



Properties, Recycling and Alternatives to PE Bags

An Interactive Qualifying Project Report

Submitted to the Faculty of

Worcester Polytechnic Institute

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

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Abstract

Plastic bags are widely used and approximately 380 billion bags are used annually in the United States alone. Only one percent of these bags are properly recycled. This presents a major problem because typical plastic bags can end up taking over 1000 years to degrade in landfills. The goal of this project was to gain an understanding of the widespread use of plastic bags, the issues concerning their disposal and the alternatives that exist. Background information on the manufacturing process and consumer use of plastic was collected through extensive research. To gain an understanding of public perception on current plastic bags and possible alternatives, consumers were surveyed online and outside of grocery stores. Mechanical properties of a variety of common plastic bags and biodegradable alternatives were evaluated using tensile testing. Accelerated aging through intense heat was used to analyze the difference in mechanical properties before and after degradation under ambient conditions for equivalent times of two years. Further information on the manufacturing and disposal processes was gathered through site visits and interviews. The various methods employed led to the conclusion that plastic bags are so widely used because of their exceptional mechanical properties and cheap production costs. Through testing, it was concluded that both PE and biodegradable bags lost about 50% of their original mechanical strength. The biodegradable bags were in the furnace for about one seventh of the time as the PE bags, yet display a similar loss in mechanical strength. There are alternatives with similar mechanical properties that degrade faster, and the major difference is cost of production. The surveys showed that 91% of the public believes that there are environmental problems associated with polyethylene bags and is willing to use alternatives. However, the cost of the degradable bags is the main concern. Companies are continuing to reduce production costs of alternative bags, but currently the best solution is to promote awareness and prevent excessive use of polyethylene bags. The findings of this project can serve as a starting point for potential changes in current bag use and provide future material options.

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Introduction

Plastic bags have many benefits that have made it the material of choice for many applications over the years. Based on chemical inertness alone, plastics are favorable for many medical uses because they prevent leakage of hazardous materials, and can prevent infection. Plastics can be made flexible, which allows for tubing and containers that can be utilized for complex medical procedures that other materials cannot provide¹.

Since plastics are easily molded into any shape, they are perfect for packaging merchandise, food, drinks, medical products, and more. Polyethylene has a high strength to weight ratio, allowing for cheaper transportation costs and lower fuel consumption¹.

Plastic materials used for food storage, visible in all supermarkets, preserves freshness and flavor due to the ability to seal out contaminants. Polyethylene materials are useful over a wide temperature range, from frozen foods to microwavable packages¹. Due to these benefits, plastics have become widely used.

Worldwide, there are 4 to 5 trillion² polyethylene plastic bags being produced annually. Americans alone use over 380 billion bags each year. Of these 380 billion, 100 billion are thrown away and only 1% of the bags thrown away are properly recycled. As it takes approximately 1000 years for a polyethylene bag to decompose, leakage of toxic substances into the soil are a detriment to both the local and extended ecosystem.

Plastic bags not only affect our local environment but also affect the world around us. Bags not properly disposed of can end up in waterways, killing approximately 1 billion seabirds and marine animals each year. Animals can easily confuse these bags for food, but are not

digestible and can result in injury or death. The bags are so thin and light that they easily ride the wind from landfills to forests, ponds, rivers and elsewhere².

Polyethylene plastic bags are petroleum-based so the manufacturing process releases harmful pollutants into the atmosphere. Some speculate that these emissions and other smog-related types of pollution accumulate over time in the atmosphere².

Countries and large corporations are beginning to realize the threat that these plastic bags pose to our planet. Many are proposing or have already enacted laws and taxes to decrease the use of polyethylene plastic bags. Many grocery stores are even rewarding customers for bringing reusable grocery bags as an alternative to these polyethylene plastic bags. Customers choosing not to use alternatives to plastic bags either find the alternatives are inconvenient or are simply unaware of the problem at hand. Some goals for the end of the project are to increase the awareness and participation of the public, and to find simple, acceptable alternatives.

Polyethylene plastic bags are currently being used all over the world but there is currently no environmentally friendly way to dispose of them. This project is important because with the statistics and information through surveys, mechanical bag testing, literature review, and interviews, we hope to encourage people to use more eco-friendly alternatives to polyethylene plastic bags.

2 Objectives

The objectives listed in this section were used to help evaluate plastic bags and its alternatives. Surveys were conducted to understand the public perception of current plastic bags. Tensile testing was used to experimentally find the mechanical properties of plastic bags and field interviews were conducted to get a better understanding of disposal issues. A comparison was also done of the polyethylene bags against biodegradable alternatives. The specific objectives highlighting the areas of concentration are listed below.

To understand the properties of the current material used in plastic bags

- Chemical structure
- Performance characteristics
- Understand why this makes the material desirable for a plastic bag

To understand the disposal issues related to plastic bags

- Recycling process in detail
- Landfills/process in detail
- Degradation (material properties)
- Financial resources and energy spent towards plastic bag removal

To understand the manufacturing process of plastic bags

- Find out where plastic bags are made
- Find out what processes and machines are used to turn the plastic into bags

- Find out what the cost of manufacturing is (overhead and production)
- Find how much energy is used in the manufacturing process

To find alternatives to current plastic bags

- Find alternatives made from various materials
- Find cost-friendly alternatives
- Find alternatives currently being used in supermarkets
- Find alternatives being developed but not yet marketed

To compare alternatives with PE bags

- What are the pros and cons of our options?
- Compare eco-friendly alternatives to cost-friendly alternatives
- Compare environmental impact of alternatives and LDPE bags
- Compare the finished products (Strength/durability)
- Will the alternative bags fulfill the needs of the consumer
- Is it worth it? Ultimately decide which alternative offers the best solution

3 Methodology

To complete the objectives laid out at the beginning of the project, various methods were employed. Surveys were conducted to gauge public perception on current plastic bags and possible alternatives. To gain an understanding of the mechanical properties of various consumer plastics, expedited degradation through the use of heat followed by tensile testing was performed on standard plastic bags and alternatives considered to be environmentally friendly. To gain further understanding of the manufacturing and disposal process, site visits and email interviews were conducted. The combination of methods helped provide a complete picture on the issue of polyethylene bags.

3.1 Survey of Public Perception

The primary goal of conducting surveys was to gain information on public opinion. The questions on the surveys would be designed in a way that would make it easy to determine the public awareness of the environmental issues with plastic bags. Through laboratory research, it is possible to learn about the physical properties and qualities of plastic bags, but only a consumer survey would allow the group to discern public opinion about plastic bags.

The survey questions were determined because the group felt that they would yield the best results in terms of public opinion. In general, the questions ask public feelings about the current plastic bags, disposal-related habits, public reaction to being rewarded for reusing bags and being charged for using bags, and consumers' willingness to use alternatives.

Before conducting any surveys, other sources were consulted for previous surveys on public perception. The only way to gauge local opinion was to conduct an original survey on a sample of the local population. The survey questions were written to quickly and easily obtain unbiased opinions. To make the survey easy for people to complete and easy to analyze, yes/no questions and simple multiple-choice questions were used. Open-ended questions were avoided, as these would not be suitable for statistical analysis. The survey was distributed on the Internet, through email, Facebook.com, and survey websites. Screenshots of the survey are shown in Figures 1 through 3.

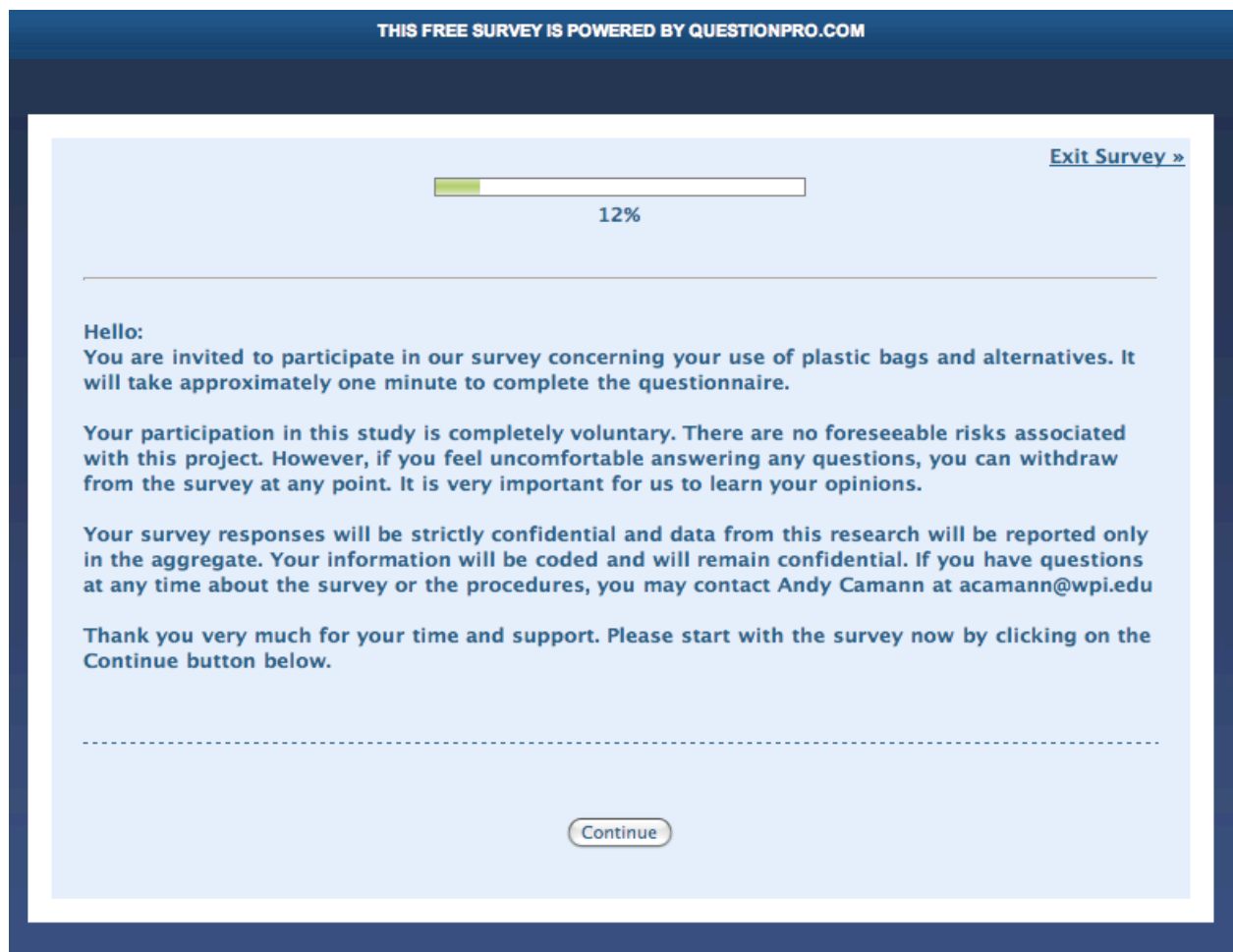
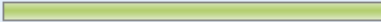


Figure 1: Start page explaining the online survey.

[« Back](#) [Exit Survey »](#)


100%

Do you think that the current plastic bags are bad for the environment?

Yes
 No

How do you dispose of plastic bags when you are finished using them?

Put them in the trash
 Recycle
 Reuse around the house, etc
 Other

If retailers rewarded you for reusing bags instead of using new ones, would you be more inclined to reuse old bags?

Yes
 No

If an alternative bag were offered, would you use that instead?

Yes
 No

Figure 2: The first four questions of the survey.

How much would you be willing to pay for *new plastic bags*?

- None
- 1 to 10 cents
- 10 to 20 cents
- 20 to 30 cents

How much would you be willing to pay for *alternative bags*?

- None
- 1 to 10 cents
- 10 to 20 cents
- 20 to 30 cents

Additional comments are welcome!

Figure 3: The final two question of the survey, plus a box the user to add comments.

Questions 1 and 2 focus on the public's perception of plastic bags and consumer disposal habits. These questions are designed to make facilitate determination of the relationship between public opinion and methods of disposal. For example, someone unaware of any problem with the plastic bags might just throw them in the trash, but someone aware of the issue might recycle in plastic bag collection bins or reuse the bags.

Questions 3 and 4 focus on usage of current plastic bags and whether people would make an effort to save plastic. The advantages of charging for plastic and rewarding for reusing

bags are twofold. Firstly, charging for new bags would encourage people to minimize plastic bag use. Secondly, a reward would encourage people to reuse bags. These two questions will reveal whether a penalty or reward will alter consumers' bag usage habits.

The options for question 5 are set up to reveal the general amount of money people would be willing to pay for these bags. The "none" option was included for those not willing to pay at all. It is a useful question because it quantifies the desired information from the survey.

Question 6 is designed to be a comparison to question 5, to compare the amount someone would pay for a plastic bag as opposed to an alternative bag. The implications of the data obtained from this survey are provided in section 6.1.

The survey was posted on <http://questionpro.com> and was sent to friends and family, and approximately 93 responses were collected during the fall of 2009. A chi square value was calculated for each question based on the following equation:

$$\sum_{i=1}^N \left(\frac{(\text{observed} - \text{expected})^2}{\text{expected}} \right) \quad \text{Equation 1}$$

where N is the number of choices for a given question. After calculating Chi Square, the p value was determined from the Chi Squared distribution table, which represents the chances that one would obtain results at least as extreme as were observed in the experiment. The results of the survey are described in the Section 6.1, and discussion can be found in Section 9.1.

An experiment was conducted at the Auburndale Shaws supermarket in early January during the course of two afternoon and evening shifts of work. As customers passed through the checkout, their choice of bags for packing was recorded. No questions were asked of the

customers regarding their choice to avoid influencing them. Discussion of the results is found in Section 6.2.

3.2 Mechanical Testing of Plastic Bags

A variety of plastic bags were collected from various stores to determine their typical mechanical characteristics. To do this, samples were collected from five different bags: a GE bag, Applebees bag, Quiznos bag, Worcester City trash bag, and a KPR bag. Each of the five different strips of plastic bags was cut for tensile testing on an Instron 5544 Uniaxial Tensile Testing machine. Each strip was 3.5cm wide and 6.5-7.5cm in length, after cardboard ends were glued onto the strips so that the Instron machine could better grip the plastic bags. Crazy glue was used to join the cardboard to the plastic bag strips and books were put on the samples to make sure the cardboard was secured. Length and width measurements of each sample were taken with a ruler before testing. The thickness of each plastic bag was measured with calipers. These measurements were used to calculate stress and strain relationships of each plastic bag sample.

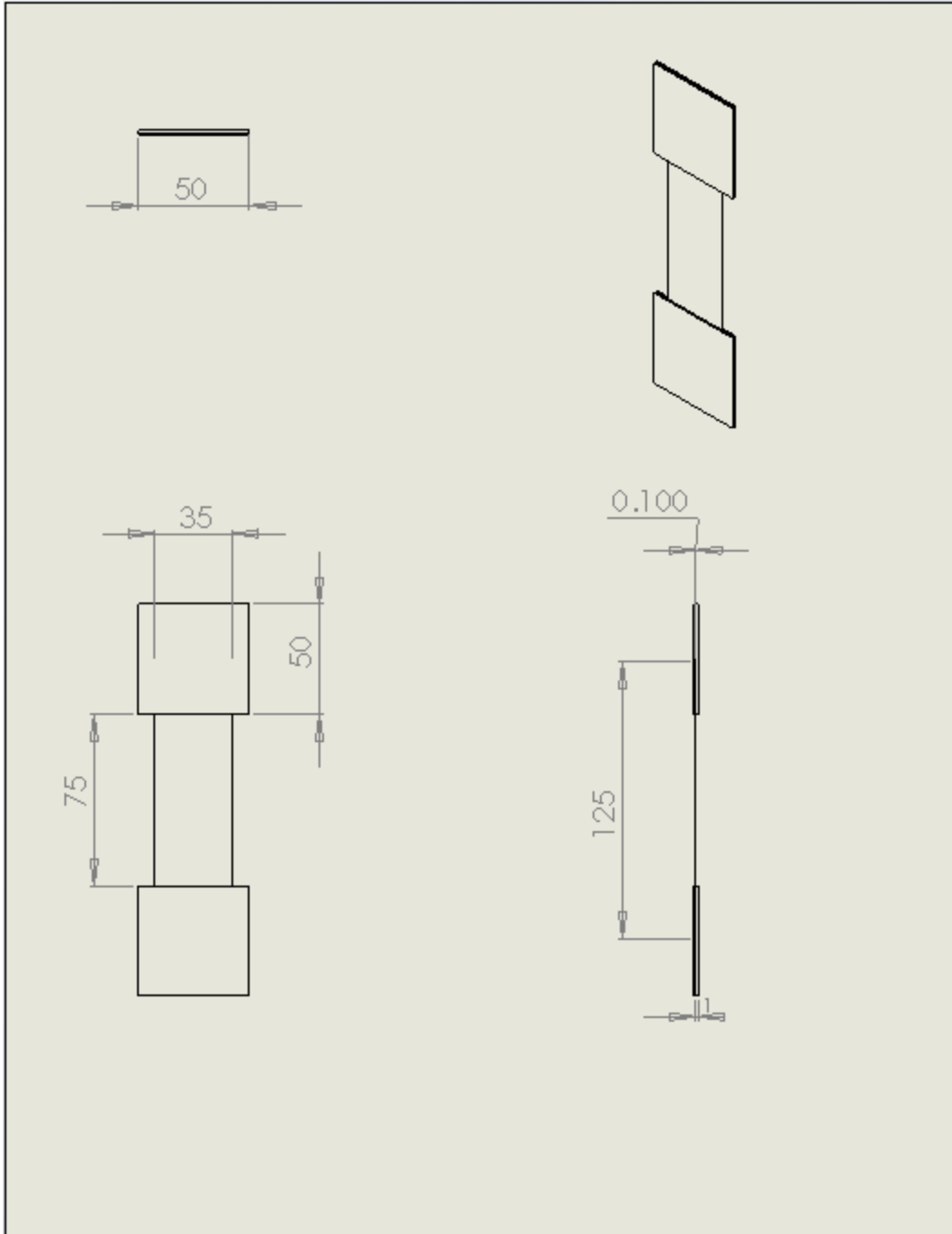


Figure 4: CAD drawing of bag setup in cardboard holders.

Testing begins by placing a sample securely into the Instron 5544 machine. Figure 5 shows a sample placed in the grips of the Instron machine. The samples are kept taut by

applying a 1N tare load, which can be done by manually adjusting the scroll wheel on the control pad of the Instron machine. Bluehill software was used to program testing methods and record data created by the Instron machine. For testing purposes, a method was created to pull the sample at a rate of 1mm/s until sample failure. Figure 6 shows a sample starting to be stretched by the Instron machine. The machine stops testing automatically once the Instron machine notices a sudden drop in the force transducer, which means the sample has snapped and there is no tension left, as seen in Figure 3.

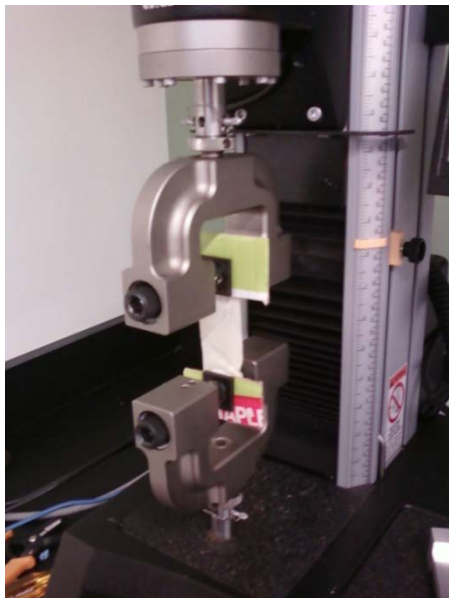


Figure 5: Sample placed in the grips of the Instron machine.

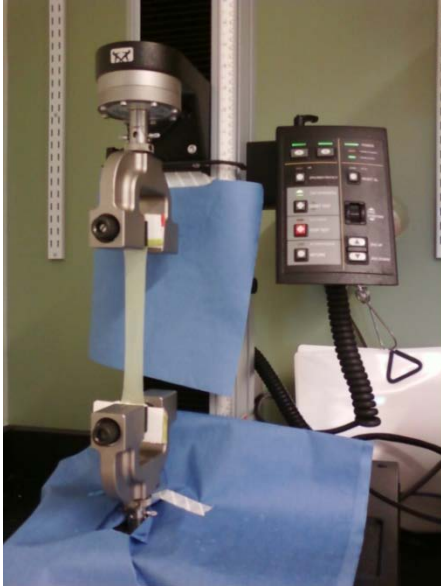


Figure 6: Instron machine beginning to stretch a sample.



Figure 7: Sample after failure.

To test if degradation has any effect on tensile strength, plastic bag samples of the same type from the previous experiment were aged in a furnace set to 100^o C for reasons that will be

explained in the next section. Leaving the bags at a higher temperature increases degradation, and the bags were later removed from the furnace and the same tensile testing was done as the original bags, from which the results may be compared.

3.2.1 The Arrhenius Equation

The Arrhenius relation³ was used to calculate the simulated time of degradation when buried in a landfill.

$$k \propto \exp\left(\frac{-E_a}{RT}\right) \quad \text{Equation 2}$$

where k is the rate constant, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. This relation may be modified into an equation with the introduction of a pre-exponential as seen below:

$$k = A \exp\left(\frac{-E_a}{RT}\right) \quad \text{Equation 3}$$

Subscripts may be added to indicate that the bag samples are being tested at different states. Let subscript 1 indicate room temperature, corresponding to negligible degradation, and subscript 2 indicate an elevated temperature, corresponding to some amount of degradation.

$$k_1 = A \exp\left(\frac{-E_a}{RT_1}\right) \quad \text{Equation 4a}$$

and

$$k_2 = A \exp\left(\frac{-E_a}{RT_2}\right) \quad \text{Equation 4b}$$

The rate constants k_1 and k_2 are inversely related to time, thus:

$$\frac{1}{t_1} = A \exp\left(\frac{-E_a}{RT_1}\right) \quad \text{Equation 5a}$$

and

$$\frac{1}{t_2} = A \exp\left(\frac{-E_a}{RT_2}\right) \quad \text{Equation 5b}$$

By dividing the two equations, one obtains the ratio of t_1 to t_2 as

$$\frac{t_2}{t_1} = \exp\left[\frac{-E_a}{R} \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right] \quad \text{Equation 6}$$

This ratio indicates that for a temperature T_2 higher than T_1 , the ratio of times t_2/t_1 will be less than unity. For this case, leaving the bags in the furnace at a higher temperature will simulate increased degradation because it will take less time to achieve the same degradation than at room temperature.

For the purposes of this experiment, it was assumed that PE bags would take 1000 years to degrade at normal conditions. Since the melting point of HDPE is 130°C , it was desirable to leave some headroom between melting point and furnace temperatures; hence the furnace was set to 100°C . The bags were left in the furnace for ten weeks, after which time they underwent the same tensile testing as was described in section 3.2. The experimental conditions are summarized in Table 1 on the next page.

Table 1: Summary of the values of the parameters used in calculating percent degradation

Parameter	Constants	Normal conditions*	Experimental conditions
T_1	-	298 K	-
T_2	-	-	373 K
E_a	26.2 kJ/mol	-	-
R	8.314 kJ/mol·K	-	-

* Normal conditions refers to what a bag would typically be subject to after disposal in a landfill, which are assumed to be averaged over the course of the four seasons, during which time temperature fluctuates.

Substituting the number into the Arrhenius equation yields

$$\frac{t_2}{t_1} = 0.9978$$

It is only theorized that plastic bags take up to 1000 years to degrade. Under that assumption for t_1 , t_2 is found to be about 997.8 years. This means that the bags left in the furnace for ten weeks at 100° C underwent about 2.12 years of degradation.

3.3 Data Acquisition from Field Interviews

In order to gain a full understanding, local waste management facilities were researched. The most prominent facility is Casella Waste Systems, Inc. A message was sent to the company, and was passed to Lisa McMenemy, who replied saying she would be willing to answer questions. The main information desired from this interview was the relationship

between plastics and waste management facilities, in terms of the amount of plastic sent to the facility annually, as well as notable costs related to processing plastics. The interview questions are in figure 8.

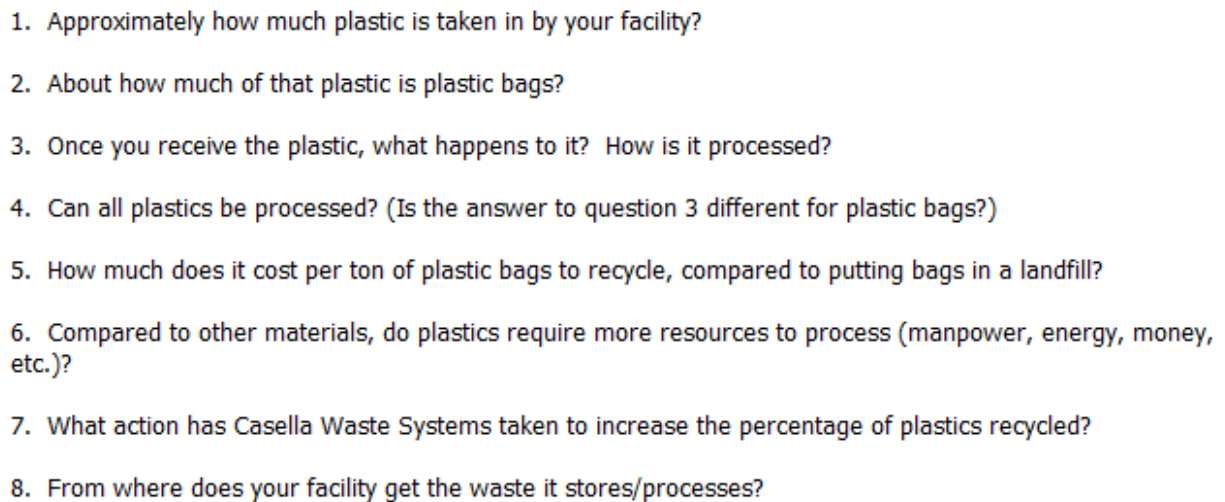
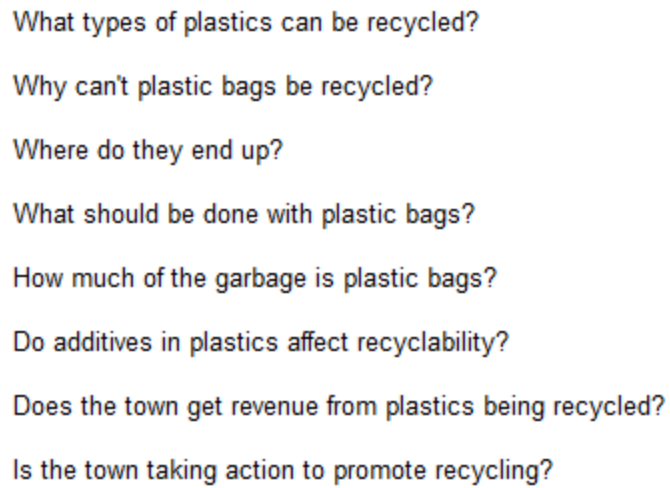
- 
- A screenshot of a document containing eight numbered interview questions. The questions are listed in a vertical column within a light gray bordered box. The text is black and left-aligned.
1. Approximately how much plastic is taken in by your facility?
 2. About how much of that plastic is plastic bags?
 3. Once you receive the plastic, what happens to it? How is it processed?
 4. Can all plastics be processed? (Is the answer to question 3 different for plastic bags?)
 5. How much does it cost per ton of plastic bags to recycle, compared to putting bags in a landfill?
 6. Compared to other materials, do plastics require more resources to process (manpower, energy, money, etc.)?
 7. What action has Casella Waste Systems taken to increase the percentage of plastics recycled?
 8. From where does your facility get the waste it stores/processes?

Figure 8: Screenshot of interview

First-hand information about local policies is also valuable to understanding the disposal of plastics. Although information regarding these policies is available, Judy Doherty of the West Boylston Solid Waste Advisory Team was contacted in order to learn more about the policies in West Boylston. The questions were based on recycling services in the town and the recyclability of plastics. The interview questions are in figure 9.



What types of plastics can be recycled?

Why can't plastic bags be recycled?

Where do they end up?

What should be done with plastic bags?

How much of the garbage is plastic bags?

Do additives in plastics affect recyclability?

Does the town get revenue from plastics being recycled?

Is the town taking action to promote recycling?

Figure 9: Screenshot of interview

4 Overview of Plastics

Research was conducted to gain a solid background on different types of plastics and their life cycle. Journal articles and online resources were used extensively to give a complete picture on all aspects of plastics with an emphasis on polyethylene because it is the most commonly used material in consumer plastic bags.

4.1 Plastics Overview

Plastic is one of the most abundant materials in the world today. It is an organic amorphous solid, and is favored for its cheap production costs, mechanical and thermal abilities, stability and its durability⁵. Plastic can be sorted into two different categories when considering thermal properties: thermoplastics and thermoset plastics. Thermoset plastics are formed by step-growth polymerization under proper conditions, allowing the condensation of bi-functional molecules. When thermoset plastics are exposed to adequate heat, they undergo chemical changes that are irreversible. Thermoplastics, however, undergo reversible processes when heated. They are linear chain molecules wherein molecules are joined end-to-end, creating large chains of molecules⁶.

There are numerous types of plastics, each serving a specific purpose. Table 2 on the next page shows a list of some common types of plastic and their everyday uses. Different chemical formulae give the material different mechanical, chemical or thermal properties. . Polycarbonate for example is a strong plastic, and one common use is the scratch-proof lenses

in eyeglasses. Figure 8 on page 26 shows some common plastics and their respective chemical formulae and mer structures.

Table 2: Uses of common plastics⁵.

Uses of synthetic plastics	
Plastic	Use
Polyethylene	Plastic bags, milk and water bottles, food packaging film, toys, irrigation and drainage pipes, motor oil bottles
Polystyrene	Disposable cups, packaging materials, laboratory ware, certain electronic uses
Polyurethane	Tyres, gaskets, bumpers, in refrigerator insulation, sponges, furniture cushioning, and life jackets
Polyvinyl chloride	Automobile seat covers, shower curtains, raincoats, bottles, visors, shoe soles, garden hoses, and electricity pipes
Polypropylene	Bottle caps, drinking straws, medicine bottles, car seats, car batteries, bumpers, disposable syringes, carpet backings
Polyethylene terephthalate (PET)	Used for carbonated soft drink bottles, processed meat packages peanut butter jars pillow and sleeping bag filling, textile fibers
Nylon	Polyamides or Nylon are used in small bearings, speedometer gears, windshield wipers, water hose nozzels, football helmets, racehorse shoes, inks, clothing parachute fabrics, rainwear, and cellophane
Polycarbonate	Used for making nozzles on paper making machinery, street lighting, safety visors, rear lights of cars, baby bottles and for houseware. It is also used in sky-lights and the roofs of greenhouses, sunrooms and verandahs. One important use is to make the lens in glasses
Polytetrafluoroethylene (PTFE)	PTFE is used in various industrial applications such specialized chemical plant, electronics and bearings. It is met with in the home as a coating on non-stick kitchen utensils, such as saucepans and frying pans

For the sake of disposal, plastics are placed into seven different groups and given a recycling code based on the material. Figure 7 shows the different types of plastic and their corresponding codes. Most services can recycle plastic with any recycling code, and the number can be found on any plastic container.

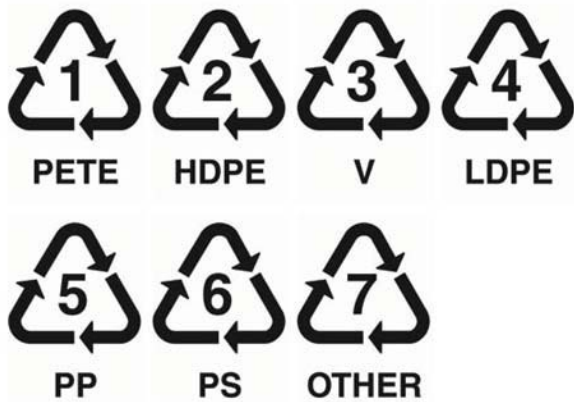


Figure 10: SPI resin identification codes⁷.

Polyethylene terephthalate (PETE) has the recycling code of 1, and is used to make peanut butter containers, food trays, water bottles, and other types of bottles. It can be recycled into fleece jackets, tote bags, furniture, carpeting and occasionally new containers. The recycling rate for PETE is around 20%⁸.

High density polyethylene (HDPE) is the number 2 plastic. It is commonly used for rigid bottles for products such as detergents, shampoo, milk and juice. HDPE can be recycled into detergent bottles, drainage piping, and lumber, among other things⁸.

The number 3 plastics are vinyls, or polyvinylchloride. They can be found in window cleaner bottles, shampoo and cooking oil bottles and clear food packaging. PVC can be recycled into paneling, flooring, mudflaps, and similar items⁸. Since PVC contains chlorine, it can release dangerous chemicals when broken down, so it should not be burned, and if used for cooking, it should not touch the food.

The fourth plastic is low-density polyethylene. It can be found in squeezable bottles, and is commonly used to make plastic shopping bags. LDPE can be recycled into liners for garbage cans, lumber, paneling and floor tile. Until recently, LDPE has not been easily recyclable through curbside programs, but services are increasing the ability to do so⁸.

Polypropylene, recycling code 5, can be found in yogurt containers, syrup bottles, straws and medical bottles. PP can be recycled into signal lights, battery cables, brooms, ice scrapers and bicycle racks. Recyclers are gradually accepting more polypropylene. Polypropylene also has a high melting point, so it is ideal for containers that must hold hot liquids⁸.

Polystyrene has recycling code 6, and is commonly used for egg cartons, carry out containers, meat trays and compact disc cases. It can be recycled into insulation, foam packing, or back into egg cartons and carry out containers. PS is known to be difficult to recycle, and should not be microwaved because recent studies have shown that it may release toxins⁸.

The seventh recycling code contains all miscellaneous plastics. Some examples are bullet-proof materials, sunglasses, DVDs, computer cases and nylon. These plastics can be recycled into plastic lumber and custom products. Polycarbonate is a number 7 and is a potential harm because studies have shown that it may release hormone disruptors⁸.

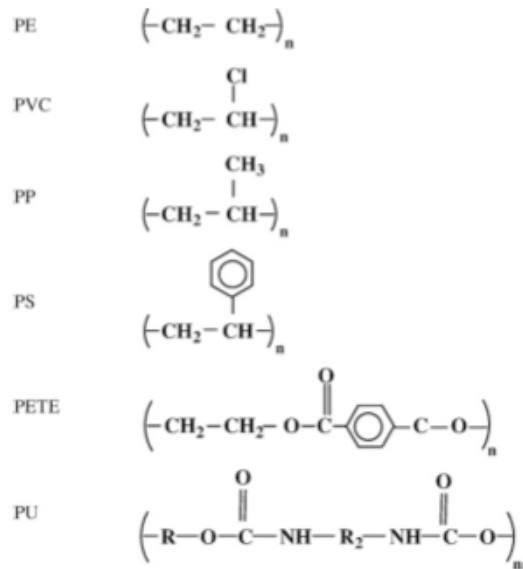


Figure 11: Common plastic Mer structures⁵.

Polyethylene is the main component of the current plastic bag. Different varieties of this material exist, arising from the extent of branching and defects. Polyethylene chains will pack in different ways, affecting the final product. Functional groups attached at the ends of chains will decrease crystallinity and hinder the chains from packing more tightly⁹.

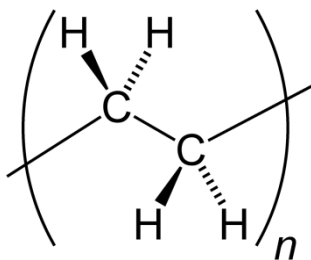


Figure 12: Mer structure of Polyethylene (C_2H_4).

High Density Polyethylene (HDPE) has few defects, allowing the chains to pack closely. There is little to no branching, thus the result is a stronger plastic. It is often used for big plastic

bags designed to carry large loads⁹. Other uses include containers, bottle caps, wire insulation, and water pipes.

Low Density Polyethylene (LDPE) has more defects than HDPE, which prevents it from packing as efficiently⁹. Often, the chains of polyethylene have branches that prevent it from crystallizing. This results in a lower density and strength. However, it is more flexible and easier to process than HDPE. Some common uses include transparent films used to seal food, and electrical insulation¹². Linear low-density polyethylene (LLDPE) is branched, like LDPE, but the branches are smaller and more frequent. This increases the density of the plastic¹⁰.

Polyethylene is a desirable material to use because of its physical and chemical properties. It can be manufactured to be flexible or strong, allowing for more potential applications. The covalent carbon to hydrogen bonds make polyethylene very stable, so its chemical inertness means it will not easily disintegrate when in contact with other substances¹¹. HDPE has a high strength to weight ratio, which makes it a good choice for many storage containers because they can hold a lot yet are light. Figure 10 shows illustrations of these three types of polymer chains.

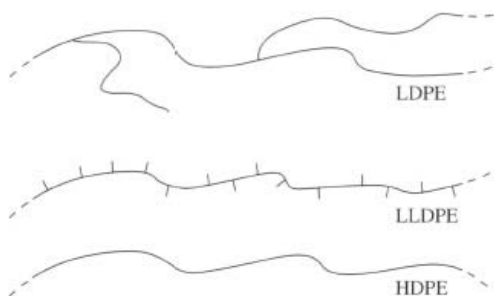


Figure 13: Illustration of polymer chains¹⁰.

The properties of plastic make it easy for manufacturing. The pliability and low melting temperature make it ideal for applications that require easy molding into a variety of shapes. Following is an overview of how plastics are manufactured.

4.2 Production of Plastic Bags

Plastics have become commonplace in today's world. The variety of types and applications seems almost limitless. Plastic bags are one of the major uses of plastics. However, the process by which these bags are produced can be detrimental to our environment. Oil and natural gas are the raw materials used in the production of plastics. This is part of the reason alternatives are being sought. From these raw materials two main types of plastic are produced. One can be reheated and remolded while the other will decompose if reheated after being formed. The former is far more common because it is easier to deal with, especially with regard to plastic bags¹¹.

Plastics have properties that make them ideal for manufacturing a variety of products, especially bags and other food storage items. Examples of such properties include resilience to chemicals, thermal and electric insulation, light weight, and versatility in how they can be processed. This makes manufacturing easier and makes them convenient for consumers. There are a variety of ways plastics can be manufactured into finished products. Some common examples are extrusion, injection molding, blow molding, and rotation molding¹¹.

Extrusion is the method used to produce plastic bags. Pellets of plastic are forced through a long heated chamber by use of a screw. Heat produced by the work done and the

heated chamber combines to melt the plastic. At the end of the chamber the molten plastic is forced through a small opening to shape the final product. The advantage to this process is products of extensive length. Products such as plastic siding would be produced by this method¹³. Figure 9 shows a machine that performs extrusion. Figures 10 through 12 show pieces of extruded plastics and the saw used to cut them down to size for consumer products from a plant visit to Plastics Unlimited, located in Worcester, Massachusetts.

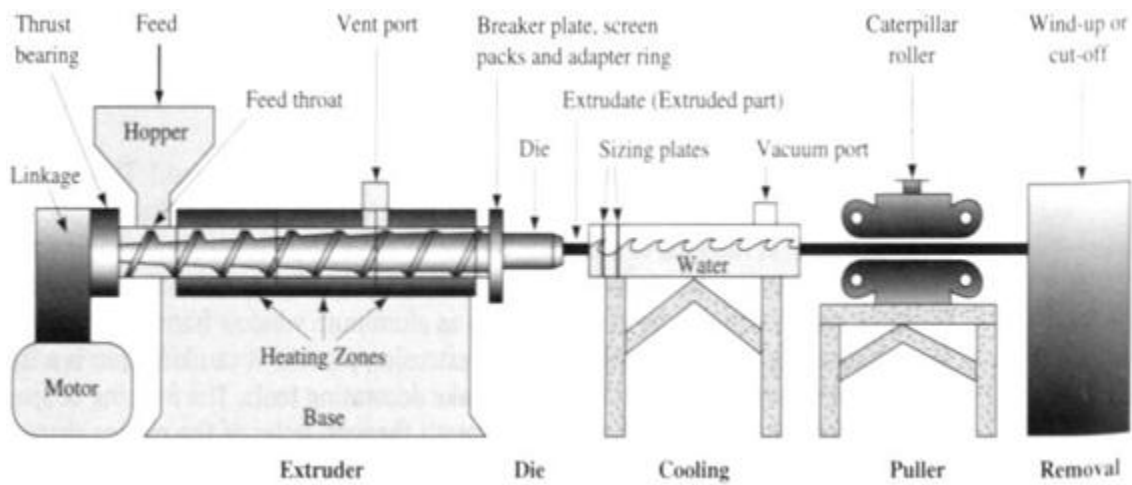


Figure 14: An extrusion machine¹³.



Figure 15: Extruded sheets of HDPE.



Figure 16: Extruded blocks of PVC.



Figure 17: Table saw for cutting sheets of plastic.

Plastic bags are made from sheets of plastic. These are produced by a similar method but by a slightly different mechanism. The plastic is forced through a series of rollers that flatten the plastic into thin sheets as shown in the figure below.

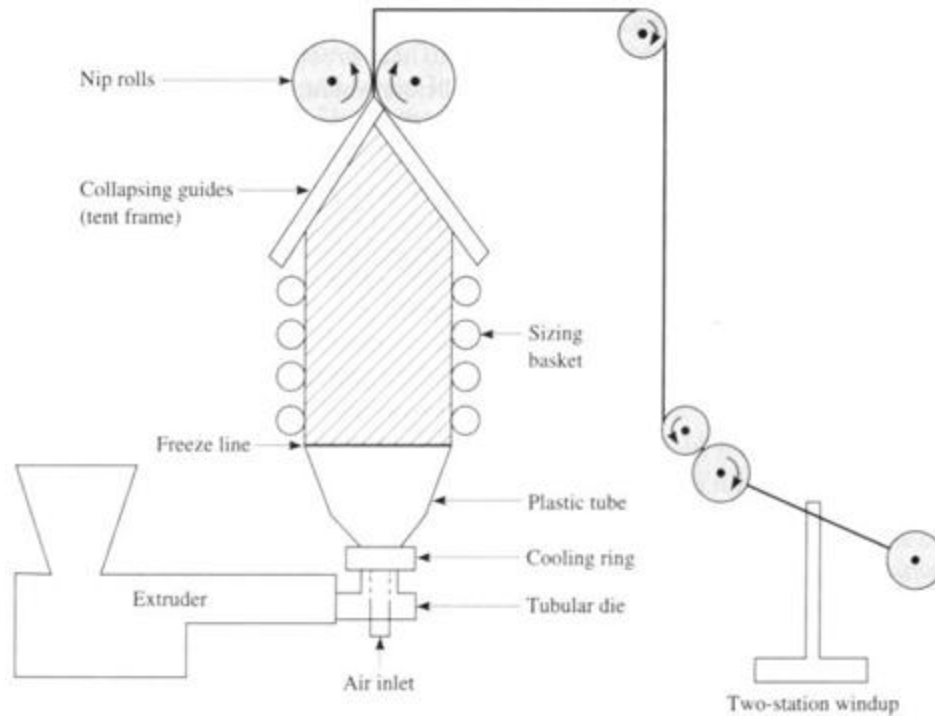


Figure 18: Extrusion machine for plastic sheeting¹³.

In both cases the plastics are cooled by air or water after being shaped. Additives are often introduced in the process to change physical properties or color. A video of the extrusion process of plastic sheeting can be found through the following link:

<http://www.youtube.com/watch?v=JpF4zgJHOJg>

Plastics come in many varieties. The primary plastics used are Polyethylene Terephthalate (PET or PETE), High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS). HDPE is used for many food packaging applications as well as grocery bags because it is a good moisture and chemical barrier; however it is not a CO₂ or oxygen barrier. LDPE is also used for plastic bags. A lower melting temperature makes it ideal for heat sealing applications, and it is very flexible and clear.

Plastics are easy to use for manufacturing and convenient for consumers due to their variety of types and properties. Unfortunately the plastics and the methods of processing may have adverse affects on the environment¹¹. It will be difficult to find alternatives that demonstrate the convenience of plastics.

4.3 Additives

Plastics in use all throughout our culture would not be the way they are without additives. Plastics on their own have many properties that make them ideal for manufacturing durable consumer items. Additives help augment these properties and add new properties often necessary to aid in the processing, manufacturing and eventual use of the plastics¹⁴.

Some of these additives are used to help in the manufacturing of the plastics. In the extrusion process there are issues like melting temperature and plastics sticking to the machines that need to be addressed. Compounds are added into the plastics to help cope with this. Process aids help mix color particles into the plastic by forming a liquid around them. Lubricants are used with plastics that become too viscous when they melt. The lubricants reduce friction between the particles themselves and the machines used in the manufacturing. Antioxidants are used to protect the plastic from the extreme heat used in the manufacturing process that can often make it brittle or adversely affect the color. The problem of plastic decomposing in the heat when it is melted is solved by additives known as heat stabilizers¹⁴. These all help make the manufacturing process easier and cheaper.

Additives can also be used for purely aesthetic reasons. Pigment additives have a variety of practical and aesthetic purposes. Plastics can be made to match in color to other pieces of larger product such as in automobiles, or just be made colorful to attract attention to consumers. Practical uses include making plastics opaque to protect light-sensitive contents, i.e., milk bottles or medicine containers. The pigments are added into the plastic before it has been melted and it must be mixed in completely to effectively color the plastic. Different compounds and mixtures are used to produce different colors and light properties. Two of the most common pigment additives are carbon black and titanium oxide. Carbon black absorbs light making plastics appear black while titanium oxide refracts light causing the plastic it is mixed with to appear white in color. Regardless of reason almost all plastics are colored in some shape or form¹⁴.

Another useful purpose of additives is to help increase the value of consumer items. This in turn ends up saving money in the long-run for consumers who will have to repair or replace the item less often. Impact modifiers are added to increase resistance to being cracked. This is useful in any plastic product that needs to have consumer durability, such as vacuum cleaners. Other additives that increase durability are light stabilizers and UV absorbers. These protect plastics from the effects of sun and light and help the plastics last longer. Flame retardant additives are obviously necessary. Without such additives, plastic products would be more prone to igniting due to something as simple as an electric spark. Mineral fillers are used to save money. They are typically cheaper than the polymers themselves and are useful because they tend to heat up and cool down quicker which speed up the manufacturing

process. Oftentimes they have other properties as well. Chalk makes the plastic more rigid and clay improves its electrical properties¹⁴.

Health and safety with plastic products is also due to the additives. Many of the additives already mentioned help make products safer, i.e., flame retardants. Additives to make plastic more durable are advantageous in products like helmets. Plastic in cars needs to be made durable yet shock absorbing in case of accident. This can be obtained with additives. Even coloring can increase safety if it warns the user of danger or helps differentiate different buttons on a machine. Plastics can be designed to withstand a large range of temperatures from freezing to being heated up quickly. PVC is an example of a plastic ideal for medicine because it is low in toxins, is flexible, transparent and easy to seal. These properties are due to additives and have made it possible to have more efficient and effective treatments because the plastic being used is easier to work with⁵. There are some additives however such as phthalates and bisphenol A that are possibly linked to long term health problems in even low exposure, however the research on this is at present inconclusive. Phthalates are used to soften plastics and bisphenol A is a sealant. These are relatively common in consumer plastics. The use of additives in plastics has made them safer and healthier for public use for the most part with some potential problems¹⁵.

Additives in plastic help make them more friendly to the environment. In cars the ease of manufacturing due to additives has caused metal parts to be replaced by plastic ones. Not only are they lighter but can also be made into more aerodynamic shapes, which increase fuel efficiency. Blowing agents that break down into nitrogen, carbon dioxide or water when

Additive	Effect
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heated can help decrease weight. These gases get absorbed into the plastic and increase its structural properties while simultaneously reducing the weight. Crop production is another example. Plastic has been developed that can be laid over crops and absorb heat. They are designed to break down once the crop comes and can then be plowed into the soil and broken down by the bacteria. These sheets help improve crop yield and provide no harm to the environment. Other additives called compatibilizers allow different types of plastics to be recycled and then melted together whereas without this different types of plastics would be incompatible and would be structurally unsound if processed together. These additives help reduce the impact of our society on the environment¹⁴.

Table 3: List of common additives

Mechanical Property Modifiers	
Plasticizers	increase flexibility
Impact modifiers	improve impact strength
Reinforcing fillers	increase strength properties
Nucleating agents	modify crystalline morphology
Surface Property Modifiers	
Slip and antiblocking agents	prevent film and sheet sticking
Lubricants	prevent sticking to machinery
Antistatic agents	prevent static charge on surfaces
Coupling agents	improve bonding between polymer and filler
Wetting agents	stabilize dispersions of filler
Antifogging agents	disperse moisture droplets on films
Chemical Property Modifiers	
Flame retardants	reduce flammability
Ultraviolet stabilizers	improves light stability
Antioxidants	prevent oxidative degradation
Biocides	prevent mildew
Aesthetic Property Modifiers	
Dyes and pigments	impart color
Odorants	add fragrance
Deodorants	prevent development of odor
Nucleating agents	improve light transmission
Processing Modifiers	
Plasticizers	reduce melt viscosity
Slip agents and lubricants	prevent sticking to processing machinery
Low-profile additives	prevent shrinkage and warpage
Thickening agents	increase viscosity of polymer solutions or dispersions
Heat stabilizers	prevent degradation during processing
Defoaming agents	reduce foaming
Blowing agents	manufacture stable foams
Emulsifiers	stabilize polymer emulsions
Crosslinking (curing) agents	crosslink polymer
Promoters	speed up crosslinking (curing)

4.4 Disposal

The additives that are employed during manufacturing also affect the disposal process. Additives that enhance mechanical properties of a plastic might make it harder to break down the material, and this could lead to some plastics not being accepted by recycling facilities. Compounds can also affect heating and melting properties such as melting viscosity and this can affect the breakdown characteristics of plastics.

The disposal of plastic bags is an important issue as they pose a problem to wildlife and the environment when not properly disposed. It is generally accepted that plastic bags take 500 to 1000 years to degrade. Although they are extremely resilient, no one can be sure that our bags will really be around in the 26th century, and the estimate of 500 to 1000 years is usually just to make the point that plastic bags would take a long time to degrade. However, there may be some validity to the claims; when subjected to respirometry tests, plastic bags do not react. A respirometry test involves a solid sample that is placed in a container with microbe-enriched compost, and then the container is aerated¹⁶. Some solid samples degrade rather quickly, but a plastic bag does not respond to the compost, because it is not recognized as edible. For that reason, scientists have come up with the range of 500 to 1000 years for the time required to biodegrade a plastic bag. If polyethylene bags really do take centuries to degrade, an alternative material would be favorable if it meant less time required to break down.

Plastics are recycled more than any other material, but since so much plastic is produced, plastic is not recycled very much in terms of percentage per ton manufactured, compared to other materials. Although the numbers vary, it is generally accepted that only 5-

8% of plastic is recycled, and some studies estimate that up to 80% is sent to landfills. According to the U.S. Environmental Protection Agency, 50% of paper is recycled, while 37% of metal and 22% percent of all glass is recycled¹⁷. This lack of plastic recycling may be due to the complex sorting and processing required. Also, plastic containers cannot be remade into new containers of the original type; instead they are usually “downcycled” into secondary recycled products.

Recycling plastics has multiple benefits. For example, recycling plastic can conserve non-renewable fossil fuel. Eight percent of the world’s oil production goes the production of plastic; half as feedstock and the rest is used during the actual manufacturing. Recycling also reduces the consumption of energy, the amount of waste put in landfills, and emissions of carbon dioxide, nitrogen oxide, and sulfur dioxide¹⁸.

There are multiple types of recycling, such as plastic process recycling. More commonly known as reprocessing, it is when the unused polymers left over from plastic production are reused as raw material. According to recent studies in the United Kingdom, plastic scraps make up about 250,000 tons of waste plastic, and 95% of it is recycled¹⁸. Reprocessing is prudent because there is always a steady supply of the scraps, and the plastic is not contaminated.

Post-use plastic recycling is the process of collecting fully used plastic, and then reusing it to make more plastic products. The most prominent issue with post-use recycling is the issue of collection. In an ideal world, all plastic products would be used to their extent, and then returned to a plant where they could be made into another plastic product. However, many products are not recycled, and often end up in landfills. Recycling of Used Plastics Limited

(RECOUP) is a group that conducts annual surveys of plastic bottle recycling in the United Kingdom. Recent studies have found that only about 5.5% of sold plastic bottles are returned¹⁸. If the population could make an effort to return more bottles, post-use recycling would become a much more useful way of conserving plastic.

Mechanical recycling describes the processes used to break down some plastic products. Trained workers sort the plastics, based on plastic type and color. Some technologies are being developed to sort the plastics by using x-ray fluorescence, infrared spectroscopy, electrostatics and flotation. After being sorted, the plastic is melted down and molded into the new designated shape. Some plastics require being shredded and then processed into granules¹⁸.

Feedstock recycling is another recycling process used. It involves the breaking down of polymers. The latest methods being researched are pyrolysis, hydrogenation, gasification and thermal cracking¹⁸. A benefit of feedstock recycling is that it is more lenient with impurities in the plastic than mechanical recycling.

As the awareness of environmental issues increases, the rates of recycling, combustion and composting are increasing, while the amount of waste that goes into landfills has been decreasing slowly every year, starting in the mid 1990s. The increase in combustion of waste is due to the modernized techniques used in the process. Mainly, these new waste-to-energy plants are more efficient with newer incinerators, but there are also methods to capture the harmful gases that are released during the combustion cycle¹⁹.

The total amount of municipal solid waste is generally stays consistent from year to year, as shown in Table 4. Fortunately, as this number does not change drastically, the amount of recycled municipal solid waste is steadily increasing. Table 5 compares different materials, and what percentage of the total weight of municipal solid waste each material makes up.

Table 4: Trends in waste disposal¹⁹.

Municipal solid waste in the US

	1993	1994	1995	1996
Total MSW (million tons)	206	209	211.5	209.7
Per capita generation (kg)	2.0	2.0	2.0	1.95
Per capita discards (kg)	1.59	1.54	1.49	1.45
Recovery–recycling, composting (%)	21	24	26	27

Table 5: Amount of materials in terms of percentage¹⁹.

Composition of materials discarded in the MSW*

Weight (%)	1995	1996
Paper and paper products	31.3	31.1
Glass	6.2	6.0
<i>Metals</i>		
Ferrous	4.7	4.8
Aluminum	1.2	1.3
Other non-ferrous	0.3	0.3
Total metals	6.3	6.4
Plastics	11.5	12.3
Rubber and leather	3.5	3.7
Textiles	4.2	4.4
Wood	6.4	6.8
Other	1.9	1.9
Food wastes	13.6	14.0
Yard trimmings	13.3	11.3
Miscellaneous inorganic wastes	2.0	2.1

* Discarded after recovery by recycling, composting.

Table 6 shows, in terms of percentage, how much municipal solid waste goes through each of the three main disposal processes. The amounts of material combusted and recycled

show slight increases between the two years, while the amount of waste being put into a landfill have decreased.

Table 6: Amount of material per process¹⁹.

Management of MSW in the US				
	1988	1990	1994	1996
Landfill (%)			60.9	55.5
Recycling/composting (%)	13	17	23.6	27.3
Combustion (%)			15.5	17.2

Keeping the benefits of plastics in mind, it is not surprising that ever since the mid 1900s, the percentage of plastics in the total municipal solid wastes has been increasing. This increase is shown in Table 7. Table 8 breaks it down even further and displays gives an idea of how much of each type of plastic makes up municipal solid waste.

Table 7: Use of plastic from 1960 to 1966¹⁹.

Growth of plastics in MSW	
Year	Plastics in MSW (%)
1960	0.5
1970	2.6
1980	5.0
1990	9.8
1992	10.6
1994	11.2
1995	11.5
1996	12.3

Table 8: Comparison of material quantities¹⁹.

Types and quantities of plastics in municipal solid waste (1000 tons)

Polyethyleneterephthalate (PET)	1700
High density polyethylene (HDPE)	4120
Low density polyethylene (LDPE/HDPE)	5010
Polypropylene (PP)	2580
Polystyrene (PS)	1990
Other	3130

Waste-to-energy plants are a very promising option for recycling plastics. Essentially, plastic is placed in special incineration chambers, and the solid wastes are burned, and the heat produced in the reaction is harnessed to generate electricity and steam. The volume of municipal solid waste can be reduced by up to 90% when subjected to this process. There are currently 32 states in the United States of America that utilize this technology¹⁹. Table 9 illustrates how much energy can be derived from some common materials:

Table 9: Energy values of materials¹⁹.

Energy values of common materials

Material	BTU/pound
<i>Plastics</i>	
Polyethylene	19 900
Polypropylene	19 850
Polystyrene	17 800
Rubber	17 800
Newspaper	8000
Leather	7200
Wood	6700
Average MSW	4500
Yard wastes	3000
Food wastes	2600
Fuel oil	20 900
Wyoming coal	9600

4.5 Degradation

Plastics are widely used for many reasons. They are cheap and easy to make, they are durable, and flexible. A prominent downside, however, is that they have created a large environmental problem; plastics are very difficult to break down. Essentially, the durability and versatility of plastic that is often considered a benefit, happens to be the biggest weakness of plastics.

There are a number of ways of speeding up the degradation process. Some synthetic polymers can be broken down by absorbing ultraviolet radiation; this initiates photolytic, photo-oxidative, and thermo-oxidative reactions that lead to the plastics being broken down⁶. Plastics can be altered with additives in order to increase the rate at which these processes occur. Biodegradation is one of the most appealing processes, but it is also very complex due to the nature of oxidation processes. Biodegradation has been defined as the process of plastic decomposing into carbon dioxide, methane, water, inorganic compounds or biomass induced by the enzymatic action of microorganisms. The ASTM standard D5988-03 states that this process must take place within 60-180 days, and must decompose 60-90% of the material²⁰. Table 11 shows a comparison of a few different types of degradation.

Table 10: Comparison of different degradation methods⁵.

Various polymer degradation routes			
Factors (requirement/activity)	Photo-degradation	Thermo-oxidative degradation	Biodegradation
Active agent	UV-light or high-energy radiation	Heat and oxygen	Microbial agents
Requirement of heat	Not required	Higher than ambient temperature required	Not required
Rate of degradation	Initiation is slow. But propagation is fast	Fast	Moderate
Other consideration	Environment friendly if high-energy radiation is not used	Environmentally not acceptable	Environment friendly
Overall acceptance	Acceptable but costly	Not acceptable	Cheap and very much acceptable

There are various types of degradation, each requiring different sources to initiate the degradation. Photo-oxidative degradation is what occurs in plastics when they are exposed to sources of light. When subjected to enough photo-oxidative degradation, plastics change visibly; they gain a slight yellow hue. This is one of the most damaging effects, along with changes in the molecular weight and weight distribution, and the depletion of mechanical properties such as tensile strength and flexibility. Different wavelengths of light have varying effects depending on the type of plastic. For example, polyethylene is most damaged by light of wavelength 300 nm, while polypropylene is damaged by light of wavelengths around 370 nm⁶. A diagram showing the process of photo-oxidative degradation is shown in figure 13.

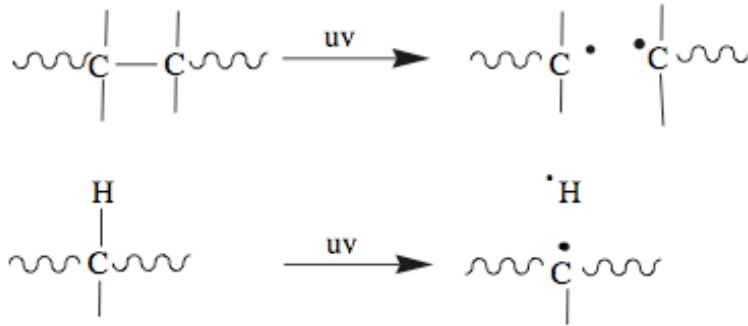


Figure 19: Illustration of UV radiation disassociating bonds in photo-oxidative degradation⁶.

The second type of degradation is thermal degradation. Under normal conditions, thermal degradation is similar to photochemical degradation; they are both different types of oxidative degradation. There are a few differences between the two processes: one is that the two have different initial steps leading to auto-oxidation, and another is that photochemical degradation occurs only on the surface, while thermal degradation occurs throughout the entire mass of plastic. Thermal degradation consists of two main processes: molecular weight is reduced during a random scission of bonds during one, and the other is a chain-end scission of C-C bonds⁶.

The ozone is another factor that leads to degradation. Small amounts of ozone in the atmosphere cause this type of degradation, and it usually causes degradation under conditions that are thought to be normal. Ozone degradation operates by targeting the unsaturation in unsaturated polymers.

Another type of degradation is mechanochemical degradation. This process of degradation is initiated when plastics are placed under mechanical stress by being exposed to

ultrasonic irradiations. The ultrasonic irradiation is simply vibration at a very high frequency, which is responsible for the mechanical forces. When this is done in a liquid medium, the vibrations constantly stretch and compress the molecules, and this creates bubbles that eventually burst. This creates rapid motion in the molecules as they adjust position, and the friction breaks apart the bonds between molecules. Although shear and mechanical forces do damage plastics, mechanochemical degradation is when the mechanical forces are aided by chemical reactions in the plastic⁶. This speeds up the process of degradation, because the plastic is being attacked in more than one way. Mechanochemical degradation is caused by free radicals that are created when stress breaks the molecular chains. When oxygen is present, these free radicals form peroxy radicals.

Catalytic degradation is a type of degradation that appears to be very promising. Polyolefins are degraded into gases and oils catalytically. A benefit of this type of reaction is that different catalysts can produce different results; in other words, through studying, scientists can figure out what catalysts must be added in order to receive a specific output from the reaction. Figure 14 shows an illustration of a catalytic reaction.

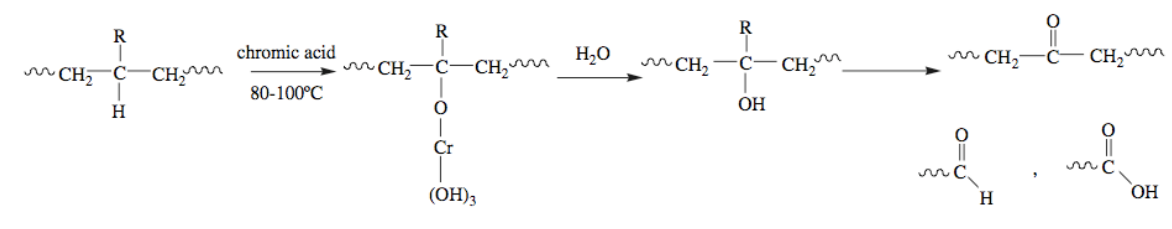


Figure 20: Illustration of chromic acid speeding up an oxidative degradation reaction⁶.

Biodegradation is one of the most well-known and appealing degradation processes. It is what occurs when microorganisms transform the composition of a sample. Biodegradation describes a process that results in changes in surface properties, loss of mechanical strength, assimilation by microorganisms, degradation by enzymes, breaking of backbone chains, and reduction of molecular weight⁶. When organic substances are aerobic condition, they yield carbon dioxide and water, while carbon dioxide and methane are formed when a substance is transformed under anaerobic conditions.

Just as the environment has different variables affecting degradation, the samples of material also have varying effects on degradation. Chemical composition factors into the degradation of plastic, for example. Long carbon chains in thermoplastics decreases the likelihood of being degraded by microorganisms; adding oxygen to the mix will increase the likelihood of being broken down by thermal degradation or biodegradation⁶. Saturation in polymer chains makes plastics resistant to oxidation.

Molecular weight is another factor when it comes to plastics degrading. A plastic with a higher molecular weight is more resistant to degradation, in general. The physical size of each molecule, in terms of space rather than weight, also affects degradation. Mechanical degradation, thermal degradation, and biodegradation are all slowed down if a plastic has large molecules.

Additives in the plastic can also lead to degradation, and this can be easily used to the advantage of the manufacturers. Metals promote thermo-oxidative degradation in plastics by increasing the activity of pro-oxidants. If oxygen is present, these pro-oxidants produce free

radicals on the polyethylene chain. Pro-oxidants also increase the rate of chain scission reactions in the polymer chain⁶. The structure of the bonds in a plastic material is another factor that will affect degradation. Head-to-head and tail-to-tail are both formations that possess weak spots, and these weak spots increase the rate of degradation. When PMMA is linked head-to-head, it is more susceptible to thermal degradation. Thermal degradation also increases when polymer chains are branched⁶. Photodegradation is less likely to occur when molecules are cross-linked, because the structure is more stable and does not allow radicals to escape.

Increased temperature and moisture both increase the chances of biodegradation. High humidity, temperature, and moisture are favorable conditions for the microorganisms responsible for biodegradation. Humidity also reduces the effectiveness of photo-stabilizers in plastics, thus making photodegradation more common in conditions with high temperature and moisture. The presence of oxygen will increase the rate of mechanochemical degradation, because oxygen reacts with the radicals that are formed during scission of molecular chain⁶. When this occurs in an atmosphere without oxygen (for example, a nitrogen atmosphere or a landfill), radicals recombine before they cause any noticeable damage.

Different types of stress lead to different reactions from the plastic. For example, observe photodegradation. When tensile stress is applied on a sample, the chains are stretched out and the molecules are more exposed to the light source. This means that under a tensile load, a sample of plastic will succumb to photodegradation at a faster rate. Compressive stress, however, does the opposite. By the same principle, when chains are compressed,

molecules are pressed closer together, making them less exposed to the light source. This leads to a slower rate of photodegradation in the plastic sample⁶.

4.6 Environmental Issues

The large increase in plastic production especially in the last 30 years has made manufacturing and packaging easier and cheaper but has also caused a major environmental issue especially with regard to marine ecosystems. Large quantities of plastic debris accumulate on beaches and in bodies of water. Fishing boats as well as recreational users of beaches carry a large portion of the blame in varying degrees depending on the area and its use. A study done in Panama showed that debris levels bounced back to about 50% of the original total only 3 months after being cleaned²¹.

These levels of plastic debris are very harmful to marine animals. Birds and fish among other species end up ingesting the plastic which then has negative effects on their well being. It was found that many species end up ingesting plastics thinking it was the prey they normally consumed. The result of having plastic in their GI system was that it would decrease the capacity of the stomach therefore decreasing the size meal animals could eat and thus decreasing the fitness and overall well being of the species studied. PCB or polychlorinated biphenyls have specifically been linked to reproductive issues and death in many marine species and pollution by this particular plastic has been on the rise lately. Entanglement in plastic is another hazard of pollution. An even less obvious issue is bacteria or microorganisms becoming

affixed to drifting plastic and ending up in ecosystems not adequately adapted to handling them²¹.

A study was done specifically on leatherback turtles. It showed that 1968 was the first year that plastic was detected in the stomach of turtles. Since then about 37% of leatherback turtles have been found to have at least some plastic in their GI tract. The number of times the amount of plastic was deemed to be lethal was a relatively low 3% but as with the species discussed earlier other health hazards can arise from consuming plastic like the inability to absorb food as efficiently as possible. It's thought that in the case of the leatherback turtles the reason for the large quantities of plastic consumption is the similarity between plastic bags and their normal food which is jellyfish²².

The issue of marine pollution is a large one and needs to be addressed from multiple angles. Legislation can help provide the negative reinforcement necessary especially with large industries like fishing. Education is another possible solution and has the potential to have a larger impact on recreational users of water and beaches.

It is no coincidence that plastic bags are so widely used; they are cheap to produce and have excellent mechanical properties. However, plastic bags also come with their disadvantages, which is why so many studies are being conducted to try to find alternatives. Additives can accumulate in landfills, but they can also be used to increase the rate of degradation. However, plastics generally take a very long time to degrade and this is what leads to the environmental issues.

5 Evaluation

Mechanical testing was done on bags that underwent expedited degradation in a heated furnace. Following this the data from the tests was analyzed in order to gather information on the mechanical properties of standard plastic bags compared to supposedly eco-friendly bags that degrade more quickly.

5.1 Mechanical Testing of Plastic Bags

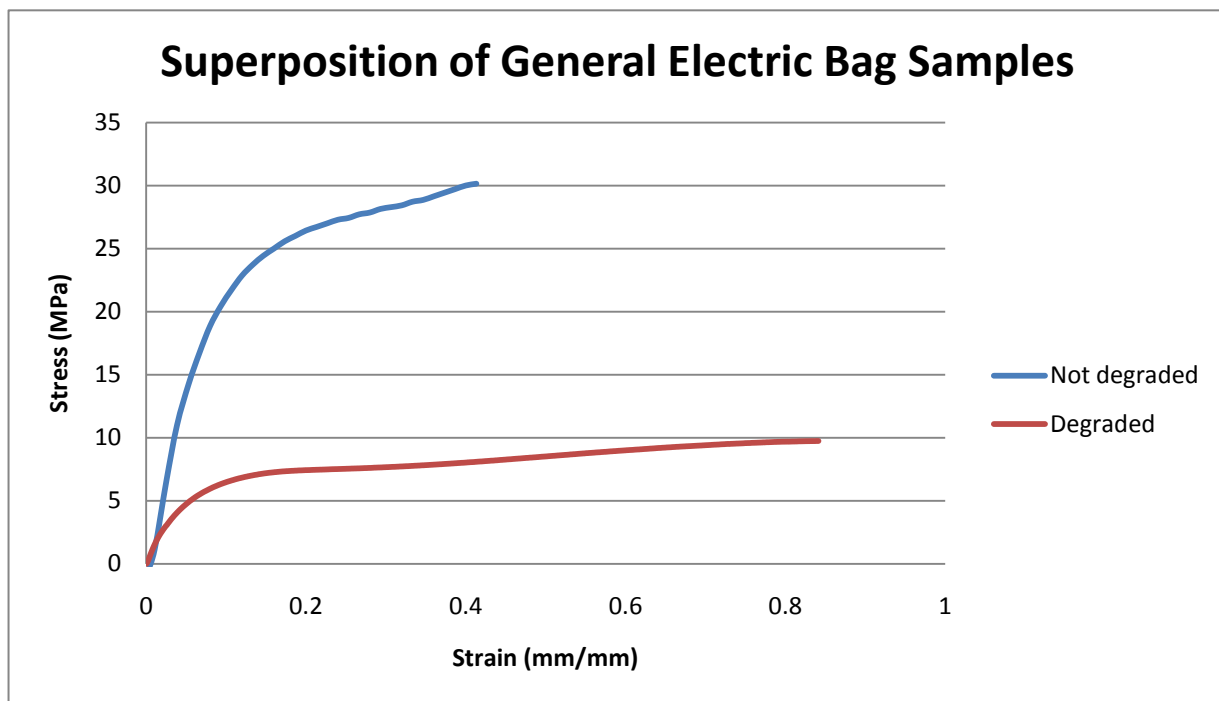


Figure 21: A superposition of the GE bag samples before and after degradation.

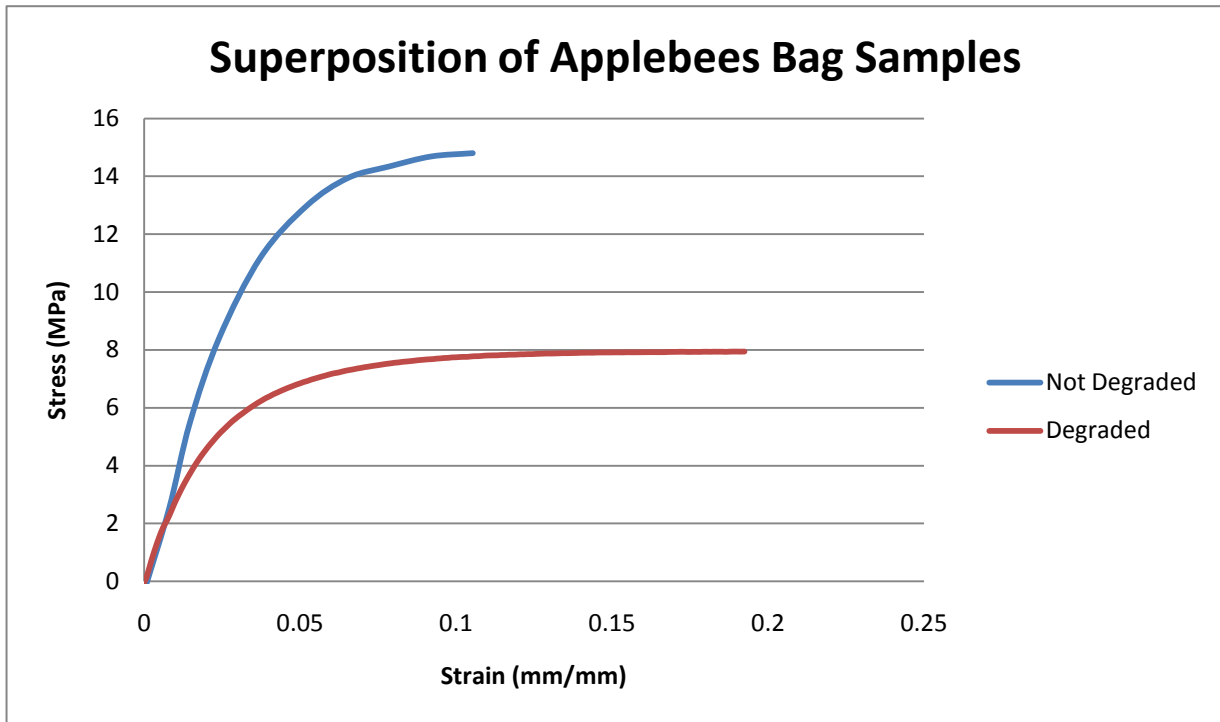


Figure 22: A superposition of the Applebees bag samples before and after degradation.

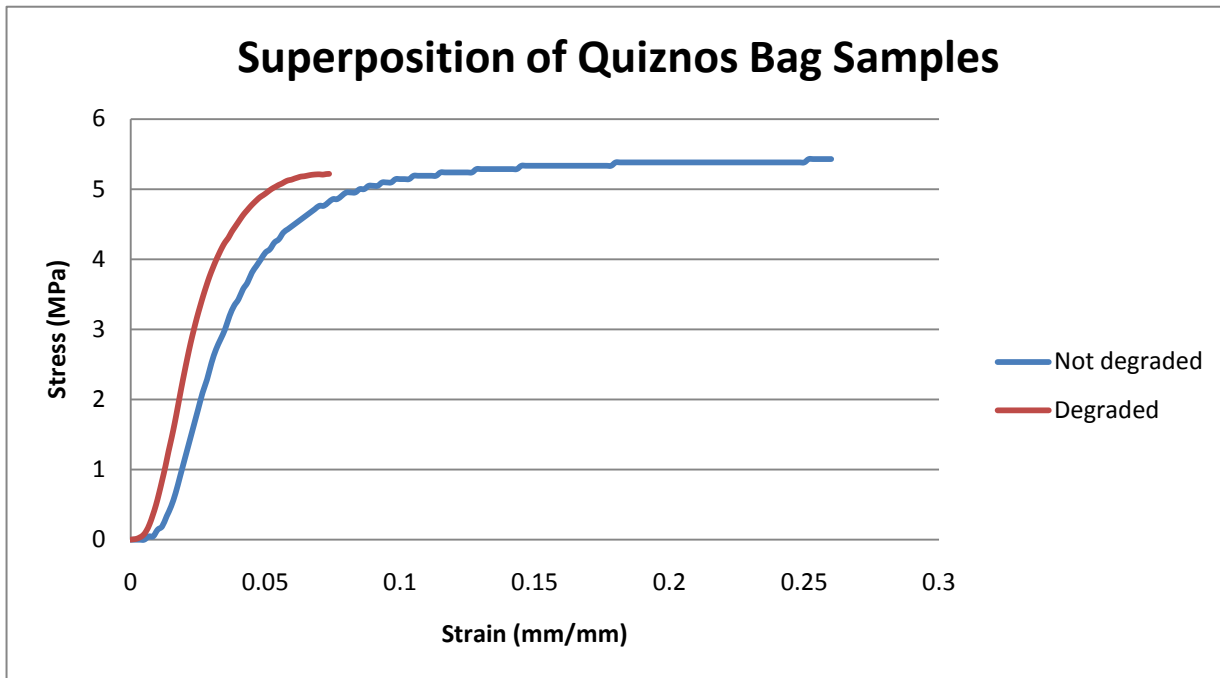


Figure 23: A superposition of the Quiznos bag samples before and after degradation.

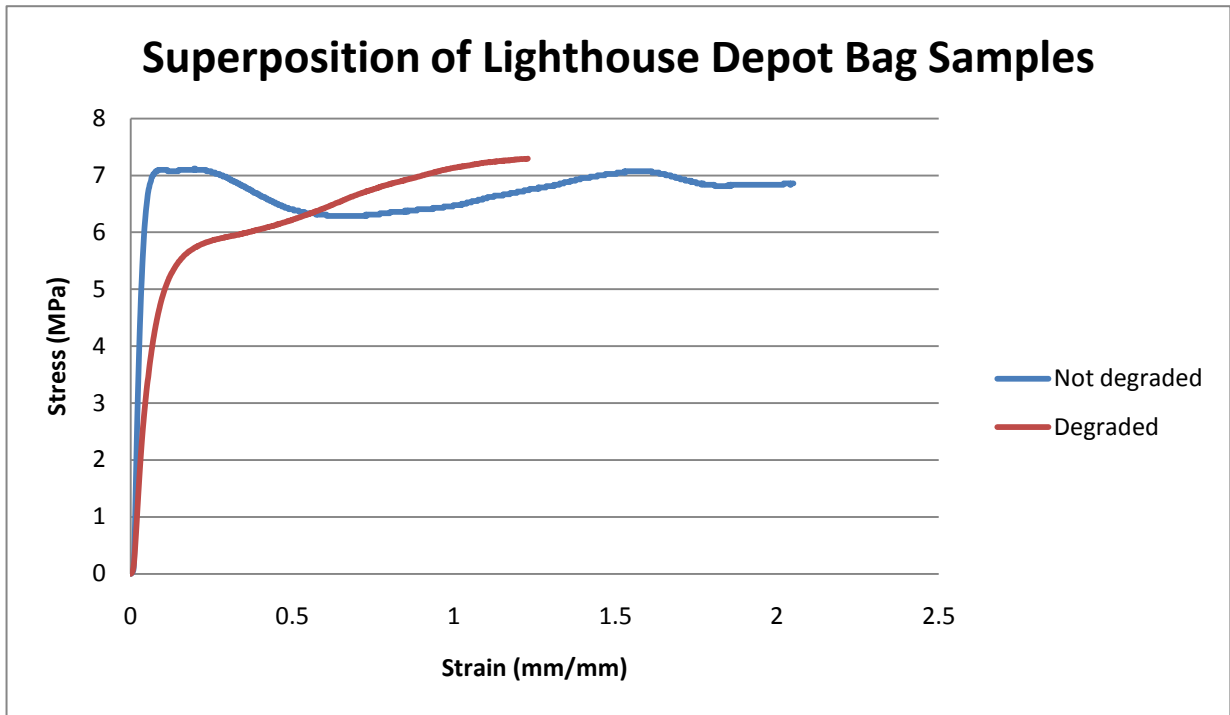


Figure 24: A superposition of the Lighthouse Depot bag samples before and after degradation.

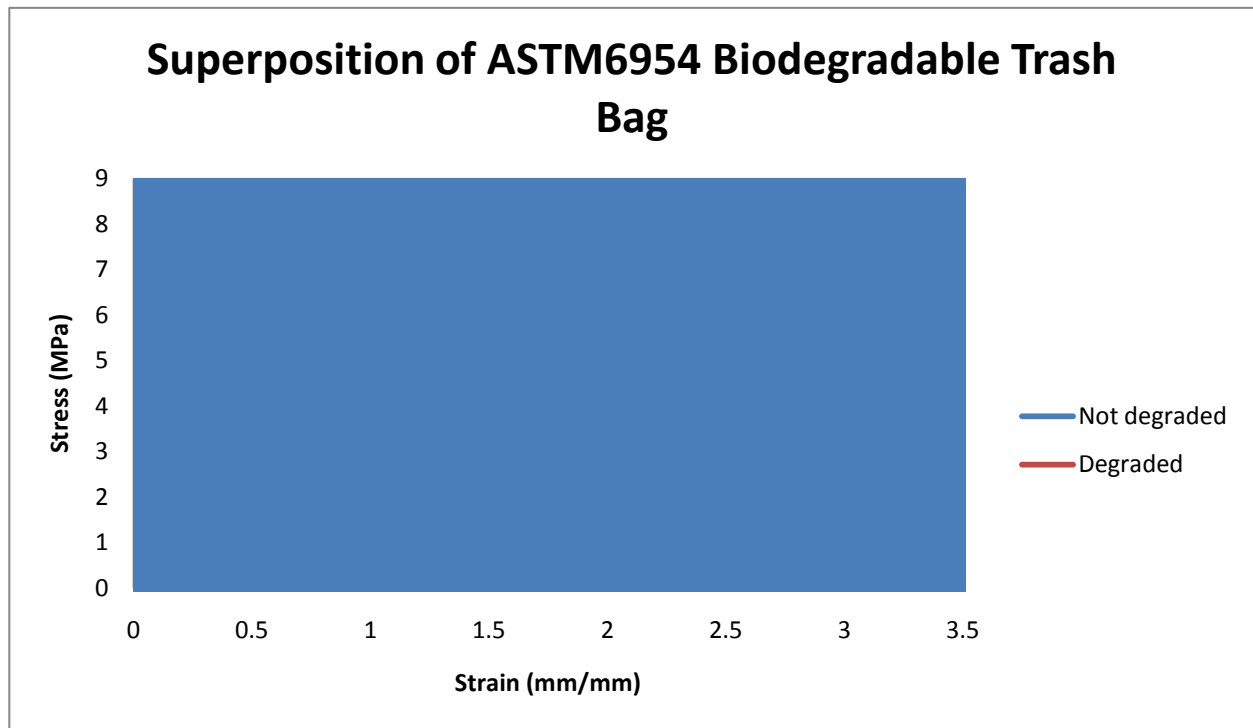


Figure 25: A superposition of the ASTM6954 bag samples before and after biodegradation.

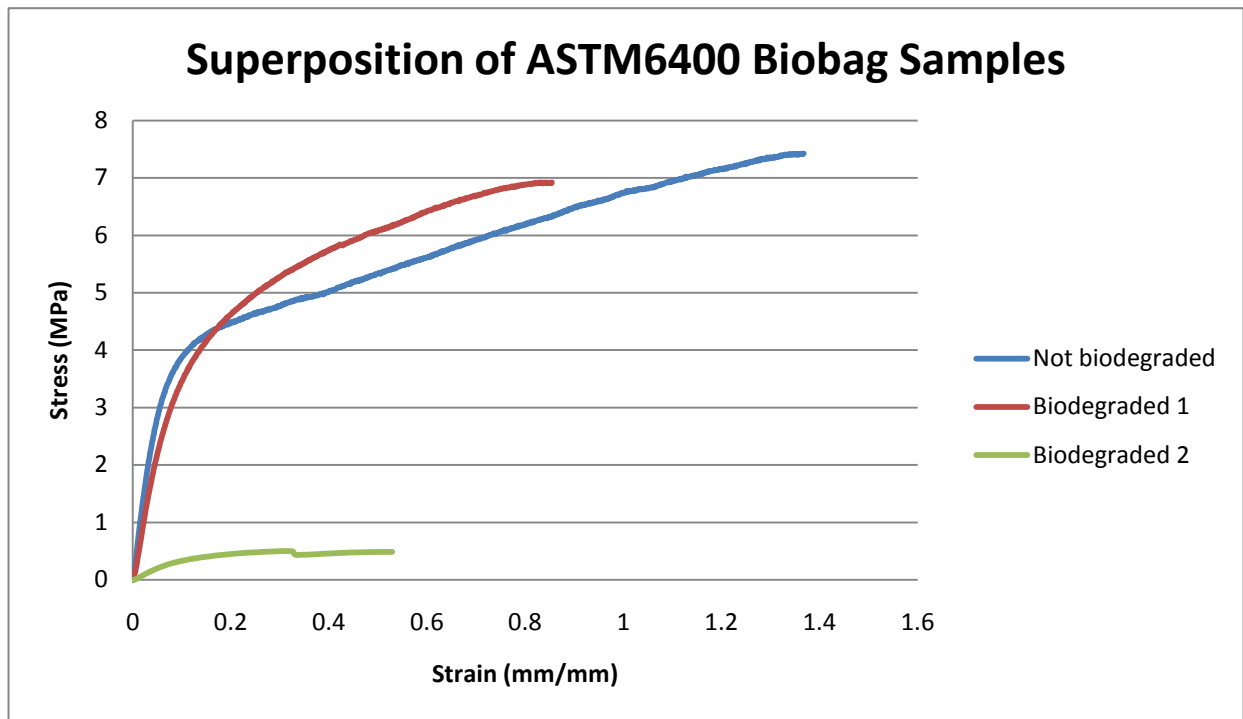


Figure 26: A superposition of the ASTM6400 bag samples before and after biodegradation.

Table 11: Pretest conditions for tensile test.

Bag	Length (cm)	Width (cm)	Thickness (mm)	Cross-Sectional Area (W x T) (mm ²)
GE Bag	7.5	3.5	0.02	0.7
Applebees	7.5	3.5	0.05	1.75
Quiznos	6.0	3.5	0.06	2.1
Worcester City Trash bag	6.5	3.5	0.02	0.7
Lighthouse Depot Bag	7.0	3.5	0.12	4.2

The Bluehill software collected data based on force applied each second and the amount of extension of each sample. Stress-strain relationships can be calculated using the pre-testing data collected in Table 11. The stress equation is

$$P = F / A \quad \text{Equation 7}$$

where F is the force applied to the sample and A is the cross-sectional area of the sample, used to calculate the stress of the sample. The strain equation is

$$\epsilon = \Delta L / L_0 \quad \text{Equation 8}$$

where ΔL is the extension (change in length) and L_0 is the original length, used to calculate the strain of the sample.

The modulus of elasticity is the plastic bag's tendency to be deformed elastically (not permanently) when there is a force applied to it. The modulus of elasticity is computed by finding the slope of the linear section on the stress-strain graph for the bag and applying the equation:

$$\text{Modulus of Elasticity} = \frac{\Delta \text{Stress}}{\Delta \text{Strain}} \quad \text{Equation 8}$$

The ultimate tensile strength is the maximum stress that the bag can withstand. From the graph, the ultimate tensile strength is simply the maximum value of stress on the stress-strain curve.

The yield strength is the stress at which the bag changes from elastic deformation to plastic deformation, permanently deforming the bag. On the graph, this is indicated by a change from linear growth to non-linear growth or decay.

Table 12: Summary of mechanical properties before degradation.

	Modulus (MPa)	Yield Strength (MPa)	Strain at Yield	Tensile Strength (MPa)	Strain at Fracture
GE	308.035	19.0	0.082	30.143	0.425
Applebees	364.286	13.4	0.057	14.743	0.106
Quiznos	121.429	4.25	0.055	5.426	0.031
Worcester Trash	146.166	12.8	0.05	26.286	5.25
Lighthouse Depot	142.223	7.0	0.07	6.857	2.05
ASTM6954 Bio Trash	65.834	4.8	0.09	8.401	3.301
ASTM6400 Weak Bio	56.537	3.6	0.08	7.422	1.368

Table 13: Summary of mechanical properties after degradation

	Modulus (MPa)	Yield Strength (MPa)	Strain at Yield	Tensile Strength (MPa)	Strain at Fracture
GE	94.288	6.1	0.085	9.754	0.8462
Applebees	268.472	6.6	0.045	7.944	0.192
Quiznos	125.849	5.1	0.052	4.378	3.808
Worcester Trash	79.150	3.6	0.065	5.710	1.193
Lighthouse Depot	66.987	4.7	0.090	7.295	1.228

ASTM6954 Bio Trash	54.892	2.6	0.065	4.713	1.451
ASTM6400 Weak Bio 1	43.553	3.4	0.100	6.923	0.854
ASTM6400 Weak Bio 2	4.029	0.34	0.105	0.489	0.529

A 0.2% rule was used to determine the yield strength. After calculating the modulus as the slope of the linear region at the beginning of the curve, a line of the form

$$y = m*x + b \quad \text{Equation 9}$$

was superimposed on the stress-strain curve. The intersection of this line and the σ - ϵ curve is the yield strength. The 0.2% rule means the superimposed line crosses the strain axis at 0.02, which corresponds to a 0.2% increase in length.

The modulus of elasticity decreased for all the bag samples after a degradation period of ten weeks, with the exception of the Quiznos bag. The yield strength also decreased for all the degraded samples, again with the exception of the Quiznos bag. The Tensile strength decreased in all the bags after degradation, with the exception of the Lighthouse Depot bag. The ASTM6400 Weak Biodegradable Sample 2 was much weaker than the non-biodegraded sample, because after removing the degraded sample from the furnace, there was a visible hole in the plastic. This severely decreased the tensile strength for that sample. A video of this particular test may be found in Appendix A. The tensile strength for the GE, Applebees and Worcester trash bag greatly diminished after 10-weeks of degradation. For example, the GE bag had a

68% reduction in tensile strength while the biodegradable trash bag had its tensile strength reduced by 44%.

The ASTM6400 Weak Biodegradable Sample 2 did not have as much of a reduction in tensile strength, because the biodegradable sample was only put into the furnace for eleven days. This is a significantly shorter amount of time than the other plastics were in for, but it still showed a significant reduction in modulus of elasticity, yield strength, and tensile strength. If the biodegradable bags were put in the furnace for the full ten weeks, they would have completely degraded and would not have been available for mechanical testing afterwards.

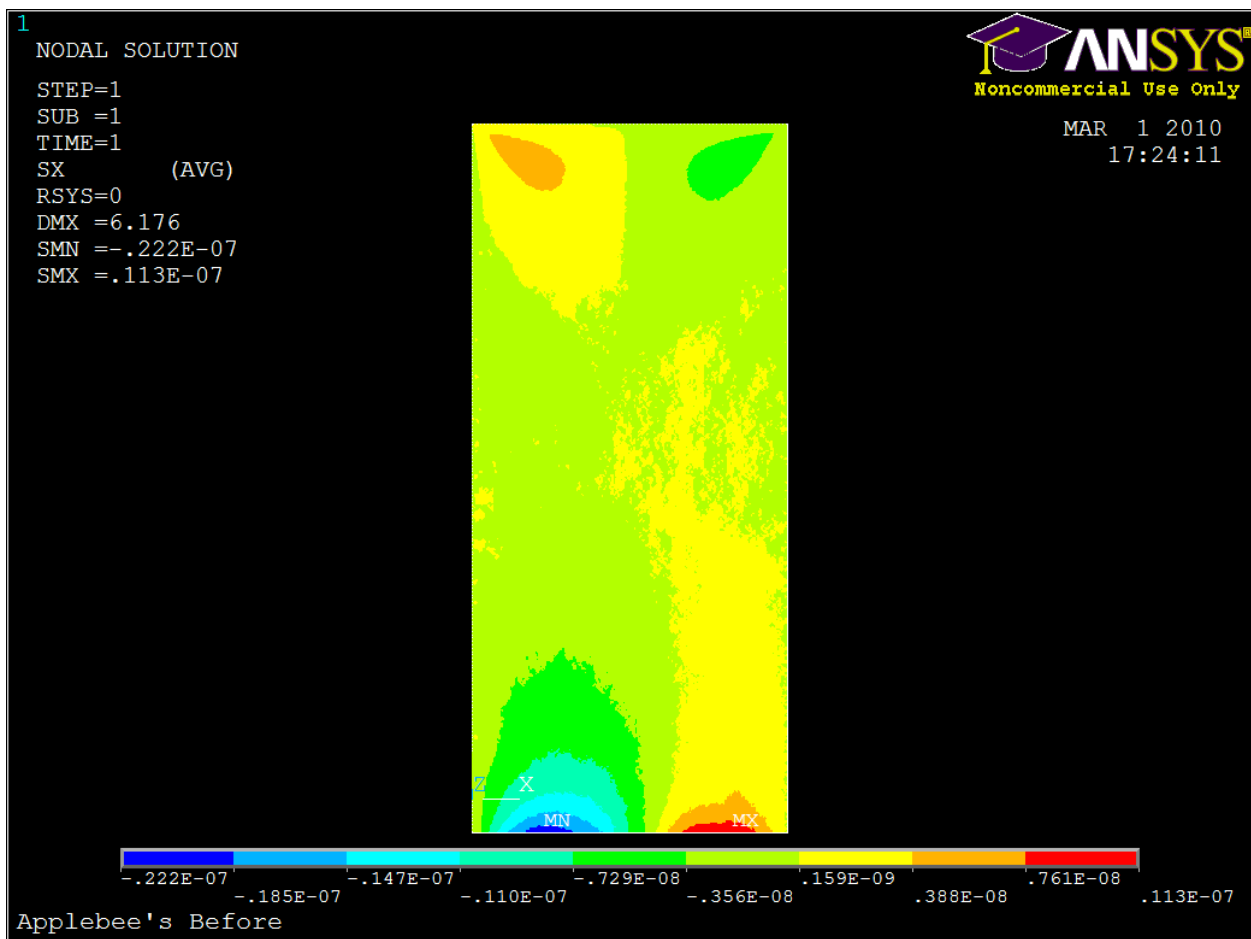


Figure 27: Finite element analysis of a plastic bag sample.

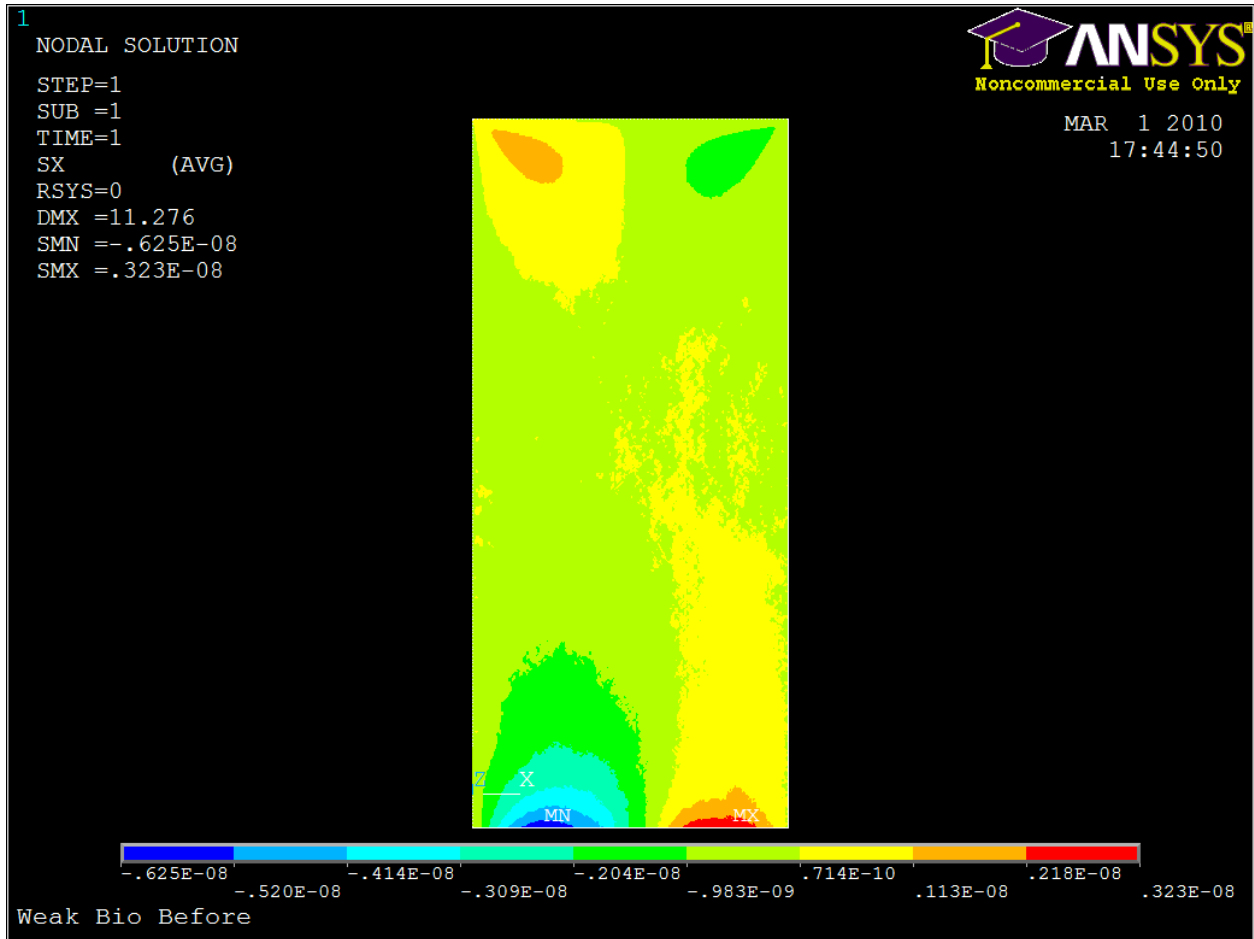


Figure 28: Finite element analysis of a plastic bag sample.

Finite element analysis was performed on two plastic bag samples, before and after their aging periods in the furnace. Figure 24 shows the stress diagram. The Applebee's bag was chosen because it had the highest elastic modulus, while the weak biodegradable bag was chosen for its low elastic modulus, so the extremes could be compared. Figure 25 shows the test of a BioBag. In each figure, the red and blue areas show the highest stress concentrations in the sample. The different signs of the stress are a result of the force being in two different directions, and a figure showing the absolute stress values would simply show red spots in the

corners. The numbers do not vary much between figures, but this is because of the configuration of the Instron machine. The machine operates to preserve a constant strain throughout the stretching, so there are varying loads on each sample, which is why the figures all appear to be very similar. The other figures are shown in Appendix A.

The mechanical testing of the bags showed that aging a plastic bag will significantly reduce its tensile strength. The plastic bags that were in the furnace for ten weeks showed considerable reductions in their mechanical properties, while the ASTM standard biodegradable bags showed similar decreases after only being in the furnace for eleven days. The test results demonstrated that the biodegradable bags indeed do degrade at a much faster rate than regular plastic bags.

6 Public Perception

Surveys were conducted with consumers at supermarkets as well as online to understand what the public perception of plastic bags and possible alternatives is. This was done to understand if there is perception that there is a problem and how open people are to possible solutions.

6.1 Survey results

Survey Results

As described in Section 3.1, the Chi Square value was calculated for each question on the survey. For clarity, the application of the formula is shown as it applies to each question.

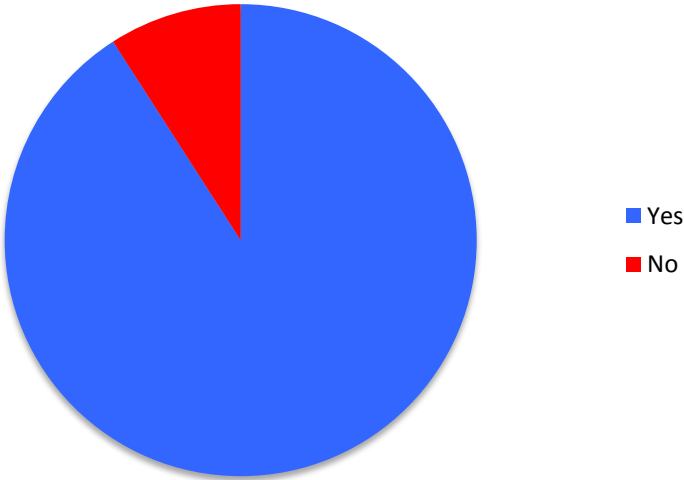


Figure 29: Pie Chart of Question 1. Do you think that the current plastic bags are bad for the environment?

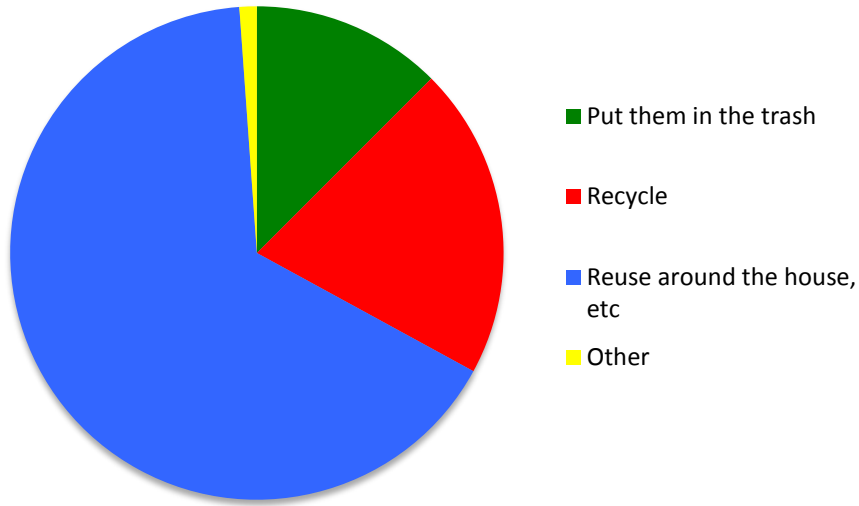


Figure 30: Pie Chart of Question 2. How do you dispose of plastic bags when you are finished using them?

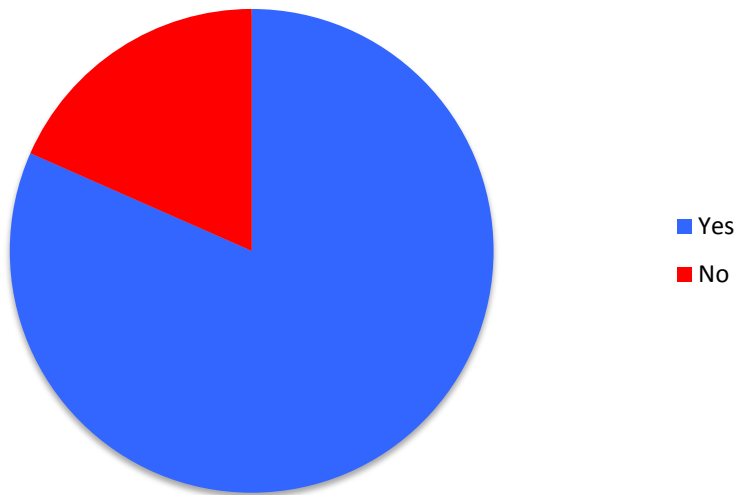


Figure 31: Pie Chart of Question 3. If retailers rewarded you for reusing bags instead of using new ones, would you be more inclined to reuse old bags?

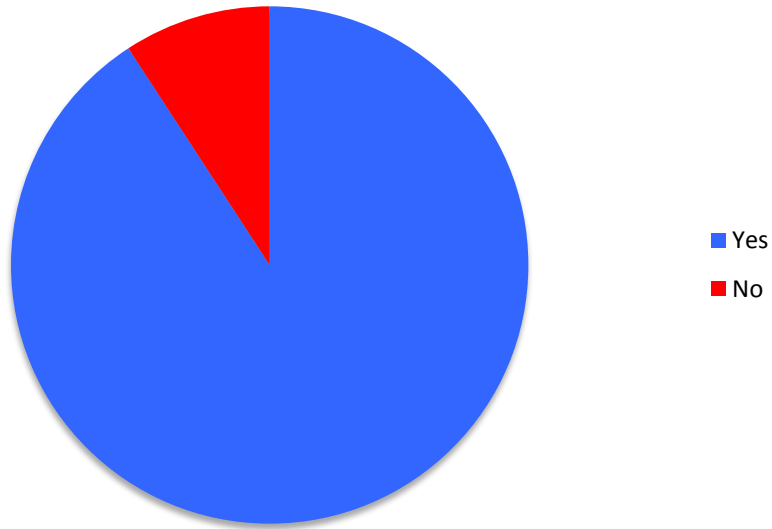


Figure 32: Pie Chart of Question 4. If an alternative bag were offered, would you use that instead?

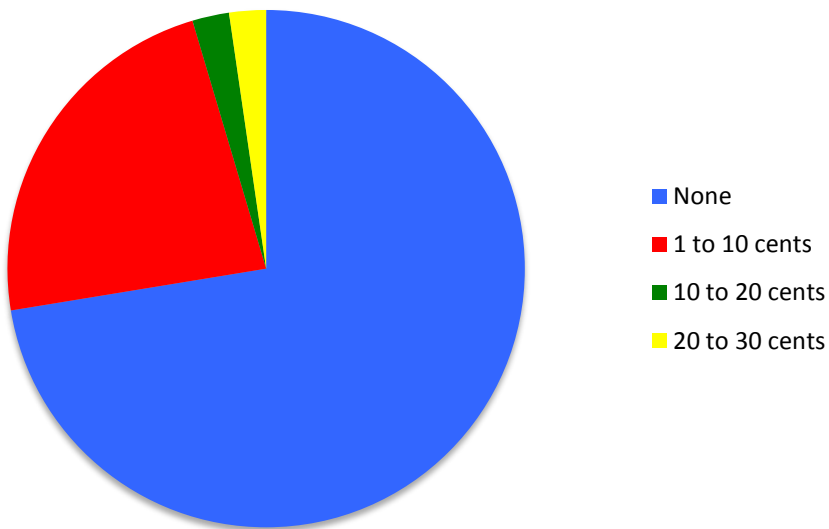


Figure 33: Pie Chart of Question 5. How much would you be willing to pay for new plastic bags?

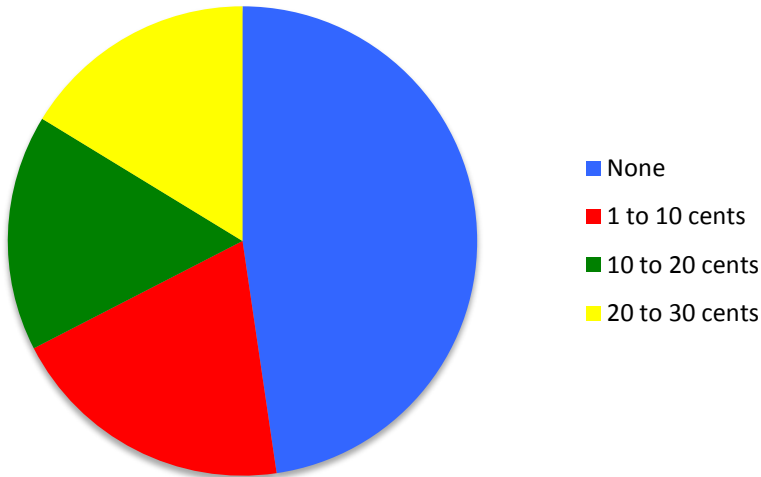


Figure 34: Pie Chart of Question 6. How much would you be willing to pay for alternative bags?

One of the questions that arose out of the survey was: Do those who think plastic bags are a problem really think this or do they just claim to be “green?” We decided to figure this out by looking at individual responses to the questions, particularly, how much people would be willing to spend on plastic bags versus alternative bags. The data is presented below:

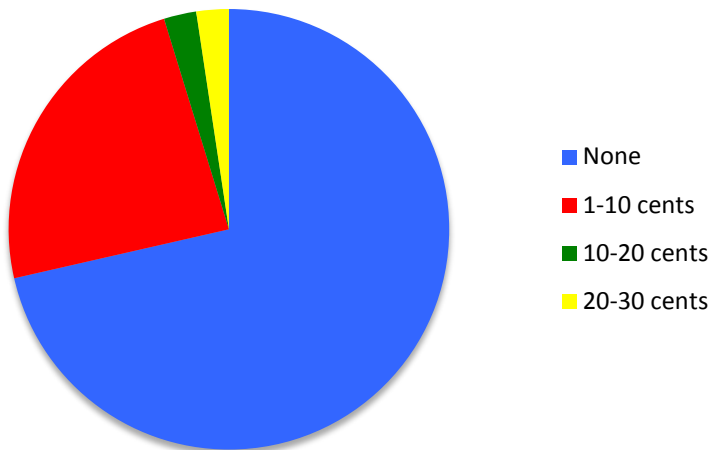


Figure 35: Breakdown of how much money people who answered yes to Question 1 on the survey are willing to spend on plastic bags.

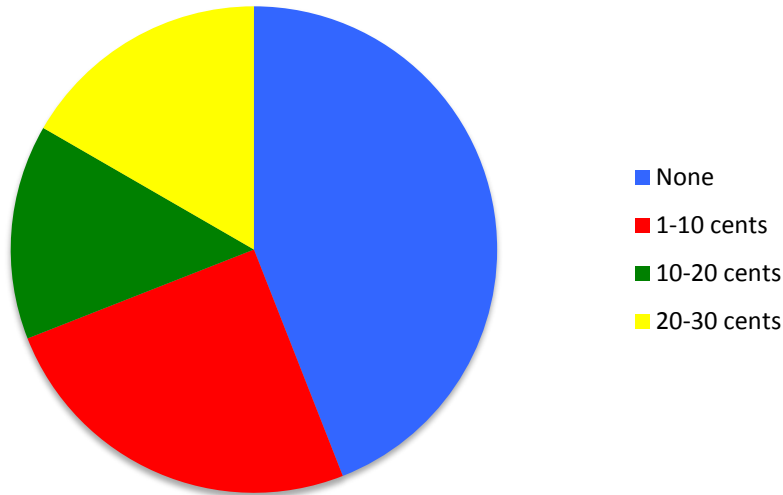


Figure 36: Breakdown of how much money people who answered yes to Question 1 are willing to spend on alternative bags.

6.2 Examining Customers' Use of Bags in a Supermarket

The chi squared, referenced in Appendix B, shows people prefer plastic to the other types, despite having 8 degrees of freedom. A quick look at the numbers reveals that people used canvas bags with about the same frequency as paper bags. Those who did not use bags only bought a couple small items, and did not feel a bag was necessary. Several customers would explain how bad plastic was for the environment when requesting paper. Customers always have their own personal reasons as to why they would use one bag over another. Most of the time there was no relation to environmental concerns. Some prefer plastic for only the cold items and paper for everything else (or even the other way around!), while some prefer insulated canvas bags for the same purpose. Some customers ask for only two or three paper bags for recycling their newspapers, and ask for everything else in plastic. Some people request

paper for heavy items and plastic for light items. Despite a wide range of reasons for bag choice, most would consistently try to use fewer bags. If a customer felt that too little was in a bag, he/she would take those items out and put them in another bag with more things. Usually this happened with eggs or bread, where the customer would be fine with easily crushed items being on top of heavier things.

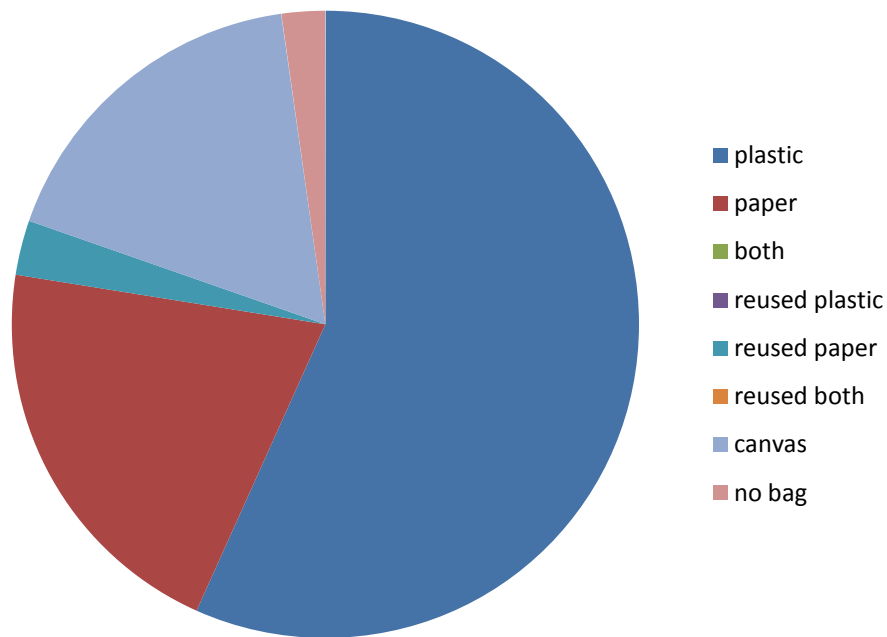


Figure 37: Preference in bag choice shows that more than half of the customers used plastic. It should be noted that zero customers reused plastic or paper in this sample.

One surprising result is, despite how liberal and “green” the residents of Newton try to be (which is backed up by the survey results), over half of the customers still used plastic bags. Often, customers leave their political views out of grocery shopping and just pick whichever bag

is most convenient. This alternative method of data collection to determine bag preference allows for less biased results.

6.3 Comparison of Original Surveys to Other Published Surveys

The Centre for Design at RMIT in Australia conducted a study on the impacts of degradable plastic bags in Australia. The results of this survey showed that in Australia, 16% of plastic shopping bags are reused, 13% are reused as bin liners, and 14% of the bags are recycled²³. These results differ from the results of the survey conducted in Worcester, which concluded that 66% of bags are reused around the house as opposed to 16%, and 20% of participants claimed to recycle plastic bags as opposed to 14% of the Australian survey takers.

Los Angeles County's Plastic Bag Working Group also studied plastic bags and their impacts on the environment. Through surveying of recycling and materials recovery facilities, the group discovered that about 90% of plastic carry out bags that are taken to these facilities are not recycled, but are actually taken to landfills. This is due to the fact that plastic bags are often very contaminated, since people usually use them to line garbage bags, and the higher contamination makes the quality of the plastic resin much lower. Bags are also contaminated when they come into contact with other contaminants in collection bins. Plastic bags also have the tendency to jam machines, which is another reason they are often not recycled²⁴.

A survey that was conducted in the United Kingdom showed that most adults in the UK would be willing to pay for alternatives to plastic shopping bags. Of the participants in the survey, 14% would be willing to pay at least £2 for a reusable woven shopping bag that would

last up to a year. 64% responded saying they were willing to pay between 50p and £1, and 11% would be willing to pay only 20p. For bags that would last about 10 trips to the store, 61% of survey takers expressed willingness to pay between 5p and 10p for the bags²⁵.

About 66% of the survey takers re-use plastic bags, 23% already use the sturdy reusable bags, and 11% admitted to throwing plastic bags away. About 61% of adults who took the survey feel that supermarkets should stop supplying free plastic bags, but the rest of the participants disagree. People in favor of free plastic bags feel that way because they feel that customers have a right to free bags, and that customers should not be penalized for forgetting to bring bags²⁵.

These results show that the public is generally beginning to accept the idea of paying extra to use environmentally friendly bags. The 11% that admitted to throwing plastic bags in the trash is about the same as the 13% of the participants in the Worcester survey who admitted to doing the same. This is a relatively low number, which is good news, but ideally it would be lower, and in order to decrease the amount of people who throw plastic bags in the trash, it is necessary to increase public awareness of the issue.

An interesting point is that some of the UK survey participants pointed out that customers should not be penalized if they forget to bring bags to the store. This applies to the idea of stores no longer offering free bags to customers. It is an often overlooked fact, but if the only option was to bring bags, this could lead to problems because not everyone would always remember to bring a bag. About a third of the UK survey takers were opposed to the possibility of no longer supplying free bags. This number can be compared to the 48% of the Worcester survey takers, who said they would not be willing to pay at all for alternative bags.

This is further evidence that a large downside to biodegradable alternatives is the higher cost, and they would be much more practical if the price per bag could be reduced.

A recycling awareness survey was conducted in London, and the numbers show that awareness has increased over the course of four years. Table 14 shows the increase in the amount of materials recycled from the year 2000 to 2004. In both years, the majority of houses recycle twice a week, but in 2004, the results are much more skewed towards twice a week, with a decrease in the other frequencies of recycling.

Table 14: Recycling activity between years 2000 and 2004²⁶.

Recycling Roadshow: recycling activity amongst households that recycle				
Frequency	2000		2004	
	Number of households	%	Number of households	%
Twice-weekly	1903	51.0	1945	81.8
Once per week	1463	39.2	316	13.3
Every 2 weeks	142	3.8	62	2.6
Monthly	127	3.4	55	2.3
unspecified	96	2.6		

Table 15 analyzes the reasons for not recycling. In 2000, a large majority of the population did not recycle because they were unaware of recycling services. However, in 2004, the number of households unaware of recycling services had dramatically decreased.

Table 15: Reasons for not recycling²⁶.

Recycling Roadshow: non-recyclers				
Reasons for not recycling	2000		2004	
	Number of households	%	Number of households	%
Lack of awareness of services	3380	86.7	531	59.7
Disinterested	195	5.0	127	14.3
Lack of time	90	2.3	73	8.2
Inadequate provision/poor service	70	1.8	64	7.2
Lack of storage space	39	1.0	58	6.5
Insufficient waste	20	0.5	32	3.6
Miscellaneous	105	2.7	4	0.5

The methods of recycling have changed during these four years, as shown in table 16. In 2000, most recyclables were in open carrier bags, but in 2004 the vast majority of recyclable materials were placed in recycling bins. This increase is most likely due to an increase in recycling awareness, and more efforts from the recycling services to take more materials.

Table 16: Recycling methods²⁶.

Recycling Roadshow: Kerbside recyclers				
Method	2000		2004	
	Number of households	%	Number of households	%
Open carrier bags	1549	48.9	507	18.2
Recycling bin	963	30.4	1798	64.5
Clear sacks	345	10.9	318	11.4
Tagged carrier bags	209	6.6	164	5.9
Reversible carrier bags	32	1.0		
Miscellaneous	70	2.2		
With garden lawn	982			
Composting practised	204			

The survey results show that most of the public is aware of the potential problems presented by plastic bags. The results also demonstrate that a fair amount of the participants

would be willing to pay a small fee for alternative bags if such a system was introduced. The amount of participants open to paying for alternatives is larger than the amount open to paying for current plastic bags.

7 Alternatives

Possible alternative plastic bags are on the market due to belief that current plastic bags are damaging to the environment. Many of these alternatives focus on decreasing the time it takes bags to degrade by either altering the material or putting in additives to increase the speed of degradation. Many of these alternatives and their properties were researched through online resources and journal articles. Two samples were also gathered and tested alongside current plastic bags.

7.1 Biodegradable Polymers

There are a number of biodegradable alternatives already on the market that consumers can use instead of polyethylene plastic bags. Biodegradation is a natural process of degrading complex organic compounds by microorganisms, such as bacteria, into simpler and smaller organic compounds. These compounds are mineralized and redistributed through elemental cycles in the biosphere of the microorganisms²⁷. The International Organization for Standards (ISO) and the American Society for Testing Materials (ASTM) have created their own definitions for biodegradable plastics, which are listed below:

ISO 472: 1988—A plastic designed to undergo a significant change in its chemical

structure under specific environmental conditions resulting in a loss of some properties

that may vary as measured by standard test methods appropriate to the plastics and

application in a period of time that determines its classification. The change in chemical

structure results from the action of naturally occurring microorganisms.

ASTM sub-committee D20.96 proposal—Degradable plastics are plastic materials that undergo bond scission in the backbone of a polymer through chemical, biological and/or physical forces in the environment at a rate which leads to fragmentation or disintegration of the plastics²⁷.

Two techniques of measuring biodegradability are commonly used. The first is a very simple process; samples are placed in composting conditions, and then weighed after a certain amount of time. The final weight is compared to the initial weight to give an idea of how much material has degraded. The other test method determines a biodegradability coefficient through testing. In this process, reaction rate constants are determined by varying incubation temperature and C/N ratios²⁸.

Biodegradable plastic bags can degrade in under two years so they are an intelligent alternative to polyethylene plastic bags found in all grocery stores, which can last in landfills for hundreds of years. Some of these biodegradable polymers include polymers with hydrolyzed backbones natural occurring polymers and blends of biodegradable and non-degradable polymers.

Polymers with hydrolyzed backbones are susceptible to biodegradation²⁷. The only high-weight molecular polyesters that are biodegradable are the aliphatic polyesters. It's been found that polyesters with medium sized monomers, from C₆ – C₁₂ in size, can be readily degraded by fungi²⁷. Synthetic polymers of this size with flexible polymer chains can be

degraded because the polymers can fit into the enzyme activation sites of these fungi. Enzyme activated degradation will not occur for rigid and bulky polymers because the large side chains block binding to the enzyme activation sites.

Polyglycolic acid (PGA) and polyglycolic acid-co-lactic acid (PGA/PL) are two examples of biodegradable polyesters. These polymers are known to biodegrade through a simple hydrolysis (addition of water) of the ester backbone. Because of this, these materials are currently used as biodegradable sutures since the hydrolysis can occur through contact of bodily fluids¹². The structures of PGA and PGA/PL can be seen below in Figure 38.

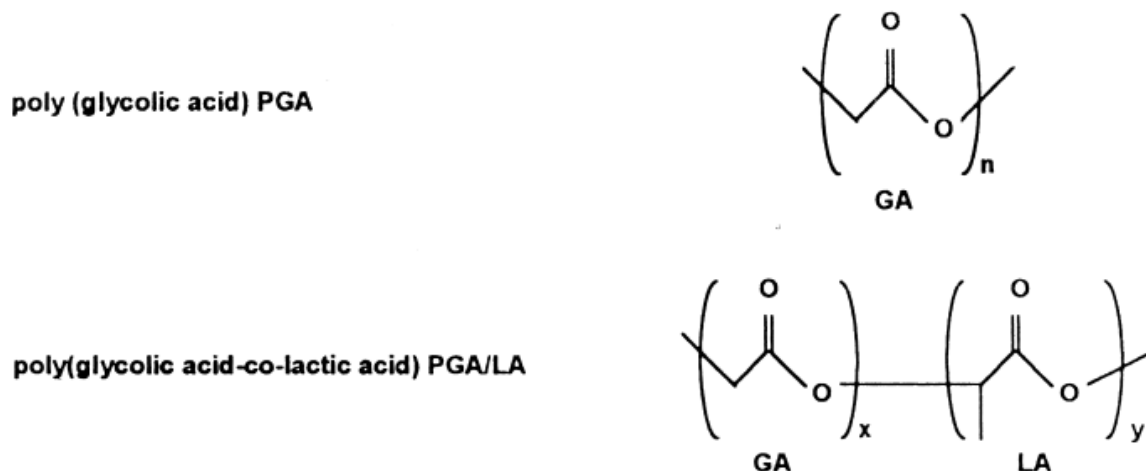


Figure 38: Mer structure of PGA and PGA/PL.

Starch is a natural occurring polymer made by many plants, such as potatoes, rice and corn. Starch has been used in making plastic films because they have low permeability, making these films useful for food packaging. Microorganisms in the soil can degrade starch-based films into harmless products. Figure 39 shows starch being degraded by enzymes with the presence of water, which represents the polymers being degraded by microorganisms in moist soil.

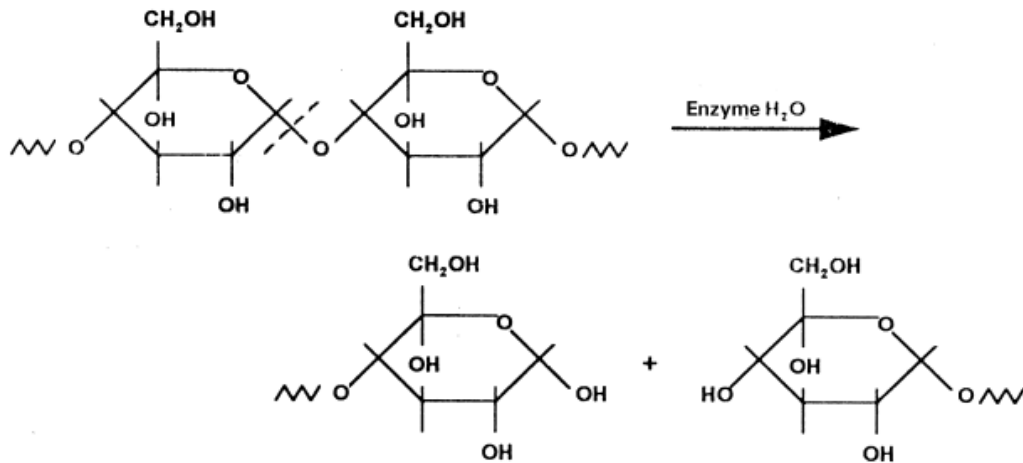


Figure 39: Starch polymer broken down.

One issue with starch-based products is that at high temperatures $\sim 150^{\circ}\text{C}$ the glucose links start to break apart. At temperatures of $\sim 250^{\circ}\text{C}$, the starch collapses because of all the energy. Another issue with starch polymers is at low temperatures, a phenomenon known as retrogradation occurs¹². Retrogradation is the reorganization of hydrogen bonds and an aligning of the molecular chain due to cooling. This phenomenon makes the resulting starch-based films very brittle. Because of these weaknesses, fully starch-based films are not the best biodegradable polymers to completely replace polyethylene.

Blending of starch and polyethylene has received a lot of attention for possible applications in the waste disposal of polyethylene-based plastics. The theory behind the blending is that if there is enough of the biodegradable polymer, once it is removed by microorganisms in a waste disposal environment, such as a landfill, the remaining polymers should lose its polymer integrity and disintegrate¹². Granular starch has been used to form these types of blended polymers. In an environment containing microorganisms, the exposed

starch granules on the surface of the blended polymer material can be enzymatically broken down. When the starch is fully ingested by the microorganisms, the sample will start to disintegrate. This effect only occurs for samples containing 30% by volume or greater of starch, but the large amount of starch will cause the plastic or film created to have less tensile strength. Table 17 shows a discussion of different biodegradable categories.

Table 17: Descriptions of Biodegradable Categories.

Category	Composition	Degradation pathway	Suitable environments for degradation
Biodegradable starch-based polymers	Starch-polyester (PCL, PLA, PBAT or AAC) blends	Hydrolysis by hydrolytic scission of the ester bonds in the chain backbone	Compostable, biodegradable and marine degradable. Suitable for degradation in controlled composting facilities, activated sludge (sewerage treatment). Also degrades in soil.
Biodegradable polyesters	Polylactic acid (PLA)	As above	As above apart from composting at 60°C within time limit for Standard
Controlled degradation masterbatch additives	Polyethylene with a prodegradant additive	Two-stage process involving, in sequence, oxidative degradation, which is normally abiotic in the first instance, followed by the biodegradation of the oxidation products.	Insufficient data but appears to be slow to degrade in compost and landfill. Fragment into fine residue in open air.

7.2 Commercialization of Alternatives

One issue we are faced with between LDPE plastic bags and their alternatives is their respective environmental impacts. Since it takes about 1000 years for a LDPE bag to completely degrade, they have a negative impact on the environment. Newly developed alternatives degrade much faster. The following is Greenpeace's definition of a biodegradable material:

Materials made from naturally occurring or biologically produced polymers are the only truly biodegradable 'plastics' available. Since living things construct these materials, living things can metabolize them²⁹.

By Greenpeace's definition, a biodegradable material must be made from biological material or manufactured through a biological process. However, this is not entirely true. The biodegradability of a polymer is actually a direct consequence of antioxidants added during the manufacturing process²⁹. One study removed this antioxidant (butylated hydroxytoluene, a fat-soluble organic compound) from sample polyethylene films and found that, under the same conditions, the film biodegraded rapidly in the presence of bacteria, while the sample with the antioxidant remained completely inert to the bacteria²⁹. On the same note, natural polymers are not always more biodegradable than synthetic polymers. Commercial thermoplastic polymers (non-biodegradable) have become essential to the packaging and foodstuffs industry. The fact that they are hydrophobic and biologically inert makes them perfect for such uses²⁹. Another way to make a plastic biodegradable is to add an ultraviolet light absorber. This makes plastic biodegrade when exposed to sunlight¹. Figure 40 depicts polyethylene plastic bags that are not able to be broken down into smaller parts in nature.

Hydrocarbon polymer plastics are a viable source of energy generation. Through the incineration of such a polymer, the amount of calorific energy produced is close to that of fuel oil. Through this process, these polymers replace the fossil fuels that would otherwise be used, ultimately reducing the CO₂ pollution of our atmosphere. Also, the thermal energy given off by the incineration of these polymers is the same as that used in their manufacturing. This is the most ecologically acceptable waste-to-energy process for these polymers²⁹.



Figure 40: The negative impact of plastic bags on the environment is illustrated in the above picture³⁰.

An example of a reusable bag is the Ecosilk Bag®. They are reusable bags that consist of 100% recycled parachute silk³². They are used until they wear down (around 5 years). When they reach the end of their useful lives, they can then be returned to the manufacturer for

credit toward future orders. From here, they are sent to a recycling plant and recycled into building material³¹.



Figure 41: Ecosilk bags³³.

BioGroupUSA's BioBag® is a 100% biodegradable and compostable plastic bag. They conform to ASTM D6400-99. It is made with Novamont's starch-based Mater-Bi®. Mater-Bi® is a blend of starch-based polymer and polyesters from vegetable oil. Chemical additives are not used to enhance decomposition, like many biodegradable bag³⁴. They will decompose in compost within 45 days, leaving behind no harmful effects. They also biodegrade in both salt and fresh water, within 14 months³⁵.



Figure 42: BioBag, 100% compostable and 100% biodegradable³⁶.

GP Plastics Corporation's PolyGreen newspaper bags are biodegradable and environmentally friendly. They completely biodegrade within three years in landfills and after only a few months in nature³⁷. This is made possible by an additive called PDQ-H. This non-toxic agent allows microbes to eat and break down the plastic. These new newspaper sleeves only cost a fraction of a cent more than their non-biodegradable predecessors. Newspaper publishers currently using this product include *The New York Times*, *USA Today*, and the *Boston Globe*³⁸.

Although not being used to make plastic bags today, a biodegradable polymer, Polylactic acid (PLA), is a good candidate for use in future plastic bags. It is currently used in plastic applications such as biomedical products, disposable eatery, and packaging. Polylactic acid is a vegetable-based bioplastic, a byproduct of cornstarch or sugarcane. It only takes 45-60 days to biodegrade when exposed to temperatures between 122°F and 145°F. The most likely reason this bioplastic is not currently being used to manufacture plastic bags is that its recyclability is unproven.

Thermoplastic starch (TPS) biodegradable plastics are starch-based plastics. Starch-based polymers typically have starch contents ranging from 10% to 90%. Higher starch content will result in a more biodegradable plastic. TPS biodegradable plastics have a starch content greater than 70%³⁹. This type of plastic is currently being used to manufacture the BioBag, a 100% biodegradable and compostable plastic bag. It is the first bag derived from corn to reach national distribution. They decompose in compost in 10-45 days. They even biodegrade in salt and fresh water within 14 months³⁵.

Another starch-based biodegradable plastic used to make plastic bags is the starch synthetic aliphatic polyester blend. These bags are made up of 50% synthetic polyester and 50% starch. Buried in soil, they completely biodegrade within eight weeks³⁹.

Organic bags made from materials such as cotton and hemp are good options. They cost more than LDPE bags, but they last longer and are more stylish. They also biodegrade within five to six months.



Figure 43: A reusable hemp bag⁴⁰.

The cost of the material used to make the bag has been a huge deciding factor in which material is used. LDPE bags are a relatively inexpensive option compared to most biodegradable bags on the market⁴¹. Ecosilk bags cost \$6.67 per bag, but they can be used for five years before they start to wear down³². Cornstarch bags are only \$0.22 for a seven-liter bag, making cornstarch bags an inexpensive option³⁴. In the case of starch synthetic aliphatic polyester blends, the coupling of starch with the synthetic polyester greatly cuts down this materials expense, as the polyester is \$4.00 per kilogram and the starch is only \$1.00 per kilogram⁴¹.

7.3 Paper vs. Plastic

Paper bags and plastic bags are both detrimental to our environment. The manufacturing process for a paper bag is actually less environmentally friendly than that of a plastic bag. In fact, it requires four times the amount of energy to manufacture a paper bag than it does to manufacture a plastic bag and twice the energy to recycle a pound of paper than to recycle a pound of plastic⁴². The production of a paper bag uses up more energy and creates more air pollution than the production of a plastic bag. In 1999, the amount of paper bags used by the United States, alone, required the cutting down of 14 million trees. Paper bags take up more space in landfills than plastic bags. In today's landfill, paper bags and plastic bags actually decompose at the same rate⁴³.



Figure 44: Paper versus Plastic⁴⁴.

7.4 Biodegradable Films for Food Packaging

The primary concern of food packaging is to preserve and protect raw foods from oxidative agents and microorganisms in order to extend their shelf-life. Petrochemical based plastics, such as polyethylene and polyesters have been used as packaging material because of their good tensile strength and the ability to block oxidative agents. The wide use of synthetic packaging films leads to a serious ecological problem because of their non-degradability⁴⁵. The commonly used packaging films are shown in Table 18.

Table 18: Packaging films commonly used⁴⁵

Film type	Monomeric unit	Characteristics
Polyethylene	Ethylene	Desirable mechanical properties, heat sealable
Polyvinylidene	Vinylidene	Desirable H ₂ O/O ₂ barrier, not very strong, heat sealable
Polyester	Ethyleneglycol + terephthalic acid	Desirable mechanical properties, poor H ₂ O/O ₂ barrier, not heat sealable
Polyamide (Nylon)	Diamine + various acids	Desirable strength, heat sealable, poor H ₂ O/O ₂ barrier
Cellophane	Glucose (cellulose)	Desirable strength, good H ₂ O/O ₂ barrier, not heat sealable.

It would be impossible to replace all of these commonly used films, but replacing even a few can help save the depleting petroleum resource. Good food packaging film prerequisites are listed below:

1. Allow for a slow but controlled respiration (reduced O₂ absorption) of the commodity;
2. Allow for a selective barrier to gases (CO₂) and water vapor;
3. Creation of a modified atmosphere with respect to internal gas composition, thus regulating the ripening process and leading to shelf-life extension;
4. Lessening the migration of lipids—of use in confectionery industry;
5. Maintain structural integrity (delay loss of chlorophyll) and improve mechanical handling;

6. Serve as a vehicle to incorporate food additives (flavor , colors, antioxidants, antimicrobial agents), and

7. Prevent (or reduce) microbial spoilage during extended storage⁴⁶.

The prerequisites listed above can be met by making composite polymers whose amount of biodegradable polymer composition can vary from one food to another. Two types of biomolecules hydrocolloids and lipids are used in combination for the preparation of biodegradable packaging films. Hydrocolloids, such as Jell-O or agar, are hydrophilic so they are poor moisture barriers but with the addition of a lipid, they can become good moisture barriers.

One example of a biodegradable film is the mixture of starch, which is hydrophilic with the hydrophobic plastic matrix. Addition of natural polymers like starch into polyethylene creates starch-LDPE films containing up to 30% starch. These films have been shown to be biodegradable upon composting. These starch-LDPE films fit perfectly into the ecosystem because of their total biodegradability. A number of aerobic and anaerobic microorganisms have been identified for biodegradation and the carbon cycle involving biopolymer degradation can be seen in Figure 45.

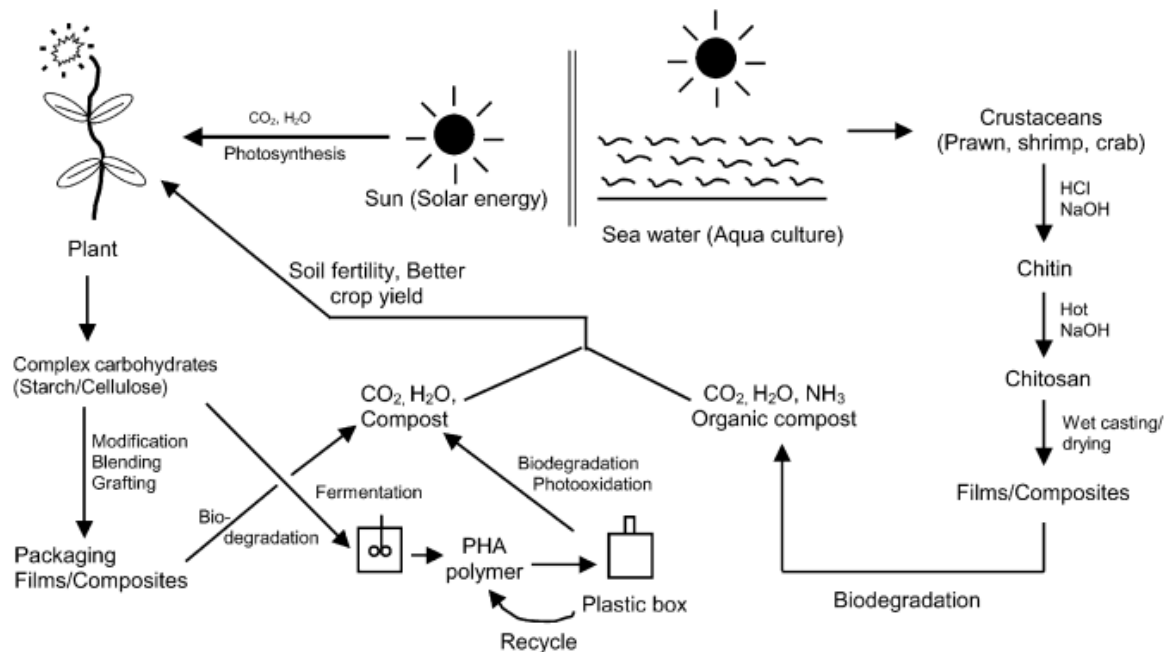


Figure 45: Carbon cycle of biopolymers.

Research on biodegradable plastics based on starch began in the 1970s and continues in various labs. Technologies have been developed for continuous production of extrusion blown films to containing 50% or more of starch mixed with polymers and water sensitivity of such films have been reduced by lamination with polyvinyl chloride⁴⁷. Combination of urea with polyols provides better plasticization of starch with good quality films. To increase compatibility of hydrophilic starch with the plastic matrix, starch granules can be surface treated with silanes⁴⁸. Pro-oxidants can also be added to enhance oxidative degradation of the synthetic polymer. Pectin is a complex anionic polysaccharide, which can be fully (high methoxy pectin) or partially (low methoxy pectin) esterified. Plasticized blends of citrus pectin and high amylase starch can give strong flexible films which are thermally stable up to 180°C⁴⁵.

Synthetic polymers are gradually being replaced by biodegradable materials. Bilayer and multicomponent films with good mechanical properties still need to be developed. Innovative techniques of food preservation and biodegradability needs to be developed and adopted in order to better the waste management process⁴⁵.

8 Case Studies in Usage Reduction and Banning of Plastic Bags

Currently, there are many supermarkets and governments looking into policies to either reduce or fully ban the use of PE bags. This chapter examines multiple case studies, and in particular, what policies/programs were used and the outcomes.

8.1 ASDA

There is much action being taken in the United Kingdom to reduce usage of polyethylene plastic bags. The Waste and Resources Action Programme (WRAP) specializes in raising awareness concerning use of raw materials, and works with businesses the public to encourage reuse in order to reduce waste⁴⁹. In 2009, WRAP compiled data of bag usage by the British population since dating back to 2006, and concluded the following, summarized in the table below⁵⁰:

Table 19: Summary of PE bag usage in the UK between 2006 and 2009⁵⁰

Year	Bag Usage (millions)	Percent Difference from 2006
2006	1330.8	-
2008	984.8	-26%
2009	638.8	-48%

The reduction in bags used between 2006 and 2008 was given as 346 million, a 26% decrease, and a 48% reduction between 2006 and 2009, from which the number of bags used can be calculated. This has largely been a voluntary effort by retailers, with encouragement

through governmental funding to promote consumers to change bag usage habits. Such an endeavor is no easy task, says British Resource Consortium (BRC) Director General Stephen Robertson. Quickly changing customer habits on a large scale is not easy. However, it shows a large commitment by customers, who have switched to bags for life and cut bag usage. Retail staff and supermarkets also deserve credit, as they have had to endure the costs to help this happen. This voluntary approach is very successful and can lead to better-informed customers and lasting positive change⁵⁰.

There are other examples of efforts to reduce plastic bag use in the UK. In 2008, ASDA, a British version of Wal-Mart, led an effort to encourage customers to purchase reusable bags for life. The campaign, called “Saving the Planet One Bag at a Time⁵¹”, intended to give consumers more bag choices at the checkout and hide PE bags from view, discouraging their use. Promotions for the initiative appeared in print, television, and ASDA stores, as can be seen in Figure 46 on the next page:



Figure 46: Easily visible in-store displays of ASDA's "Saving the Planet One Bag at a Time" program encourage people to reuse bags⁵¹.

ASDA altered its bags by increasing recycled content, and decreasing size and thickness. In 2008, 250 tons of plastic bags were recycled and reduced usage by over 500 million bags⁵¹.

ASDA continued its campaign into 2009 by initiating efforts to further raise awareness of alternative bags and encourage consumers to reuse them. Slogans such as "ASDA, Saving You Money Everyday" and "Don't forget to reuse your bags!"⁵¹ increase exposure of the campaign. Customers often have to wait in line at the checkout for several minutes, and as a result, ASDA has installed signs on registers to remind people one last time during their trip to the store to invest in reusable bags.

8.2 Sainsbury's

Britain's third largest supermarket chain, Sainsbury's, wanted to implement methods of reducing plastic bag use, and has surveyed its customers to figure out why they do not reuse bags they already have. As a result of the research, two interesting figures were found. First, 73% of customers want to be rewarded for reusing bags; however, about 50% would forget to bring them in to the store⁵². Therefore, the supermarket has initiated a three-part plan to encourage more people to change their bag usage habits. The first part is called 'Remind' that involves displays throughout the stores reminding people to reuse bags and buy reusable ones, sometimes called "bags for life." In addition, thousands of cashiers were trained to offer bags for life for those who did not bring their own. The second part is called 'Reward,' in which customers are given so-called Nectar Points for buying reusable bags and reusing old plastic bags through the Nectar Point Reward⁵² program. Since its inception, over 300 million points have rewarded. These points resemble electronic money that may be spent on an online Nectar store for various household items, entertainment, and even vacations. The final aspect of the program is called 'Remove.' In October 2008⁴, Sainsbury's stopped providing free PE bags in all of its supermarkets. Its convenient stores continue to offer them, but are hidden from view so that customers do not immediately think to use them. More durable and reusable bags are encouraged, and though they cost money, will be replaced for free upon wearing out. Some examples are shown in the figure 46 on the next page.



Figure 47: A variety of reusable bags are in use at Sainsbury's to reduce PE bag consumption⁵³.

These bags are made of various materials, such as 100% recycled plastic, plastic bottles, and jute⁵³. The jute plant has an external bark, under which fibers may be extracted and processed into a yarn via prolonged submersion in water and separation from roots. They are spun into yarn, and can be woven into interlocking structures as a final product⁵⁴. The bag with the label “I stow away” can be folded into a compact form that can easily fit into cargo pockets, pocketbooks, etc. This makes it more likely that customers will use them when shopping because they will already have the bags with them when in the store.

Sainsbury's is a prime example of successful business-customer interaction to achieve some change. Through research and action, the supermarket chain has managed to raise

awareness of the PE bag issue and millions of customers have adopted new practices concerning their bag use.

8.3 Tesco

Tesco, a British supermarket and merchandise giant, has programs similar to Sainsbury's to reduce PE bag use. In August 2006, Tesco introduced its Green Clubcard Points program, which rewards customers for reusing bags. In three years, over three billion⁵² bags have been saved as a result of this program. Similar to Sainsbury's, there is extensive use of in-store displays reminding customers to reuse and recycle, as can be seen in Figure 48.



Figure 48: Eye-catching signs raise awareness and encourage people to reuse bags, reminding them of the environmental benefits⁵².

Tesco has also introduced a new plastic bag with additives approved by the US Food and Drug Administration and European Union Scientific Committee on Food. Oxo-biodegradable chemicals are added that promote degradation into smaller pieces. Oxo-biodegradation is the process by which ultraviolet (UV) and oxidative processes initiate a decrease in the molecular weight of the plastic⁵⁵. Once the bag has transformed into smaller pieces, micro-organisms digest the plastic as food, leaving behind H₂O, CO₂, trace salts, and biomass⁵⁶. Oxo-biodegradable materials constitute 1-3% by weight of the plastic being used⁵⁵. Figures of Tesco's new bags are shown below in figures 49 and 50.



Figure 49: Tesco's new bags shown during three stages of oxo-biodegradation. The bags are capable of degrading in 60 days⁵⁶.

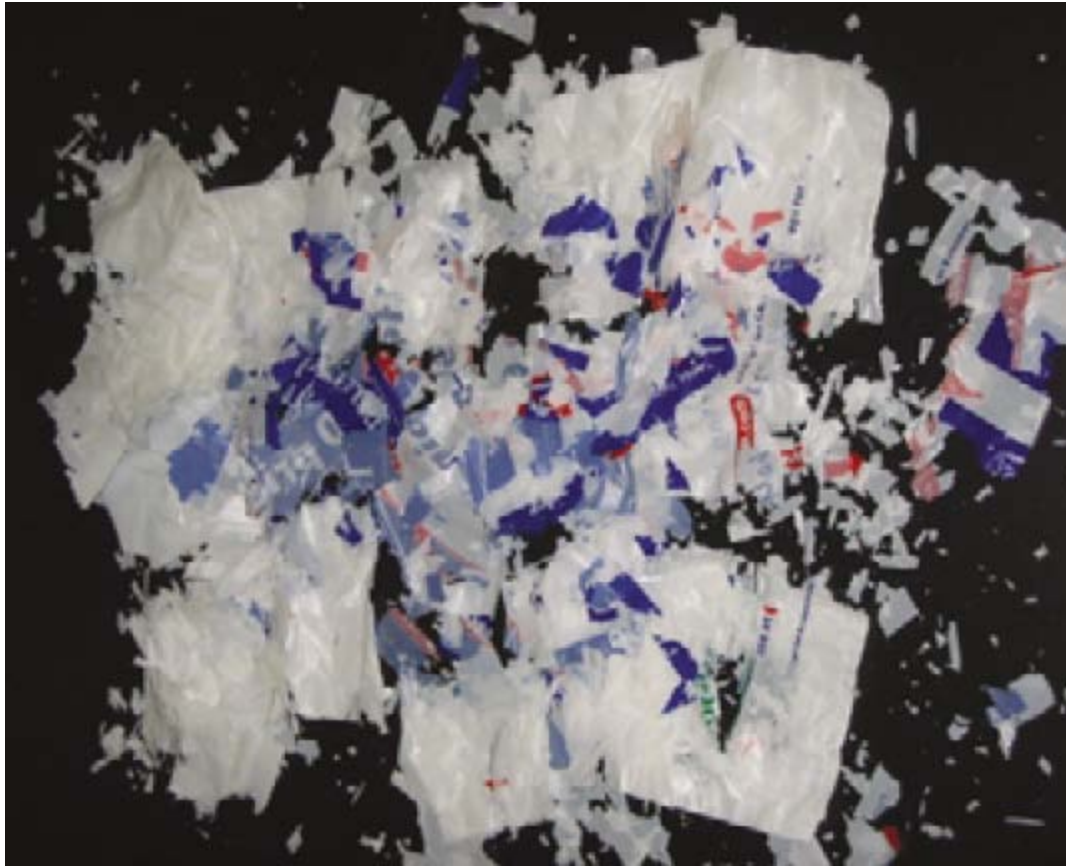


Figure 50: Tesco bag after some degradation. At this stage, micro-organisms process the rest of the bag, leaving behind no harmful byproducts⁵⁶.

Tesco also has a delivery service that gives out even more points than shopping in stores. Groceries and other products are delivered to the customer, and no bags are used in this process. It is reported that about half of Tesco's customers utilize its delivery option⁵².

It should come as no surprise that large corporations implementing such extensive programs can be costly, both in planning and execution, yet the dedication toward raising awareness about the PE bag issue shows that people are serious about solving the problem.

8.4 Waitrose

Waitrose is one other supermarket in the United Kingdom that tried new programs to encourage reusable bag use. It ran a three-month trial period in early 2008 in four stores⁵² before expanding the program to all of its stores. The goals were similar to those of ASDA and Tesco: hide PE bags from view, offer cheap “bags for life” (shown in figure 42) to customers, and ask if customers need bags. Waitrose noticed about an 1100% increase⁵² in sales of bags for life, followed by a decline as customers started reusing them. At the same time, PE bag usage dropped by around 45%-50% as customers used alternative bags. Similar to Tesco, customers reported a tendency to forget to bring their reusable bags into the store, which prompted signs reminding customers to bring in their bags. This program was successful during the trial period in the four stores, so Waitrose decided to extend the program to more than 200 of its stores.



Figure 51: Waitrose reusable bags are large and durable enough to hold many groceries⁵².

8.5 Australia

Several of Australia's states have either implemented or are in the process of implementing plastic bag bans. Motivation for this comes about from the success of Ireland's PlasTax, a tax imposed on all PE bags that resulted in a 90% decrease in bag use⁵⁷ there. Additionally, other problems have been observed that have prompted action. These include littering, consumption issues, and degradability²³. The table below summarizes bag usage in Australia on a yearly basis:

Table 20: Total bag use in Australia per year²³

Bag Type	Number	Tonnes of plastic (Reid 2003)	Level of litter	Potential for recycled content	Potential for recycling programs	Current suppliers of degradable bags
HDPE Shopping bag	6 billion	36 000	Significant	High	High	ValPak/ Jonmar/ Detmark/ Plaspak/ Bagsplus
LDPE Shopping bag	900 million	16 000	Significant	High	High	As above
Bait Bags	11 million		Significant	Low	Low	Jonmar
Green waste/ Compost bags	19 million	204	Insignificant	Med	Low	
Bread Bags	365 million	20 000	Significant	Low	Medium	Earthstrength (Lloyd Brooks)
Ice bags	Unknown	200	Significant	Low	Low	Jonmar
Freezer bags	700 million	1 600	Insignificant	Low	Low	Earthstrength
Garbage bags	250 million	800	Insignificant	High	Low	Jonmar
Kitchen tidy bags	330 million	1 800	Insignificant	Low	Low	Jonmar/ Earthstrength
Sandwich/ Storage bags	800 million	2 000	Significant	Low	Low	
Produce bags	1 billion	2 500	Insignificant	Low	Med	

Approximately three percent⁵⁸ of bags were recycled in 2001 and 2002, while almost all the rest eventually ended up in a landfill, either after some or no reuse. It is estimated that 50-80 million are littered from either waste activities or from personal use⁵⁷. The shape of PE bags makes them suitable to be blown away, which is one reason why they end up as litter. These are a several reasons why Australian governments wanted to study ways of reducing bag use to reduce waste and raise awareness of the environmental impact of PE bags. Over the last few years, efforts have been made to accomplish this through bans on PE bags.

South Australia began its official plastic bag ban in May 2009. It was the first state of Australia⁵⁰ to do so, and hopes to set an example for the rest of the nation. The four-month process required the state government to aid retailers in making a transition from PE bags to reusable bags. As a result of this ban, South Australia hopes to eliminate around 400 million⁵⁰ bags from landfills every year.

A progress report six months after the ban took effect already shows positive results. By late 2009, 200 million PE bags⁵⁹ had already been saved from use, which is about 800 tons⁶⁰. Nine in ten shoppers bring reusable bags with them to stores, which is up from six in ten before the ban was enacted. To enforce the ban, retailers may be charged a \$5000 fine for offering PE bags and suppliers a \$20,000 fine. South Australia did not wish to be the only state to ban plastic bags, and hoped others would adopt similar bans.

In 2010, The Northern Territory plans to phase out PE bags from use in conjunction with its climate change legislation. Jay Weatherill, Australia's Environment and Conservation Minister has commended the Northern Territory for following in South Australia's footsteps on

a PE bag ban: He appreciates that the Northern Territory Government has recognized that South Australia's ban on PE bags has so far succeeded. He also commends their decision to follow South Australia's lead on reducing the amount of plastic bags going to litter and landfill. South Australia will continue to encourage other States to push for a national ban on PE bags¹⁴.

8.6 Ireland

Driven by pollution to its coastline and negative impact on tourism, Ireland introduced in March 2002 a "PlasTax"—a mandatory 20-cent tax on all PE bags used for purchases in Ireland. Ireland's plastic bag consumption per person per year dropped from 328 to 21 (a 95% decrease) in less than one year²⁴. Nearly all Irish now carry reusable bags, not wanting to pay to tax when shopping. This type of tax has therefore changed consumers' habits, which has helped reduce the number of bags that litter the land. Robert Bateman, the president of Roplast Industries, a company north of San Francisco that makes both plastic and reusable bags, says charging for bags has some benefits because they are used more responsibly. For example, one may be able to use two bags instead of six². This responsible use is what the taxes aim for – using fewer new bags each time one goes to the store will ultimately reduce bag consumption.

However, not all are too quick to join the cause. The American Plastics Council claims that a similar PE bag tax "would cost tens of thousands of jobs and result in an increase in energy consumption, pollution, landfill space, and grocery prices as store owners increase reliance on more expensive paper bags as an alternative²."

8.7 San Francisco

In March 2007, San Francisco became the first city in the United States to ban plastic bags. All supermarkets that generate \$2 million or more would have three options:

- Biodegradable that mention “green cart compostable” and “reusable” and have a solid green line around the entire bag.
- Paper bags that mention “reusable” and “recyclable” and contain at least 40% recycled content.
- Reusable cloth bags at least 2.5 millimeters thick²⁴.

One year later, San Francisco extended this ban to pharmacy chains with over five stores located in the city. Fines were implemented to enforce this policy – \$100 for the first offense, \$200 for the second, and \$500 for the third and all following offenses for the same year⁶¹.

It is estimated that approximately 127 million plastic bags were saved from use by the ban, a number based on 2006 statistics, which indicate that supermarkets supplied 70% of the 181 million bags from that year⁶².

Despite the ban, Roplast experienced an increase in business. This is largely due to the fact that it does not make standard polyethylene bags. It specializes in making thicker, stronger bags, holding five to six times as much as original ones. Due to their strength, they are also reusable. In the long run, these can cut plastic use⁶³. Roplast also offers biodegradable bags that conform to the ASTM6400 standard for biodegradation⁶⁴. Roplast’s wide range⁵ of reusable bag options has made it a popular supplier of bags in San Francisco.



Figure 52: One of Roplast's many thick, reusable bags⁶⁴.

8.8 Walmart

Together with the Environmental Defense Fund, Walmart has announced a plan to reduce plastic bag waste by 33% by 2013, or about 135 million pounds of waste. Walmart's senior vice president for sustainability Matt Kistler claims that by offering improved recycling options and reusable bags, plastic waste will be cut by about 9 billion pounds⁶⁵. There will be economic as well as environmental benefits of these efforts. California would save \$25 million per year on disposing plastic bags to landfills.



Figure 53: One style of Walmart's new reusable bags that discourages excess use of bags⁶⁵.

Walmart's three-part plan encourages reducing the plastic content in its bags, reusing bags to prevent unnecessary consumption of new ones, and recycling of unwanted bags. Between 2007 and 2008, it is estimated that enough reusable bags have been sold to decrease PE bag usage by one billion⁶⁵.

One key issue to consider with degradable and biodegradable bags is their ability to degrade in landfills. Most "include a flexible membrane (geomembrane) overlaying two feet of compacted clay soil lining the bottom and sides of the landfill, protect groundwater and the underlying soil from leachate releases⁶⁶." This means that landfills have a solid boundary that prevents any material from entering or leaving. This has the advantage of helping to protect the local environment; however, it also limits natural processes such as oxo-degradation and photo-degradation. Many alternative types of plastic bags that are being introduced as a result

of these new policies, including PE bags with additives to increase degradation, depend on these processes. Therefore, when they end up in a landfill, they may not be able to degrade as quickly as advertised. Despite this, many of the efforts that have been made to reduce bag use have succeeded in doing so. Millions of people have changed their shopping habits to use fewer bags and reuse any new ones they obtain, and as a result, billions of bags have been saved from entering landfills.

9 Discussion

Through the use of surveys and interviews, information on public perception and issues concerning recycling was extracted. There are various policies on recycling that were researched, and discussion on their effectiveness is presented in this chapter.

9.1 Survey Discussion

It is evident from looking at the p-value for each question in our consumer survey that there is a strong statistical significance at the five percent ($\alpha = 0.05$) level. This means the results are not random; we conclude that people do indeed care about the plastic bag issue and that they do consider alternative types of bags when shopping.

The results of the first question clearly indicate that people think the current plastic bag poses a problem to the environment. This is tied to the second question as well, which indicates that 86% of people try to reuse or recycle plastic bags. Therefore, we have extracted what we intended from these questions: we have found that peoples' opinions on plastic bags affect what they do with bags after using them.

The results of the third question suggest that if stores rewarded customers for reusing their own bags, customers would do so. This is important because as more stores implement policies toward the use and reuse of plastic bags, customers will make more of an effort to save plastic.

Our results for the fourth question suggest that people would prefer an alternative bag to the current plastic bag if that were offered at a store.

Questions five and six were meant to gauge how much people would be willing to spend on polyethylene bags and alternatives, and the Chi Square tests suggest that people are generally unwilling to pay for any type of bag. However, looking at basic trends in the responses for these questions suggests that people are more willing to pay for alternatives than plastic bags.

One important aspect to consider when performing Chi Squared analyses is that it does not provide us with any reasoning behind the responses. For example, from Question 3 we do not know if people will try to reuse their plastic bags to cut down on consumption or just because they can save some money. In addition, our results for Question 4 suggest that people prefer alternatives, but we cannot say for sure if this is because people are trying to save the environment, or because these bags might be stronger and more convenient to use.

Referring to Figures 9 and 10, both p-values suggest that people are strongly against having to pay for any type of bag. This could mean that peoples' negative opinions on plastic bags are just a result of hype over environmental issues. If people truly believed plastic bags posed a problem and were willing to do something about it, they would be willing to have to pay for new bags from the stores.

9.2 Local Policy Discussion

The Mass DEP partnered with large group of Massachusetts supermarkets known as the MFA or Massachusetts food association in an effort to cut down on plastic bag usage by 33% by the year 2013. This voluntary program is in reaction to the common occurrence of plastic bags

frequently being used only once and thrown away. Grocery stores distribute over 1.5 billion paper and plastic bags annually. Efforts are being made by the grocery stores to be less wasteful in the distribution of the plastic bags. Education of store employees on the environmental effects of the bags as well as ways to be more frugal is part of this solution. Other aspects of the program include pushing reusable bags as well as the reuse of plastic bags through the use of customer incentives. Part of the goal of the program is also to increase the number of bags used that are made from recycled material or biodegradable materials. Stores across the state are also putting plastic bag recycling machines next to current bottle and can machines that are already in place. MFA president Christopher Flynn portrayed his optimism when he said "Reducing paper and plastic bag use in our state is not only good for the environment, but good for business," said MFA President Christopher Flynn. "We expect this incentive-based, voluntary approach to maintain a balance between environmental stewardship and consumer choice⁶⁷."

Worcester along with local towns Shrewsbury and Grafton as well as other cities across Massachusetts and the country are adopting PAYT, which stands for "Pay As You Throw". This means that residents have to pay extra for city trash bags and that garbage will only be accepted in these bags. This program is motivated in two different ways. By charging for trash bags the city raises money to offset the cost of waste removal. By charging people to get rid of trash the program also hopes to motivate people to recycle more⁶⁸.

Recycling in Worcester has also become easier due to a partnership with Casella Waste Systems. Casella uses a system called zero-sort recycling. This system makes it so that

homeowners don't have to sort their recycling at the curb. All recycling is put together in bins at the curbs. This makes it easier for people to recycle which should in turn increase the amount recycling. The system also reduces waste removal costs for the city. The zero sort system works because Casella sorts the recycling at their plant in Auburn. A system of filters and human workers sort the recycling into various categories. Large cardboard is filtered out first after the trash is picked out by workers. Following this, glass is sorted out and as well as paper. Newspaper is filtered out after this. Following this, the metal and plastic containers are sorted out by a large magnet. The last step is to sort the plastic containers by type⁶⁸.

Shrewsbury also uses the PAYT program to increase recycling. Shrewsbury requires more sorting than Worcester but is still fairly easy as Shrewsbury only requires the separation of paper from the other recyclable material. All plastics numbered 1-7 are accepted and put together at the curb. The town of Shrewsbury website encourages homeowners to compost leaves and yard waste⁶⁹.

Grafton is currently implementing the PAYT program and anticipates a 20% reduction in trash disposal costs with current costs being around \$500,000. The cost of recycling will stay the same and the town only has to pay for the cost of hauling recyclables and not the cost of disposing them⁷⁰.

More information could be gathered about these programs by talking to local officials. Interviews were conducted with an official involved in the West Boylston solid waste program as well as a representative from Casella.

9.3 Interviews with Local Officials

Interviews were conducted to obtain first-hand information from knowledgeable individuals. The benefit of personal interviews is that the questions can be tailored to extract the exact information desired. For example, in the interview conducted with a member of a solid waste advisory team, the questions pertained to public perception of plastic bags, as well as how that specific town handles the disposal of plastic bags. In the interview conducted with a staff member of a local waste management plant, the questions were engineered to obtain more general information about plastic disposal, such as how much of the total solid waste is plastic, and what a waste management plant would do with plastic bags. Interviews would also serve as a means to find out the general problems behind plastic bags, and how those problems can be solved.

An interview of Judy Doherty was conducted via email. She is a chairperson of the West Boylston Solid Waste Advisory Team. The purpose of the interview was to gather information pertaining to local plastic bag policies and local disposal of plastic bags. Through the interview, it was determined that in West Boylston waste management services recycle plastics with any of the 7 recycling numbers. Although Ms Doherty is unsure why plastic bags cannot be recycled, she did point out that they may be taken back to the stores where they originated. Ms. Doherty added that some stores offer money as a reward to customers who return plastic bags. With PAYT, the town charges \$0.50 for small (15-gallon) bags and \$1.00 for large (33-gallon) bags, thus reducing excessive use of plastic bags, and in the end, this cuts disposal costs. The full interview can be found in Appendix C.

This program is used to limit the population's use of plastic bags in an attempt to reduce the amount of plastic used and to reduce the costs of disposal. West Boylston launched this program in the summer of 2009 with the intent of saving money. The money made by bag sales goes towards the costs of waste disposal. Over the past five years, costs of waste disposal have risen by 68%, and West Boylston's costs of waste management reached over \$400,000 a year; picking up a bag of trash costs the town \$2.38 on average⁷¹. The Solid Waste Advisory Team hopes to save about \$120,000 annually after starting the PAYT program. The PAYT program is currently used by over 125 municipalities in Massachusetts, including Sutton, Upton, Clinton, Shrewsbury, Northborough and Worcester. Shrewsbury has lowered trash by 40% using PAYT⁷².

In the second interview, municipal development representative for Casella Recycling Lisa McMenemy was contacted. Casella Recycling is a waste management plant known for its recent Zero-Sort policy. This policy makes it easier for the population, since they do not have to separate roadside recyclables. The company is also one of New England's largest landfill operators.

For this particular interview, the questions were engineered to make it possible to extract information regarding the relationships between plastic and waste management plants. This includes the amount of plastic sent to the plant as well as the general cost to maintain a plant that processes plastics.

According to Ms. McMenemy, the Charlestown facility received 9,661 tons of plastic in 2009, none of which was plastic bags. The material is baled, and then sold to a mill. The mill

then processes the material; most mills have different processes, but in general, the material is shredded, cleaned and then melted.

Casella accepts plastics that belong to any of the seven recycling codes at their two Massachusetts plants. However they cannot accept plastic bags in their residential mix because the bags damage and jam the equipment. If Casella received a bulk of only plastic bags, they could be processed, but if the bags are mixed with anything, they cannot be processed. Ms. McMenemy also made it clear that plastics take more money and energy to process. The fact that plastics are less efficient than other materials in terms of processing is a downside, and it would be beneficial to figure out a more cost and energy effective way of processing plastic bags. The full interview can be found in Appendix C.

10 Conclusions

- It is estimated that between 500 billion to 1 trillion bags are used worldwide every year. Of these bags, most are made of LDPE. This is due to their excellent mechanical properties and low manufacturing costs. They have the tensile strength and ductility to be the material of choice for numerous packaging applications. Mechanical testing shows that typical bags have a tensile strength ranging from 6 MPa to 30 MPa. Polyethylene's chemical inertness ensures that it will not interfere with the packaging process.
- From the surveys, it is apparent that most of the public is aware of the potential problems behind plastic shopping bags. About 52% of survey takers demonstrated a readiness to pay a small fee for alternative bags. About 28% of participants would be willing to pay for new plastic bags, which shows that charging for plastic bags would decrease excessive use. These numbers illustrate that the public would rather be paying for alternative bags than for polyethylene shopping bags.
- Additives can be used to enhance a plastic's ability to degrade, and they can be used in combination with degradation inducers such as ultraviolet radiation, composting and thermal degradation. These combinations can greatly increase the rate of degradation of a plastic, but the costs must be taken into account.
- The pay-as-you-throw program is currently one of the better methods as far as increasing awareness and decreasing excessive use of garbage bags. The municipalities that have adopted this program have seen a significant decrease in the amount of garbage generated, and the program also has the benefit of increasing revenue to the

town. This revenue can be used to improve waste services, so the program has more than one benefit.

- Worcester in particular has decreased the amount of trash collected and increased the amount of recycling including plastic bags due to its use of the pay as you throw program and its partnership with Casella which used zero sort recycling.
- From the tensile testing that was conducted, it is clear that available biodegradable bags, Go Green bags and BioBags, have adequate tensile strength when compared to elastic moduli than others, but this meant they were more rigid which lead to a lower strain at fracture. For example, Applebee's bags have a tensile strength of about 14.7 MPa with a strain of 0.1 at fracture, while BioBags have a tensile strength of about 7.4 MPa with a strain of 1.4 at fracture. In general, the biodegradable bags have sufficient mechanical properties, but these properties are more sensitive environmental elements such as heat and humidity.
- Many of the case studies examined were on rather small scales with respect to global policies, but the changes taking place now are only affecting small regions of the world. In order to make a global impact on bag reduction, the types of policies described in the case studies must be adopted worldwide. It will require the cooperation among governments, corporations, and the people. This will be a long-term change, and will take time to achieve.
- Any long-term changes in what types of bags are used at the checkout will not come about soon. There is still much to be done as far as lowering manufacturing costs,

increasing public awareness, and legislating policies requiring new bags. This will involve the work of many people and could take years to finalize.

- There are many things that can be done in the short-term to cut back on unnecessary bag use. This begins with public awareness – making sure people understand that PE bags may be reused and recycled when done. As was seen in the chapter on case studies, retailers would often place signs throughout their stores reminding people of the environmental impacts of bags and to reuse their bags instead of letting them go to landfills or litter.

With research, there is potential for changes in current bag use and future material options. As manufacturing processes are refined and costs lowered, these new materials may be introduced into the mainstream, possibly replacing polyethylene bags.

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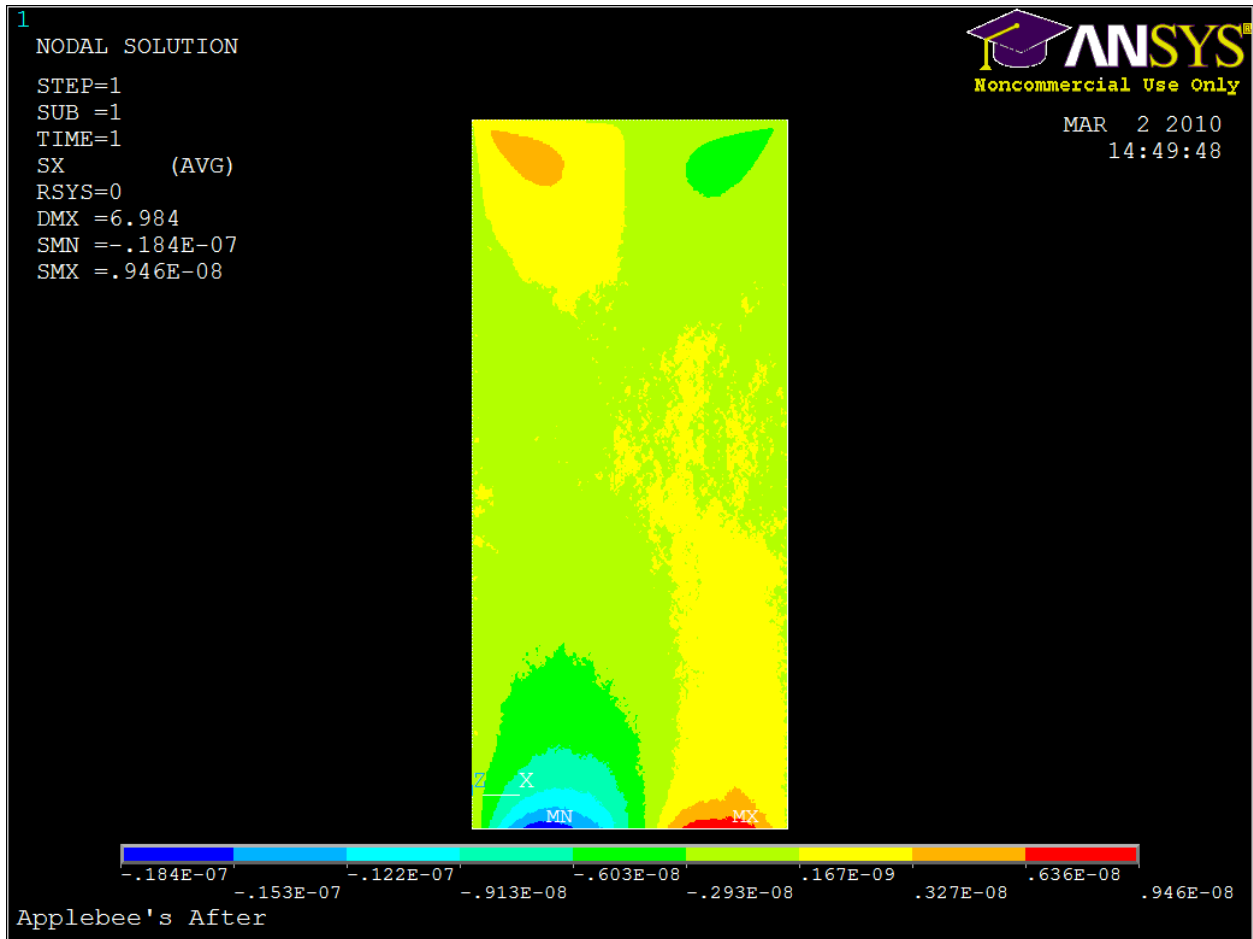
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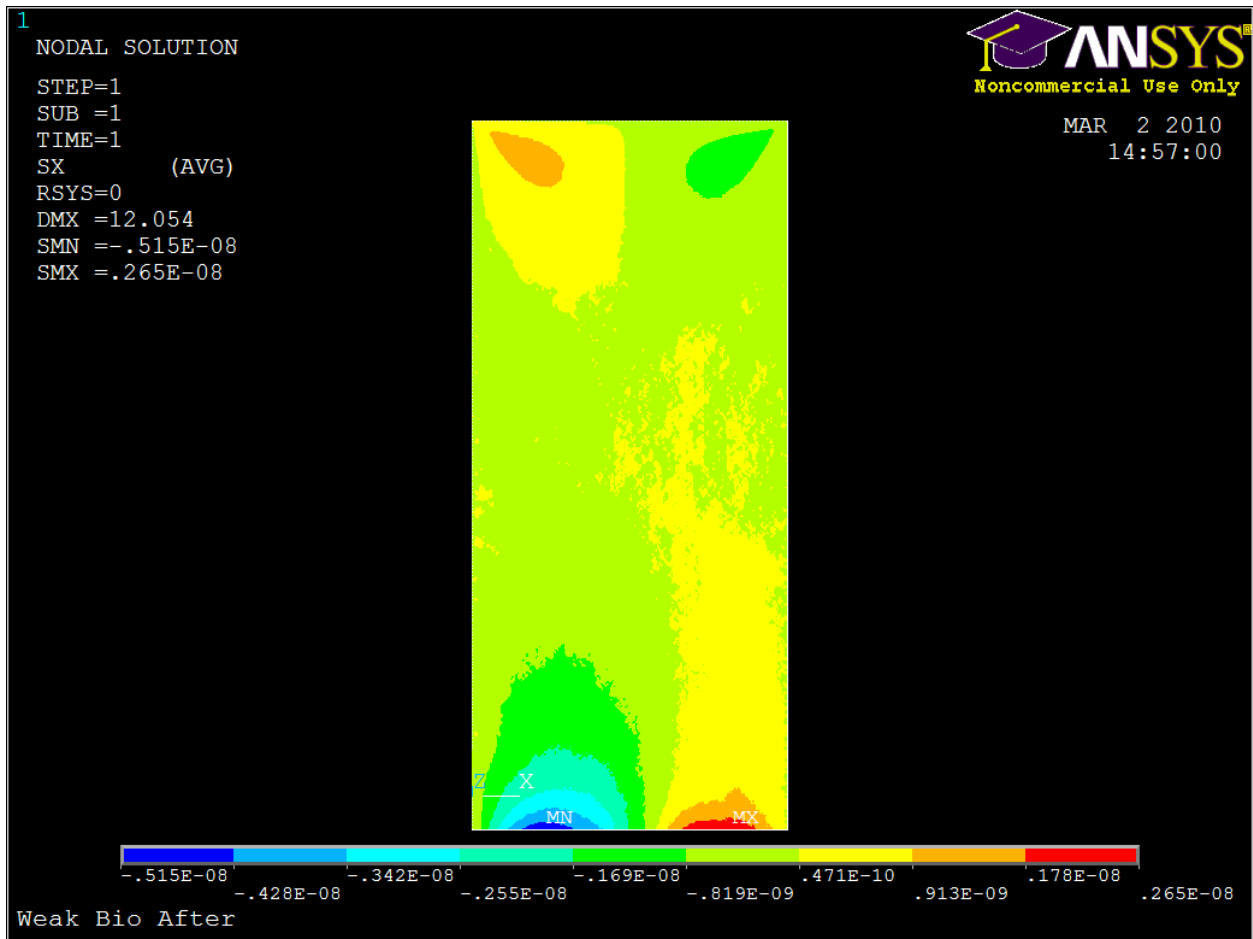
Appendix A: Mechanical Test Results

Appendix B: Survey Results

Appendix C: Field Interviews

Appendix A: Mechanical Test Results





The following links lead to the raw data worksheets from mechanical testing:

- [Applebees.xlsx](#)
- [GE.xlsx](#)
- [Quiznos.xlsx](#)
- [Worcester Trash Bag.xlsx](#)
- [Lighthouse Depot.xlsx](#)
- [ASTM6954 Bio Trash Bag.xlsx](#)
- [ASTM6400 BioBag.xlsx](#)

The following video is the ASTM6400 “Weak Biodegradable 2”

[Weak Biodegradable Bag 2.AVI](#)

Appendix B: Survey Results

Question 1:

Do you think that the current plastic bags are bad for the environment?

-Yes: 85

-No: 8

$$\frac{(85 - 46.5)^2}{46.5} + \frac{(8 - 46.5)^2}{46.5} = 63.7527$$

$p < 0.01$

Question 2:

How do you dispose of plastic bags when you are finished using them?

-Put them in the trash: 12

-Recycle: 18

-Reuse around the house, etc: 62

-Other: 1

$$\frac{(12 - 23.25)^2}{23.25} + \frac{(18 - 23.25)^2}{23.25} + \frac{(62 - 23.25)^2}{23.25} + \frac{(1 - 23.25)^2}{23.25} = 92.5054$$

$p < 0.01$

Question 3:

If retailers rewarded you for reusing bags instead of using new ones, would you be more inclined to reuse old bags?

-Yes: 76

-No: 16

$$\frac{(76 - 46)^2}{46} + \frac{(16 - 46)^2}{46} = 39.1304$$

$p < 0.01$

Question 4:

If an alternative bag were offered, would you use that instead?

-Yes: 84

-No: 8

$$\frac{(84 - 46)^2}{46} + \frac{(8 - 46)^2}{46} = 62.7826$$

$p < 0.01$

Question 5:

How much would you be willing to pay for new plastic bags?

- None: 67

-1 to 10 cents: 21

-10 to 20 cents: 2

-20 to 30 cents: 2

$$\frac{(67 - 23)^2}{23} + \frac{(21 - 23)^2}{23} + \frac{(2 - 23)^2}{23} + \frac{(2 - 23)^2}{23} = 122.696$$

$p < 0.01$

Question 6:

How much would you be willing to pay for alternative bags?

-None: 42

-1 to 10 cents: 21

-10 to 20 cents: 14

-20 to 30 cents: 14

$$\frac{(42 - 22.75)^2}{22.75} + \frac{(21 - 22.75)^2}{22.75} + \frac{(14 - 22.75)^2}{22.75} + \frac{(14 - 22.75)^2}{22.75} = 23.1538$$

$p < 0.01$

A breakdown of the survey to determine if people who think there is a problem with PE bags are actually willing to pay for alternatives is provided below.

1. Willing to pay for new plastic bags?

None: 60

1-10 cents: 20

10-20 cents: 2

20-30 cents: 2

$$\frac{(60 - 21)^2}{21} + \frac{(20 - 21)^2}{21} + \frac{(2 - 21)^2}{21} + \frac{(2 - 21)^2}{21} = 106.857$$

$p < 0.01$

2. Willing to pay for alternative bags?

None: 37

1-10 cents: 21

10-20 cents: 12

20-30 cents: 14

$$\frac{(37 - 21)^2}{21} + \frac{(21 - 21)^2}{21} + \frac{(12 - 21)^2}{21} + \frac{(14 - 21)^2}{21} = 18.381$$

$p < 0.01$

Appendix C: Field Interviews

Interview with Judy Doherty of the West Boylston Solid Waste Advisory Team:

1. What types of plastics can be recycled?

In West Boylston we recycle # 1-7 plastics.

2. Why can't plastic bags be recycled?

I don't know why but plastic bags can go back to the store where they originated. I try to avoid taking them to begin with – using totes or cardboard boxes instead.

3. Where do they end up?

Plastic bags often end up in the garbage. Our PAYT program depends on plastic bags. We discussed this at length before implementing the program and most folks thought that even with a toter program residents would be using plastic liners in their kitchen buckets and trash.

4. What should be done with plastic bags?

I like to reuse the plastic bags that I acquire. For instance, when I had a baby in diapers I used them to dispose of poop diapers. Now that my 3 year old is out of diapers, I use less but still put kitty litter and cat poop in plastic bags. Also, I get money back at some stores by returning plastic bags.

5. How much of the garbage is plastic bags?

In West Boylston, ultimately all trash goes into PAYT bags.

6. Do additives in plastics affect recyclability?

I don't know about additives.

7. Does the town get revenue from plastics being recycled?

The town does not get money for the plastic recyclables BUT so far it avoids disposal costs for recyclables.

8. Is the town taking action to promote recycling?

Yes. The town charges \$0.50 for small bags and \$1.00 for large thereby making some small amount for bags but avoiding disposal costs as people change their behaviors and put out a lot less trash.

Interview with Lisa McMenemy, Municipal Development Representative of Casella Waste Systems:

1. Approximately how much plastic is taken in by your facility?

Our Charlestown facility received 9661 tons last year

2. About how much of that plastic is plastic bags?

zero

3. Once you receive the plastic, what happens to it? How is it processed?

We separate the material by the different commodities, bale it, then sell to a mill- who then runs through their process of shredding it, cleaning it, and melting it, each mill has a little different process but this is the simple version

4. Can all plastics be processed? (Is the answer to question 3 different for plastic bags?)

We accept plastics number 1 thru 7 at our two Massachusetts plants- We do not accept plastic

bags in our residential mix as plastic bags jam and damage our equipment and we have no way or sorting these either nor the space it would take a few months to get a full load of plastic bags if we did have the capability to sort it. If we were to receive a full load of clean plastic bags and only plastic bags we can recycle them, but we have not way to sort them when they come in with all other material

5. How much does it cost per ton of plastic bags to recycle, compared to putting bags in a landfill?

We do not process plastic bags.

6. Compared to other materials, do plastics require more resources to process (manpower, energy, money, etc.)?

For our Charlestown facility no one man power as we have many optical sorts that sort the plastics for us, but yes to the energy and money.

7. What action has Casella Waste Systems taken to increase the percentage of plastics recycled?

Casella has invested in the latest optical technology to capture the highest return of plastics

8. From where does your facility get the waste it stores/processes?

Are you referring to where do we get the recyclable material from? If so we receive from local haulers, businesses and municipalities.