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Improving the Durability and Oxidative Stability of High-Density Polyethylene (HDPE) Using UV-531 and UV-783 Additives

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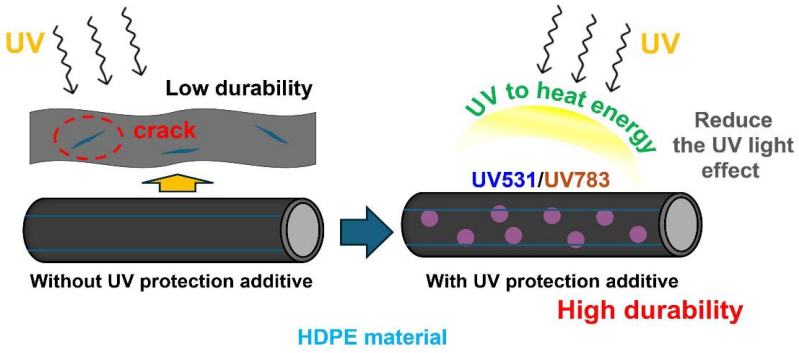
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Abstract
This study investigates the effects of two ultraviolet (UV) stabilizers, UV-531 and UV-783, on the durability, oxidation stability, and dimensional stability of high-density polyethylene (HDPE) materials. HDPE samples were prepared with varying additive contents (1% and 2% by weight) for 2 types of UV additives to evaluate HPDE's resistance against UV-induced degradation. These results found that HPDE with UV additives of UV-531 and UV-783 with 1-2 wt.% showed good longitudinal reversion, oxidation induction time (ISO 11357), and weathering resistance compared to HPDE without using UV additives. Inherently, we found that both UV-531 and UV-783, stabilizers improved the oxidation induction time (OIT) and tensile strength retention after accelerated aging. More importantly, the UV-531 additive exhibited superior stabilization performance compared to UV-783, particularly at 1.0 wt%, showing a 30% increase in OIT and maintaining over 95% tensile strength after UV exposure. The findings demonstrate the effectiveness of UV-531 as an efficient stabilizer for outdoor HDPE applications requiring long-term durability.

Keywords: HDPE, UV Stabilizer, Weathering Resistance, Oxidation Induction Time, UV-531, UV-783

Graphical abstract



1. Introduction

High-density polyethylene (HDPE) is one of the most important polyolefins in modern industry, valued for its high strength-to-density ratio, chemical resistance, and ease of processing. It is widely used in outdoor applications such as pipes, geomembranes, containers, and agricultural films [1-2]. However, prolonged exposure to ultraviolet (UV) radiation and environmental oxygen leads to photo-oxidative degradation, resulting in polymer chain scission, cross-linking, surface cracking, and discoloration [3-4]. Such degradation severely compromises mechanical integrity and limits service life, posing challenges for applications requiring long-term weather resistance.

Over the past few decades, extensive research has been conducted to enhance the UV and thermal stability of HDPE through the incorporation of stabilizing additives. Traditional approaches have employed hindered amine light stabilizers (HALS), UV absorbers, and antioxidants either individually or in synergistic combinations [5-6]. HALS compounds, such as Tinuvin 770 or Chimassorb 944, are effective in trapping free radicals and delaying oxidative chain reactions, while UV absorbers like benzophenones and benzotriazoles (e.g., UV-531, UV-326) absorb harmful UV energy and dissipate it as heat [7]. These stabilizers have been shown to improve oxidation induction time (OIT), tensile strength retention, and color stability under accelerated aging conditions [8-9].

Despite these advances, comparative studies focusing on the performance differences among specific UV stabilizers under identical test conditions remain limited. Most prior works have investigated either a single additive or general stabilization mechanisms rather than conducting a direct performance evaluation between different UV stabilizer chemistries and concentrations. For instance, Kim et al. [10] reported improvements in OIT and surface morphology of HDPE with HALS-based additives, while Li and Zhao et al. [11] emphasized the synergistic role of combined UV absorber–antioxidant systems. However, quantitative

comparisons between benzophenone-type (e.g., UV-531) and HALS-type stabilizers (e.g., UV-783) under the same degradation protocols are still scarce in the literature.

In addition, recent research in sustainable polymer design and circular economic strategies has much attention focus on prolonging material lifetime and enhancing recyclability rather than solely improving initial performance [12-13]. From this perspective, improving the long-term weatherability and oxidation resistance of HDPE can reduce replacement frequency, material waste, and environmental footprint, aligning with global sustainability goals.

In this work, we study the effects of two ultraviolet stabilizers—UV-531 (a benzophenone-type UV absorber) and UV-783 (a hindered amine light stabilizer)—on the durability, oxidation stability, and dimensional stability of HDPE. HDPE samples containing different additive concentrations (1 wt% and 2 wt%) were analyzed through standardized testing methods to assess resistance to UV-induced degradation. The novelty of this research lies in its comparative and quantitative assessment of distinct UV stabilizer chemistries and their influence on the physicochemical aging behavior of HDPE over time. The outcomes not only provide a practical guideline for selecting stabilizers in outdoor HDPE applications but also contribute to the broader framework of circular economy in polymer materials, where extending product lifespan is a key sustainability objective.

2. Experimentals

2.1. Materials

High-density polyethylene (HDPE, Model HS 3490LS), supplied by Borouge, Singapore, was used as the base polymer for HDPE pipe production. The commercial HDPE has a density of 949 kg m^{-3} (without additives) and a melt flow rate (MFR) of 0.25 g/10 min. Industrial carbon black (Model PN 050ANF, ~50% purity, China) was incorporated to improve the pipe's durability, UV shielding, and color uniformity. Two types of ultraviolet (UV) stabilizers were selected for this study included UV-531 (2-Hydroxy-4-n-octoxybenzophenone, chemical formula $C_{21}H_{26}O_3$, CAS No. 1843–05–6, China), a benzophenone-type UV absorber that protects polymer chains by absorbing high-energy UV radiation and converting it into harmless thermal energy. UV-783 (mixture of bis(2,2,6,6-tetramethyl-4-piperidyl) sebacate and methyl 1,2,2,6,6-pentamethyl-4-piperidyl sebacate, approximate chemical formula $C_{40}H_{80}N_2O_8$, CAS No. 65447–77–0, China), a hindered amine light stabilizer (HALS) that scavenges free radicals generated during photo-oxidation and interrupts the degradation chain reactions. All raw materials were used as received, without any further purification or pretreatment.

2.2.Experimental manufacturing of Investigation of two types of UV stabilizers for enhancing HDPE durability

The overall process for producing HDPE pipes is carried out with steps such as commercial HDPE pellets (HS 3490LS, Borouge, Singapore) were first dried at 85 °C for 45 min in a dehumidifying dryer to remove moisture and prevent hydrolytic degradation during processing. Subsequently, the dried HDPE was physically blended with carbon black (PN 050ANF, China) and one type of UV stabilizer—

either UV-531 **or** UV-783—at the desired additive concentrations of 1 wt% and 2 wt%**.** Each UV additive was evaluated individually, without combination, to determine its independent effect on material performance. The blended mixtures were prepared in a high-speed mixer for 10 min at 500 rpm to ensure uniform dispersion before extrusion. The compounded materials were then processed using a single-screw extruder. During extrusion, the temperature profile of the barrel was maintained between 170 °C and 200 °C from the feeding to the die zone to ensure complete melting and homogeneous mixing. A vacuum degassing system removed entrapped air and volatiles, while a metal mesh filter was installed at the die entrance to eliminate impurities. The molten polymer was extruded through a circular die head to form the pipe shape. After exiting the die, the hot pipe was passed through a vacuum calibration and cooling tank**,** where a water spray system (15–18 °C) was used to rapidly cool and solidify the pipe, maintaining precise dimensional stability. The cooled pipe was then pulled by a tractor unit to control wall thickness and surface smoothness and finally coiled using an automatic winder for storage and further testing. A HDPE sample (without UV stabilizer) was also produced under identical conditions and used as the control for comparison. The detailed formulations and sample codes are provided in Table 1.

Table 1 Formulas of the HDPE containing different UV additives (%wt)

Sample	HDPE	UV531	UV783	Carbon black	Total	**Denote sample**
HDPE/C	97.5	–	–	2.5	100	S0
HDPE/C/UV531	97.5	1.0	-	2.5	100	S-UV531-1%
HDPE/C/UV531	96.5	2.0	-	2.5	100	S-UV531-2%
HDPE/C/UV783	97.5	-	1.0	2.5	100	S-UV783-1%
HDPE/C/UV783	96.5	-	2.0	2.5	100	S-UV783-2%

2.4. Characterizations

Carbon black content determination

The carbon black content of the HDPE/C and HDPE/C/UV531+AO1010 samples was determined according to ASTM D1603**.** Pre–weighed specimens were placed in tared combustion boats and introduced into a tube furnace at 600 °C under a continuous flow of dry, oxygen–free nitrogen. After the prescribed residence time, the combustion boats containing residual carbon were cooled under nitrogen purge and reweighed. The boats were then transferred to a muffle furnace at 600 °C to oxidize the carbon residue completely. Upon complete oxidation, the combustion boat was cooled to room temperature and weighed again. The carbon black content for each specimen was calculated using the formula (1):

$$\text{Carbon black (\%)} = \frac{W_r - W_0}{W_s} \times 100 \qquad (1)$$

(Where W_r is the mass of the residue from the tube furnace, W_0 is the mass of the residue from the muffle furnace, W_s is the original mass of the sample)

Longitudinal reversion analysis

The longitudinal reversion of the HDPE/C and HDPE/C/UV531+AO1010 specimens was evaluated in accordance with ISO 2505:2005. Test specimens consisted of pipe sections with a length of 200±20 mm, marked circumferentially with two fiducial lines at a precise distance of 100 mm. The initial distance between the marks (L_0) was measured after conditioning at 23±2 °C, then specimens were immersed in a heated liquid bath at a specified temperature. After heating and re-reconditioning to 23±2 °C, the final distance between the marks (L) was measured. The percentage of longitudinal reversion (R_L) for each specimen was calculated using the formula (2):

$$R_L(\%) = \frac{L_0 - L}{L_0} \times 100 \qquad (2)$$

Oxidation induction time (OIT)

Thermal stability and oxidation resistance of the HDPE/C and HDPE/C/UV531+AO1010 samples were investigated using a DSC–3 Mettler Toledo (Switzerland). Samples were heated from 25 to 200 °C under 1 atm oxygen pressure with a heating/cooling rate of 10 °C min^{-1}, according to ISO 11357. The oxidation induction time (OIT) when adding UV531 and AO1010 additives was determined using the tangent method.

Artificial weathering test

Weather resistance of the HDPE/C and HDPE/C/UV531+AO1010 samples is evaluated according to Vietnam standard 7699–2–5:2011 (equivalent to IEC 60068–2–5:2010). The test specimens were placed in a Xenon test chamber (Model HT–HD150L, China) for 1440 h, simulating the solar radiation spectrum, with a total radiant exposure of 5.0 GJ m^{-2}, corresponding to approximately 14–15 yr of outdoor service. After exposure, the tensile strength of the specimens was measured using a universal testing machine (Gotech, Model AI 7000M, China) to evaluate the durability of HDPE materials.

3. Results and discussion

3.1. Effect of UV531 and UV783 on Carbon black content of UV-Stabilized HDPE

In this study, the carbon black content of various HDPE samples was determined following the ASTM D1603 standard to ensure accuracy and objectivity. The analyzed samples included the reference sample M0 and the UV-stabilized samples S-UV531-1%, S-UV531-2%, S-UV783-1%, and S-UV783-2%, where the sample codes indicate the type of UV stabilizer (UV531 or UV783) and its weight

percentage added to HDPE. The analytical results for each sample are presented in **Figure 3.1.**

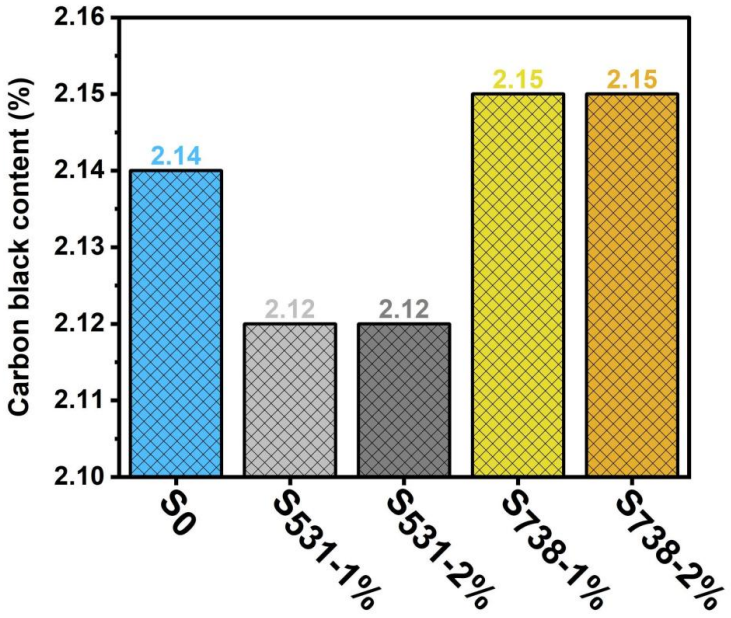


Figure 3.1. Carbon black content analysis of HDPE samples

The results show that all HDPE samples exhibited a carbon black content ranging from 2.12% to 2.15%**,** with a variation of only 0.03% compared to the reference sample (S0). This narrow deviation indicates excellent consistency and uniformity in the blending and compounding processes, reflecting strict control during both material preparation and analysis [14]. The carbon black contents of S-UV531-1%, S-UV531-2%, S-UV783-1%, and S-UV783-2% were all close to that of S0 (2.14 wt.%), confirming the stability of carbon dispersion within the HDPE matrix. Such stability ensures the reproducibility of sample composition, which is crucial for maintaining consistent mechanical and optical performance [15]. In accordance with industrial standards for rubber, elastomeric composites, and polymer-based materials, a carbon black level within this range is considered optimal to ensure essential technical properties such as abrasion resistance, UV protection, and thermal stability [16]. Moreover, the carbon black content significantly affects the light reflectivity and surface color uniformity of the polymer, contributing to enhanced oxidation resistance and color stability [13].

3.2. Effect of UV531 and UV783 on longitudinal reversion of UV-Stabilized HDPE

The longitudinal reversion of HDPE pipe specimens was evaluated to indicator of the thermal dimensional stability of thermoplastic materials when subjected to heat during service life. The dimensional stability of HDPE is directly associated with its crystalline structure, molecular weight distribution, and processing [15]. The measured results for all test samples are summarized in **Table 3.1** and illustrated in **Figure 3.2.** These data provide insight into how the addition of UV stabilizers (UV-531 and UV-783) at different concentrations influences the heat-induced dimensional changes of HDPE, serving as a key criterion for long-term performance evaluation in outdoor and pressurized piping applications [13].

Table 3.1. Results of Longitudinal Reversion Analysis of HDPE Samples

Sample	Additives	Additive content (wt%)	Longitudinal change after 1 hour at 110 °C (%)
S0	Without additives	0%	1.26
S- UV531-1%	UV-531	1%	1.23
S-UV531-2%	UV-783	1%	1.25
S-UV783-1%	UV-531	2%	1.25
S-UV783-2%	UV-783	2%	1,24

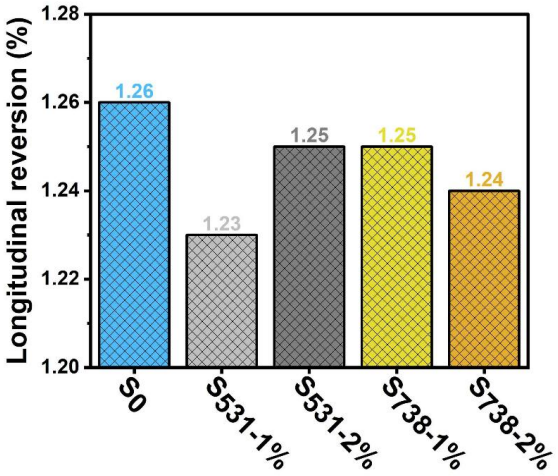


Figure 3.2. Effect of UV531 and UV783 on longitudinal reversion of UV-Stabilized HDPE

It can be seen that the reference sample S0 (without UV stabilizer) exhibited the highest dimensional change of 1.26%, whereas samples containing UV additives showed slightly lower shrinkage values, ranging from 1.23% to 1.25%. Among them, S-UV531-1% displayed the lowest reversion value (1.23%), suggesting that UV-531 enhances the polymer's structural stability more effectively than the unstabilized sample. The S-UV531-2% and S-UV783-1% samples both recorded 1.25%, demonstrating a similar improvement compared to S0. Meanwhile, S-UV783-2% showed a value of 1.24%, comparable to S-UV531-2%, indicating that increasing UV-783 concentration did not significantly improve or degrade dimensional stability.

From these data, we can see that the use of UV stabilizers (UV-531 and UV-783) not only protects HDPE from UV-induced photo-oxidation but also contributes to the stabilization of the polymer structure under thermal stress [13,15]. However, the differences observed among the stabilized samples suggest that the influence of the additives on this property is relatively less and may be affected by other factors such as initial crystallinity, dispersion uniformity of additives within the polymer matrix, or differences in the degradation pathways of the stabilizers [2]. From these results, it can be concluded that adding UV stabilizers at 1–2 wt% does not negatively impact the dimensional stability of HDPE. The formulation containing 1 wt% UV-531 yielded the excellent thermal stability performance, although the difference compared with other compositions was minimal. This demonstrates flexibility in addition to the type and concentration of UV stabilizers to meet specific application requirements in long-term outdoor use of HPDE.

3.3. Effect of UV531 and UV783 on Weathering Resistance of HDPE with and without UV Stabilizers

Weathering resistance is one of the most critical factors determining the long-term retention of the mechanical and morphological properties of polymeric materials when exposed to outdoor environments. Prolonged ultraviolet (UV) radiation, temperature fluctuations, and humidity can accelerate photo-oxidative degradation**,** leading to chain scission, embrittlement, and surface cracking [15-16]. In this experiment the weathering resistance of HDPE samples was evaluated using a total UV irradiation energy of 5 GJ/m²**.** This exposure level corresponds to approximately 14–15 years of natural outdoor weathering under standard environmental conditions [2, 13]. The test aims to simulate the long-term degradation behavior of HDPE materials and assess the protective effectiveness of UV stabilizers in maintaining polymer integrity during extended service life.

Table 3.1. Evaluation of the effect of uv531 and uv783 on weathering resistance of HDPE with and without UV stabilizers

Sample	Additive type	Additive content (wt%)	Morphological observation after testing	Initial tensile strength (MPa)đầu (MPa)	Tensile strength after testing (MPa)	Tensile strength retention (%)
S0	Without additives	0	No visible deformation or color alteration observed	29.53	26.67	90.31
S- UV531-1%	UV-531	1	No visible deformation or color alteration observed	31.72	30.17	95.11
S- UV783-1%	UV-783	1	No visible deformation or color alteration observed	30.84	27.42	88.91
S- UV531-2%	UV-531	2	No visible deformation or color alteration observed	30,41	28.71	94.40
S- UV783-2%	UV-783	2	No visible deformation or color alteration observed	30,67	28.68	93.51

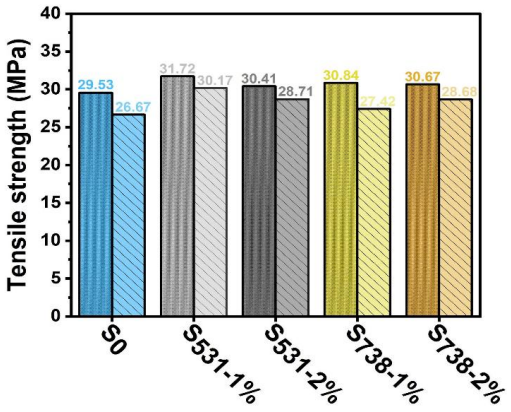


Figure 3.1 Effect of UV531 and UV783 on Weathering Resistance of HDPE with and without UV Stabilizers

The results presented in **Table 3.2** and **Figure 3.3** show that all samples exhibited without visible deformation, surface cracking, or color change after the weathering test can be detected. This finding indicates that the HDPE matrix possessed high intrinsic quality and inherent weatherability, even in the absence of stabilizers [15]. However, a clear distinction was observed in terms of mechanical property degradation. The control sample (M0) showed a decrease in tensile strength from 29.53 MPa to 26.67 MPa, corresponding to a 9.69% reduction. This significant loss demonstrates the susceptibility of HDPE to UV-induced chain scission and oxidation reactions, which progressively deteriorate the polymer network [2,13]

In contrast, UV-stabilized samples exhibited superior mechanical retention performance, particularly those containing UV-531. The sample S-UV531-1% retained 95.11% of its original tensile strength, while S-UV531-2% maintained 94.4%, indicating excellent resistance to photodegradation. Conversely, UV-783 formulations showed lower efficiency: S-UV783-1% retained 88.91%, the lowest among the stabilized samples, whereas S-UV783-2% achieved 93.51%, demonstrating a concentration-dependent effect.

These results confirm that UV-531 (benzotriazole-based stabilizer) provides superior photostabilization compared to UV-783 (HALS-based stabilizer). A 1 wt% concentration of UV-531 was sufficient to achieve optimal protection, while UV-783 required higher loading to reach comparable performance. The results align with previous findings that UV absorbers, such as UV-531, effectively dissipate harmful radiation energy and suppress free-radical formation, whereas HALS compounds act primarily through radical scavenging mechanisms that depend strongly on concentration and dispersion uniformity [16].

Overall, these results show all UV-stabilized HDPE samples met morphological and mechanical standards after accelerated weathering, confirming the efficacy of UV stabilizers in prolonging material lifespan. Among them, UV-531 at 1 wt% demonstrated the most effective balance between stabilization performance and additive economy compared to UV-531 sample and without UV additives, suggesting the optimal UV531 additive suitable for long-term outdoor HDPE applications.

3.4. Effect of uv531 and uv783 on on the oxidation induction time (oit) of HDPE materials

Table 3.2 Effect of UV531 and UV783 on on the Oxidation Induction Time (OIT) of HDPE Materials

Sample	Additive type	Additive content (%wt)	Oxidation Induction Time (OIT) 200 °C (min:s)
S0	Without UV additive	0	16:20
S- UV531-1%	UV-531	1	21:10
S- UV783-1%	UV-783	1	19:30
S- UV531-2%	UV-531	2	21:30
S- UV783-2%	UV-783	2	19:40

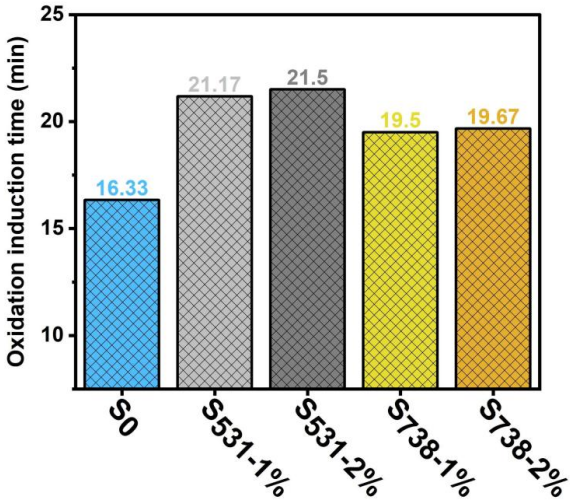


Figure 3.2 Effect of UV531 and UV783 on on the Oxidation Induction Time (OIT) of HDPE Materials

As shown in **Table 3.3** and **Figure 3.4**, the addition of UV stabilizers had a positive effect on the oxidative stability of HDPE. The oxidation induction time (OIT) reflects the material's resistance to thermal-oxidative degradation; a higher OIT value indicates greater thermal stability and improved resistance to long-term aging, particularly under outdoor exposure conditions [3,16]. The OIT parameter provides valuable insight into the effectiveness of UV stabilizers in inhibiting oxidative reactions within the polymer matrix and serves as a reliable indicator of the expected service lifetime of HDPE materials under prolonged environmental exposure. It can be seen that the unstabilized sample (M0) exhibited an OIT of 16 min 20s, while all samples using UV additives in the HPDE showed significantly higher values. For example, the S-UV531-1% and S-UV531-2% recorded OITs of 21 min 10s and 21 min 30s, respectively—about 30% higher than the control. This improvement indicates that UV-531 enhances oxidation resistance indirectly by absorbing UV radiation and thereby reducing the formation of free radicals responsible for polymer chain scission [13]. The S-UV783-1% and S-UV783-2 % showed OITs of 19 min 30s and 19 min 40s, respectively, representing an 18–20% increase compared with S0. Although UV-783 was less effective than UV-531, it still contributed positively to the thermal stability of HDPE [14]. When increasing the stabilizer concentration from 1 wt % to 2 wt % produced no significant gain in OIT for either additive, suggesting that thermal stabilization tends to plateau around 1 wt % or that additive dispersion within the HDPE matrix has reached its optimum limitation [15].

It is worth noting that UV-531 is a benzotriazole-type UV absorber, while UV-783 is a hindered amine light stabilizer blend. Their distinct stabilization mechanisms—UV absorption versus radical scavenging—explain the differences in performance [16]. To comprehensively evaluate the effects of UV additives (UV-531 and UV-783) and their concentrations on the characteristics of HDPE, summary of the properties of virgin HDPE and HDPE materials containing UV-531 and UV-783 additives were shown in **Table 3.4**.

Firstly, the UV-531 additive exhibited superior overall performance across three critical parameters: thermo-geometric stability (ΔL), oxidative induction time (OIT), and retention of tensile strength after aging. Notably, a concentration of 1 wt.% UV-531 was identified as the optimal formulation in terms of both technical efficiency and cost-effectiveness, with no significant improvement observed at 2 wt.% unless specifically required. Conversely, UV-783 showed moderate enhancement, particularly at higher concentrations, suggesting that its optimal dosage should exceed 1 wt.%. Both additives did not adversely affect thermal stability or carbon black content.

Secondly, when comparing these findings with previous studies, the dimensional change (ΔL) values of all UV-modified samples (1.23–1.26%) remained nearly identical to the control sample (M0 = 1.26%), indicating negligible impact on the geometrical stability of HDPE under thermal stress. This result is corresponding to [11], indicated that UV stabilizers primarily influence photo-oxidative properties while having minimal effect on the original dimensional stability of HDPE.

Thirdly, the control sample (S0) exhibited an OIT of 16 min 20s, whereas UV-modified samples demonstrated marked improvement. For example, the UV-531

(M-UV531-1%: 21:10 min; M-UV531-2%: 21:30 min) outperformed UV-783 (M-UV783-1%:: 19:30 min; M-UV783-2%:: 19:40 min), confirming UV-531's stronger antioxidant effect. This result corresponds to the previous study [13] that found the superior stabilization of UV-531 to its high UV absorption capacity and uniform dispersion within polyolefin matrices.

In terms of mechanical retention, the control (S0) retained 90.31% tensile strength, while UV-531 samples exceeded 94% outperforming UV-783 samples that effectiveness appeared concentration- and dispersion-dependence. These findings are consistent with the previous work [16] emphasizing that stabilizer performance is governed not only by chemical structure but also by dosage and synergism with other additives. From above results, we can see that the UV-531 demonstrated superior photo-oxidative stability compared with UV-783, reflected by higher OIT and post-aging tensile strength. Nevertheless, UV-783 at 2 wt.% (M2) also yielded favorable outcomes, with tensile strength retention (93.51%) above the control. These findings are consistent with the prevailing consensus that UV stabilizers enhance HDPE longevity by mitigating chain scission and improving oxidative resistance [15-16].

Table 3.3 Summary of the properties of virgin HDPE and HDPE materials containing UV-531 and UV-783 additives

Sample	UV Additives type	Additive contents (%wt)	ΔL (%)	OIT (min:s)	Tensile strength after aging test (%)	Carbon black content (% wt.)
M- UV531-1%	Without UV additive	0	1.26	16:20	90.31	2.14
M- UV783-1%	UV-531	1	1.23	21:10	95.11	2.12
M- UV531-2%	UV-531	2	1.25	21:30	94.40	2.12
M- UV783-2%	UV-783	1	1.25	19:30	88.91	2.15
M- UV531-1%	UV-783	2	1.24	19:40	93.51	2.15

4. Conclusions

This work studied the effects of two ultraviolet (UV) stabilizers—UV-531 and UV-783—on the durability, oxidation stability, and dimensional stability of high-density polyethylene (HDPE). It was confirmed that the incorporation of both stabilizers significantly enhanced the oxidation induction time (OIT) and tensile strength retention after UV exposure compared to without using UV additives. Interestingly, UV-531 demonstrated superior stabilization performance, especially at 1wt%, but achieving a 30% improvement in OIT and maintaining over 95% of tensile strength after accelerated weathering. These results highlight UV-531 as a promising and efficient stabilizer for outdoor HDPE applications that demand long-term environmental resistance and mechanical integrity. The study provides a

practical basis for optimizing additive formulations to extend the service life of polymeric materials in harsh conditions.

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