Mechanical Properties and Degradation of Commercial Biodegradable Plastic Bags

REPORT FOR A MAJOR QUALIFYING PROJECT

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Abstract

The properties of six biodegradable commercial plastic bags, including BioBag, Flushdoggy, Green Genius, Oxobiodegradable, Rascodog, and World Centric, were examined. The effects of UV radiation, moisture exposure, and weathering on mechanical properties were studied. The creep, tensile, and thermal degradation behavior of the bags were investigated. Most bags exhibited mechanical properties similar to traditional bags. All the bags generally started to degrade thermally at around 400°C. UV radiation, moisture, and weathering had little effect on thermal degradation. Oxobiodegradable and Flushdoggy became especially brittle after accelerated aging while the properties of the traditional bags remained relatively similar. The data indicated that biodegradable plastic bags may offer an alternative to traditional plastic bags. The results from this work were accepted for publication in ANTEC 2011 proceedings.

Acknowledgements

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1.0 Introduction

Polyethylene (PE) bags have been used for over 5 decades for a variety of storage and packaging applications. This past year, 1 million tons of plastic bag waste was generated in the U.S.[1] The primary challenge in disposing these bags after use is its lack of degradation in the polymer.[1] Thus, plastic bags are one of the largest contributors to the material waste produced in the United States. Only a fraction of the plastic bags are recycled or reused, resulting in a significant contribution to landfills as well as a large deficit of plastic waste.[2] This can be evidenced from Table 1 below. Out of 30.05 million tons of plastic waste generated, only 2.12 million tons was recovered.[2] In 2008, about 55 percent of the total MSW (Municipal Solid Waste) was directly transported into landfills in the U.S.[2] Additionally, resins and colors added into PE have only made the material more difficult to recycle.[3] This is especially the case when plastic manufacturers blend multiple resins.

Material	**Weight Generated**	**Weight Recovered**	**Recovery as Percent of Generation**
Plastic	30.05	2.12	7.1%

Table 1: Generation and Recovery of Plastics (in millions of tons) in the United States' Municipal Solid Waste (MSW) for 2008

In order to overcome these problems, a new type of plastic bag is being developed by many commercial companies. These bags are called "biodegradable" plastic bags. A "biodegradable" plastic is defined by ASTM standard D6400 as "a degradable plastic in which the degradation results from the action of naturally occurring microorganisms". The ASTM D6400 standard lists that in order for bags to be considered biodegradable, they must disintegrate during composting so that any remaining plastic is not readily recognizable. Bags that consist of one polymer must have 60% of the organic carbon converted to carbon dioxide while bags that have more than one polymer must have 90% converted if the polymer is present.[3] Biodegradable bags are usually manufactured using a variety of methods, of which include utilizing other polymer systems that are obtained from natural sources, mixing PE with various fillers and resins, combining PE with various enzymes, and combining PE with additives, such as pro-oxidants.[4] This allows biodegradable bags to degrade quicker than traditional polyethylene bags.

Biodegradable plastics present their own economic and processing-related obstacles. They are usually more expensive than PE, they cannot be processed easily and the mechanical properties may not be comparable.[4] Although there is some information available about these biodegradable plastic bags, reliable mechanical property data or degradation characteristics are not readily accessible for consumers or manufacturers.[4] The purpose of this project is to analyze the mechanical properties of common commercial biodegradable plastic bags and examine the effects of various testing procedures on such bags.

2.0 Background

2.1 Properties of Polyethylene

Polyethylene is used for a variety of purposes, from packaging applications to pipes. Approximately 30% of the plastic used in the year 2004 are used for packaging purposes and piping.[1] Other uses for plastics have been for milk cartons, toys, bags, packing tape, and cable insulation. PE is even used heavily in the agricultural industry and used for creating green houses and put on the soil for mulching film.[5] Plastics, specifically modern-day PE, have replaced other materials for packaging because of their excellent properties which are listed in Table 2. Not only is PE a relatively cheap material (69 cents per pound), but its physical properties are much greater than other materials.[1] They have a high strength and elongation percentage which allows them to be durable in any application, are lightweight, and are also a good insulator. Polyethylene is also water resistant which in terms of packaging, provides a huge advantage over paper bags and other wrapping materials.[1]

Density	58.6-59.9 lb/ft^3
Price	.689-.758 USD/ lb
Young's Modulus	.0901-.13 10^6 psi
Tensile strength	3-6.5 ksi
Yield Strength	2.6-4.21 ksi
Elongation	200-800 % strain
Fracture Toughness	1.31-1.57 ksi.in.$^{0.5}$
Melting point	257-269 F
Electrical Conductor or insulator	Good Insulator

Table 2: Mechanical Properties of Polyethylene[6]

As a result of the all-purpose qualities of polyethylene, it makes it very difficult to recycle and dispose of. Most times after polyethylene products have been used, they are thrown out and inevitably become extra waste.[3] PE is resistant to biotic degradation to a large degree, making it more difficult to dispose of. It also has a large molecular weight due to the CH_2

molecules it is composed of. Cells of microorganisms have difficulty breaking it down due to its size.[3]

2.2 Developments in Biodegradable Plastic Bags

In recent years, scientists have devised several approaches to make plastic bags more biodegradable. Some of the major approaches are: i) Mixing PE with various fillers (i.e. starch) and resins, ii) Combining PE with additives, such as pro-oxidants, iii) Combining PE with various enzymes, and iv) Use of other polymer systems that are obtained from natural sources and can be completely biodegradable.[4]

2.2.1 Use of Fillers

The first method involves using fillers like starch to create a PE blend, sometimes with up to 40% filler. However, after the filler biodegrades, the PE matrix remains and the original biodegradability problem arises. While adding starches to PE can alleviate some of the problems of recycling, the base polymer is still non-degradable.[3]

2.2.2 Use of Pro-oxidants

Pro-oxidants seem promising, as oxidized PE samples become more susceptible to enzyme action and mechanical breakdown.[3] In recent times, scientists have made efforts to make PE more biodegradable by focusing on PE’s polymer matrix. Polyethylene’s structure can be altered with the use of additives like pro-oxidants, which come in the form of stearates or ligand compounds. Pro-oxidants are particularly promising, as they enable the photo- and thermo-oxidation of the polymer chains. As the material becomes oxidized, it becomes more susceptible to microbial attack and enzymatic action. The oxidation approach increases PE’s hydrophilicity and lowers the molecular weight, targeting the two material properties that make PE resistant to degradation.[3] These properties are the focus of other approaches to PE, including organic fillers and PE-resin blends.

2.2.3 Inclusion of Enzymes

Enzymes can assist in the breakdown of the polymer, but their degradation action is relatively slow and incorporating them into the polymer during processing can pose challenges. However, several strains of the bacteria species *Pseudomonas* have been consistently recognized for efficiently degrading PE, which can make some versions of plastic bags more degradable.[4] Additionally, artificial strains of PE are developed that are more inclined to degrade.[7]

2.2.4 Naturally Derived Polymers

In recent years, several new polymers derived from natural sources such as cellulose, starch, wood flour and polylactic acid (PLA) have emerged as potential replacements for PE. These polymers can be blended with each other or with PE to enhance biodegradability.[4] PLA is usually produced from lactic acid which in turn comes from wet milling corn via starch fermentation. [4] It is usually blended with starch which, although can be brittle, the starch increases the biodegradability of the PLA and lowers the cost. Plasticizers such as glycerol, sorbitol and triethyl citrate can also be added to decrease the possibility of brittleness; these plasticizers have a low molecular weight to ensure the biodegradability is not affected.[4]

3.0 Objectives

The research and experimentation conducted in this project was performed to accomplish three main goals:

- To analyze the mechanical properties of common commercial biodegradable and traditional plastic bags under various testing conditions
- To compare the properties of biodegradable and traditional plastic bags
- To determine which degradation factors have the greatest effect on the mechanical properties

4.0 Methodology

4.1 Materials (sample size)

Six bags, advertised as biodegradable, were purchased from various suppliers for mechanical property testing. Furthermore, two traditional polyethylene bags were obtained from a local supermarket for experimentation and comparison. The selection of bags was also based on creating a wide variety of bag types, including shopping bags, trash bags, and dog waste bags. Each bag name and the type of material they are made of is listed in Table 2, where E and F on the table are the traditional plastic bags and the other letters are the biodegradable bags. A photograph of the different bag types used in this study is shown in Figure 1 of Section 5.1 ANTEC Conference paper.

	Bag Name	Main Material	Details	Typical Uses	ASTM	Degradation time	Price (quantity)
A	BioBag	Mater-Bi	Cornstarch, sunflower oil	Shopping	D6400	8-14 months	$148.98(500)
B	Flushdoggy	PVA	-	Dog waste	None	-	$19.99(100)
C	Green Genius	LLDPE with Ecopure	100% LLDPE, Ecopure additive	Trash	D5511	1-15 years	$5.00(15)
D	Oxobiodegradable	LDPE	100% LDPE	Shopping	None	-	$.39(1)
E	Trad. Shopping	PE	100%	Shopping	None	-	-
F	Trad. Trash	HDPE	100%	Trash	None	-	$3.99(10)
G	Rascodog	HDPE	cornstarch	Dog waste	D6400	< 1 year	$7.99(90)
H	World Centric	Corn Starch	70% starch, 30% polyester	Trash	EN 13432	3-6 months	$3.00 (10)

Table 2: Summary of the properties of the bags used in the study

4.1 Initial Properties and Sample Creation

The color, thickness, and weight of each bag type were evaluated before preparing the bag samples. Thickness was measured using the DVT600, a laser based high-resolution camera (pixel-based measurements). For each bag, thickness was measured at least 3 times at various locations on the bag and the average value of these measurements was recorded as the thickness for that bag type.

The plastic bags were cut into two specific sizes to be used as samples for tensile or creep tests. The sample sizes were determined according to ASTM standards of the specific test. Samples were usually cut using a Universal Laser Systems ILS9.75 device shown in Figure 1 below, but some samples were hand cut with the use of a template and an extractor knife. All cuts were generally performed parallel to the longitudinal axis as well as away from printed logos to maintain consistency.

Figure 1: Universal Laser Systems ILS9.75

4.2 Tensile Tests

Tensile tests were conducted using sample sizes listed in ASTM D882-09 and they were loaded into an Instron 5569 machine (depicted in Figure 2) which pulled the samples apart at a rate of 3 N/min. The samples are held with two grips and are taped to small pieces of square cardboard to avoid tearing. The program Bluehill served as a data acquisition program to obtain the stress and strain placed on the samples.

Figure 2: Instron 5569

4.3 Creep Tests

Creep samples were also cut specifically according to ASTM D2990-09 and were loaded onto a custom built creep testing device under respective weights. The weights were applied for 12 hours or until fracture. The change in strain was visually recorded using a high definition camera at certain periods of time, with a main focus on the first three minutes of creep. Creep tests were conducted before and after each degradation test at room temperature and a humidity of around 35%. The creep data was modeled using Burger's Model, depicted below in Figure 3. The variables that are used in the equation are listed in Table 4 of Section 5.1 ANTEC Conference paper. The creep device used was a custom made device and is shown in Figure 4 as a model in SolidWorks.

$$\varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\sigma_0 t}{\eta_1} + \frac{\sigma_0}{\eta_2}\left[1 - \exp\left(-\frac{E_2 t}{\eta_2}\right)\right]$$

Figure 3: Burger's Model

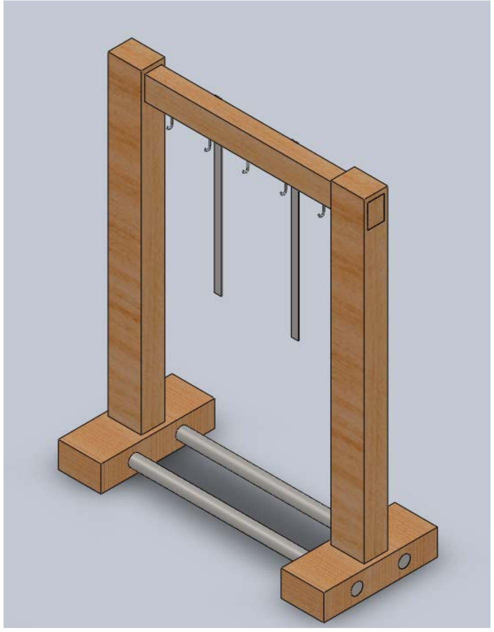

Figure 4: CAD model of Creep Testing Device

4.4 Thermo Gravimetric Analysis

Small samples of the bags were placed in a TA Instruments Q50 Thermo Gravimetric Analyzer (shown in Figure 5) to evaluate the % mass loss relative to the temperature change. The Q50 TGA apparatus uses a cylindrical oven that increases the temperature from room temperature to 600°C at a rate of 10°C/min. The oven is filled with nitrogen gas to prevent combustion.

Figure 5: TA Instruments Q50 Thermo Gravimetric Analyzer

4.5 Radiation Tests

The degradation of samples under UV light exposure was examined using a UVP Transilluminator device depicted in Figure 6. Samples were placed on the Transilluminator and exposed to UV light for 5 minutes at a time, with 5 minute rest intervals to prevent the device from overheating. A number of samples were exposed to UV light for 5 minutes, 15 minutes, and 30 minutes total. As dictated by standard ASTM D2990-09, the UV light had a wavelength of 360 nm. The intensity of the UV light used was 9100 mW/cm^2.

Figure 6: UVP Transilluminator

4.6 Moisture Tests

Square samples (76 mm x 76 mm) of each bag type were submerged in a water bath at 23°C±2°C for 24 hr. After being submerged, the samples were hand-dried and placed in a desiccator for at least 72 hours before being weighed to determine if the bags absorbed any water. Another non-related test was run with submerging samples for 24 hours and then dried for tensile testing, creep testing, and TGA testing. This was done to observe the changes in the mechanical properties and thermal degradation after exposure to moisture.

4.7 Weathering Tests

5 Tensile and Creep samples of each bag type were buried under the soil for three weeks and four months to determine samples were buried outdoors under soil at a depth of around 400 mm. Samples of the bags were buried to test the weathering behavior of the plastic. The samples were then recovered and tested for tensile and creep properties.

4.8 Accelerated Aging Tests

Accelerated aging of bag samples was simulated with the use of thermal degradation. Thermal degradation was achieved by placing tensile and creep samples in a Cole Parmer 5015-58 furnace at 100°C for 3 weeks. For each bag type, at least 5 tensile and 5 creep samples were placed in the furnace. A furnace exposure of 3 weeks (t_2) at 100°C simulates 0.5 years (t_1) of degradation at room temperature according to the Arrhenius equation in Figure 7 below.[8] An activation energy of 26.2 kJ/mol (Q) was used in determining the simulation time.

$$t_2 = t_1.\exp\left[\frac{Q}{8.314}\left(\frac{1}{298}-\frac{1}{373}\right)\right]$$

Figure 7: Arrhenius equation

5.0 Conference Paper

Upon completion of the project, the findings were written, submitted and accepted into the ANTEC 2011 Plastics Conference. The conference paper as well as its results are posted below.

5.1 ANTEC Conference Paper

Abstract

The properties of six biodegradable commercial plastic bags, including BioBag, Flushdoggy, Green Genius, Oxobiodegradable, Rascodog, and World Centric, were examined. The effects of UV radiation, moisture exposure, weathering and thermal degradation on the tensile properties were studied. The creep and tensile behavior of the bags were also investigated. Most of the bags exhibited mechanical properties similar to traditional bags. One bag that had extensively higher properties was the Flushdoggy bag, which is based on PVA. All the bags generally start to degrade thermally at around 400°C. BioBag and World Centric exhibited significant mass loss around this temperature. Other bags were not affected appreciably. Exposure to UV light did not have much of an effect on tensile properties. UV radiation, moisture, and weathering all had little effect on thermal degradation. Oxo-biodegrable and Flushdoggy became especially brittle after accelerated aging, although Flushdoggy still exhibited strong tensile properties. The data indicated that biodegradable plastic bags may offer an alternative to traditional plastic bags.

I. Introduction

Polyethylene bags have been used for over 5 decades for a variety of storage and packaging applications. This past year, 1 million tons of plastic bag waste was generated in the U.S [1]. The primary challenge in disposing these bags after use is its lack of degradation in the polymer [1]. Thus, plastic bags are one of the largest contributors to the material waste produced in the United States. Only a fraction of the plastic bags are recycled or reused, resulting in a significant contribution to landfills [2]. In 2008, about 55 percent of the total MSW (Municipal Solid Waste) was directly transported into landfills in the U.S [2]. In addition, the use of additives introduces additional complexities for recycling the bags.

In order to overcome these problems, a new type of plastic bag is being developed by many commercial companies. These bags are called "biodegradable" plastic bags. A "biodegradable" plastic is defined by ASTM standard D6400 as "a degradable plastic in which the degradation results from the action of naturally occurring microorganisms". The ASTM D6400 standard lists that in order for bags to be considered biodegradable, they must disintegrate during composting so that any remaining plastic is not readily recognizable. Bags that consist of one polymer must have 60% of the organic carbon converted to carbon dioxide while bags that have more than one polymer must have 90% converted if the polymer is present [3].

In recent years, scientists have devised several approaches to make plastic bags more biodegradable. Some of the major approaches are: i) Mixing PE with various fillers (i.e. starch) and resins, ii) Combining PE with additives, such as pro-oxidants, iii) Combining PE with various enzymes, and iv) Use of other polymer systems that are obtained from natural sources and can be completely biodegradable [4]. While adding starches to PE can alleviate some of the problems of recycling, the base polymer is still non-degradable [5]. Pro-oxidants seem promising, as oxidized PE samples become more susceptible to enzyme action and mechanical breakdown [5]. Enzymes can assist in the breakdown of the polymer, but their action is relatively slow and incorporating them into the polymer during processing can pose challenges. In addition, several strains of the bacteria species *Pseudomonas* have been consistently recognized for efficiently degrading PE, which can make some versions of plastic bags more degradable [4]. In recent years, several new polymers derived from natural sources such as cellulose, starch, wood flour and polylactic acid (PLA) have emerged as potential replacements for PE. These polymers can be blended with each other or with PE to enhance biodegradability [4]. Plasticizers such as glycerol, sorbitol and triethyl citrate can also be added to decrease the possibility of brittleness; these plasticizers have a low molecular weight to ensure the biodegradability is not affected [4].

Biodegradable plastics present their own economic and processing-related obstacles. They are usually more expensive than PE, they cannot be processed easily and the mechanical properties may not be comparable [5]. Although there is some information available about these biodegradable plastic bags, reliable mechanical properties data or degradation characteristics are not readily available for consumers or manufacturers [5]. The purpose of this project is to analyze the mechanical properties of common commercial biodegradable plastic bags and examine the effects of weathering and UV exposure on tensile properties.

II. Methodology

Six bags that are claimed to be biodegradable by the manufacturer were obtained from various suppliers as shown in Table 1. In addition, 2 traditional polyethylene bags obtained from a local supermarket were also tested for comparison. The bags were selected so as to obtain at least one representative sample from each of the major categories described in the preceding paragraphs. A photograph of the various bags used in this study is shown in Fig. 1. The as-received bags were examined for differences in color, thickness and weight (Table 2). The thickness was measured using a laser based high-resolution camera named the DVT600. For each bag, at least 3 values of thickness were measured at various locations and the average values are shown in Table 2.

The degradation behavior of the bags was studied using a variety of techniques. Initially, a square sample (76 mm) was cut from each bag and submerged in water at 23°C±2°C for 24 hr. The samples were then removed from water, dried thoroughly and weighed to determine the % weight loss. The thermal degradation behavior was studied using a TA Instruments Q50 Thermo Gravimetric Analyzer. Samples were tested at a heating rate of 10°C/min. The degradation of the sample under UV light exposure was examined with a UVT Transilluminator device. The samples were sectioned according to ASTM D2990-09 and subjected to UV light with a wavelength of 360 nm for 5 minutes per each side.In order to simulate the thermal degradation of the sample after approximately 0.5 years, accelerated aging experiments were conducted. In this case, standard tensile (ASTM D882-09) (at least 5 samples from each bag) and creep (ASTM D2990-09) samples (at least 5 samples from each bag) were placed in a Cole Parmer 5015-58 furnace at 100°C for 3 weeks. The equivalent time at 100°C (t_2) to represent degradation at room temperature after 0.5 years (t_1) was calculated by using the Arrhenius equation [6]:

$$t_2 = t_1.\exp\left[\frac{Q}{8.314}\left(\frac{1}{298}-\frac{1}{373}\right)\right] \qquad (1)$$

An activation energy Q of 26200 J/mol was used in the above equation [6]. Based on equation (1), the degradation behavior after 0.5 years can be simulated by aging the samples for about 3 weeks at 100°C. In order to measure the weathering behavior of the plastic, standard tensile (ASTM D882-09) and creep (ASTM D2990-09) samples were buried outdoors under soil at a depth of around 400 mm for 3 weeks. The samples were then recovered and tested for tensile and creep properties.

To measure the tensile properties, test samples were cut according to ASTM D882-09. The samples were cut using a Universal Laser Systems ILS9.75 device and were generally sectioned parallel to the longitudinal axis. The tensile properties were measured at a rate of 3 N/min using an Instron 5569 machine. Both creep and tensile properties were measured for each sample before and after each degradation test. The creep samples were cut to size according to ASTM D2990-09 and loaded with appropriate weights. (Table 2) The variation in strain with time was then recorded with a high definition camera. The creep tests were conducted at room temperature and at a humidity of around 35%. The stress was maintained on the sample for at least 12 hr or until fracture. Several samples were tested under each condition listed in the previous paragraph.

III. Results

A visit to the local supermarket has indicated that biodegradable plastics are making inroads in consumer choice for bags and packaging applications. Some of the bags may exhibit properties that are similar to traditional plastics as shown in Fig. 2. For example, it is apparent from the data in Fig. 2 that the properties of Green Genius biodegradable trash bag are comparable to the traditional PE trash bags. The price per bag for the two types of bags is also similar indicating that Green Genius may be an alternative to regular trash bags. In general, the bags have tensile strengths of about 1 to 2 MPa and a ductility in excess of 100%. Also, Oxobiodegradable and World Centric bags have similar strength as the traditional bags, but they have much lower ductility. While several bags exhibit ductility greater than about 150%, the Rascodog , Oxobiodegradable and the World Centric bags show much lower ductility values (~50 to 70%). Note that the Flushdoggy bag (based on PVA) has a much better combination of strength (5 MPa) and ductility (150%) than the traditional bags. PVA is a perfect choice for a dog waste bag because it is water-soluble.

Various degrading agents can have a significant effect on the tensile properties of traditional and biodegradable bags. An example of the deterioration is in mechanical properties of Biobags after exposure to UV light, weathering, exposure to moisture and accelerated aging is shown in Fig. 3. After 0.5 years, the ductility of Biobags can be expected to decrease by about 100%. The bags also may become brittle and thus enable efficient disposal. BioBag also does not lose its strength even after prolonged exposure (24 hr) to moisture. This property may be commercially useful for biodegradable shopping bags that may be used in all weather conditions. The manufacturers of BioBag claim on their website that significant degradation will occur upon weathering.. However, after 3 weeks of weathering, no significant effects were observed. But the influence of weathering may require longer times to show pronounced effects. The data shown in Fig. 3 indicate that Biobags lose almost 50% of their initial strength upon exposure to UV light. This drastic reduction in strength may have resulted because of the high wavelength of the UV light (360 nm) and an irradiance of 9100 mW/cm^2 used during the experiment. Under normal exposure to sunlight, the bags may be exposed to a wavelength of light typically around 400-800 nm (source) and an irradiance of 120 W/m^2 hence, may not exhibit the levels of degradation experienced in the current bags.

Exposure to moisture for 24 hr did not result in a significant mass loss for most bags. The Flushdoggy sample however, lost almost 40% of its mass after 24 hr exposure to moisture. Thermal degradation of plastic bags is a mechanism by which the bags can lose mass and properties. TGA data shown in Fig. 4 and 5 indicate that most of the bags undergo rapid mass loss around 400°C. UV exposure or weathering for 3 weeks did not significantly affect the thermal degradation behavior of the Green Genius bag as shown in Fig. 5. The Flushdoggy bag based on PVA starts to degrade at lower temperatures and exhibits several transitions. All the bags lost most of their mass above 400°C. World Centric, Bag H in Figure 4, behaved differently than the rest of the bags by having a significant mass drop at a low temperature of 50.6°C. This bag consists of 70% corn starch and 30% polyester according to the manufacturer. Both corn starch, and in some cases, polyester, may initiate degradation at temperatures below 100°C. In a study on the kinetics of thermal degradation applied to starches, it was observed that corn starch begins its mass loss at around 45°C [7]. Further, it has been shown that the addition of corn starch to other polymers enhances the overall rate of degradation [8]. Hence the mass loss at 50.6°C observed in World Centric (Fig. 4) may correspond to these phenomena.

The bags used in this study exhibited various levels of creep as shown in Fig. 7 and 8. For all the bags, creep strains start to become significant after about .6 hours. The highest levels of creep were observed in Green Genius bags based on LLDPE. Flushdoggy bags, which have the highest tensile strength, also exhibited almost no creep strain over a period of 12 hr. The measured creep behavior for PE bags (E and F) is consistent with the creep data reported in the literature [9]. Overall, the traditional trash bag and the Green Genius trash bag produced the most significant creep with the fastest creep rates. The creep in biodegradable bags was generally lower than in the traditional PE bags. The samples that were exposed to degradation factors (e.g. weathering, UV, aging, moisture) had reduced creep strains or became so brittle that they broke as soon as stress was applied (e.g. BioBag, Oxobiodegradable bags). According to Fig. 9, weathering and UV exposure caused the Biobag samples to fracture at an earlier time than samples that were not degraded.

In order to model long-term creep behavior of the samples, a simplified version of the Burger's model was applied to the measured data. The Burger model as depicted in Fig. 10, is a combination of the Maxwell and Kelvin-Voigt systems in series. The strain predicted by this model is given by the following equation [9]:

$$\varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\sigma_0 t}{\eta_1} + \frac{\sigma_0}{\eta_2}\left[1 - \exp\left(-\frac{E_2 t}{\eta_2}\right)\right] \qquad (2)$$

Where σ_0 is the applied constant stress, t is the time and E_1, E_2, η_1 and η_2 are model constants shown in Fig. 10. The measured data were fit to this equation and best fits were obtained with the model constants shown in Table 4. It can be noted that the free spring constant in Rascodog and traditional shopping bags are the highest, which is in consistence with the stress-strain data shown in Fig. 2. The model also indicates that both Rascodog and Oxobiodegradable bags have low creep components.

IV. Conclusions

Biodegradable plastic bags are rapidly emerging as a convenient alternative to traditional plastic bags. Various brands of degradable bags are now commercially available. Six of the commercial biodegradable plastics bags were tested to determine their mechanical properties and degradation behavior. It was observed that, in general, these bags had properties similar to conventional plastic bags. Bags such as Green Genius and BioBag can serve equally well as traditional bags. Also, PVA and cornstarch based bags, such as Flushdoggy and BioBag, can degrade completely upon exposure to various degrading agents. Because of their beneficial effects in minimizing landfill contribution, it is expected that the use of such bags will increase.

V. Acknowledgements

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VI. References

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Table 1: Summary of the properties of the bags used in the study, the names of the supplier, the price, the principal polymer, the degradation time of the bag given by the supplier, and the corresponding ASTM standard that each bag has to adhere to.

	Bag Name	Main Material	Details	Typical Uses	ASTM	Degradation time	Price (quantity)
A	BioBag	Mater-Bi	Cornstarch, sunflower oil	Shopping	D6400	8-14 months	$148.98(500)
B	Flushdoggy	PVA	-	Dog waste	None	-	$19.99(100)
C	Green Genius	LLDPE with Ecopure	100% LLDPE, Ecopure additive	Trash	D5511	1-15 years	$5.00(15)
D	Oxobiodegradable	LDPE	100% LDPE	Shopping	None	-	$.39(1)
E	Trad. Shopping	PE	100%	Shopping	None	-	-
F	Trad. Trash	HDPE	100%	Trash	None	-	$3.99(10)
G	Rascodog	HDPE	cornstarch	Dog waste	D6400	< 1 year	$7.99(90)
H	World Centric	Corn Starch	70% starch, 30% polyester	Trash	EN 13432	3-6 months	$3.00 (10)

Table 2: Color, thickness, mass, and stress applied for creep tests

	Bag Name	Color	Mass 42x42mm (g)	Creep Weights (kg)	Thickness (mm)	Width (mm)	Stress (Pa)
A	BioBag	White	0.1673	0.35	0.106666667	13	2.47355
B	Flushdoggy	White	0.2415	0.4	0.3	13	1.00512
C	Green Genius	Transparent Black	0.2415	0.35	0.095	13	2.77732
D	Oxobiodegradable	Green	0.3747	0.55	0.223333333	13	1.85648
E	Trad. Shopping	Transparent Beige	0.1065	0.35	0.056666667	13	4.65610
F	Trad. Trash	Black	0.1543	0.35	0.113333333	13	2.32805
G	Rascodog	Transparent Grey	0.0836	0.35	0.063333333	13	4.16599
H	World Centric	Clear	0.0847	0.25	0.07	13	2.69230

Table 3: Critical reaction temperature of each plastic bag type during the Thermo Gravimetric Analysis.

Bag Type	T_{cr} (°C)	Mass Lost (%)
BioBag	370	33
Green Genius	395	15
Flushdoggy	453	16
Oxobiodegradable	380	12
Traditional Shopping	400	8
Traditional Trash	400	6
Rascodog	385	12
World Centric	387	30

Table 4: Creep model constants calculated from the experimental data

	Bag Name	E_1(MPa)	E_2(MPa)	η_1(MPa*s)	η_2(MPa*s)
A	BioBag	1.94	500	300	2000
B	Flushdoggy	0.767	1400	1700	800
C	Green Genius	2.22	1400	1250	1200
D	Oxobiodegradable	1.0302	1400	1880	200
E	Trad. Shopping	4.175	2300	15000	500
F	Trad. Trash	1.695	800	1750	2000
G	Rascodog	12.33	500	2000	300
H	World Centric	1.95	50	2750	600

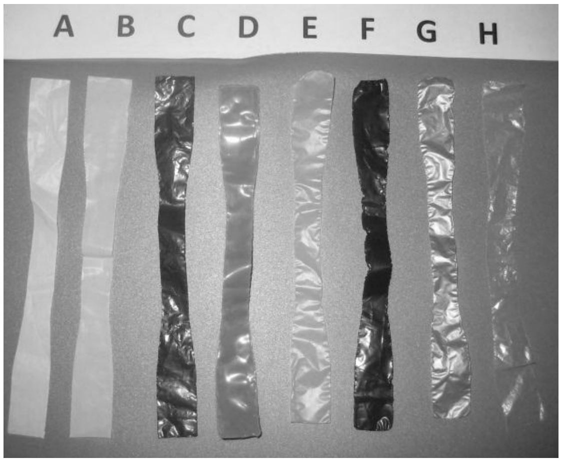

Figure 1: Types of bags and creep samples sectioned from the bag. The legend corresponds with the data shown in Table 1

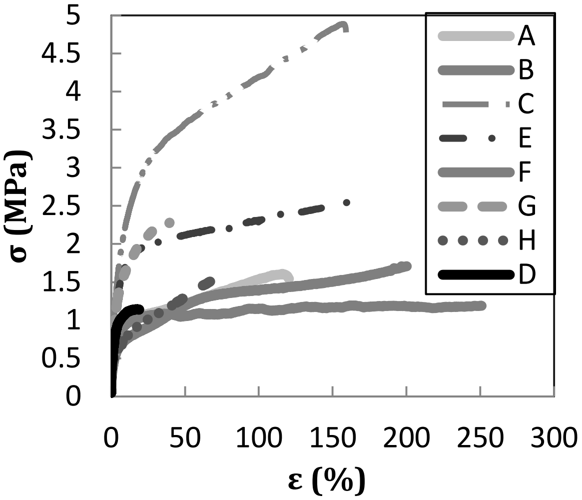

Figure 2: Typical measured stress-strain curves for the samples tested. The legend corresponds to the labels shown in Table

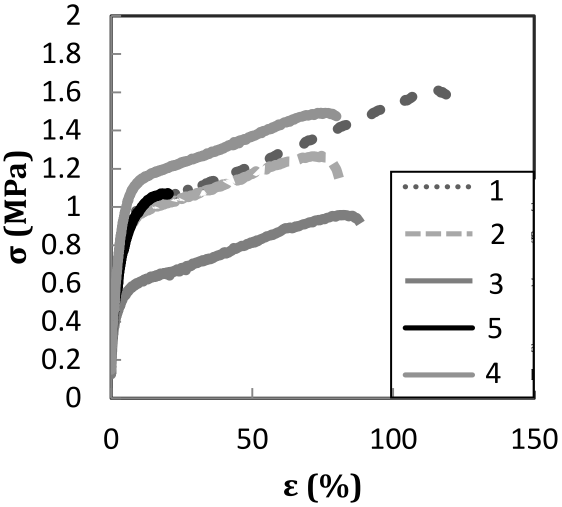

Figure 3: Measured stress-strain curves for Biobag under different conditions; 1: As received, 2: 24hr moisture exposure, 3: UV Exposure, 4: Soil Weathering, 5: Accelerated Aging

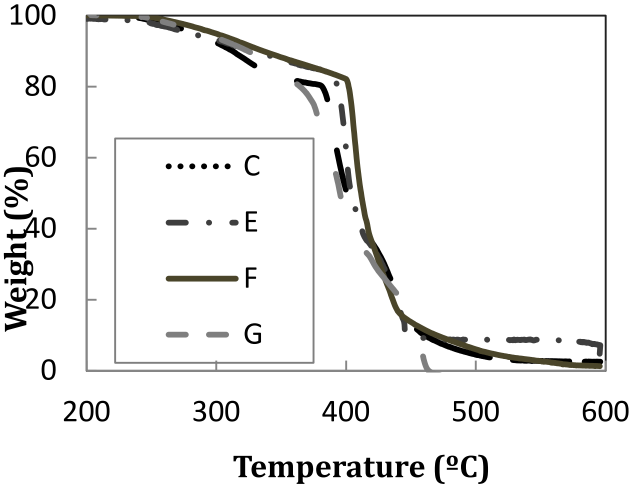

Figure 5: TGA data at a heating rate of 10ºC per minute. The legend corresponds to the data on Table 1

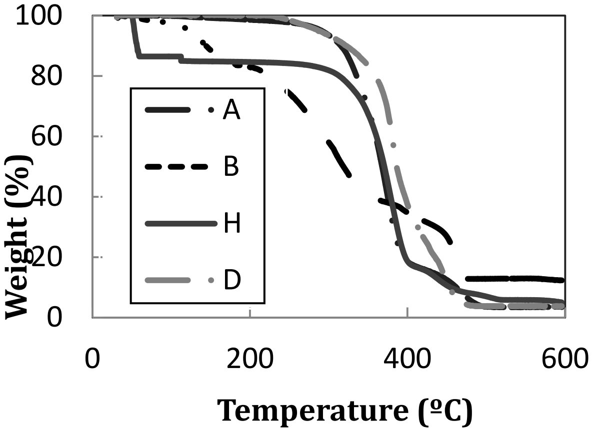

Figure 4: TGA data at a heating rate of 10ºC per minute. The legend corresponds to the data on Table 1

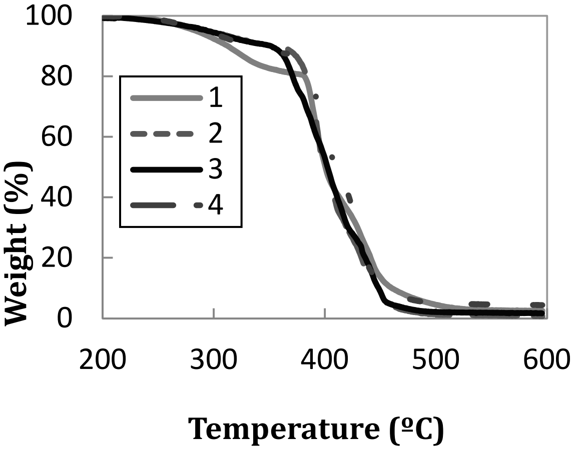

Figure 6: TGA data for Green Genius samples with a heating rate of 10ºC. Each number corresponds to a different condition; 1: As received, 2: 24 hr moisture exposure, 3: UV Exposure, 4: Soil Weathering

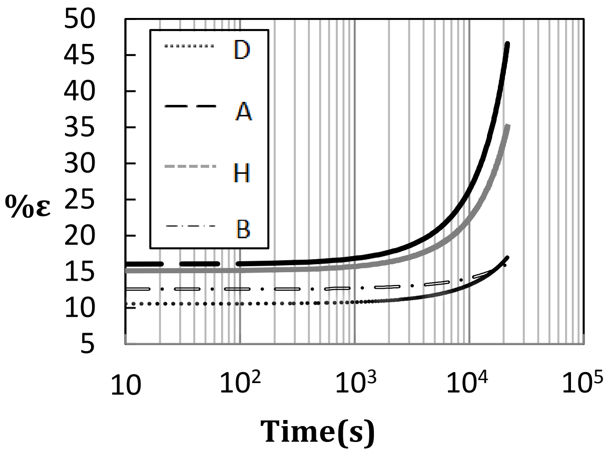

Figure 7: Variation of creep strain with time for the samples tested. The legend corresponds to the labels shown in Table 1

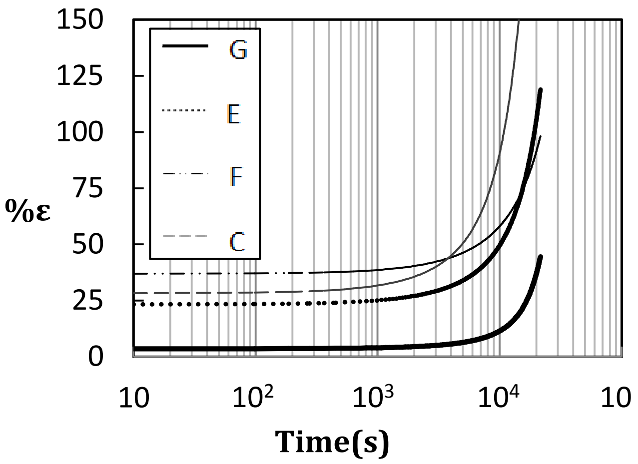

Figure 8: Variation of creep strain with time for the samples tested. The legend corresponds to the labels shown in Table 1

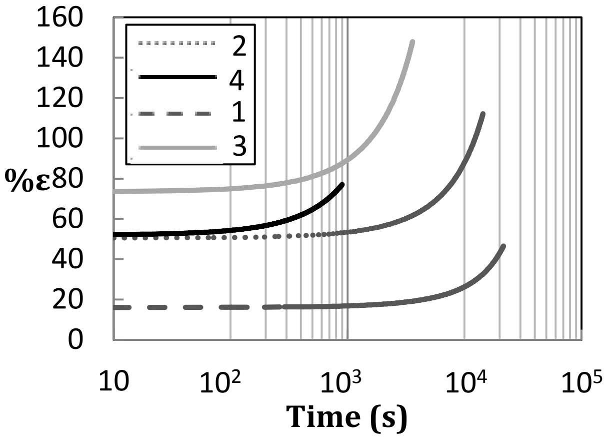

Figure 9: Creep Strain as a function of time in BioBag that have been subjected to various degradation procedures; 1: As received, 2: 24 hr moisture exposure, 3: UV Exposure, 4: Soil Weathering

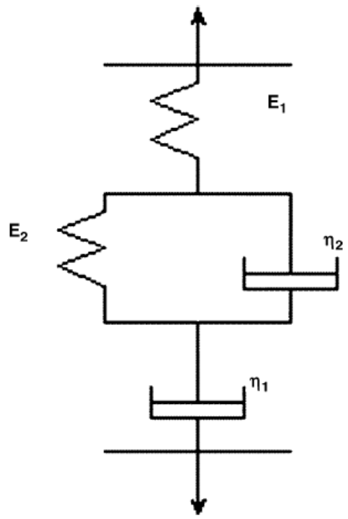

Figure10: Burger's model diagram

6.0 Further Results

More tests were conducted after the ANTEC Conference paper submission for further results to confirm the objectives stated. These results have been analyzed and will be used for a journal paper submission.

6.1 Tensile

The Oxobiodegradable plastic bag was also analyzed for its change in tensile properties under various testing procedures. Samples of the Oxobiodegradable bag were tested under UV exposure in 30 minutes, submerged in water for 24 hours, weathered for 4 months, and aged for around .5 years. Figure 8 depicts these conditions in a stress-strain curve.

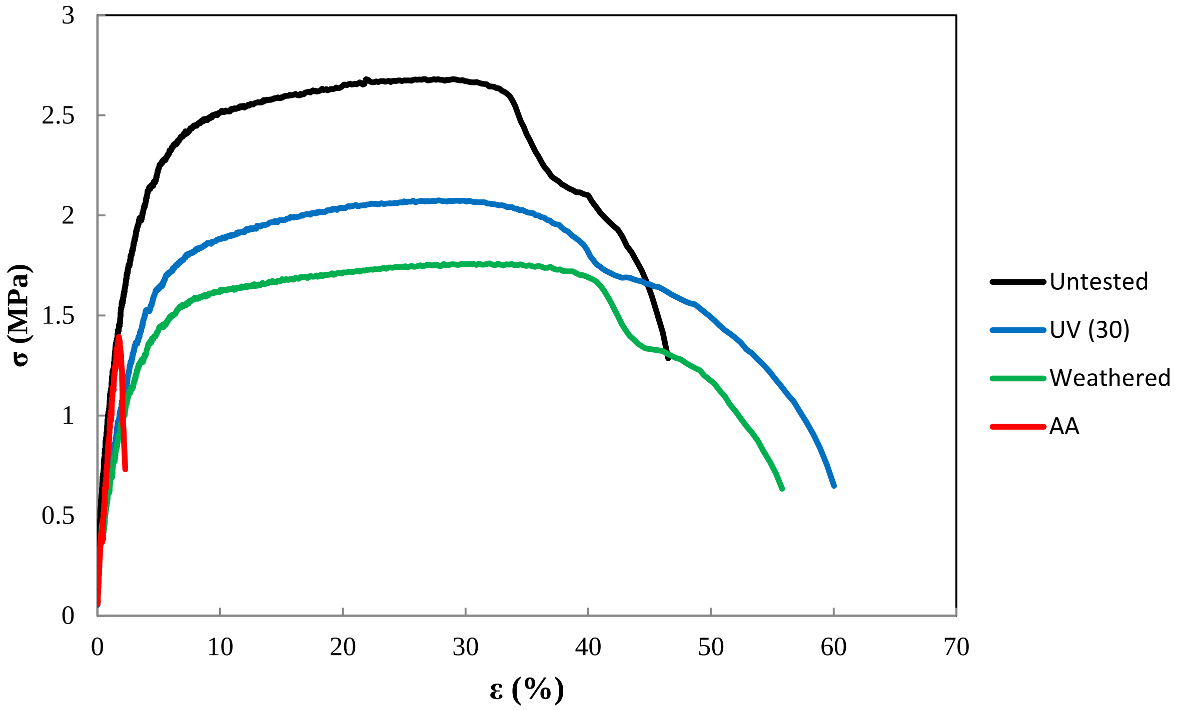

Figure 8: Measured stress-strain curves for Oxobiodegradable under various conditions

After analyzing the data, it is apparent that UV exposure for a 30 minute interval did not have a significant effect on the samples. It appears that the samples after a UV exposure of 30 min does not lower the amount the samples elongate. The tensile strength difference between them is around .5 MPa, which is not that much of a change. However, the 30 min UV exposed samples did appear to elongate more according to the graph. This is thought to just be an anomaly however, and when other tests were done, the elongation of the 30 min UV samples varied.

The accelerated aged Oxobiodegradable samples showed significant degradation upon tensile testing. The tensile strength of Oxobiodegradable bags decreases around 1.3 MPa after being aged about half a year. The elongation of the Oxobiodegradable bags also decreased about 50%. This degradation shows that Oxobiodegradable bags if aged longer can be effectively disposed of in landfills after proper heat treatments due to the weakened properties of the bags.

All eight types of bags were buried for a second time after the ANTEC submission for 4 months, considerably longer than the previous time the samples were buried. The results of these weathered samples are all graphed in Figure 9, not including the Flushdoggy and World Centric bags. The World Centric samples after being buried for 4 months sustained a great deal of degradation and could not be tested due to the samples not being intact. The Flushdoggy samples also could not be tested because of its adverse reaction to the moisture. Flushdoggy samples absorb the moisture that comes in contact with it at the cost of much of its strength, which made the bags impossible to test.

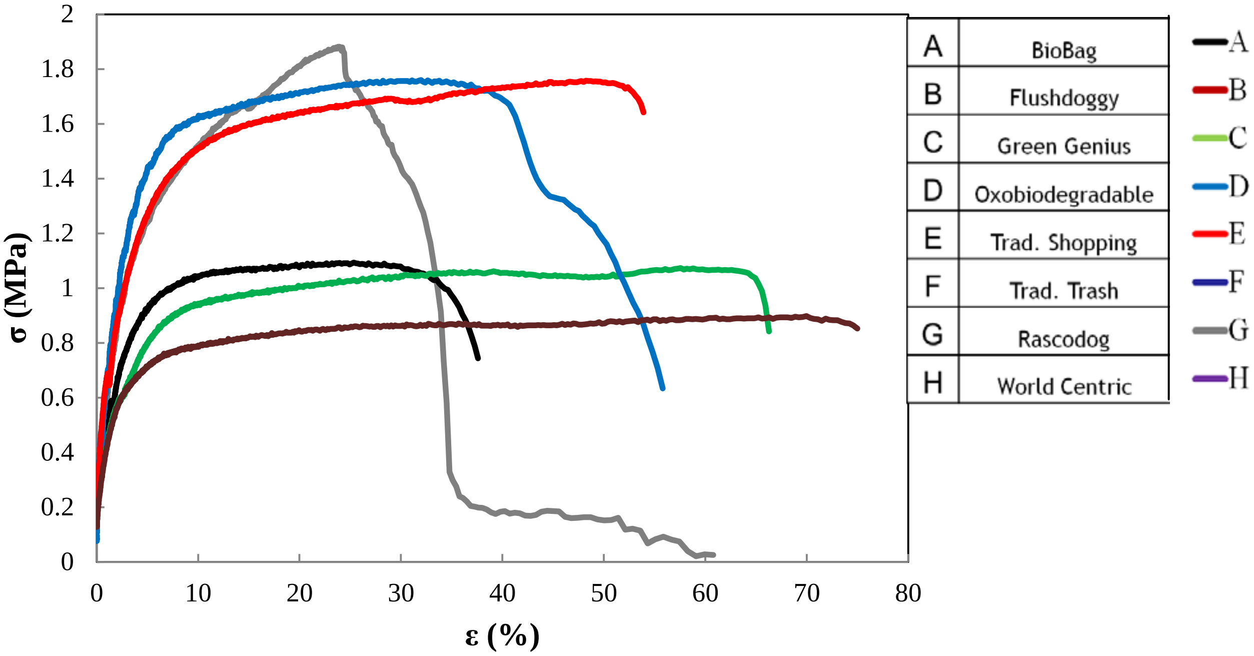

Figure 9: Weathered sample stress-strain curves

From observing Figure 9, it is apparent that the traditional shopping bag still retains strong properties after being weathered. The tensile strength of the weathered traditional shopping bags and the untested shopping bags are extremely similar. The only property that is affected is the elongation of the bag, in which it decreases by around 120%, a large change. Also a visual observation of the weathered shopping bag shows almost no difference compared to the untested bag. This result strengthens the argument that traditional plastic bags are relatively difficult to degrade. The traditional trash bag also loses 120% of its elongation after being buried and loses .5 MPa of tensile strength, which again is not a significant change compared to the other types of bags. Rascodog bags also appear to be completely unaffected by the weathering process, and retain their tensile strength and % elongation even after being buried in the ground. It is still relatively unclear whether Rascodog does degrade within a year under landfill conditions, however after 4 months no change was noticed.

6.2 Creep

After exposing the samples to UV lighting, the samples exhibited reduced creep. As the UV exposure time increased, the samples became more brittle and less elastic. The creep results for the 5 minute exposure group and the 15 minute exposure group are shown below in Figure 10 and 11, respectively. In addition, a 30 minute UV exposure was examined, but the creep results were not significantly different from those observed with the 15 minute exposure group. It was determined that the effect of UV radiation diminishes as the exposure time increases.

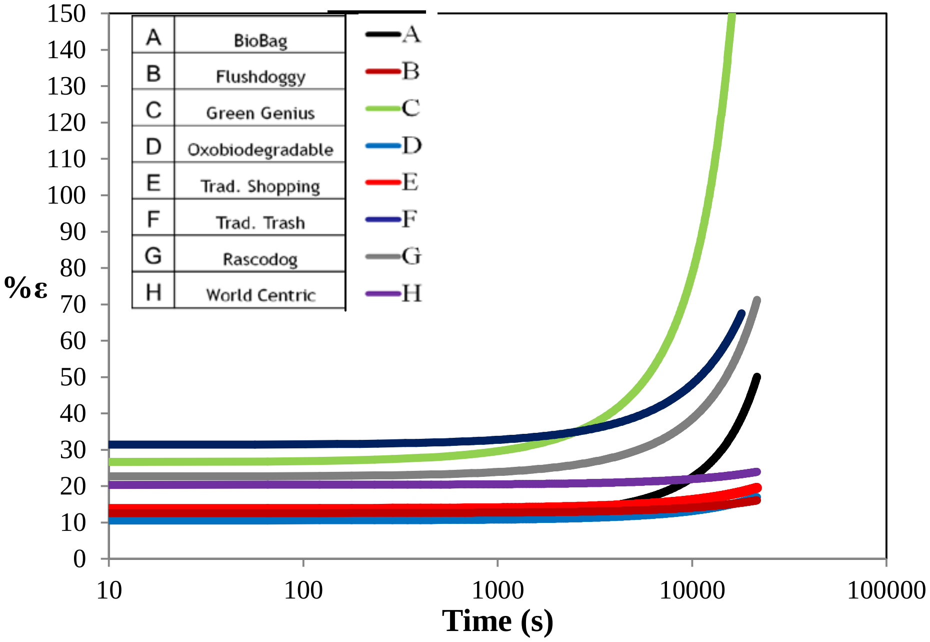

Figure 10: 5 minute creep strain with time graphs for all samples tested

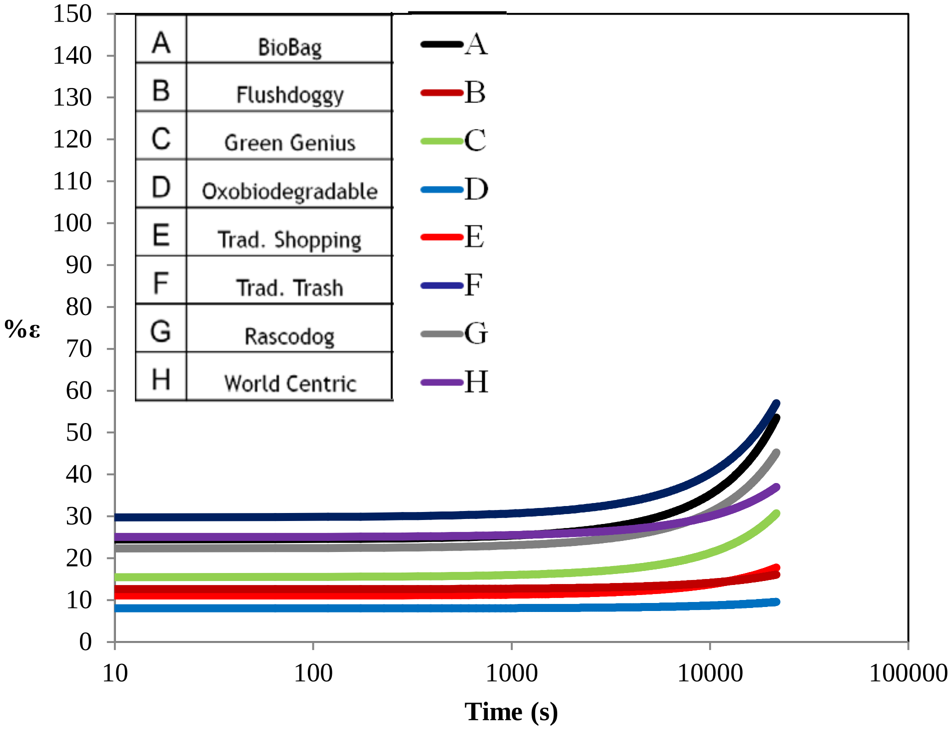

Figure 11: 15 minute creep strain with time graphs for all samples tested

The reduced creep of the bag samples can be attributed to the crosslinking of polymer chains induced by UV light. When exposed to UV light, polyethylene and other plastics develop cross-links in their microstructure, thus strengthening the material. In turn, UV light alters the viscoelastic properties of the plastic. The results of our creep tests illustrate that the bag samples became more brittle and exhibited lower strain, which suggests that the structure of the samples changed.

As shown in the creep results, Green Genius samples experienced the most dramatic change in creep behavior between the 5 and 15 minute exposure times with a decrease of 120%. The traditional trash bag, traditional shopping, Oxobiodegradable, and Flushdoggy samples, on the other hand, exhibited substantially less change in creep behavior as UV exposure time increased, which implies that they are less susceptible to UV radiation. It is important to note that the UV light used for the experiments was rated at an intensity of 9100 mW/cm^2, compared to about 136 mW/cm^2 for sunlight. A much longer exposure period would be required to reproduce our results with sunlight instead of an illuminator; without further testing, the two scenarios cannot be compared directly. In line with our objectives, these creep tests were used to determine how the viscoelastic properties of the bag samples were altered by UV light.

6.3 TGA

The effects of various testing conditions on samples were conducted to examine the thermal degradation of each plastic bag. All control samples of each bag experienced significant mass loss around 400°C; this can be evidenced in Figure 12. The critical reaction temperatures also fluctuated around this temperature and represent where major mass loss occurs. In Table 3, the critical temperatures for several samples are provided. Exposure to moisture and UV radiation for both 5 minutes and 30 minutes did not result in a significant effect on samples. Weathering for 3 weeks did not yield significant effects. Although the Flushdoggy bag under 30 minute UV radiation experienced rapid mass loss 200° less than the control sample's critical temperature. Irradiation on PVA film causes a loss in its thermal stability. Increasing the intensity or length of irradiation on PVA will result in accelerated and substantial mass loss at a significantly lower temperature then without irradiation.[9]

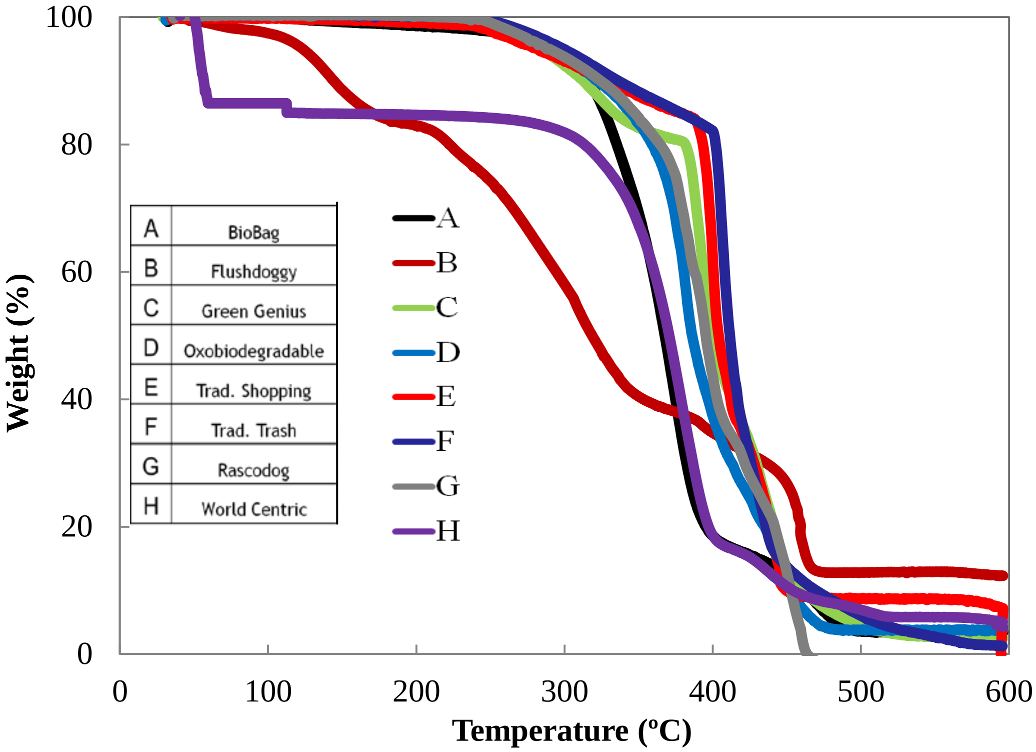

Figure 12: Untested TGA data for all samples

Bag Type	**T_{cr} (°C)**	**Mass Lost (%)**
BioBag	370	33
Green Genius	395	15
Flushdoggy	453	16
Oxobiodegradable	380	12
Traditional Shopping	400	8
Traditional Trash	400	6
Rascodog	385	12
World Centric	387	30

Table 3: Critical reaction temperatures of each plastic bag type during TGA.

Accelerated Aging for 3 weeks and weathering for 4 months did not significantly affect the thermal degradation behavior of the Green Genius bag as evidenced below in Figure 13. Although these temperatures are not ones encountered normally by consumers, it is an integral property when these bags are disposed of and sent to landfills. Landfills typically include a furnace where waste is sent and exposed to high temperatures in order to be turned into ash before it is buried in the ground to degrade. These results show that there are little to no change in thermal properties. This is advantageous because disposed Green Genius bags will have a predictable mass loss regardless of outside conditions.

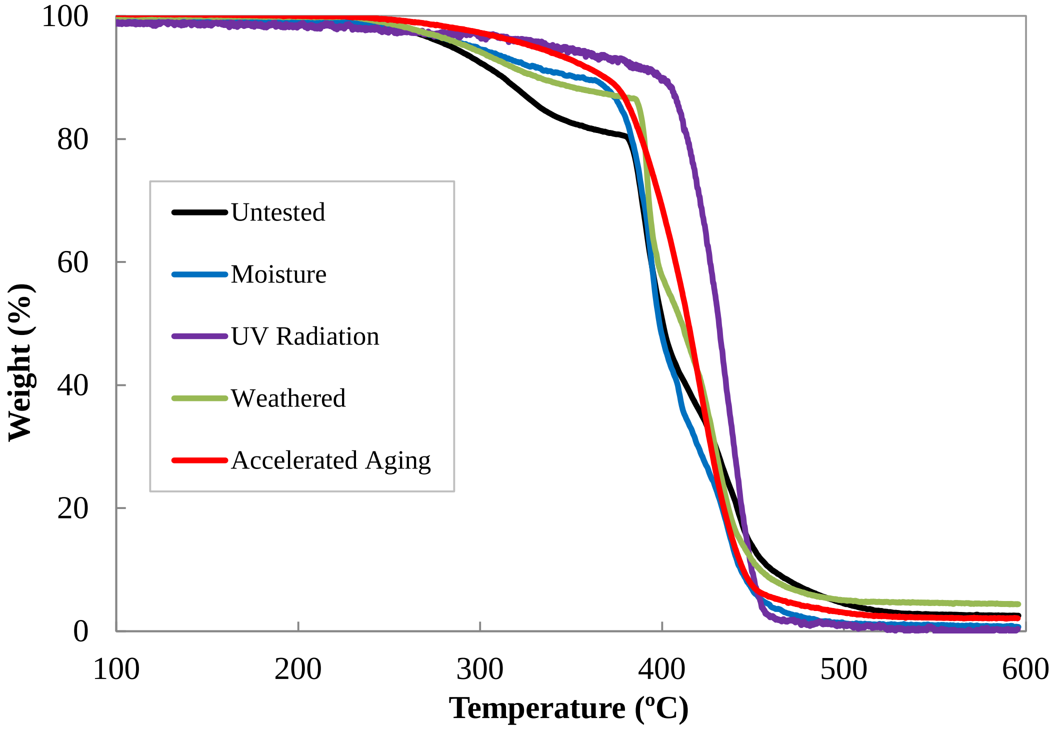

Figure 13: TGA data for Green Genius samples under various conditions at heating rate of 10°C/minute.

7.0 Conclusions

Biodegradable plastic bags are rapidly emerging as a convenient alternative to traditional plastic bags. Various brands of degradable bags are now commercially available. Six of the commercial biodegradable plastics bags were tested to determine their mechanical properties and degradation behavior. It was observed that, in general, these bags had properties similar to conventional plastic bags. Bags such as Green Genius and BioBag can serve equally well as traditional bags according to our results. Also, PVA and cornstarch based bags, such as Flushdoggy and BioBag, can degrade completely upon exposure to various degrading agents. It was also found that UV treatment has various effects on the bags; in some bags UV exposure can decrease the properties while in other tests UV exposure does not have that much of an effect. Weathering after four months appeared to affect the traditional plastic bags much less than the biodegradable bags according to the tensile results, which proves that traditional plastic bags are tougher to degrade than biodegradable ones. Although to counter this, Rascodog bags showed very little decrease in properties after the four months even though it is declared biodegradable by manufacturers. Therefore, because of biodegradable bags beneficial effects in minimizing landfill contribution due to their ability to degrade at a faster rate than traditional plastic bags, it is expected that the use of such bags will increase.

8.0 Recommendations

From this data, it is recommended that manufacturers of traditional plastic bags start to research alternative materials or additives that can be added to their products to increase degradation times. The data in the report clearly shows that the biodegradable plastic bags currently have tensile, creep, and thermal degradation properties that are very close to traditional plastic bags, with the added benefit of faster degradation times. Also, currently most biodegradable bags must be tested according to different ASTM standards in order to be considered biodegradable. This ensures that a universal definition for biodegradability can be followed by manufacturers. The data found in this report has shown that the biodegradable bags that followed the ASTM standards are comparable, so using a material that is difficult to degrade is no longer acceptable.

Although manufacturers do have a major role in ensuring biodegradable plastic bags are being used, either incentives or laws need to be made by the government to make more plastic bag manufacturers start developing biodegradable bags. Manufacturers should not be allowed to profit off of making bags that only serve to cause more pollution. There are better solutions that can significantly decrease the amount of waste that is accumulated in landfills. If no steps are taken, manufacturers have no reason to change their bag creation methods. Additionally, clearer criteria for a plastic material to be considered “biodegradable” should be outlined. Many companies litter phrases that are variations of “green” to intentionally mislead consumers into thinking what they are purchasing is not detrimental to the environment, when in actuality there is very small portion of its disposal or production that is environmentally friendly.

Finally, it is recommended from this report that more types of biodegradable and traditional plastic bags are tested for mechanical properties. The results gathered cannot truly represent all biodegradable bags that are currently being manufactured, and therefore a larger group of bags needs to be tested. Also it is recommended that other experiments be ran on these bags such as NMR Spectroscopy to find the chemical properties of the molecules that make up the plastic bags. With more experiments, the bags can be more thoroughly analyzed and the reason for its mechanical properties understood easier.

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