Model

![2-domain Tait pvT model](image)
## Material Data Summary

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>NatureWorks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade name</td>
<td>NatureWorks 3051D+</td>
</tr>
<tr>
<td>Material ID</td>
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</tr>
<tr>
<td>Family abbreviation</td>
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<tr>
<td>Filler</td>
<td>Cork</td>
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<tr>
<td>Percent filler</td>
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</tr>
<tr>
<td>Data source</td>
<td>Other</td>
</tr>
<tr>
<td>Date tested</td>
<td>29-Sep-10</td>
</tr>
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<td>Data status</td>
<td>Confidential</td>
</tr>
<tr>
<td>Default Shrinkage</td>
<td>Uncorrected</td>
</tr>
<tr>
<td>Model</td>
<td></td>
</tr>
</tbody>
</table>

### Cross WLF Viscosity Model
- **n**: 0.4055
- **Tau (Pa)**: 93025.4
- **D1 (Pa.s)**: 32583100
- **D2 (K)**: 363.15
- **D3 (K/Pa)**: 0
- **A1**: 15.264
- **A2 (K)**: 51.6

### Juncure loss coefficients
- **C1**: 0
- **C2**: 0

### Moldflow Viscosity Index
- VI(199)0196

### Measured MFR
- Temperature (C): 0
- Load (kg): 0

### Specific heat (J/kg.K)
- Temperature (C): 972.5

### Thermal conductivity (W/m.K)
- Temperature (C): 0.131

### Melt density (kg/m3)
- 921.5

### Solid density (kg/m3)
- 1040.0

### Mold temperature (C)
- 25

### Melt temperature (C)
- 200

### Mold temperature range
- Minimum (C): 4
- Maximum (C): 40

### Melt temperature range
- Minimum (C): 160
- Maximum (C): 260

### Ejection temperature (C)
- 95

### Transition temperature (C)
- 105

### Tait PVT model coefficients
- **MPL**
  - **b5 (K)**: 388.15
  - **b6 (K/Pa)**: 0.00000005
  - **b1m (m3/kg)**: 0.001019
  - **b2m (m3/kg.K)**: 7.831E-07
  - **b3m (Pa)**: 136000000
  - **b4m (1/K)**: 0.00728
  - **b1s (m3/kg)**: 0.00009856
  - **b2s (m3/kg.K)**: 2.671E-07
  - **b3s (Pa)**: 227700000
  - **b4s (1/K)**: 0.00316
  - **b7 (m3/kg)**: 0.00003276
  - **b8 (1/K)**: 0.06353
  - **b9 (1/Pa)**: 9.922E-09

### Mechanical properties data
- **MIT**
  - Elastic modulus [E1] (Pa): 26300000000
  - Elastic modulus [E2] (Pa): 2628000000
  - Poissons ratio [v12]: 0.27
  - Poissons ratio [v23]: 0.40
  - Shear modulus [G12] (Pa): 965880000

### Transversely isotropic CTE data
- **Alpha1 (1/C)**: 0.000104
- **Alpha2 (1/C)**: 0.000104

### Cross-WLF viscosity model

### 2-domain Tait pvT model
**MATERIAL DATA SUMMARY**

<table>
<thead>
<tr>
<th>Manufacturer</th>
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<tbody>
<tr>
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<td>Filler</td>
<td>Cork</td>
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<tr>
<td>Percent filler</td>
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<td>Data source</td>
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<td>Date tested</td>
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<td>Confidential</td>
</tr>
<tr>
<td>Default Shrinkage Model</td>
<td>Uncorrected</td>
</tr>
</tbody>
</table>

| Mold temperature (C) | 25                     |
| Melt temperature (C) | 200                    |
| Mold temperature range | Minimum: 4  
                          Maximum: 40                  |
| Melt temperature range | Minimum: 160  
                          Maximum: 260               |
| Ejection temperature (C) | 95                      |
| Transition temperature (C) | 105                    |

**Cross WLF Viscosity Model**
- **n**: 0.402
- **D1 (Pa.s)**: 1739000000
- **D2 (K)**: 363.15
- **D3 (K/Pa)**: 0
- **A1**: 17.44
- **A2 (K)**: 51.6

**Juncture loss coefficients**
- **C1**: 0
- **C2**: 0

**Moldflow Viscosity Index**
- **VI(199)0225**

**Measured MFR**
- **Temperature (C)**: 0
- **Load (kg)**: 0

**Specific heat (J/kg.K)**: 839.7
- **Temperature (C)**: 25

**Thermal conductivity (W/m.K)**: 0.113
- **Temperature (C)**: 25

**Melt density (kg/m3)**: 888.3
- **Solid density (kg/m3)**: 998.0

**Tait PVT model coefficients**
- **b5 (K)**: 388.15
- **b6 (K/Pa)**: 0.00000005
- **b1m (m3/kg)**: 0.001059
- **b2m (m3/kg.K)**: 7.831E-07
- **b3m (Pa)**: 137000000
- **b4m (1/K)**: 0.00532
- **b1s (m3/kg)**: 0.001026
- **b2s (m3/kg.K)**: 2.671E-07
- **b3s (Pa)**: 227700000
- **b4s (1/K)**: 0.00316
- **b7 (m3/kg)**: 0.00003276
- **b8 (1/K)**: 0.06353
- **b9 (1/Pa)**: 9.922E-09

**Mechanical properties data**
- **Elastic modulus [E1] (Pa)**: 20730000000
- **Elastic modulus [E2] (Pa)**: 20700000000
- **Poissons ratio [v12]**: 0.21
- **Poissons ratio [v23]**: 0.42
- **Shear modulus [G12] (Pa)**: 760360000

**Transversely isotropic CTE data**
- **Alpha1 (1/C)**: 0.000116
- **Alpha2 (1/C)**: 0.000116

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**Cross-WLF viscosity model**

**2-domain Tait pvT model**

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Bibliography


