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ORIGINAL ARTICLE

Study of the Effect of Ultraviolet Exposure Duration on Polypropylene Properties

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ABSTRACT – Prolonged exposure to ultraviolet (UV) radiation significantly alters the chemical, thermal, and mechanical properties of polypropylene (PP), leading to degradation and reduced material performance. This study aims to investigate the effect of exposure length to UV on the chemical properties (functional and thermal) and mechanical properties (tensile strength) of PP. Specimens were subjected to UV exposure for 0 (control), 125, 175, 225, 275, 325, 375, and 625 days. FTIR analysis indicates UV exposure chemically degrades polypropylene (PP) by generating new oxygenated groups (–OH and C=O at 3368 cm^{-1} and 1586 cm^{-1}) and damaging its main molecular structure (C-H at 2949 cm^{-1}, 2867 cm^{-1}, and 841 cm^{-1}). Prolonged UV exposure alters the thermal properties of polypropylene (PP), as indicated by DSC analysis, which shows broadening and shifting of the melting peak (175–180 °C) due to crystallinity changes and increased oxidation. The mechanical properties also deteriorate, with a critical reduction in tensile strength, particularly between 225 and 375 days, indicating an accelerated degradation phase. After 625 days, tensile strength declines by approximately 59%, confirming the substantial impact of extended UV exposure on PP's durability.

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INTRODUCTION

PP is a versatile thermoplastic polymer widely used in various applications due to its excellent mechanical properties, low cost, and chemical resistance [1]. It plays an integral role in producing outdoor-use products such as garden furniture, automotive parts, storage containers, and agricultural equipment [2]. These applications often expose PP to direct sunlight, where UV radiation becomes a significant factor influencing its durability and performance [3].

Outdoor-use PP products are essential in daily life, providing practicality and sustainability in various settings. For instance, garden furniture ensures comfort in outdoor spaces, while automotive parts made from PP contribute to lightweight and fuel-efficient vehicles. However, prolonged exposure to UV radiation leads to the degradation of plastics, characterized by discoloration, surface cracking, loss of mechanical strength, and reduced lifespan [4]. This degradation not only impacts the functionality and aesthetics of the products but also generates economic and environmental concerns, as the premature failure of such products increases waste and replacement costs.

Several studies have explored the effects of UV exposure on the properties of various plastics. The research by [5] discusses the photodegradation of polyethylene (PE), polystyrene (PS), and PP under UV irradiation, highlighting significant changes in their mechanical properties. It notes that both materials experience a reduction in tensile strength and elongation at break due to the formation of free radicals and subsequent chain scission. These alterations are attributed to the aging effects induced by UV exposure, leading to a deterioration in the structural integrity of the polymers, which is critical for understanding their environmental impact as microplastics.

Similary, The study by [6] indicates that UVC irradiation significantly affects polypropylene (PP) and high-density polyethylene (HDPE), leading to changes in color and mechanical properties. However, polystyrene (PS) is not specifically mentioned in the findings. Other materials like polycarbonate (PC), polybutylene terephthalate (PBT), and low-density polyethylene (LDPE) exhibit smaller changes under UVC exposure. Dark colors in plastics may mask degradation processes but do not prevent chemical changes. Overall, PP and HDPE show notable degradation under UVC irradiation.

In addition, the previous study [7] primarily focused on polypropylene (PP) and polyethylene terephthalate (PET), revealing that UV exposure significantly degrades these materials, with clear polypropylene (CPP) showing the highest mass loss and carbonyl formation. Black polypropylene (BPP) exhibited less degradation due to carbon black's protective effect. Polyethylene (PE) was not specifically addressed in this research. Overall, UV irradiation leads to increased mass loss, crystallinity, and carbonyl indices in PP, indicating susceptibility to photooxidative degradation.

A study investigating the effects of UV-induced aging on the mechanical and thermal properties of polypropylene composites reinforced with palm nanodate fibers found that after 500 hours (approximately 21 days) of exposure, the

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tensile strength decreased by approximately 9% [8]. Another study reported that after 1000 hours (approximately 42 days) of accelerated aging, the tensile strength of polypropylene decreased by 67.42% [9]. However, in a study examining polypropylene sacks exposed to outdoor weathering for 21 days (approximately 500 hours), a tensile strength reduction of up to 88.3% due to photo-oxidation was observed [10].

Previous studies did not specifically investigate the effects of prolonged UV exposure (longer that previous exposure of previous research) on the chemical and mechanical properties of PP, nor did they examine the critical phase of PP degradation. Given the critical role of PP in outdoor applications and the detrimental effects of UV exposure, it is imperative to conduct further research on the influence of long UV radiation duration on the material properties of PP. This study aims to investigate the effect of prolonged UV exposure on the chemical (functional and thermal) and mechanical properties (tensile strength) of PP and examine the critical phase of PP degradation during those prolonged UV exposure. Such studies will provide valuable insights into the degradation mechanisms and guide the development of improved formulations or protective measures to enhance the longevity and performance of PP products in outdoor environments.

EXPERIMENTAL METHOD

Materials and Instruments

The material used in this study is polypropylene (PP) obtained from PT Itochu Indonesia. The PP has a melt flow index (MFI) of approximately 20–25 g/10 min, a density of 0.90–0.91 g/cm³ (ASTM D1505), and a melting temperature (Tm) of approximately 165 °C. The material is isotactic polypropylene with an isotacticity of 90–95%.

This work utilizes several pieces of equipment, including Differential Scanning Calorimetry (DSC) (4000 PerkinElmer, Massachusetts) for analyzing the thermal properties of PP test specimens, Fourier Transform Infrared (FTIR) spectroscopy (Frontier C96600 PerkinElmer, Massachusetts) for analyzing the functional group PP test specimens, Universal Testing Machine (UTM) (ETM-D, China) for measuring mechanical strength (tensile strength). The UV test chamber (Wowen, China) is used for simulating UV exposure to PP test specimens.

Method and Procedure

The PP was prepared into dumbbell-shaped test specimens, referring to ISO 527-2:2012, as shown in Figure 1. PP test specimens were placed into the UV test chamber (Wowen, China). Testing 1 day in UV test chamber equal to simulate 28-30 days for outdoors test. PP test specimens were exposed to UVB-313 with 0.67 W/m^2 lamp light intensity for 4 variations, such as 0 day (control), 175, 225, 275, 325, 375, and 625 days.

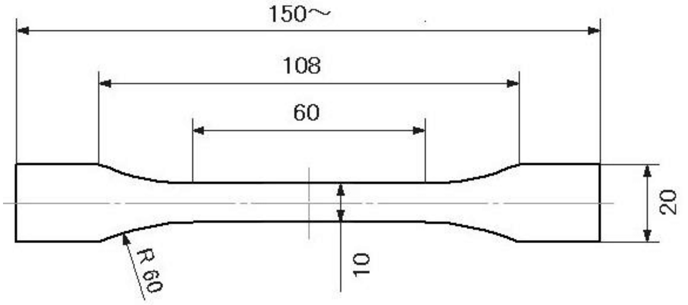

Figure 1. PP test specimen

Each PP test specimen variation was characterized for its functional group differences using Fourier Transform Infra Red (FTIR) spectroscopy (Frontier C96600 PerkinElmer, Massachusetts). The spectra were recorded in the range of 4000–650 cm^{-1} with a resolution of 4 cm^{-1}, and 32 scans were accumulated for each measurement.

The thermal properties of each PP test specimen were characterized using Differential Scanning Calorimetry (DSC) (4000 PerkinElmer, Massachusetts). The heating rate was set at 10°C/min, and the samples were scanned from 28°C to 428°C under a nitrogen atmosphere with a flow rate of 20 mL/min.

Comparison of mechanical properties (tensile strength) of PP test specimens measured using a Universal Testing Machine (UTM) (ETM-D, China). The tests were conducted at a crosshead speed of 50 mm/min, and the gauge length of the specimens was set according to ISO 527-2:2012.

RESULT AND DISCUSSION

Effect of UV to functional group characteristics of PP

The FTIR spectra displayed in the graph (Figure 2) illustrate the effect of UV exposure duration on the changes in % transmittance of functional groups in PP. The spectra represent four exposure durations: 0, 125, 375, and 625 days. These results reveal significant changes in the intensity and presence of absorption bands at various wavenumber, reflecting chemical structure modifications in PP due to photo-oxidative degradation.

At the initial condition (0 day), the spectrum exhibits strong absorption bands around 2949 cm^{-1} and 2867 cm^{-1}, corresponding to the asymmetric and symmetric stretching of C-H bonds in methyl ($-CH_3$) and methylene ($-CH_2$) groups [11]. After 125 days of exposure, the intensities of the bands at 2949 cm^{-1} and 2867 cm^{-1} decrease, signifying the onset of C-H bond degradation. The spectrum exhibits a weak band at 3368 cm^{-1} at 0 day, indicative of hydroxyl (-OH) groups, likely originates from moisture. But, the hydroxyl band at 3368 cm^{-1} begins to intensify after 125 days of exposure, indicating the formation of oxidation products such as alcohols or hydroperoxides. As stated by [12], the band at 3368 cm^{-1}, indicative of hydroxyl (-OH) groups, is associated with the oxidative degradation of polypropylene (PP) due to UV irradiation. This absorption is characteristic of the oxidation process in the polymer, suggesting that the presence of hydroxyl groups results from oxidative reactions rather than solely from moisture. The study indicates that the appearance of these groups is linked to the degradation of PP in the living organism environment, supporting the hypothesis of oxidation. Furthermore, the band at 1167 cm^{-1}, associated with C-O groups, becomes more prominent. The reaction of the formation of –OH and C-O bonds due to the oxidation reaction of the PP chain as shown in Figure 3 [13]. Additionally, characteristic bands such as those at 1455 cm^{-1} and 1375 cm^{-1} represent the C-H deformation of methyl and methylene groups of PP [14]. The dominant band at 841 cm^{-1}, associated with out-of-plane C-H vibrations in the crystalline structure of PP, indicates a relatively intact molecular structure [14], [15].

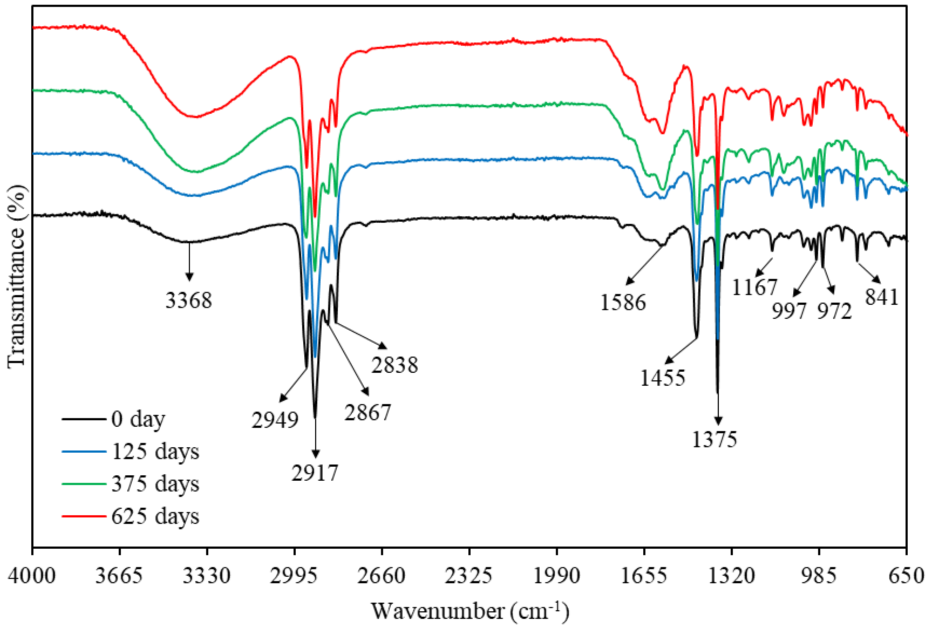

Figure 2. FTIR spectra of PP in various UV duration exposure

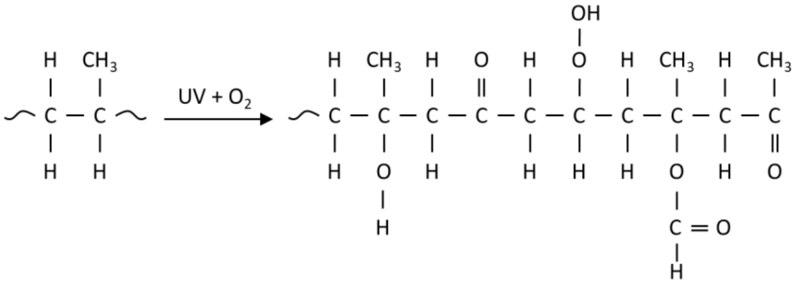

Figure 3. The reaction in PP chain due to the oxidation reaction (Adopted from [13])

At 375 days, the increase in intensity of the band at 3368 cm^{-1} becomes more pronounced, suggesting the accumulation of additional oxidation products. A new band at 1586 cm^{-1}, indicating the presence of carbonyl (C=O) groups, becomes evident, signifying oxidation of the polymer's main chain [16], [17]. The intensity of the band at 841 cm^{-1} diminishes, reflecting the degradation of the crystalline backbone structure of PP [15], [18]. The degradation (scission) reaction of PP by UV exposure in presence of oxygen that form C=O bond is shown in Figure 4. The oxidation process transpires not only on the secondary carbon-centered radical generated by chain scission but also engages with the primary volatile site on the adjacent chain [19].

After 625 days of UV exposure, photo-oxidative degradation progresses further. The intensity of the carbonyl band at 1586 cm^{-1} continues to rise, indicating more extensive oxidation. The hydroxyl band at 3368 cm^{-1} becomes highly dominant, reflecting the formation of oxygenated degradation products [12]. The declining intensities of the bands at

2949 cm^{-1}, 2867 cm^{-1}, and 841 cm^{-1} indicate severe damage to C-H bonds and the crystalline structure of the polymer [11].

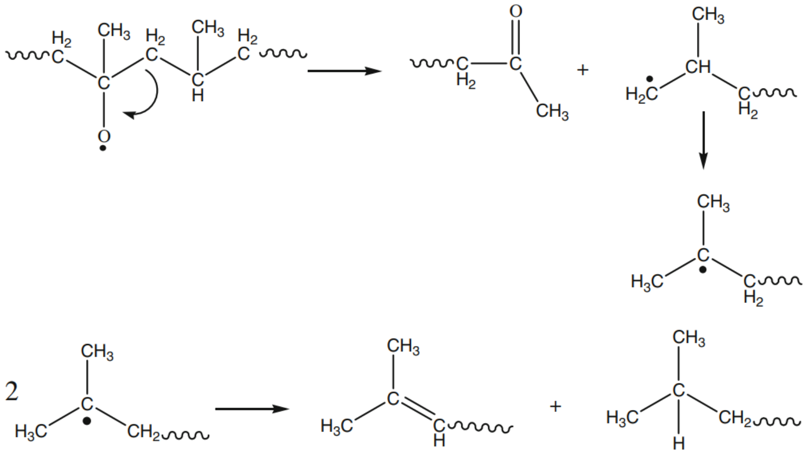

Figure 4. Scission reaction of PP by UV exposure in presence of oxygen (Adopted from [19])

Overall, the FTIR spectra demonstrate that UV exposure induces chemical degradation in PP, characterized by the formation of new oxygenated groups (hydroxyl and carbonyl) and the deterioration of the primary molecular structure. These findings confirm that the chemical stability of PP significantly decreases with prolonged UV exposure. Based on the research [20], the oxidation rate of PP increased significantly after 700 hours and the oxygen uptake at 3000 hours reached 3000 mmol/kg. This increase in oxygen update allows the formation of more -OH, C-O, C-H, C=O bonds. This is qualitatively confirmed from the FTIR spectra in Figure 2. Ultimately, more PP chain breaks and decreased tensile strength (mechanical properties) of PP will be discussed in the next section.

Effect of UV to thermal properties of PP

The DSC spectra presented in Figure 5 illustrate the effect of UV exposure duration on the thermal behavior of PP. The analysis considers four UV exposure conditions, highlighting significant changes in the material's thermal properties. The key changes observed include variations in the melting behavior (endothermic) and possible recrystallization or oxidation (exothermic) events.

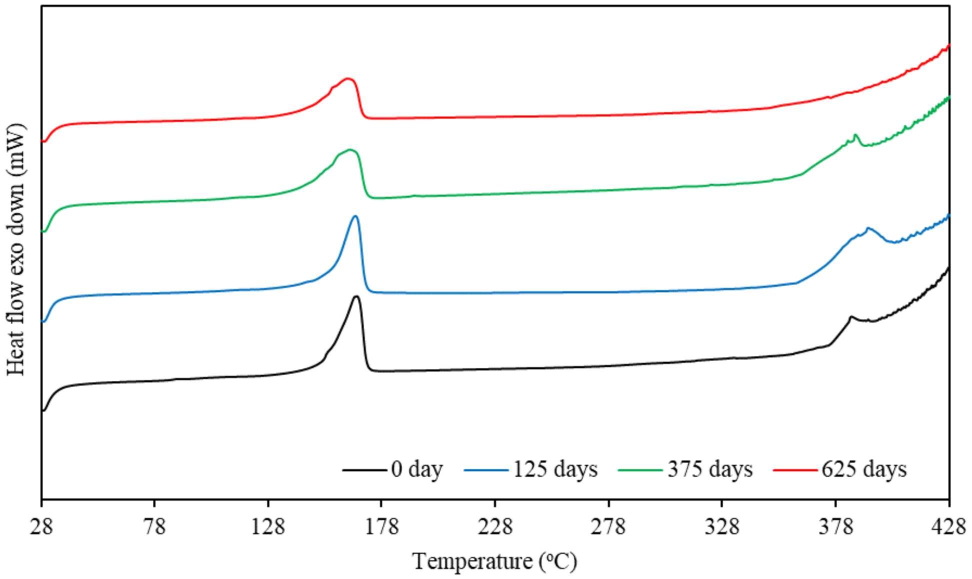

Figure 5. Degradation reaction of PP by UV exposure in present of oxygen

For the initial condition (0 days), an endothermic peak appears around 175–180 °C, indicating the melting of the crystalline phase of PP. This is consistent with the melting behavior of non-degraded PP, as previously reported in literature [21], [22]. As UV exposure increases, the peak broadens and shifts, suggesting degradation-induced changes in crystallinity. Additionally, small exothermic peaks appear in aged samples, which could indicate recrystallization of shorter polymer chains or secondary crystallization due to molecular scission and oxidation. At temperatures above 400

°C, a rapid increase in heat flow is observed, corresponding to the thermal decomposition of PP. This degradation is likely due to chain scission and oxidation reactions, as also reported in previous studies [23], [24].

After 125 days of UV exposure, the endothermic peak at 175–180 °C slightly shifts and broadens, indicating a disruption in the crystalline phase of PP due to early-stage photo-oxidation and polymer chain scission [25], [26]. Above 400 °C, the heat flow increases more steeply compared to the 0-day condition, suggesting the onset of thermal degradation and oxidation of the polymer backbone.

At 375 days of UV exposure (green), the melting peak further broadens, reflecting increased disorder in the crystalline phase. Additionally, a small exothermic feature may suggest the recrystallization of shorter polymer chains or the formation of oxidation-induced crystalline regions. Above 400 °C, the heat flow increase is more pronounced, indicating intensified polymer degradation and oxidative fragmentation of C-C bonds [27], [28].

After 625 days of UV exposure (red), the most substantial changes occur. The melting peak becomes sharper and slightly shifts, indicating an increase in crystallinity due to molecular rearrangement of degraded chains. However, at higher temperatures (>400 °C), a drastic heat flow increase is observed, reflecting severe thermal decomposition involving chain scission, oxidation, and fragmentation of long polymer chains into lower molecular weight products.

Overall, the DSC spectra demonstrate that UV exposure leads to photo-oxidative degradation, altering both the crystallinity and thermal stability of PP. The 175–180 °C range highlights changes in the crystalline phase, while temperatures above 400 °C indicate progressive thermal decomposition. These effects are consistent with oxidation-induced degradation, chain scission, and structural rearrangements caused by prolonged UV exposure.

Effect of UV to tensile strength of PP

Table 1 illustrates the effect of UV exposure duration on the tensile strength of polypropylene (PP), while Figure 6 depicts the relationship between UV exposure duration and the decline in tensile strength. Tensile strength is measured in N/mm², and the UV exposure duration ranges from 0 to 625 days. The data is accompanied by standard deviation values to indicate measurement variations. The results demonstrate a significant reduction in tensile strength with increasing UV exposure duration.

Table 1. Effect of UV to tensile strength of PP

Exposure duration (days)	Tensile strength (N/mm^2)	Deviation standard
0	18.530	1.398
125	17.242	1.655
175	16.529	0.315
225	15.617	0.243
275	14.246	0.236
325	11.247	0.216
375	9.436	0.276
625	7.550	0.600

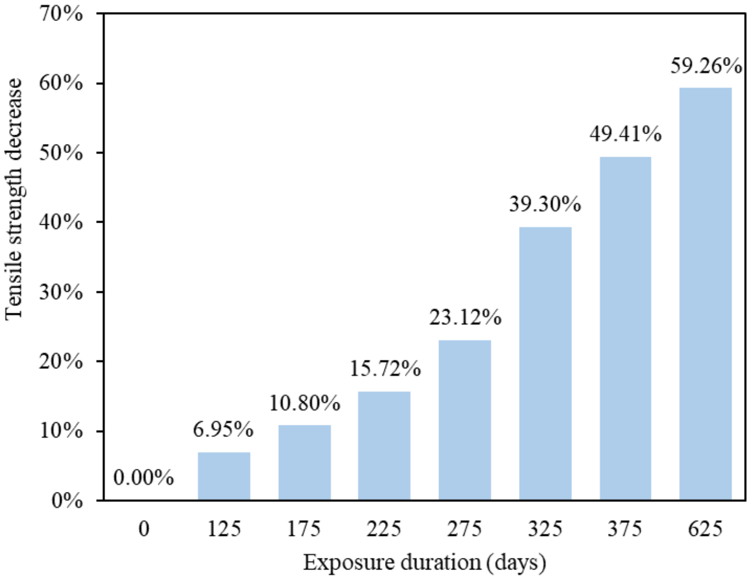

Figure 6. Effect of UV exposure to tensile strength decrease of PP

At the initial condition (0 day), the tensile strength of PP was recorded at 18.530 N/mm², with a standard deviation of 1.398. This value reflects the material in an optimal condition, unaffected by UV exposure. However, after 125 days of exposure, the tensile strength decreased to 17.242 N/mm² (7% reduction), with a slightly higher standard deviation of 1.655. This indicates the onset of early damage, although the reduction is relatively minor, as the material requires an induction period before significant degradation occurs.

A sharper decline in tensile strength was observed after 375 days of exposure, where the value dropped drastically to 9.436 N/mm², approximately 49% of the initial value. The standard deviation of 0.276 suggests significant decreasing of tensile strength of PP. This decrease aligns with the photo-oxidation process, which causes molecular chain scission and weakens the material's mechanical properties. A study by [29] explains that photodegradation in PP tends to escalate exponentially after the induction period, particularly when the material's initial resistance to UV exposure begins to diminish.

The critical phase of degradation can be identified between 275 and 325 days, where the tensile strength loss accelerates significantly. Based on Figure 6, the percentage of tensile strength decrease rises from 23.12% at 225 days to 39.30% at 325 days, indicating a rapid breakdown of the material's structural integrity. This phase corresponds to the progression from the induction period to an advanced stage of degradation, where chain scission reactions become dominant, leading to embrittlement and surface cracking. The deviation standard values remain relatively low in this phase, suggesting a consistent degradation trend across samples.

After 625 days of exposure, the tensile strength of PP further decreased to 7.550 N/mm², approximately 59% of the initial value. A standard deviation of 0.600 indicates significant decreasing of tensile strength of PP. This significant reduction highlights the cumulative impact of prolonged UV exposure, including the formation of microcracks on the surface and changes in the material's chemical properties. UV-induced degradation leads to extensive crosslinking and oxidation, resulting in structural damage that diminishes the material's mechanical strength [30], [31].

This data underscores the importance of UV degradation protection in practical applications of PP, such as through the incorporation of UV stabilizers. A study by [32] demonstrated that photostabilizer additives, specifically UV light absorbers (UVA), are employed to protect polymer materials from UV degradation. Thus, the data presented in the Table 1 not only provides insight into the direct effects of UV exposure but also emphasizes the need for developing mitigation strategies to enhance the durability of PP in environments with high sunlight exposure.

This experiment is in line with the research of [33]. The results showed that PP is the most sensitive polymer to ultraviolet degradation, which results in a decrease in the tensile strength and hardness of the material, resulting in the formation of cracks on the surface of PP plastic. In addition, research by [34] states that sunlight and UV radiation can reduce the tensile strength of polystyrene (PS) plastics. This proves that degradation due to UV can affect various types of plastics.

CONCLUSION

This study demonstrates that prolonged UV exposure significantly affects the chemical, thermal, and mechanical properties of polypropylene (PP). FTIR analysis reveals that UV exposure chemically degrades polypropylene (PP) by generating new oxygenated groups (–OH and C=O at 3368 cm^{-1} and 1586 cm^{-1}) and damaging its main molecular structure (C-H at 2949 cm^{-1}, 2867 cm^{-1}, and 841 cm^{-1}). Prolonged UV exposure alters the thermal properties of polypropylene (PP), as indicated by DSC analysis, which shows broadening and shifting of the melting peak (175–180 °C) due to crystallinity changes and increased oxidation. After 625 days, a significant rise in heat flow above 400 °C reflects severe thermal degradation, confirming that extended UV exposure accelerates polymer decomposition. The most critical finding is the accelerated degradation of tensile strength, which occurs after approximately 225-375 days of UV exposure, marking the transition from an induction phase to rapid mechanical deterioration. Beyond 375 days, degradation continues at a slower rate, ultimately reducing tensile strength by 59% after 625 days.

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