Effects of Ultraviolet Radiation on Recycled and Virgin HDPE Corrugated Pipes Used in Road Drainage Systems

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Abstract

High-density polyethylene (HDPE) pipe is one of the materials of interest for use in road drainage systems. The combination of ultraviolet (UV) light, temperature, and moisture can produce weak spots and lead to pipe degradation during the storage, installation, and repair process. The objective of this study was to evaluate changes in the chemical, morphological structure, and thermomechanical properties of recycled and virgin pipes under UV exposure. Laboratory accelerated aging tests were conducted by exposing pipes to UV for 3600 hours with an irradiance of $0.89 \text{ W}/(\text{m}^2 \text{ nm})$ at a wavelength of 340 nm. A cycle of 12 hours—comprised of 8 hours of UV radiation at 60°C and 4 hours of no UV radiation at 50°C corresponding to no water condensation—was performed to condition the specimens. HDPE specimens were taken out after 3600 hours and analyzed with FTIR (Fourier-transform infrared spectroscopy), SEM (scanning electron microscopy), DSC (differential scanning calorimetry), oxidative-induction time (OIT) measurements, and tensile tests. The results show that the recycled pipes maintained good properties and were not significantly affected by UV radiation, similarly to the virgin pipes. Statistical analysis using one-way analysis of variance (ANOVA) shows that there was no significant difference between tensile strength, elastic modulus, and hardness measurements before and after UV exposure. There were only a few small changes in the surface of the pipes. The addition of carbon black, antioxidants, and UV stabilizers prevented further aging of the pipes during UV exposure.

1. Introduction

In recent years, thermoplastic pipes have become one of the most widely used materials for culverts and other highway applications [1]. High-density polyethylene (HDPE) is one of the materials of interest for these applications due to its numerous advantages. HDPE pipes are generally lighter, more flexible, and easier to install than other types of pipes as well as involving entail low maintenance costs and greater resistance to chemical attack [2–6]. Once the manufacturing process has been completed, however, pipes are often stored outdoors for a period of time before being installed. During the storage, installation, and repair process, the combination of ultraviolet (UV) light, temperature, and moisture can produce weak spots and lead to pipe degradation. The presence of impurities during the manufacturing process causes the pipes to absorb UV radiation. Since PE materials only contain C–C and C–H bonds, they are considered to be easily susceptible to degradation when exposed to high temperatures and UV radiation [7]. Culverts used in road drainage systems incur damage to their end openings due to UV radiation [7–9]. UV degradation can alter the physicommechanical, chemical, and macromolecular structure of the polymer [10, 11]. This degradation can alter color, tensile strength, elastic modulus, and impact strength of the materials [9, 12]. The presence of free radicals leads to chain scission, which usually takes place in the amorphous phase and at the amorphous-lamellar interface [13], whereas the crystalline phase remains inert [14]. In fact, UV stabilizers such as carbon black are integrated into pipes to prevent UV-induced reactions. In general, BNQ 3624-120 (2016) [15] and ASTM D4218 (2015) [16] require a minimum of 2–4% carbon black in pipes. Carbon black helps protect pipes against UV-radiation damage by limiting penetration to the external surface of the pipe wall (corrugated parts).

Attwood et al. (2006) studied the effects of UV degradation on recycled polyolefin blends. Tests were performed using QUV accelerated weathering testers with an irradiance of 0.68 W/m^2 at 340 nm. The process included 8 hours of UV radiation at 60°C and 4 hours of condensation at 50°C. Test exposure time was 1000 to 5000 hours. The results showed that UV radiation had little effect on tensile, impact, and chemical properties; melt flow tests; gloss; and color analyses. Some surface changes were, however, observed [17].

Maria et al. (2011) studied the impact of UV radiation on PE pipes under IR-microscopy. The samples tested contained a phenolic stabilizer (Irganox 1010) as a primary antioxidant, a processing stabilizer (Irgafos 168), carbon black, and UV stabilizers. The specimens were exposed to UV radiation for 144 to 2208 hours. IR-microscopy and OIT measurements revealed loss of the phenolic antioxidant Irganox 1010 in the outer pipe wall. No changes in the degree of crystallinity were noted [18].

Jassim et al. (2017) evaluated the tensile strength at break of medium-density polyethylene (MDPE) water pipes made with and without carbon black after exposure to UV radiation for 200 hours. The results showed that the tensile strength at break for MDPE pipe made with carbon black was higher than that of virgin MDPE pipe. The tensile strength at break after exposure to UV radiation was unchanged, however, due to the carbon black playing a key role as a UV stabilizer [19].

Jiang et al. (2019) investigated the influence of UV absorbers on the UV resistance of HDPE. They concluded that the HDPE samples maintained their thermal and mechanical properties after exposure to UV irradiation for 600 hours under the aging condition of 0.51 W/m^2 and a wavelength of 350 nm. In addition, slight changes in crystallinity were noted before and after exposure to UV radiation [20].

The incorporation of UV stabilizers, carbon black, and antioxidants in the polymer matrix helps limit the impact of UV radiation on the properties of materials. Past studies, however, have focused on HDPE films or HDPE water pipes. In contrast, very little has been developed about the effect of UV radiation on corrugated HDPE pipes used in road drainage systems. In addition, the current use of recycled HDPE pipes is of interest due to their sustainability and cost-effectiveness as compared to virgin pipes [6, 21–24]. Recycling products can reduce the carbon footprint, the use of raw materials, energy requirements, water consumption, and greenhouse-gas emissions in the production process [25, 26]. The main objective of our study was to assess the effect of UV radiation on the properties of recycled and virgin corrugated HDPE pipes used in road drainage systems. The techniques FTIR (Fourier-transform infrared spectroscopy) and SEM (scanning electron microscopy) were used to investigate the formation of degradation and any changes in pipe-wall morphological parameters. The thermal properties and crystallinity of the HDPE pipes were assessed with DSC (differential scanning calorimetry). The OIT measurements were conducted to profile antioxidant concentrations. In addition, the mechanical properties of the recycled and virgin HDPE corrugated pipes—such as tensile strength and hardness—were investigated before and after accelerated UV exposure.

This study is a part of ongoing research between the University of Sherbrooke and Quebec's Ministry of Transportation (MTQ) to jointly investigate the short- and long-term performance of new corrugated HDPE pipes made with or without recycled resins for use in road drainage systems under North American climate

conditions. The study included six new corrugated HDPE pipes from three different North American manufacturers, including three HDPE pipes made with virgin resins and three HDPE pipes made with recycled resins.

2. Experimental Methods

2.1. Material

Six new corrugated HDPE pipes used in non-pressure road drainage systems (e.g., storm drainage and storm sewers) were provided by North American manufacturers. The pipes contained 2–4% carbon black: two were manufactured with post-consumer recycled resins (A-R and D-R); one with post-industrial recycled resins (B-R); and three with virgin resins (A-V, B-V, C-V). The letters A, B, C, and D designate the manufacturers; R stands for recycled resin and V for virgin resin. Post-consumer recycled (PCR) materials are waste materials discarded by consumers and reused in new pipes. The recycling process involves shredding, washing, homogenizing, and pelletizing. Post-industrial recycled (PIR) materials are pipe scrap generated during the manufacturing process. Regrind pipe is produced by shredding, mixing with the raw material, and drawing by extrusion without changing the process parameters. This type of regrind can be considered a pseudo-source of recycled resins. Each pipe measured 900 mm in diameter and 3000 mm in length. Table 1 provides the pipe properties.

Table 1
Properties of the investigated HDPE pipes

Property	Method (ASTM)	Specimen					
		A-R	A-V	B-R	B-V	C-V	D-R
Density (g/cm ³)	D792-13 [27]	0.988	0.977	0.976	0.987	0.976	0.964
MFI (g/10 min)	D1238-13 [28]	0.103	0.077	0.066	0.061	0.115	0.058
10 ⁻³ M _n molecular weight (gmol ⁻¹)	-	11.9	7.3	9.5	8.3	5.4	9.0
10 ⁻³ M _w molecular weight (gmol ⁻¹)	-	405	323	542	413	449	392
CB (%) content	D5805-00-19 [29]	3.0	2.8	3.0	2.5	2.5	3.2
Hardness (HD)	-	56	55	55	60	65	61
Softening temperature by DMA	-	54	52	45	45	52	58
Softening temperature by TMA	-	51	50	45	45	45	54
Mass loss (°C)	E2550-17 [30]	390	375	415	420	413	413
Tensile strength (MPa)	D638-14 [31]	25.12	23.58	18.83	17.44	19.81	22.56
Note: MFI = Melt flow index; CB = carbon black; DMA = dynamic mechanical analysis; TMA = thermomechanical analysis, ASTM = American Society for Testing and Materials.							

2.2. Specimen preparation

Small specimens (15 mm x 15 mm) were cut from the corrugated part of the pipes with the exception of tensile specimens. To avoid bending due to the shape of the corrugated part and facilitate cutting, the tensile specimens were taken from the pipe liner (Fig. 1). The specimens cut from the corrugated parts of pipes A-R, A-V, B-R, B-V, C-V, and D-R were 7.30, 7.30, 7.80, 7.80, 3.25, and 4.50 mm thick, respectively. The tensile specimens cut from pipes A-R, A-V, B-R, B-V, C-V, D-R were 4.80, 4.40, 7.50, 7.60, 2.70, and 3.80 mm thick, respectively. The sections below provide details about specimen shape and dimensions.

2.3. UV aging

Specimens were placed under fluorescent UVA in a test chamber that simulates the spectral irradiance of daylight, as shown in Fig. 2. To reduce the effect of humidity on the UV aging of the pipes, the cycles for irradiance of 0.89 W/(m² nm) at a wavelength of 340 nm in accordance with ASTM D4329 (2013), procedure A [32], were modified in our study. Specimen conditioning consisted of a 12-hour cycle, comprised of 8 hours of UV radiation at 60°C and 4 hours with no UV radiation at 50°C, corresponding to no water condensation. The text exposure time was 3600 hours.

2.4. Spectroscopy analysis

Fourier-transform infrared spectroscopy (FTIR-4600 spectrometer) was used to assess the changes in chemical structure in the HDPE pipes before and after exposure to UV radiation. With the device in attenuated total reflection (ATR) mode, a single spectrum of 32 scans was recorded at a resolution of 4 cm^{-1} . A rectangular specimen (15 mm x 15 mm) was analyzed over the 4000 to 1000 cm^{-1} wavenumber range. The test specimen thickness corresponding to the pipe wall thickness (corrugated part) was 7.30, 7.30, 7.80, 7.80, 3.25, and 4.50 mm for A-R, A-V, B-R, B-V, C-V, and D-R, respectively. The FTIR spectra of the specimens before UV exposure are considered the reference spectra. The surface spectra in direct (top) and nondirect (bottom) UV exposure through the specimen thickness were analyzed and compared to the reference spectra.

2.5. Microscopy observation

Scanning electron microscope (SEM) observations were carried out on a Hitachi S-4700 at a voltage of 5 kV. Our study investigated the surface morphologies of unexposed and UV-exposed HDPE specimens (15 mm x 15 mm). The specimens received a palladium–gold coating prior to analysis to prevent charging. Moreover, energy dispersive spectrometry (EDS) was then conducted to study the chemical composition of certain pipes.

2.6. Thermal analysis

The melting point and melting enthalpy of the HDPE pipes were determined with a differential scanning calorimetry device (DSC 6000 from Perkin-Elmer). Specimens of 5 to 10 mg were cut from both unexposed and UV-exposed HDPE pipe specimens. The measurement was performed under nitrogen at a scanning rate of $20^{\circ}\text{C}/\text{min}$ from 30°C to 205°C . The melting point and melting enthalpy were determined by drawing a baseline below the melting peak. The degree of crystallinity was calculated from the ratio of the melting enthalpy of the specimens to the melting enthalpy of 100% crystalline polyethylene (287 J/g) [33].

The OIT of the unexposed and UV-exposed HDPE pipe specimens was measured with differential scanning calorimetry (DSC 6000 by Perkin-Elmer) in accordance with ASTM D3895 (2019) [34]. A 5 to 10 mg specimen was heated from room temperature to 200°C at a rate of $30^{\circ}\text{C}/\text{min}$ under nitrogen. After an isotherm of 1 minute, the gas was switched to oxygen. After some time, an exothermic peak appeared and the time corresponding to the onset was taken as the OIT value. Figure 3 provides a typical OIT assessment from a recorded time-based thermal curve.

2.7. Mechanical testing

The tensile properties of HDPE pipes were evaluated according to ASTM D638 (2014) [31] with dog-bone specimens. Tensile specimens were punched directly from the pipe liner with a stainless-steel die. The specific geometry of the specimens is described in detail in ASTM D638 (2014) and illustrated in Fig. 4. This test was conducted at 23°C with an MTS universal testing machine equipped with a 5 kN load cell. A constant crosshead speed was maintained at $50\text{ mm}/\text{min}$. A 634.12F-24 extensometer was used to measure sample extension. The stress–strain curve of the unexposed and UV-exposed HDPE specimens

was reported after five replicates. The average tensile, elastic modulus values, and standard deviation were determined for each pipe.

The hardness of specimens before and after exposure to UV radiation was measured by a Shore hardness durometer using the D (HD) scale according to ASTM D2240 (2015) [35]. This digital durometer has an impact rod with a 30° conical point. The force was applied manually for 15 seconds and the hardness value recorded. A rectangular specimen (15 mm x 15 mm) with a thickness not less than 6 mm was used. Three specimens for each pipe and three readings at three different locations were recorded for each specimen. The average value of each specimen is presented herein.

3. Results

3.1. FTIR analysis

FTIR analysis was performed to assess the degree of degradation. Figures 5a, b, c, d, e, and f show the FTIR spectra of unexposed and UV-exposed HDPE specimens after 3600 hours of aging. For all specimens before and after exposure to UV radiation, the spectra show typical bands of C–H groups at 2913 cm^{-1} and 2847 cm^{-1} , attributed to asymmetric and symmetric stretching vibrations, respectively. The presence of bending vibrations from the CH_2 is visible at 1465 cm^{-1} [36]. Based on the results, the top and bottom surfaces of specimens before UV exposure presented the same chemical structure. There were no differences between pipes made with recycled or virgin resin. This observation is quite similar to specimens after UV exposure. In contrast, peaks of very low intensity at 1717 cm^{-1} and 1140 cm^{-1} , corresponding to the presence of C–O or C=O groups, were detected upon oxidation at the top surface compared to specimens before UV exposure [37]. In addition, the presence of a very small peak corresponding to O–H groups was observed at 3380 cm^{-1} after UV exposure. It can be concluded that UV exposure produced very small structural modifications on the top surface caused by oxidation. These light changes can in no way induce modifications that would affect material integrity.

3.2. SEM/EDS analysis

SEM analysis of the surface of the HDPE pipes before and after exposure was carried out to observe any changes caused by UV radiation (Fig. 6). In general, as the SEM micrographs show, the specimen surfaces were relatively smooth at scan widths of $100\text{ }\mu\text{m}$ and $10\text{ }\mu\text{m}$ before UV exposure. After 3600 hours of irradiation, the specimen surface at the scan width of $100\text{ }\mu\text{m}$ evidenced no morphological changes. At the scan width of $10\text{ }\mu\text{m}$, some cracks were observed on the surface of pipes A-V and D-R, possibly due to UV radiation. These microcracks only occurred on one light area (contaminant) of the sample surfaces and not on the darkest areas (resin). EDS (energy dispersive spectrometry) analysis revealed that these two areas had different chemical compositions (Fig. 7). The darkest areas were constituted of elements in the resin compound (mainly carbon); the lightest areas contained nitrogen, sulfur, and oxygen. Consequently, it may be assumed that the cracked areas did not result from the PE but rather from a contaminant probably

deposited during the manufacturing process. The results are then quite consistent with the findings from FTIR analysis.

3.3. Thermal behavior

Specimens before and after UV exposure were studied in order to investigate thermal properties and primarily the degree of crystallinity. The melting point and melting enthalpy of the HDPE pipes were measured with DSC. The degree of crystallinity was calculated from the ratio of the melting enthalpy of the specimens to the melting enthalpy of 100% crystalline polyethylene (287 J/g), as shown in Table 2. The results show that the melting point decreased (3°C to 9°C) after 3600 hours of UV exposure. As a result, a slight decrease of 0–4% of the melting enthalpy value resulted in a slight decrease of 0–4% crystallinity. It should be noted that photo-oxidative degradation usually takes place in the amorphous phase and in the amorphous-lamellar interface of the semicrystalline polymer [13, 38]. In fact, the incorporation of antioxidants into pipes prevents the formation of free radicals during the manufacturing process. Hence, they prevent the degradation of pipes exposed to UV radiation.

Table 2
Melting temperature and crystallinity of the HDPE pipes before and after UV exposure

Specimen	Before UV Exposure			After UV Exposure		
	Melting point (°C)	Melting enthalpy (J/g)	Degree of crystallinity (%)	Melting point (°C)	Melting enthalpy (J/g)	Degree of crystallinity (%)
A-R	153	135	47	145	132	46
A-V	153	139	49	144	137	48
B-R	143	102	36	138	105	36
B-V	144	132	46	138	131	45
C-V	151	151	53	146	147	51
D-R	148	149	52	145	143	50

OIT is commonly used to evaluate the thermal-oxidative resistance of polymers and the depletion rate of antioxidants in their products [39–41]. Our study took OIT measurements to investigate the depletion rate of antioxidants of unexposed and UV-exposed HDPE specimens. Table 3 shows a decrease in OIT values after 3600 hours of UV exposure. The OIT decrease indicates the consumption of antioxidants in pipes. The reduction also depends on the thickness of the HDPE specimens. The difference between the OIT values of the exposed direct (top) and indirect (bottom) surface depends on specimen thickness, as shown in Table 3. This difference is clear with the specimens 7.30 and 7.80 mm in thickness. In contrast, there were no differences in OIT between the two sides in the thinner 3.25 and 4.50 mm samples. It should be pointed out that the initial OIT values between pipes were different, assessed based on the initial antioxidant content and type in each pipe. This information is a professional secret and was unavailable to the authors. In

addition, it can be concluded that all the investigated pipes met the OIT minimum of 20 minutes in ASTM D3895 (2019) [34], in which the antioxidant content was sufficient to withstand oxidation by UV radiation. The results of OIT measurements are in good agreement with the FTIR, SEM, and DSC analyses, in which antioxidants are consumed and prevent pipe degradation during UV exposure.

Table 3
OIT values of HDPE pipes before and after exposure to UV

Specimen	Thickness (mm)	OIT (min) - Before UV Exposure	OIT (min) - After UV Exposure	
			Top surface	Bottom surface
A-R	7.30	90	52	71
A-V	7.30	87	51	74
B-R	7.80	103	62	79
B-V	7.80	106	58	70
C-V	3.25	33	23	24
D-R	4.50	86	67	68

3.4. Mechanical behavior

The tensile test of specimens was carried out to determine the tensile strength and elastic modulus of the HDPE pipes. Figures 8a, b, c, d, e, and f present the typical stress–strain curves for unexposed and UV-exposed HDPE specimens with five replicates for each pipe. The figures show that the stress–strain behavior of the pipes was governed by three regions: (1) elastic (linear and nonlinear), (2) neck propagation, and (3) plastic regions. The initial portion of the stress–strain curve is defined as the elastic deformation region where the elastic modulus is defined as the slope of the stress–strain curve. The maximum point on the stress–strain curve is called the yield point. The area corresponding to the reduced stress value is often called a neck. The area with relatively stable stress values is the development phase of the neck. The initial tensile strength of pipes A-R, A-V, B-R, B-V, C-V, and D-R pipes was 25.12, 23.58, 18.83, 17.44, 19.81, and 22.56 MPa, respectively. After 3600 hours of UV radiation, the tensile strength of the pipes remained almost unchanged at 23.39, 23.19, 18.45, 17.40, 19.79, and 22.36 MPa for pipes A-R, A-V, B-R, B-V, C-V, and D-R pipes, respectively (Fig. 9a). Figures 8a, b, c, d, e, and f show that the elongation of all specimens was more than 4.0 mm/mm before UV exposure. After exposure to UV radiation for 3600 hours, the elongation at break of specimens B-R and B-V remained at 4.0 mm/mm, but this value varied for the other specimens. The elongation at break of specimens A-R, A-V, C-V, D-R was 1.5 to 2.9 mm/mm, 0.8 to 3.5 mm/mm, 0.5 to 1.65 mm/mm, and 0.9 to 3.2 mm/mm, respectively. The UV radiation did not significantly affect the tensile strength of the pipes. Figures 8a, b, c, d, e, and f show a variation in the elongation values at break. The behavior also varied from one manufacturer to the next and from one specimen to next from the same manufacturer. The pipes from manufacturers A, C, and D did not have uniform behavior in that they more fragile than those from manufacturer B. Figure 9b provides the elastic modulus of the specimens, showing that the elastic modulus of all the specimens decreased after UV exposure for 3600 hours. The standard

deviation of the calculations was, however, relatively large for specimens A-R, C-V, and D-R. In fact, the addition of antioxidants and carbon black further inhibited the effect of UV radiation.

Table 4 gives the results of the hardness analysis; hardness was measured with a Shore D durometer. Table 4 shows that a slight decrease in hardness was observed for all specimens. For semicrystalline polymers such as HDPE, the factors affecting hardness act mainly on the crystalline region. In fact, polymer chains in the crystalline region are denser than those in the amorphous region [42]. Consequently, the slight differences in hardness values between the HDPE pipes before and after UV exposure were caused by variations in the contents of the crystalline phase (Table 2).

Table 4
Hardness of the HDPE pipes before and after UV exposure

Specimen	Hardness (HD)	
	Before UV Exposure	After UV Exposure
A-R	56	51
A-V	55	49
B-R	55	53
B-V	60	56
C-V	65	61
D-R	61	57

3.5. Statistical Analysis

Table 4 and Fig. 9 show that there was variation in tensile strength, modulus of elasticity and hardness of pipes before and after UV exposure. Therefore, a statistical analysis was performed to clarify if there were any significant differences between the measurements. In the present study, one-way analysis of variance (ANOVA) was used. In general, there is no significant difference between measurements if they meet the following conditions: (1) the F-value is less than the F-critical, or (2) the P-value is greater than the selected alpha level (0.05). As shown in Tables 5, 6 and 7, the F value is less than the critical F value and the P value is greater than 0.05 for tensile strength, modulus of elasticity and hardness before and after exposure to UV. It is important to emphasize that there was no statistically significant difference in these measurements before and after UV exposure. Therefore, the tensile strength, modulus of elasticity and hardness of pipes can be considered relatively unchanged after UV exposure

Table 5
One-way ANOVA of tensile strength before and after UV exposure

Specimen	Description	Sum of squares	df	Mean square	F-value	P-value	F-critical
	Between groups	7.5	1	7.5	1.726	0.225	5.318
A-R	Within groups	34.9	8	4.4	–	–	–
	Total	42.4	9	–	–	–	–
	Between groups	0.4	1	0.4	0.130	0.728	5.318
A-V	Within groups	23.4	8	2.9	–	–	–
	Total	23.8	9	–	–	–	–
	Between groups	0.4	1	0.4	1.329	0.282	5.318
B-R	Within groups	2.1	8	0.3	–	–	–
	Total	2.5	9	–	–	–	–
	Between groups	0.004	1	0.004	0.011	0.921	5.318
B-V	Within groups	3.047	8	0.381	–	–	–
	Total	3.051	9	–	–	–	–
	Between groups	0.001	1	0.001	0.001	0.979	5.318
C-V	Within groups	8.939	8	1.117	–	–	–
	Total	8.940	9	–	–	–	–
	Between groups	0.1	1	0.1	0.092	0.769	5.318
D-R	Within groups	8.1	8	1.0	–	–	–
	Total	8.2	9	–	–	–	–

Table 6
One-way ANOVA of elastic modulus before and after UV exposure

Specimen	Description	Sum of squares	df	Mean square	F-value	P-value	F-critical
	Between groups	34052.7	1	34052.7	4.959	0.068	5.987
A-R	Within groups	41204.7	6	6867.5	–	–	–
	Total	75257.4	7	–	–	–	–
	Between groups	11166.1	1	11166.1	5.585	0.051	5.591
A-V	Within groups	13995.3	7	1999.3	–	–	–
	Total	25161.4	8	–	–	–	–
	Between groups	2189.6	1	2189.6	1.589	0.254	5.987
B-R	Within groups	8269.9	6	1378.3	–	–	–
	Total	10459.5	7	–	–	–	–
	Between groups	382.5	1	382.5	1.399	0.282	5.987
B-V	Within groups	1639.7	6	273.3	–	–	–
	Total	2022.2	7	–	–	–	–
	Between groups	1871.9	1	1871.9	0.403	0.549	5.987
C-V	Within groups	27856.6	6	4642.8	–	–	–
	Total	29728.5	7	–	–	–	–
	Between groups	7505.4	1	7505.4	2.061	0.211	6.608
D-R	Within groups	18209.5	5	3641.9	–	–	–
	Total	25714.9	6	–	–	–	–

Table 7
One-way ANOVA of hardness before and after UV exposure

Specimen	Description	Sum of squares	df	Mean square	F-value	P-value	F-critical
	Between groups	40.8	1	40.8	2.065	0.201	5.987
A-R	Within groups	118.7	6	19.8	–	–	–
	Total	159.5	7	–	–	–	–
	Between groups	70.5	1	70.5	4.342	0.082	5.987
A-V	Within groups	97.5	6	16.2	–	–	–
	Total	168.0	7	–	–	–	–
	Between groups	7.5	1	7.5	1.875	0.220	5.987
B-R	Within groups	24	6	4.0	–	–	–
	Total	31.5	7	–	–	–	–
	Between groups	22.5	1	22.5	4.588	0.076	5.987
B-V	Within groups	29.5	6	4.9	–	–	–
	Total	52.0	7	–	–	–	–
	Between groups	28.0	1	28.0	5.708	0.054	5.987
C-V	Within groups	29.5	6	4.9	–	–	–
	Total	57.5	7	–	–	–	–
	Between groups	21.1	1	21.1	3.992	0.093	5.987
D-R	Within groups	31.8	6	5.3	–	–	–
	Total	52.9	7	–	–	–	–

4. Discussion

The use of recycled HDPE pipes is of current interest given the sources of recycling material. Compared to virgin pipes, recycled pipes are more sustainable and cost-effective. Using recycled plastics can reduce a product's carbon footprint. Indeed, a product with 100% recycled content would have a carbon footprint 24% smaller [25]. Recycling products can reduce the use of raw materials, energy requirements, water consumption, and greenhouse-gas emissions in the production process [25, 26]. Our study investigated the effect of UV radiation on the properties of recycled and virgin HDPE pipes. Table 8 shows that UV radiation produced only small changes in the pipe surface, and it did not significantly affect the pipes made with virgin or recycled material.

Table 8
The effect of UV radiation on the pipes made from recycled or virgin HDPE

Type of HDPE	Specimen	Before and After UV Exposure						
		FTIR	SEM	Degree of crystallinity	Tensile strength	Elongation at break	Elastic modulus	Hardness
Recycled	A-R	√	□	□	□	√	□	□
	B-R	√	□	□	□	□	□	□
	D-R	√	√	□	□	√	□	□
Virgin	A-V	√	√	□	□	√	□	□
	B-V	√	□	□	□	□	□	□
	C-V	√	□	□	□	√	□	□
Note: □ = no changes or remained constant; √ = negligible changes.								
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- FTIR analysis shows that negligible structural modifications occurred on the top surface after UV exposure. In the case of manufacturer A, the peak of carbonyl stretching vibration at 1717 cm^{-1} was observed with virgin pipes (A-V). In contrast, the peak of carbonyl stretching vibration did not appear for either recycled or virgin pipes from manufacturer B. This peak was detected for recycled pipes from manufacturer D. In addition, the peak of polyhydroxyl stretch at 3380 cm^{-1} was detected in all the pipes. The SEM results were similar for specimens after UV exposure. When the scanning width was $10\text{ }\mu\text{m}$, some cracks appeared on the surface of virgin pipes (A-V) from manufacturer A and recycled pipes (D-R) from manufacturer D. This was not observed for either recycled or virgin pipes from manufacturer B.
- DSC analysis shows that the melting points for the recycled and virgin pipes from the same manufacturer (only A and B) were the same before and after UV exposure. The degree of crystallinity remained constant for both recycled and virgin pipes after 3600 hours of UV exposure. In general, the presence of impurities during the manufacturing process caused the recycled pipes to easily absorb UV radiation compared to the virgin pipes. However, based on OIT measurements, it appears that antioxidants were consumed as a result of UV exposure. In other words, they prevented the formation of free radicals. Consequently, the thermal properties of recycled and virgin pipes remained constant under the effect of UV radiation.
- The tensile strength, elastic modulus, and hardness of the HDPE pipes made with recycled or virgin material were relatively unaffected after UV exposure. In contrast, the elongation at break decreased from 12–87% of the initial elongation at break for both recycled and virgin pipes.

Based on the results, the pipes are made from recycled or virgin resins were relatively unaffected by UV radiation. These results are in good agreement with the finding from other studies [17–20, 43]. It should be

emphasized that the presence of carbon black, antioxidants, and UV stabilizers had a synergistic effect on the UV stabilization of the recycled and virgin HDPE pipes.

5. Conclusions

The effects of UV radiation on the chemical, microstructure, thermal, and tensile properties of new corrugated HDPE pipes made with or without recycled resins used in road drainage systems were assessed. The following conclusions can be drawn from the study:

1. The incorporation of carbon black, antioxidants, UV stabilizers helped limit the formation of free radicals during the aging process. Therefore, it prevented the degradation of the HDPE pipes during UV exposure.
2. Before being exposed to UV radiation, the recycled and virgin pipes had the same chemical and morphological structures. Small changes, probably due to the presence of a contaminant on the surface of certain pipes, were observed in FTIR and SEM analysis after UV exposure.
3. While the antioxidants in the pipes were partly consumed due to UV exposure, the minimum 20-minute OIT requirement for withstanding oxidation was met. In addition, statistical analysis using one-way analysis of variance (ANOVA) shows that there was no significant difference between measures of tensile strength, modulus of elasticity and hardness before and after exposure to UV. Therefore, it can be considered that the pipes made from virgin or recycled resins maintained adequate thermal (melting point, degree of crystallinity) and mechanical (tensile strength, elastic modulus, hardness) properties after exposure to UV radiation. The elongation at break was, however, reduced. Achieving this level of UV protection required a minimum of 2–4% of carbon black added to the resin compound, depending on the presence or absence of other antioxidants or UV stabilizers.
4. The findings of the current study would be the premise upon which recycled HDPE becomes one of the most widely used materials in the future. On the other hand, recycled HDPE should be used for floating solar applications where the material is subjected to direct sunlight.

Declarations

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

A sectional view of an HDPE pipe showing the location of the corrugation and liner.

Figure 2

Specimens placed for aging in the UV chamber.

Figure 3

Evaluation of OIT from recorded time-based thermal curve.

Figure 4

Typical dog-bone specimens for evaluating tensile strength.

Figure 5

FTIR spectra of HDPE pipes before and after UV exposure: a) A-R, b) A-V, c) B-R, d) B-V, e) C-V, and f) D-R.

Figure 6

Morphological structure of HDPE pipes before and after UV exposure at scan widths of 100 μm and 10 μm .

Figure 7

EDS analysis and chemical composition of lightest (contaminant) and darkest areas of A-V and D-R pipes.

Figure 8

Typical tensile stress–strain behaviors of the HDPE pipes before and after UV exposure: a) A-R, b) A-V, c) B-R, d) B-V, e) C-V, and f) D-R.

Figure 9

Mechanical properties of the HDPE pipes before and after UV exposure: a) tensile strength and b) modulus of elasticity.