

Exploring the Thermal Stability and Durability of Polymer-Based Materials: A Comprehensive Analysis of Plastic Bag Lifespan

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Abstract – Polymer materials, ubiquitous in modern society, present a pressing environmental challenge due to their non-degradable nature and pervasive presence in ecosystems worldwide. This study delves into the thermal properties and time life of plastic bags, aiming to unravel the intricate properties of polymer-based materials. Through rigorous scientific investigations, including differential scanning calorimetry and thermogravimetric analysis, this research seeks to elucidate key thermal properties such as maximum operating temperature and degradation temperature. By estimating product lifetime, we can assess the environmental impact of the material by determining how long it persists in the environment before breaking down. This research is poised to significantly advance the understanding of polymer degradation kinetics and the development of eco-friendly alternatives to traditional plastics.

Keywords: Polymer degradation kinetics, thermal properties, product lifetime, thermal stability

I. Introduction

The term "polymer" originates from the Greek roots *poly* and *meros*, signifying "many parts." Polymers constitute extensive molecular structures composed of numerous monomers. The accommodation of monomers, the diverse synthesis of chain structures, and the resultant array of shapes contribute to polymers possessing an extensive array of properties, several of which are distinctly unique to this class of materials.^[1]

The synthetic polymer industry produces over 10,000 materials used in a diverse array of products. These polymers can be classified in several ways: based on their source (natural or synthetic), chain structure (linear, branched, or crosslinked), polymerization mode (addition or polycondensation), molecular configuration (amorphous, semicrystalline, or crystalline), thermal characteristics (thermoplastic or thermoset), as well as common and specialized applications determined by their properties, among other criteria.^[2]

The classification of common and specialized use is depicted in the figure 1:

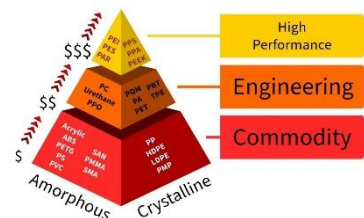


Figure 1: Polymer classification based on cost-performance.

Plastics represent low-cost, commodity thermoplastic polymers. The properties exhibited by polymers are contingent upon several factors including chemical structure, architecture, molecular weight (MW), and molecular weight distribution (MWD).^[3] On account of their inherent properties, polymeric materials can undergo molding, extrusion, and melting processes to attain diverse shapes, films, or filament formations.^[4]

From the instant we awaken, our environment is inundated with plastic-made items, encompassing toothbrushes, personal hygiene products, containers, televisions, clothing, wires, resins, and an array of other commodities.^[5] In contemporary society, envisioning life devoid of polymeric materials seems challenging, given its multitude of advantages including low production costs (requiring minimal energy), low maintenance requirements, corrosion resistance, lightweight nature, and remarkable durability.^[6]

The proliferation of plastic stemmed from a series of historical developments; in the 19th century, the rising demand for ivory spurred the quest for alternatives, catalyzing a period of experimentation. Eventually, the modern conception of plastic emerged through years of trial and error. By 1940, advancements in machinery facilitated mass production, initially prioritizing the manufacture of weaponry during wartime. However, following World War II, the use of plastics skyrocketed, marking a quadrupling in consumption. Plastic-producing enterprises seized upon this momentum, diversifying their product lines to include toys, containers, furniture, and various other commodities, thereby propelling a rapid expansion in the usage of these materials.^[7] In addition to this, plastics revolutionized medicine, cars, construction, electronics, and adhesives and made space travel possible.^[8]

However, what was once perceived as a solution has now become a pressing issue. The enduring longevity of plastics, a key attribute that rendered them indispensable, also poses a significant challenge: their slow degradability, and in some cases, non-biodegradability. Virtually every piece of plastic ever produced persists in the environment, contributing to the accumulation of plastic waste on a global scale.^[5]

The escalation of plastic production has been exponential, surging from 2.3 million tons in 1950 to a staggering 448 million tons by 2015. Projections indicate that production rates are poised to double by 2050. Notably, single-use plastics constitute 40% of the total plastics manufactured annually, comprising items utilized for mere minutes or hours yet persisting in the environment for up to 500 years.^[8] Daily, an astonishing volume of plastic, equivalent to the contents of 2,000 garbage trucks, finds its way into oceans, rivers, and lakes. Annually, this translates to a staggering 19-23 million tons of plastic pollution infiltrating water bodies and ecosystems, posing significant threats to marine life and environmental sustainability.^[9]

As plastics make their way into the sea, exposure to sunlight, wind, and waves initiates a process of fragmentation, breaking down plastic into minute particles measuring one-fifth of an inch in diameter or smaller. These microplastics infiltrate all bodies of water and have been detected across every corner of the globe, from Mount Everest, the highest mountain, to the Mariana Trench, the deepest depression on Earth.^[8]

The detrimental effects of plastic extend beyond its sheer production volume, every facet of the plastic lifecycle takes a toll on the planet. From the environmental repercussions of extracting fossil fuels for plastic production to the health risks posed by the toxins released into the environment during incineration. Moreover, the devastating consequences on marine life and diverse ecosystems underscore the urgent need for comprehensive measures to mitigate the pervasive harm inflicted by plastic pollution.^[5]

One potential avenue for addressing the plastic pollution crisis involves the adoption of degradable plastics, encompassing various categories such as biodegradable, oxo-degradable, hydro-degradable, and compostable plastics. Biodegradable plastics are designed to be assimilated by bacteria or fungi, thereby yielding environmentally benign byproducts. Oxo-degradable plastics, on the other hand, rely on additives

that trigger oxidation reactions to facilitate degradation. Hydro-degradable plastics feature polar groups that are susceptible to hydrolysis, fostering their breakdown over time. These diverse approaches to degradability offer promising avenues for reducing the environmental impact of plastic waste.^[6]

The surge in demand for materials capable of withstanding severe and critical conditions without compromising their properties has become increasingly pronounced in recent years. Consequently, the imperative to enhance the thermal stability of materials has emerged as a pivotal concern. Thermal stability denotes the capacity of a substance or material to resist chemical or physical alterations when subjected to elevated temperatures. This attribute is influenced by factors such as chemical composition, molecular size, bond strength, the presence of additives and the presence of impurities.

High thermal stability holds paramount importance for polymers owing to its multifaceted implications for processing, performance, and safety. Polymers with high thermal stability can endure the elevated temperatures inherent in diverse processing techniques, thereby ensuring the efficiency of manufacturing processes while preserving structural integrity. Moreover, they demonstrate resilience across a broad spectrum of service temperatures, thereby upholding mechanical strength and dimensional stability.

From a safety perspective, high thermal stability serves to mitigate risks associated with degradation, melting, or the release of gases when exposed to heat, thereby safeguarding both property and human well-being. This characteristic further augments durability and reliability, particularly within industries such as automotive, aerospace, electronics, and construction, where polymers are subjected to harsh environmental conditions. Consequently, high thermal stability contributes to the enhanced versatility, functionality, and longevity of polymer-based products across an array of applications.^[11]

In this study, the thermal stability, and various thermal properties of three purportedly biodegradable plastic bags retrieved from supermarkets, alongside one fabric bag, will be examined. Additionally, the lifespan of these bags will be evaluated.

II. Experimental

Table 1. Description of the samples

Sample	Characteristics and appearance
1	Highly versatile biodegradable polyethylene plastic bag, slightly opaque in appearance
2	D2W biodegradable polypropylene plastic bag is characterized by its slight rigidity and transparency
3	A plastic bag of a lighter brown color exhibits flexibility and is labeled as 100% recycled and biodegradable.
4	Non-woven fabric bag; these fabrics or fabric-like materials are made from semi-crystalline thermoplastics.

Different tests were carried out to study the thermal properties of the materials, which will be described below.

A. Differential scanning calorimetry

Differential scanning calorimetry (DSC) was carried out in a DSC Q20 by TA Instruments under a nitrogen flow of 50 ml/min and a heating rate of 20°C/min. Three methods were used, method 1 was used in samples 1 and 2, method 2 in sample 3, and method 3 in sample 4. Method 1 consists of heating the sample from -80°C to 200°C; the second method is heating the sample from -80°C to 200°C in the first scan and from -80°C to 20°C; finally, the third method is heating the sample from 20°C to 180°C in the first scan and from -80°C to 190°C in the second one.

B. Thermogravimetric analysis

The Thermogravimetric analyses (TGA) were performed in an STA 1500 Instrument Specialist from room temperature and up to 800 °C at three different temperature ramps: 10, 15, and 20 °C/min. With this, the weight loss can be monitored, the maximum decomposition temperature can be obtained, as well as the maximum operating temperature, and the estimated product life. ^[13]

C. Estimated product life

Thermogravimetric Analysis (TGA) provides a method for accelerating the lifetime testing of polymers so that short-term experiments can be used to predict in-use lifetime.

The material is heated at different rates (the same ones mentioned in the TGA analysis) and after determining the decomposition temperatures, the kinetic activation energy is then determined from a plot of the logarithm of the heating rate versus the reciprocal of the temperature of constant decomposition level. The plotted data should produce a straight line, in which the slope is the kinetic activation energy, and it equals the value of the derivative term ($d\log\beta/(d(1/T))$) in the following equation:

$$E = \frac{-R}{b} \left[\frac{d\log\beta}{d\left(\frac{1}{T}\right)} \right] \quad (1)$$

Where:

E = Activation Energy (J/mol)

R = Gas Constant (8.314 J/mol K)

T = Temperature at Constant Conversion (K)

β = Heating Rate (°C/min)

b = Constant, approximation derivative

The value for the constant b will vary depending upon the value of E/RT. Therefore, an iterative process

must be used where E is first estimated by replacing in equation (1) the suggested b (0.457) and the calculated slope; next calculate the value for E/RT_c, where T_c is the temperature at constant conversion for the heating rate closest to the midpoint of the experimental heating rates, then, using the obtained value for E/RT_c, choose a corresponding value for b. *

Since the activation energy has been obtained, an analysis of the lifetime of the polymer concerning different temperatures can be done by using the following equation:

$$\log t_f = \frac{E}{2.303RT_f} + \log \left[\frac{E}{\beta R} P(\chi_f) \right] \quad (2)$$

Where:

t_f = Estimated Time to Failure (min)

E = Activation Energy (J/mol)

T_f = Failure Temperature (K)

R = Gas Constant (8.314 J/mol K)

P(χ_f) = A function whose values depend on E at the failure temperature.

T_c = Temperature at constant conversion at β (K)

β = Heating rate (°C/min)

To estimate the time until failure (t_f), the temperature (T_c) is determined corresponding to the constant conversion point, using a slow heating rate (β) of 10 °C/min. Then the activation energy (E) and T_c to compute the ratio E/RT. This ratio is subsequently employed to identify the logarithm of the probability of failure P(χ_f) from a predefined numerical integration table. By taking the antilogarithm, the numerical value for P(χ_f) is obtained. Finally, selecting a value for the failure (or operating) temperature (T_f) enables the calculation of t_f using equation 2 provided above.

By rearranging the equation 2, the maximum use temperature (T_f) for a given lifetime (t_f) can be obtained. ^[14]

$$T_f = \frac{E/2.303R}{\log t_f - \log \left[\frac{E}{\beta R} P(\chi_f) \right]} \quad (3)$$

III. Results & Analysis

A. Thermogravimetric analyses

Below are the graphs obtained for the TGA analysis shown as figure 2, 3, and 4. For simplicity and ease of comparison, all samples are depicted on the same ramp in the same table and graph.

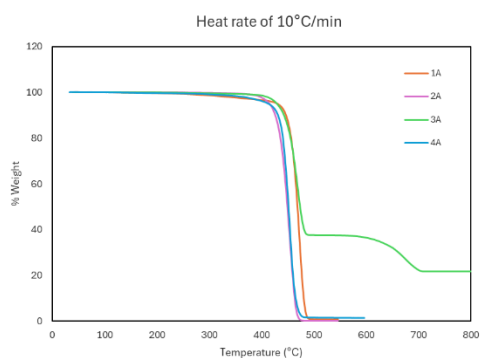


Figure 2. Samples Tested at a rate of 10°C/min.

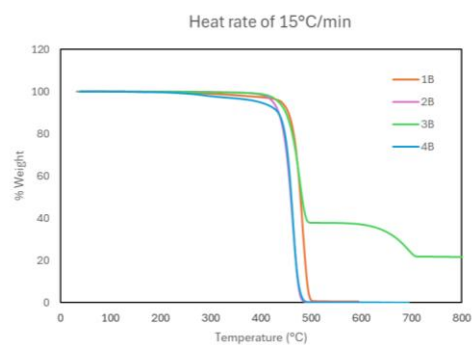


Figure 3: Samples Tested at a rate of 15°C/min

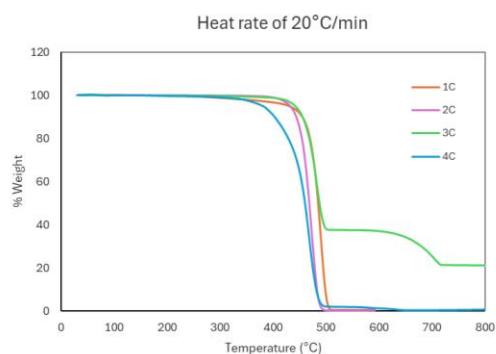


Figure 4: Samples Tested at a rate of 20°C/min.

Table 2A. Thermal properties obtained from TGA at a rate of 10°C

Sample	T _{op} (°C)	T _{id} (°C)	T ₈₀ (°C)	T _{dmax} (°C)
1	240.79	399.71	455.37	471.80
2	362.73	404.76	434.53	454.53
3	333.75	408.82	454.76	469.91
4	306.91	401.60	441.04	454.35

Table 2B. Thermal properties obtained from TGA at a rate of 15°C

Sample	T _{op} (°C)	T _{id} (°C)	T ₈₀ (°C)	T _{dmax} (°C)
1	224.78	401.01	464.30	482.30
2	355.53	403.66	444.97	463.39
3	278.63	406.85	461.80	476.79
4	214.49	379.41	447.06	463.13

Table 2C. Thermal properties obtained from TGA at a rate of 20°C

Sample	T _{op} (°C)	T _{id} (°C)	T ₈₀ (°C)	T _{dmax} (°C)
1	206.65	411.86	469.70	490.52
2	349.09	400.63	454.07	472.70
3	243.25	398.01	468.12	482.94
4	225.57	336.10	428.32	468.35

Abbreviations in Table 2A, 2B and 2C denote the following terms:

T_{op} = Maximum operating temperature

T_{id} = Initial decomposition temperature

T₈₀ = Temperature at which 80% of the weight is lost

T_{dmax} = Maximum thermal decomposition rate

The maximum operating temperature of a material denotes the point at which it commences weight loss, thus serving as the upper operational threshold. Subsequently, the initial decomposition temperature signals the onset of significant weight loss, and T_{dmax} represents the temperature at the maximum rate of weight loss, in other words, the decomposition temperature. , and it can be associated with the thermal stability of the material; consequently, a higher T_{dmax} indicates greater thermal stability.

In the thermal analysis graphs, various thermal properties were successfully obtained, revealing a similar trend among the materials across the three ramps. Upon examining the results, it becomes apparent that all the samples used exhibit a relatively low maximum operating temperature, with the lowest being sample 1, followed by sample 4, sample 3, and finally sample 2; this implies that sample 2 can be used at higher temperatures without compromising its properties and without the risk of breaking or causing harm to anyone.

Notably, sample 2 experiences the most significant weight loss within a narrower temperature range, as depicted in Tables 2A, 2B, and 2C, therefore, the sample degrades more rapidly or within a limited temperature range compared to other samples. This behavior may have various implications, such as lower thermal stability of the sample, a different chemical

composition that makes it more susceptible to thermal degradation, and the presence of additives that influence the degradation process, among other factors.

The higher the T_{dmax}, the greater the material's thermal stability, indicating that sample 1 shows the highest thermal stability among the samples. However, the fact that it has a higher T_{dmax} implies that a greater amount of energy is required to process and degrade it, which is more challenging and costly.

Regarding sample 3, in figures 2, 3, and 4, a variation in the trend can be observed around 40% mass loss; this is attributed to some additive in high proportions, causing its thermal properties to change. Therefore, it could be assumed that the polymer's maximum degradation temperature occurs before this variation, with the subsequent observed degradation corresponding to the additive.

Understanding the thermal properties mentioned earlier is essential for different reasons. Firstly, it enables the determination of the maximum operating temperature of polymers, critical for ensuring their structural integrity and functional performance across diverse industrial applications. Moreover, insights into the decomposition temperature and T_{dmax} offer invaluable guidance on the thermal stability of polymers, aiding in the judicious selection of materials for specific environmental conditions and manufacturing processes.

B. Differential scanning calorimetry

Below are the graphs obtained from the analysis DSC for all the samples.

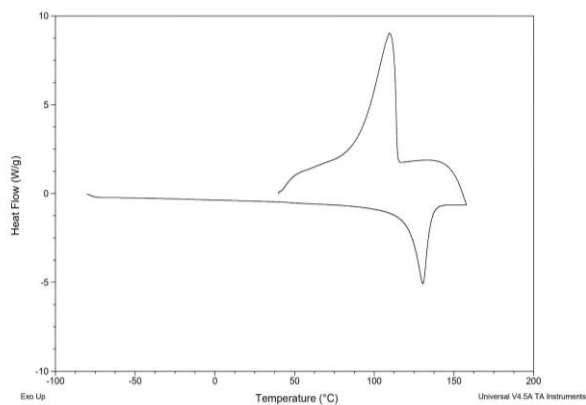


Figure 5: Differential Scanning Calorimetry Analysis of Sample 1

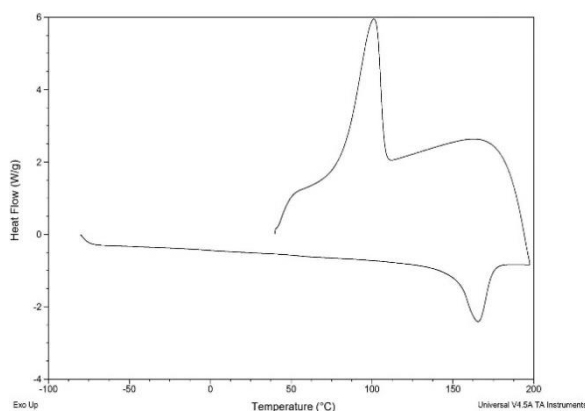


Figure 6: Differential Scanning Calorimetry Analysis of Sample 2

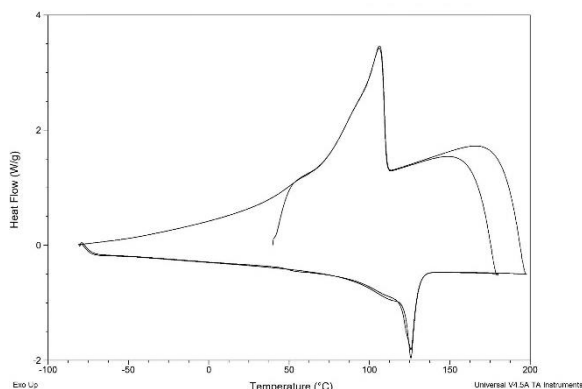


Figure 7: Differential Scanning Calorimetry Analysis of Sample 3

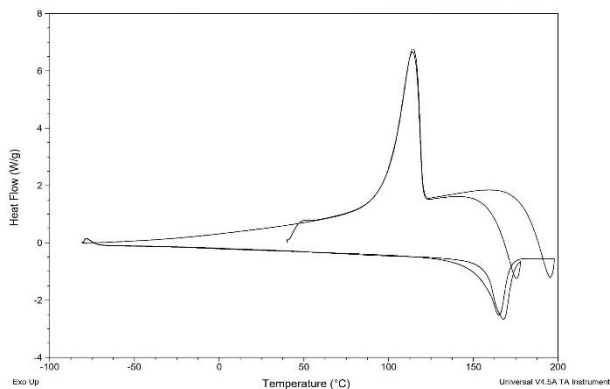


Figure 8: Differential Scanning Calorimetry Analysis of Sample 4

Referring to Figure 5, the analysis delves into a profile showcasing a fusion enthalpy of 131.25°C, notably low compared to other materials.

As shown in Figure 6, sample 2 displays a higher fusion enthalpy (165°C); this higher fusion enthalpy value indicates a greater amount of energy required for the material to transition from its solid to liquid phase compared to the other samples. The elevated fusion enthalpy may be attributed to several factors, including the molecular structure, crystallinity, and chemical composition of the material. A higher fusion enthalpy suggests stronger intermolecular forces and a more tightly packed molecular arrangement within the substance.

The fusion enthalpy of sample 3 (Figure 7), standing at 125°C, is notably the lowest among the samples analyzed. This observation could stem from several factors inherent to the composition and molecular structure of the material. For instance, a lower fusion enthalpy may indicate weaker intermolecular forces within the substance, resulting in less energy required to transition from a solid to a liquid state. Additionally, it could suggest a molecular arrangement that offers less resistance to the disruption of

solid-phase order, facilitating the transition to a liquid state at comparatively lower temperatures.

Furthermore, Sample 3 exhibits a slight curvature at approximately 110°C, which coincides with a potential glass transition temperature. This observed transition could be solely due to the presence of the additive or oligomer itself, or it could indicate an alteration of the material's inherent glass transition temperature through modified intermolecular interactions. The additive may influence the molecular structure of the material, potentially impacting the packing and mobility of polymer chains, thereby causing a shift in the glass transition temperature.

As depicted in Figure 8, sample 4 exhibits a fusion enthalpy of 163°C. Interestingly, the glass transition temperature remains undetectable in all samples, except sample 3, likely due to equipment limitations. Literature suggests this transition occurs around -100°C, yet the instrument's maximum capacity reaches only -80°C. This discrepancy underscores the importance of understanding equipment constraints and potential disparities between theoretical expectations and experimental observations in thermal analysis. [15]

Table 3. Thermal properties obtained from the DSC.

Sample	1	2	3	4
T_g (°C)	—————	—————	104.08	—————
T_m	131.25	165	125	163
ΔH_m (J/g)	68.86	125.7	43.41	67.20

The abbreviations utilized in Table 3 denote the following terms:

T_g = Glass transition temperature

T_m = Melting temperature

ΔH_m = Enthalpy of Fusion

The glass transition temperature marks the point at which a solid material undergoes increased elasticity, transitioning from a rigid to a more flexible state. Additionally, the fusion enthalpy, or melting temperature, signifies the transition of a solid to a liquid state. ^[16]

If Table 3 is examined and compared to Tables 2A, 2B, and 2C, it's evident that the enthalpy of fusion is much lower than the maximum operating temperature, indicating that although the material does not lose weight, it does change its state. This aspect must be considered when seeking to utilize these materials. Additionally, understanding the enthalpy of fusion provides insights into the energy required for the material to transition from a solid to a liquid state, further informing its processing and application considerations.

Polymers like polyethylene and polypropylene, widely used in plastic bag manufacturing, typically exhibit T_g values well below room temperature. The T_g represents the temperature at which the polymer transitions from a hard, glassy state to a rubbery, amorphous state. Since plastic bags need to remain flexible and pliable at room temperature and above, their T_g tends to be significantly lower, allowing them to maintain their desired properties over a wide range of temperatures. The approximate T_g of -120°C ensures that the plastic bags remain flexible and resilient under normal environmental conditions, contributing to their usability and functionality in everyday applications. ^[15]

The enthalpy of fusion is the amount of heat required to melt a given polymer. The higher the enthalpy of

fusion, the more energy is required for this change, and it is also associated with stronger intermolecular forces. Polymers with a larger enthalpy of fusion are generally more rigid and less flexible. As shown in Tables 1 and 3, sample 2, which has the highest enthalpy of fusion, also has the most rigid appearance.

This can be explained by the fact that stronger intermolecular forces between polymer chains restrict their mobility, making the polymer stiffer. Conversely, polymers with weaker intermolecular forces have more chain mobility, resulting in greater flexibility. ^[17]

Comprehension of the glass transition temperature enables predictive modeling of polymer behavior under varying temperature regimes, leading to informed decisions in polymer synthesis and processing. Finally, a thorough understanding of the enthalpy of fusion provides crucial insights into the phase transitions and material transformations inherent in polymer systems, driving innovation in the design and development of advanced polymer materials with tailored properties.

C. Estimated product life.

Figures 9, 10, 11, 12, 13, 14, 15 and 16 illustrate the sample lifetimes as a function of temperature. This study did not assess the biodegradability of these samples, but rather only their behavior at different temperatures.

The study contemplates the existence of two distinct temperature systems: a low-temperature system and a high-temperature system. This consideration assumes that the material could either be applicable in everyday applications or recycled and subjected to extreme heating.

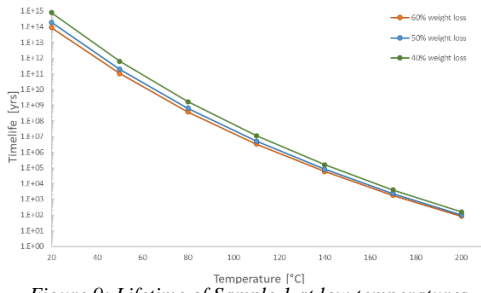


Figure 9: Lifetime of Sample 1 at low temperatures

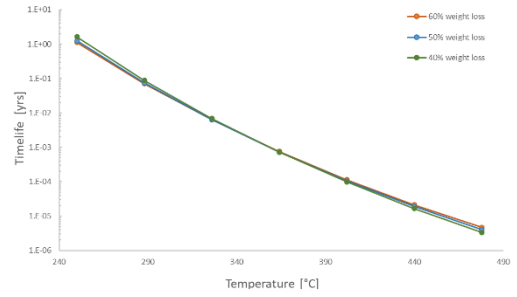


Figure 10: Lifetime of Sample 1 at high temperature

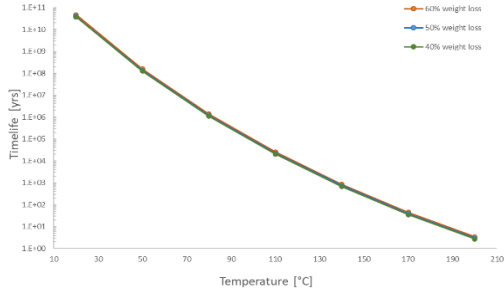


Figure 11: Lifetime of Sample 2 at low temperatures

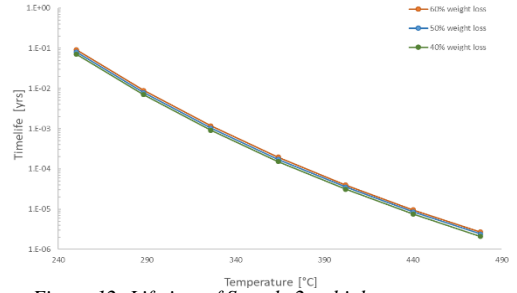


Figure 12: Lifetime of Sample 2 at high temperatures

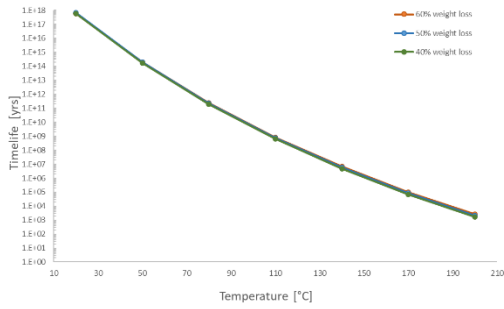


Figure 13: Lifetime of Sample 3 at low temperatures

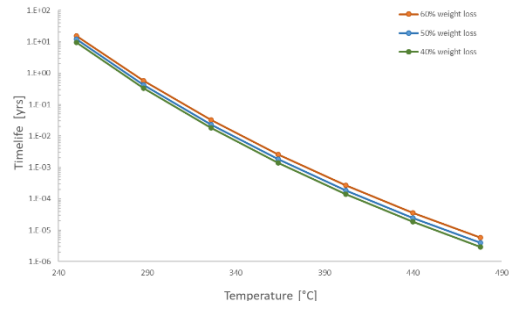


Figure 14: Lifetime of Sample 3 at high temperatures

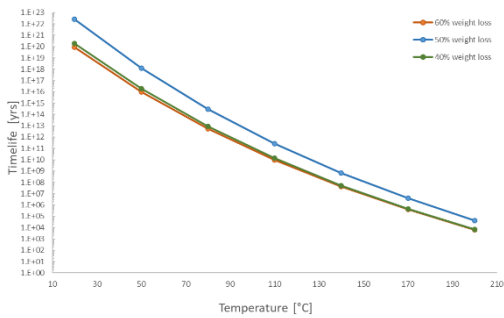


Figure 15: Lifetime of Sample 4 at low temperatures

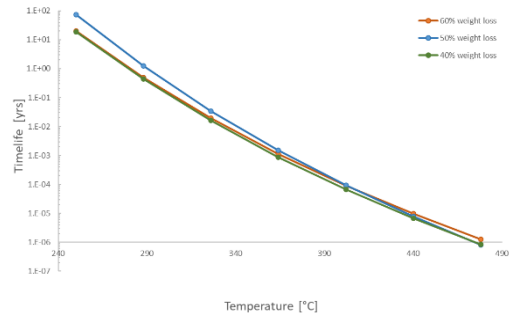


Figure 16: Lifetime of Sample 4 at high temperatures

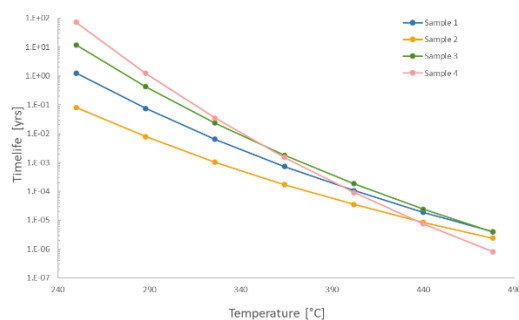


Figure 17: Lifetime of the different samples at 50% weight loss

Table 4: Lifespan of the samples at low and high temperatures.

Sample	Timespan at 20°C (years) *	Timespan at 200°C (years)	Timespan at 500°C (years)
Sample 1	4.80×10^{16}	9,313.414	8.62×10^{-05}
Sample 2	2.23×10^{12}	162.340	6.37×10^{-05}
Sample 3	3.60×10^{19}	103,577.137	6.71×10^{-05}
Sample 4	1.18×10^{22}	415,609.599	1.66×10^{-05}

* The displayed lifespan is without any additional treatment, only heating, thus it does not measure the biodegradability of the samples.

The intersection of the lines in Figures 10, and 16, representing the different weight loss values as a function of temperature, suggests a change in the composition of the samples, which could be due to the degradation of organic compounds. In contrast, figures 12 and 14 exhibit the behavior of samples 2 and 3, where the lines do not intersect each other. This behavior could be considered "normal" for petroleum-based polymers.

This behavior could be attributed to several factors. One possibility is that the petroleum-based polymer in Figures 12 and 14 has a different molecular structure than the other samples. This difference in molecular structure could lead to different physical properties, such as melting point and glass transition temperature, which could affect the way the polymer chains interact with each other.

Another possibility is that the petroleum-based polymer in Figures 12 and 14 has a different degree of crystallinity. Crystallinity is the degree to which a polymer is ordered at the molecular level. A higher degree of crystallinity can lead to a higher melting point and a stiffer polymer.^[18]

At high temperatures (500°C), the lifetime is very short for all samples, being less than a minute, as shown in Figures 9, 11, 13, and 15. However, the fact that a high temperature is required for their degradation implies a higher energy cost, as well as an economic cost.

Nevertheless, as observed in Figures 10, 12, 14, and 16, at low temperatures near room temperature, the samples have an extremely long lifetime. For instance, sample 1 with a weight loss of 60% has a lifetime of 8.91×10^{13} years when

the temperature is constant at 20°C (this lifetime is without considering any treatment).

At elevated temperatures, a similar behavior is observed in samples with different weight losses. This implies that the same amount of mass can be lost at different temperatures. Therefore, the lowest temperature can be chosen, which leads to lower energy consumption.

Understanding the kinetics and thermal degradation involved in controlling the thermal stability of a material is critical to predicting its overall service life; this is valuable because the costs of premature failure in actual end-use can be high.^[13]

IV. Conclusions

Based on TGA analysis, sample 1 exhibits superior thermal stability at high temperatures, as evidenced by its higher T_{dmax} value. However, sample 2 possesses a higher heat of fusion and maximum operating temperature. These properties suggest that sample 2 is more stable at lower temperatures, where melting and other thermal events are more likely to occur.

Therefore, the choice of which sample is more thermally stable depends on the specific application and temperature range of interest. Sample 1 may be a better choice for high-temperature applications, while sample 2 may be more suitable for low-temperature applications.

Regarding the lifetime of the samples, sample 4 exhibited the longest lifetime at lower temperatures, indicating its superior persistence in ambient conditions without thermal treatment; in contrast, sample 2 had the shortest lifetime, as shown in figure 17.

Conversely, at high temperatures, sample 4 exhibited the shortest lifetime, while sample 2 demonstrated the longest lifetime. This contrasting behavior highlights the complex relationship between temperature and material stability. Sample 4, which may possess favorable properties at low temperatures, becomes less stable under high-temperature conditions, resulting in a significantly reduced lifetime. On the contrary, sample 2, which may be less suited for low-temperature applications, showcases superior stability at high temperatures, leading to a prolonged lifetime.

Sample 4, a fabric bag, is currently being offered as a replacement for plastic bags. However, from a thermal study perspective, its behavior is like that of plastic bags. When compared to sample 2, which was found to be the most stable at low temperatures both in terms of T_{dmax} and lifetime, the values obtained are similar. In the case of T_{dmax} , sample 2 had an average value of 463°C across the different ramps, while sample 4 had a value of 461.9°C. Regarding lifetime, at a temperature of 20°C, sample 2 has a lifetime of 4.02×10^{10} years, and sample 4 has a lifetime of 2.6×10^{22} years, which means that sample 2 has the shortest lifetime.

Taking this into account, sample 4 would not be a very effective replacement for plastic bags if it persists in the environment for a longer time.

These findings emphasize the importance of comprehensive thermal characterization in materials synthesis and selection. By evaluating various parameters, such as T_{dmax} , melting temperature, and maximum operating temperature, the optimal material can be identified for specific applications and temperature ranges.

V. Acknowledgments

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