



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

Khanh Q. Nguyen¹ · Patrice Cousin¹ · Khaled Mohamed¹ · Mathieu Robert¹ · Adel El-Safty² · Brahim Benmokrane¹

Accepted: 15 March 2022

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

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 h with an irradiance of 0.89 W/(m² nm) at a wavelength of 340 nm. A cycle of 12 h—comprised of 8 h of UV radiation at 60 °C and 4 h 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 h 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.

Keywords High-density polyethylene (HDPE) pipe · Recycled and virgin pipes · UV aging · Road drainage systems · Chemical, morphological structure, and thermomechanical properties

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

✉ Mathieu Robert
Mathieu.Robert2@USherbrooke.ca

Khanh Q. Nguyen
Quoc.Khanh.Nguyen@USherbrooke.ca

Patrice Cousin
Patrice.Cousin@USherbrooke.ca

Khaled Mohamed
Khaled.Mohamed@USherbrooke.ca

Adel El-Safty
adel.el-safty@unf.edu

Brahim Benmokrane
Brahim.Benmokrane@USherbrooke.ca

¹ Department of Civil Engineering, University of Sherbrooke, Sherbrooke, QC J1K 2R1, Canada

² Department of Civil Engineering, University of North Florida, Jacksonville, FL, USA

drainage systems incur damage to their end openings due to UV radiation [7–9]. UV degradation can alter the physico-mechanical, 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 to 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. 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 h of UV radiation at 60 °C and 4 h of condensation at 50 °C. Test exposure time was 1000 to 5000 h. 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. 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 h. 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. 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 h. 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 h 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.

Experimental Methods

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% to 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 [27].

Specimen Preparation

Small specimens (15 mm × 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.

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 [33], were modified in our study. Specimen conditioning consisted of a 12-h cycle, comprised of 8 h of UV radiation at 60 °C and 4 h with no UV radiation at 50 °C, corresponding to no water condensation. The test exposure time was 3600 h.

Spectroscopy Analysis

Fourier-transform infrared spectroscopy (FTIR-4600 spectrometer) was used to assess the changes in chemical

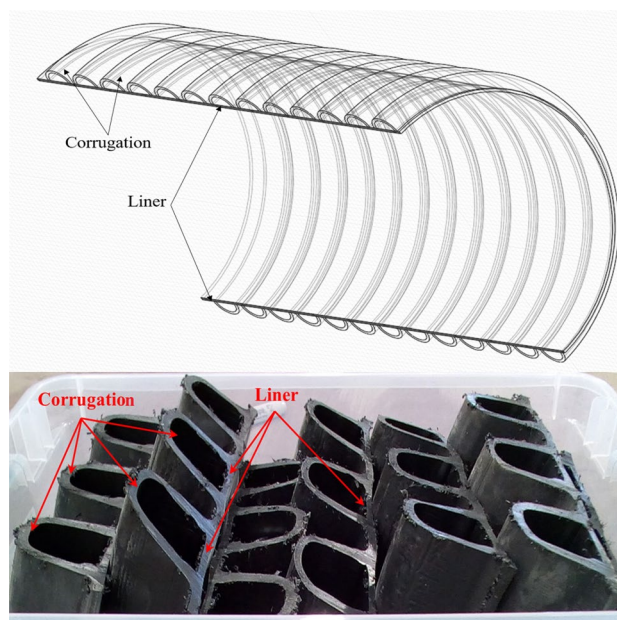


Fig. 1 A sectional view of an HDPE pipe showing the location of the corrugation and liner

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 × 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 indirect (bottom) UV exposure through the specimen thickness were analyzed and compared to the reference spectra.

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 [28]	0.988	0.977	0.976	0.987	0.976	0.964
MFI (g/10 min)	D1238-13 [29]	0.103	0.077	0.066	0.061	0.115	0.058
10 ⁻³ M _n molecular weight (g/mol)	—	17.8	14.7	17.0	15.3	16.0	19.0
10 ⁻³ M _w molecular weight (g/mol)	—	150	153	169	163	146	151
CB (%) content	D5805-00-19 [30]	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 [31]	390	375	415	420	413	413
Tensile strength (MPa)	D638-14 [32]	25.12	23.58	18.83	17.44	19.81	22.56

MFI Melt flow index, *CB* carbon black, *DMA* dynamic mechanical analysis, *TMA* thermomechanical analysis, *ASTM* American Society for Testing and Materials

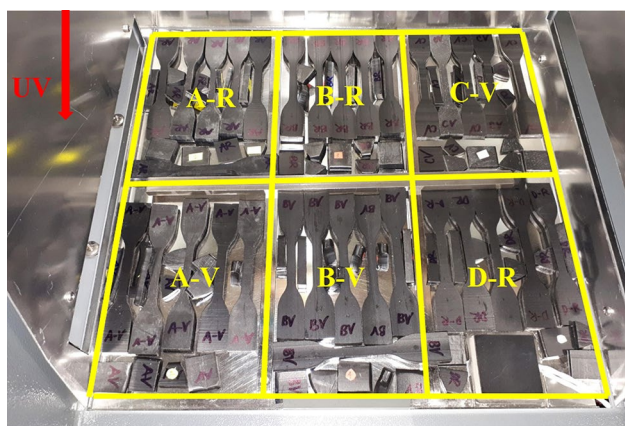


Fig. 2 Specimens placed for aging in the UV chamber

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 × 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.

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 °C/min from 30 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) [34].

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) [35]. A 5 to 10 mg specimen was heated from room temperature to 200 °C at a rate of 30 °C/min under nitrogen. After an isotherm of 1 min, 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.

Physico-mechanical Testing

The average molecular weight and polydispersity index of the HDPE used in the pipes before and after UV exposure was determined with high-temperature gel permeation chromatography (Agilent model Infinity II multidetector HT-GPC), using 1,2,4-trichlorobenzene as the solvent at 160 °C. An HDPE sample of at least 20 mg was dissolved in 10 mL of the solvent. The flow rate was 1 mL/min, and the equipment was calibrated with polystyrene standards.

The tensile properties of HDPE pipes were evaluated according to ASTM D638 (2014) [32] 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 mm/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) [36]. This digital durometer has an impact rod with a 30°

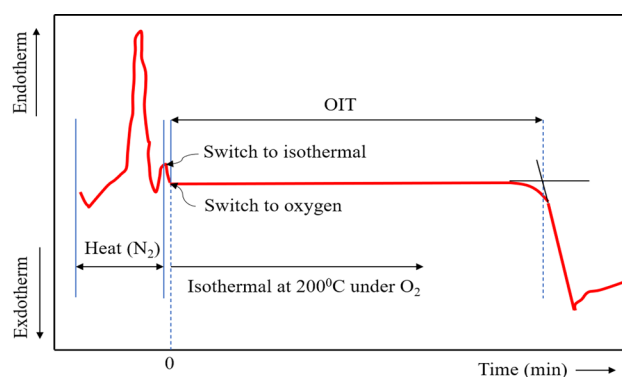


Fig. 3 Evaluation of OIT from recorded time-based thermal curve

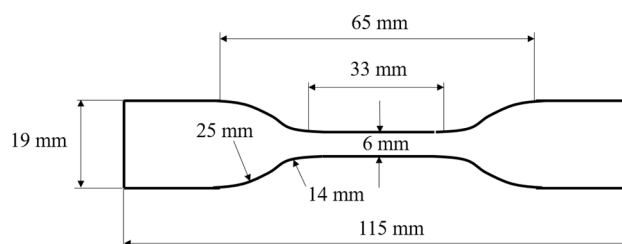


Fig. 4 Typical dog-bone specimens for evaluating tensile strength

conical point. The force was applied manually for 15 s, and the hardness value recorded. A rectangular specimen (15 mm × 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.

Results

FTIR Analysis

FTIR analysis was performed to assess the degree of degradation. Figure 5a–f show the FTIR spectra of unexposed and UV-exposed HDPE specimens after 3600 h 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} [37]. Bands at 2913, 2847, and 1465 cm^{-1} were investigated as typical bands of HDPE. These FTIR spectra correspond to the reference spectrum of HDPE [38, 39]. 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 [40]. It should be noted that vinyl groups (C=C) and carbonyl groups (C=O) as well as O–H (3380 cm^{-1}) were present on the surface of the pipes after oxidation but not on the reference pipes [41, 42]. Consequently, it could be assumed that UV exposure oxidized the surface of the pipes [43, 44]. However, it must be mentioned that this light degradation is superficial and does not affect the integrity of the material since carbon black prevents the penetration of UV deeper in the polymer.

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 μm and 10 μm before UV exposure. After 3600 h of irradiation, the specimen surface at the scan width of 100 μm evidenced no morphological changes. At the scan width of 10 μm , some cracks were observed on the surface of pipes A-V and D-R, possibly due to UV radiation. The presence of vinyl and carbonyl groups observed under FTIR created more brittle materials, which

led to the formation of superficial microcracks in specimens A-V and D-R [41, 42]. 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. The EDS spectrum shows peaks at around 0.29 and 0.55 keV corresponding to carbon and oxygen, respectively. Nitrogen and sulfur were detected in the lighter area, which was presumably contaminated, but not present in the darker zones constituted of neat resin. It should be noted that the samples were wiped with alcohol prior to analysis to prevent contamination. Consequently, it could be assumed that it was not the HDPE itself that was microcracked, but rather a contaminant probably deposited during the manufacturing process.

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 to 9 $^{\circ}\text{C}$) after 3600 h of UV exposure. As a result, a slight decrease of 0% to 4% of the melting enthalpy value resulted in a slight decrease of 0 to 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, 45]. 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.

OIT is commonly used to evaluate the thermal-oxidative resistance of polymers and the depletion rate of antioxidants in their products [46–48]. 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 h of UV exposure. The OIT decrease indicates the consumption of antioxidants in pipes. The reduction also depends on the thickness of the HDPE specimens [49]. 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

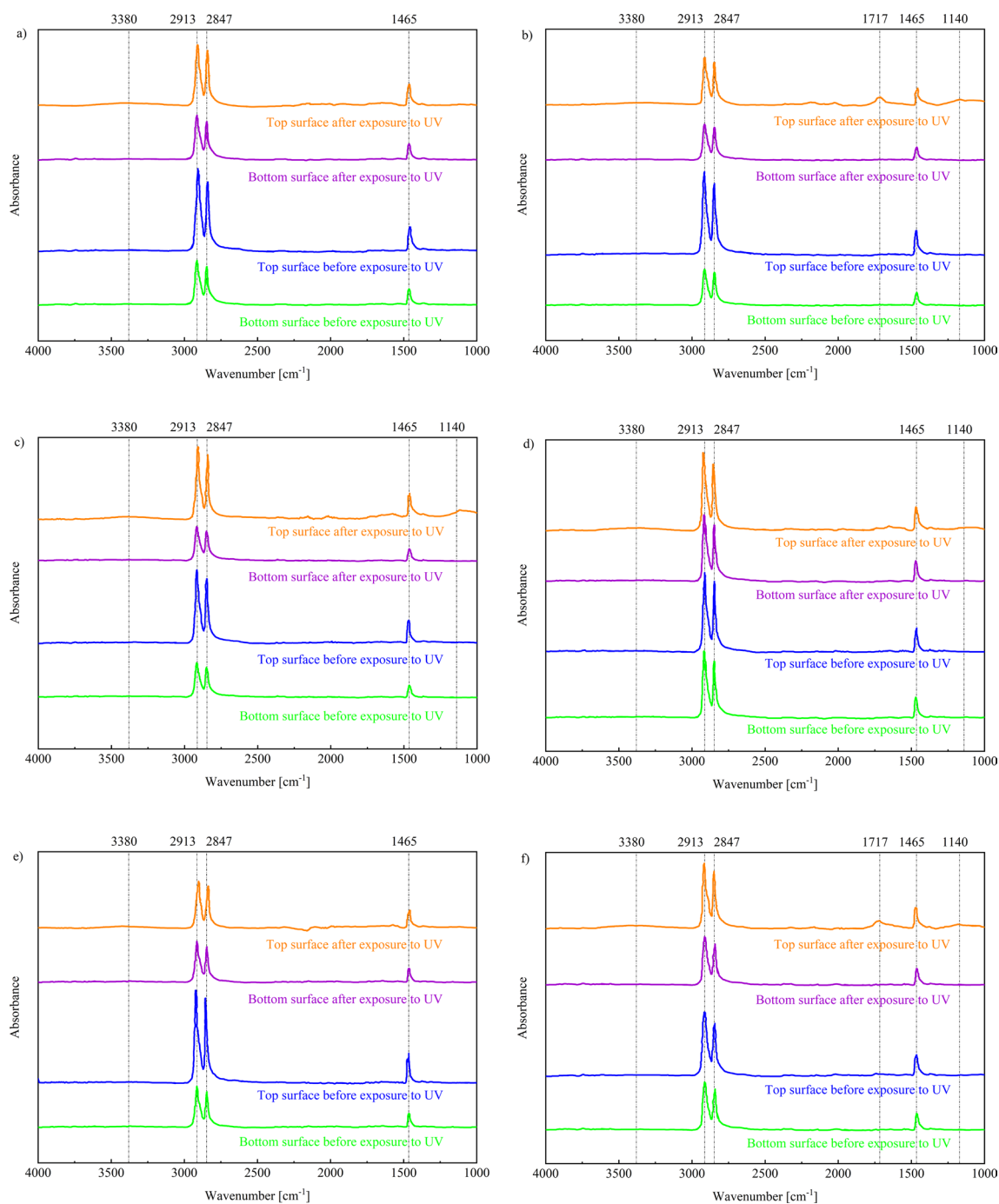


Fig. 5 FTIR spectra of HDPE pipes before and after UV exposure: **a** A-R, **b** A-V, **c** B-R, **d** B-V, **e** C-V, and **f** D-R

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. In general, HDPE pipes are stabilized with common additive packages such as Irganox 1010 (I-1010) and Irgaphos 168 (I-168). Once stabilized with 0.1% I-1010, 0.1% I-168, and 2% carbon black, the OIT value reaches between 60 and 80 min [21, 50]. Since OIT is a linear function of the antioxidant concentration, its

value can be used to estimate the antioxidant concentration [51]. In our study, the values of the antioxidant concentration in the pipes were extrapolated from past research that used this relationship [21, 50, 51]. These values were found to be 0.1% I-168 for all pipes along with 0.13, 0.12, 0.15, 0.15, 0.05, and 0.12% I-1010 for specimens A-R, A-V, B-R, B-V, C-V, and D-R, respectively (Table 4). As shown in Table 4, the antioxidant content present in specimen C-V was the

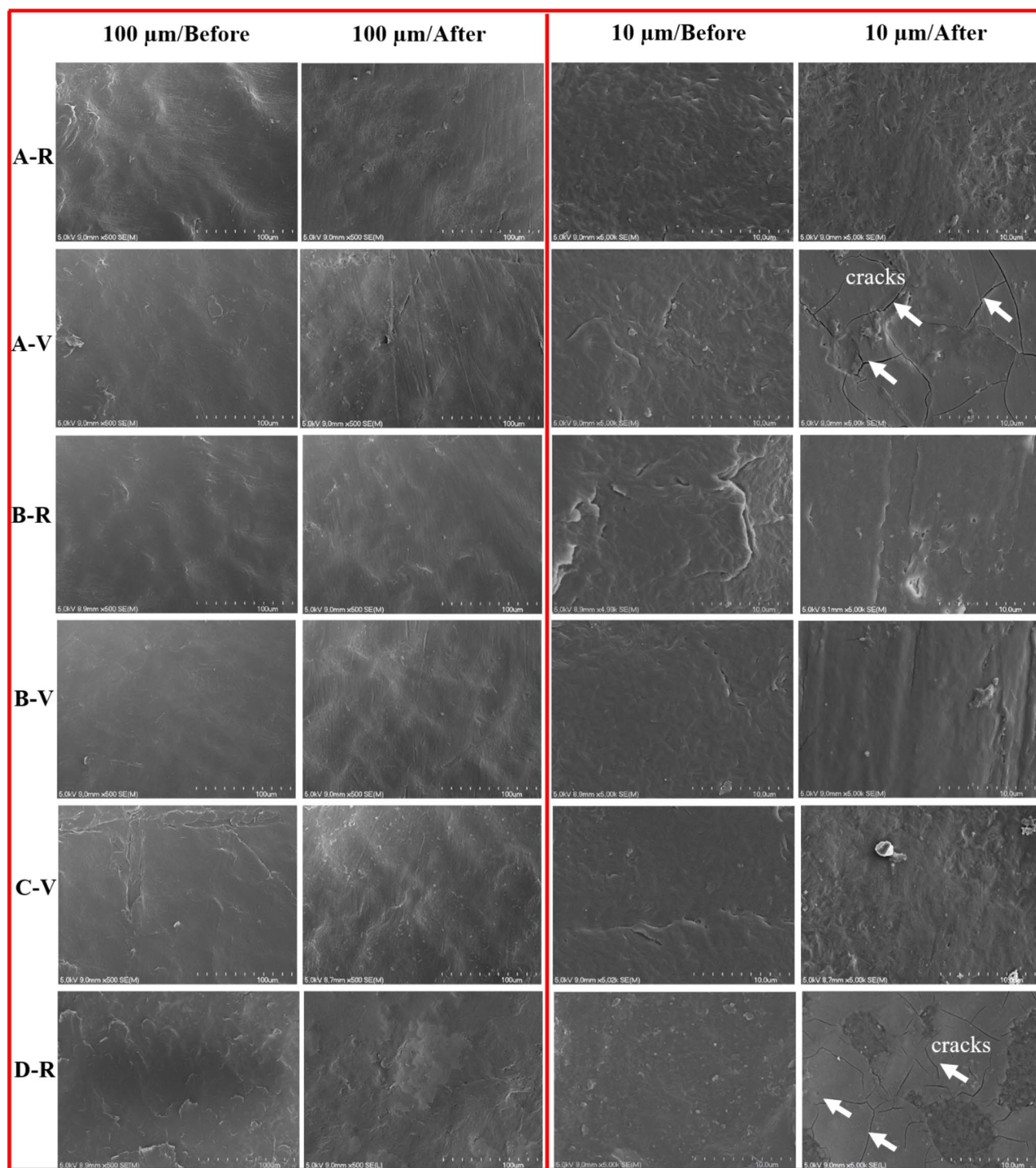


Fig. 6 Morphological structure of HDPE pipes before and after UV exposure at scan widths of 100 μm and 10 μm

lowest of all specimens. In addition, it can be concluded that all the investigated pipes met the OIT minimum of 20 min in ASTM D3895 (2019) to withstand oxidation from UV radiation [35]. These OIT results are in good agreement with

the FTIR, SEM, and DSC analyses, in which antioxidants were consumed and prevented pipe degradation during UV exposure.

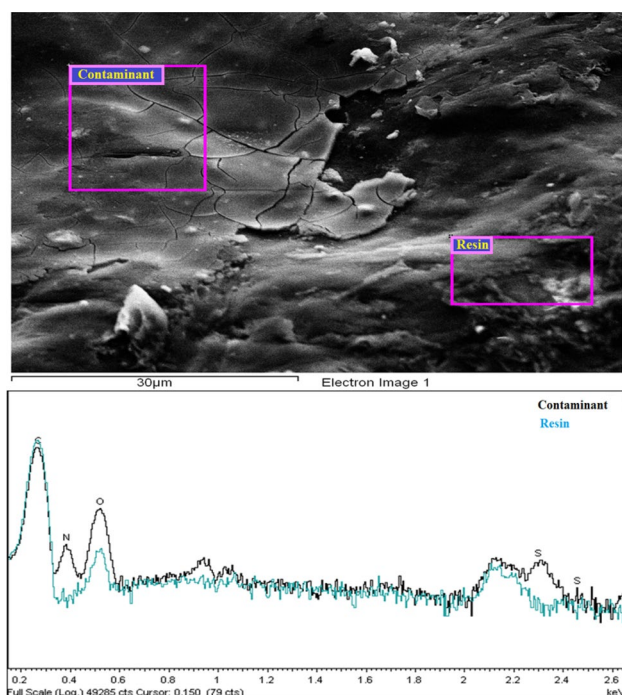


Fig. 7 EDS analysis and chemical composition of lightest (contaminant) and darkest areas of A-V and D-R pipes

Physico-mechanical Behavior

Table 5 presents the molecular parameters, including weight-average (M_w), number-average (M_n), and polydispersity (M_w/M_n), of the pipes before and after UV exposure, whereas Fig. 8a–f show the molecular-weight distribution (MWD) curves. The MWD curves are basically the same for all the unexposed and UV-exposed HDPE specimens, except for the C-V specimens. It is evident that the C-V specimens had lower levels of antioxidants and carbon black than the other specimens. This slight difference of behavior between the C-V specimens and the other pipes could be explained by the lower level of antioxidants, as calculated previously. Furthermore, the C-V specimens were thinner,

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

Table 4 Antioxidant concentration in the pipes

Specimen	I-168 (%)	I-1010 (%)
A-R	0.1	0.13
A-V	0.1	0.12
B-R	0.1	0.15
B-V	0.1	0.15
C-V	0.1	0.05
D-R	0.1	0.12

more material was close to the surface and more susceptible to UV radiation.

The tensile test of specimens was carried out to determine the tensile strength and elastic modulus of the HDPE pipes. Figure 9a–f present the typical stress–strain curves for unexposed and UV-exposed HDPE specimens with five replicates for each pipe. The initial tensile strength of pipes A-R, A-V, B-R, B-V, C-V, and D-R pipes was 25.12 ± 2.94 , 23.58 ± 2.39 , 18.83 ± 0.68 , 17.44 ± 0.85 , 19.81 ± 1.48 , and 22.56 ± 1.08 MPa, respectively. After 3600 h of UV radiation, the tensile strength of the pipes remained almost unchanged at 23.39 ± 0.25 , 23.19 ± 0.39 , 18.45 ± 0.27 , 17.40 ± 0.20 , 19.79 ± 0.23 , and

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

Table 5 Average molecular weight and polydispersity of the HDPE pipes before and after UV exposure

Specimen	Before UV exposure			After UV exposure		
	$10^{-3} M_n$ (g/mol)	$10^{-3} M_w$ (g/mol)	M_w/M_n	$10^{-3} M_n$ (g/mol)	$10^{-3} M_w$ (g/mol)	M_w/M_n
A-R	17.8	150	8	22.7	144	6
A-V	14.7	153	10	15.8	151	10
B-R	17.0	169	10	15.5	167	11
B-V	15.3	163	11	15.7	161	10
C-V	16.0	146	9	12.4	125	10
D-R	19.0	151	8	18.3	156	9

22.36 ± 0.93 MPa for pipes A-R, A-V, B-R, B-V, C-V, and D-R pipes, respectively (Fig. 10a). Figure 9a–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 h, 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. Figure 9a–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 10b provides the elastic modulus of the specimens, showing that the elastic modulus of all the specimens decreased after UV exposure for 3600 h. 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 6 gives the results of the hardness analysis; hardness was measured with a Shore D durometer. Table 6 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 [52]. 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).

Statistical Analysis

Table 6 and Fig. 10 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 7, 8 and 9, 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.

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, recycling products can reduce the use of raw materials, energy requirements, water consumption, and greenhouse-gas emissions in the production process [25, 26]. In fact, recycled HDPE can reduce total energy consumption, resulting in a lower carbon footprint of the product [53]. Pipes made of post-consumer recycled HDPE blended with virgin HDPE generate approximately 50% fewer greenhouse gas emissions than virgin HDPE [54]. Our study investigated the effect of UV radiation on the properties of recycled and virgin HDPE pipes. Table 10 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.

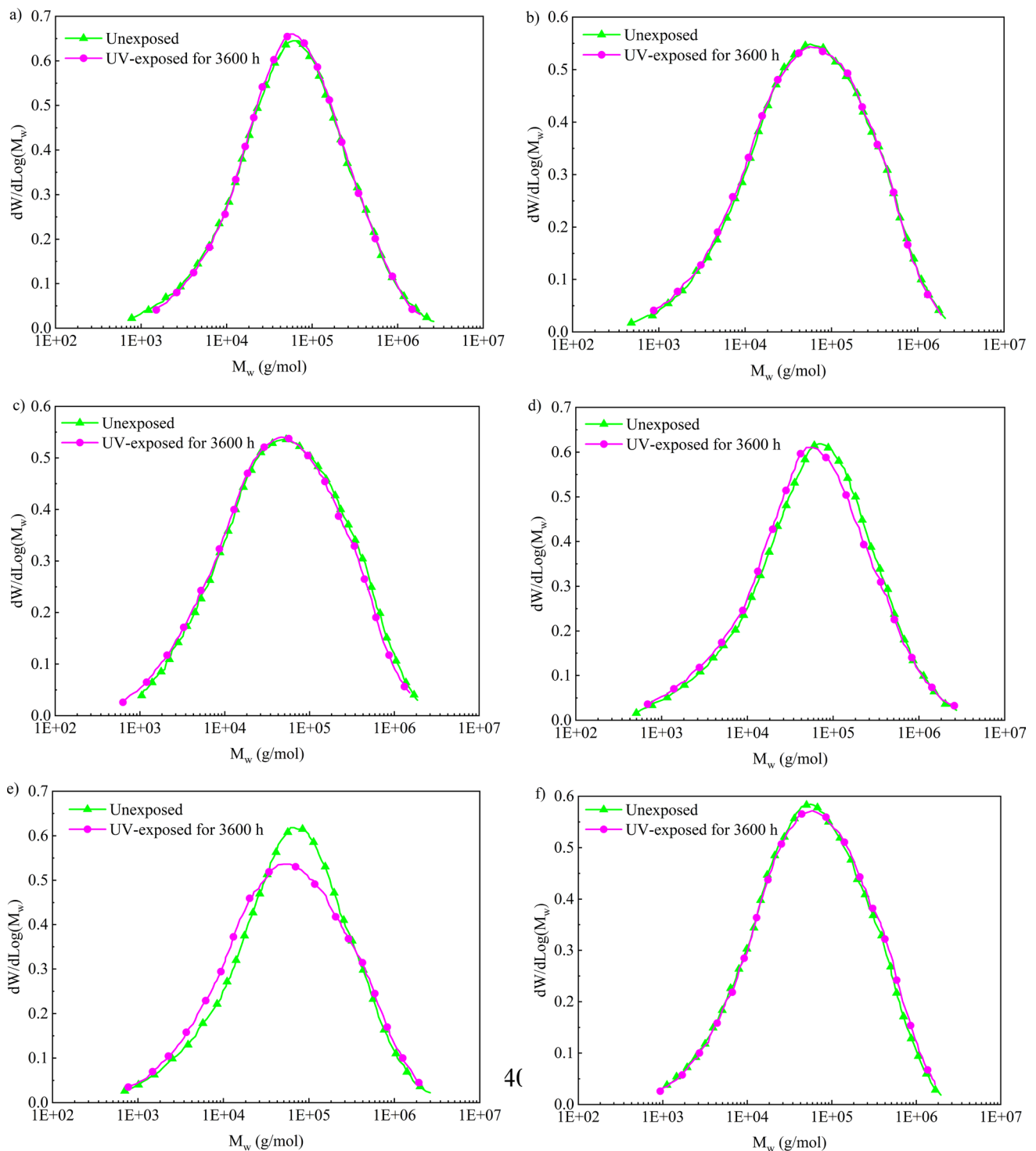


Fig. 8 Molecular-weight distribution curves of the HDPE pipes before and after UV exposure: **a** A-R, **b** A-V, **c** B-R, **d** B-V, **e** C-V, **f** D-R

- 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

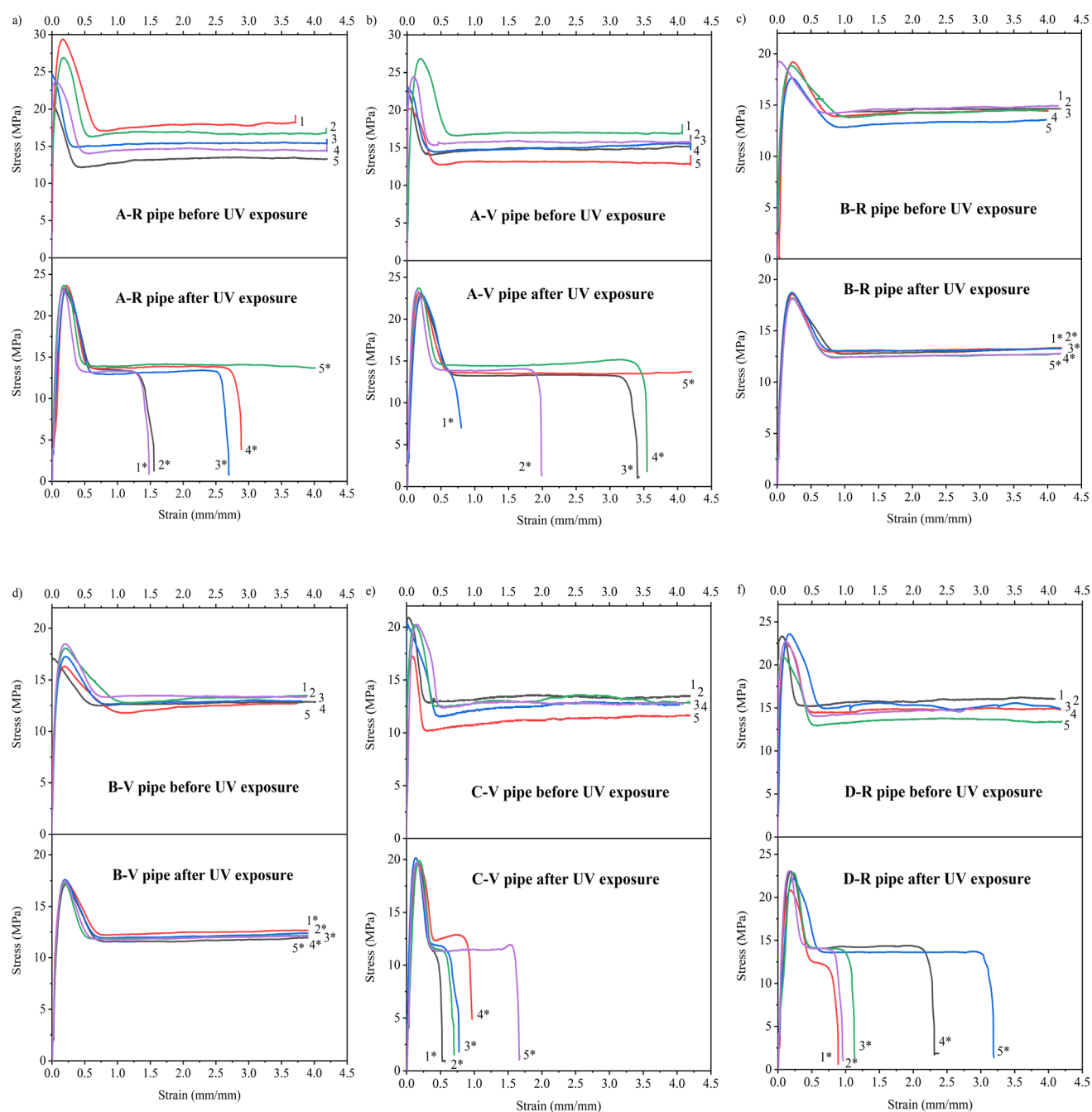


Fig. 9 Typical tensile stress–strain behaviors of the HDPE pipes before and after UV exposure: **a** A-R, **b** A-V, **c** B-R, **d** B-V, **e** C-V, and **f** D-R

similar for specimens after UV exposure. When the scanning width was 10 μm , 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 h 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

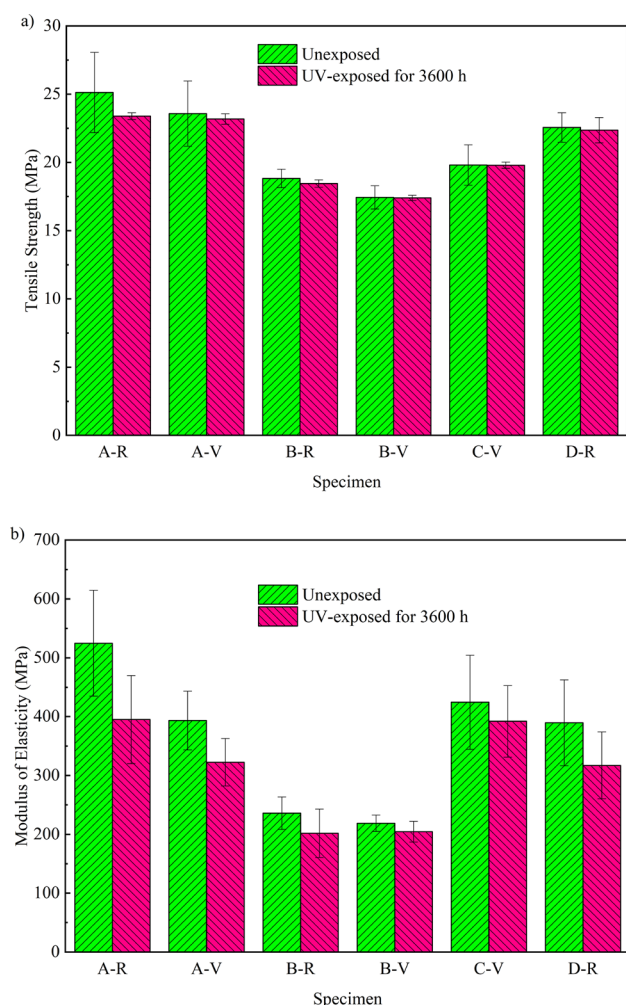


Fig. 10 Mechanical properties of the HDPE pipes before and after UV exposure: **a** tensile strength and **b** modulus of elasticity

Table 6 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

and virgin pipes remained constant under the effect of UV radiation.

- The molecular weight, 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 to 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, 55]. 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.

Conclusions

UV radiation from sunlight might adversely affect the microstructure, functional properties, and durability of polymers. In this study, the effect of UV radiation on HDPE pipes used for drainage applications was investigated, using the type of material (virgin or recycled HDPE) as a parameter. The microstructure, thermal, chemical, and physico-mechanical properties of HDPE pipes were assessed. More specifically, the following conclusions were drawn.

1. The incorporation of carbon black, antioxidants, and stabilizers mitigated the formation of free radicals and prevented the degradation of the HDPE pipes.
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 after UV exposure, the minimum 20-min OIT requirement for withstanding oxidation was met. The average molecular weight of HDPE pipes was unchanged before and after UV exposure. In addition, statistical analysis using one-way analysis of variance (ANOVA) shows that there was no significant difference between

Table 7 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
A-R	Between groups	7.5	1	7.5	1.726	0.225	5.318
	Within groups	34.9	8	4.4	—	—	—
	Total	42.4	9	—	—	—	—
A-V	Between groups	0.4	1	0.4	0.130	0.728	5.318
	Within groups	23.4	8	2.9	—	—	—
	Total	23.8	9	—	—	—	—
B-R	Between groups	0.4	1	0.4	1.329	0.282	5.318
	Within groups	2.1	8	0.3	—	—	—
	Total	2.5	9	—	—	—	—
B-V	Between groups	0.004	1	0.004	0.011	0.921	5.318
	Within groups	3.047	8	0.381	—	—	—
	Total	3.051	9	—	—	—	—
C-V	Between groups	0.001	1	0.001	0.001	0.979	5.318
	Within groups	8.939	8	1.117	—	—	—
	Total	8.940	9	—	—	—	—
D-R	Between groups	0.1	1	0.1	0.092	0.769	5.318
	Within groups	8.1	8	1.0	—	—	—
	Total	8.2	9	—	—	—	—

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 physico-mechanical (molecular weight, 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 to 4% of carbon black added to the resin compound, depending on the presence or absence of other antioxidants or UV stabilizers.

- 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.

Table 8 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
A-R	Between groups	34,052.7	1	34,052.7	4.959	0.068	5.987
	Within groups	41,204.7	6	6867.5	—	—	—
	Total	75,257.4	7	—	—	—	—
A-V	Between groups	11,166.1	1	11,166.1	5.585	0.051	5.591
	Within groups	13,995.3	7	1999.3	—	—	—
	Total	25,161.4	8	—	—	—	—
B-R	Between groups	2189.6	1	2189.6	1.589	0.254	5.987
	Within groups	8269.9	6	1378.3	—	—	—
	Total	10,459.5	7	—	—	—	—
B-V	Between groups	382.5	1	382.5	1.399	0.282	5.987
	Within groups	1639.7	6	273.3	—	—	—
	Total	2022.2	7	—	—	—	—
C-V	Between groups	1871.9	1	1871.9	0.403	0.549	5.987
	Within groups	27,856.6	6	4642.8	—	—	—
	Total	29,728.5	7	—	—	—	—
D-R	Between groups	7505.4	1	7505.4	2.061	0.211	6.608
	Within groups	18,209.5	5	3641.9	—	—	—
	Total	25,714.9	6	—	—	—	—

Table 9 One-way ANOVA of hardness before and after UV exposure

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

Table 10 The effect of UV radiation on the pipes made from recycled or virgin HDPE

Type of HDPE	Specimen	Before and after UV exposure		SEM	Degree of crystallinity	Tensile strength	Elongation at break	Elastic modulus	Hardness	Molecular weight
		FT IR								
Recycled	A-R	✓		○	○	○	✓	○	○	○
	B-R	✓		○	○	○	○	○	○	○
	D-R	✓		✓	○	○	✓	○	○	○
Virgin	A-V	✓		✓	○	○	✓	○	○	○
	B-V	✓		○	○	○	○	○	○	○
	C-V	✓		○	○	○	✓	○	○	✓

○ = no changes or remained constant; ✓ = negligible changes

Acknowledgements This research received financial support from the Natural Science and Engineering Research Council of Canada (NSERC), the Ministry of Transportation of Quebec (MTQ), and the University of Sherbrooke Research Centre on Composite Materials (CRUSMaC). The authors are also grateful to the technical staff of the structural laboratory at the University of Sherbrooke, especially Jérôme Lacroix and Steven MacEachern, for their technical assistance.

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

Declarations

Conflict of 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.

References

- Gassman SL, Schroeder AJ, Ray RP (2005) Field performance of high density polyethylene culvert pipe. *J Transp Eng* 131(2):160–167. [https://doi.org/10.1061/\(ASCE\)0733-947X\(2005\)131:2\(160\)](https://doi.org/10.1061/(ASCE)0733-947X(2005)131:2(160))
- P. Pipe Institute PPI Handbook (2008) Chapter 3 - material properties, p 61
- Petroff LJ (2013) Occasional and recurring surge design considerations for HDPE pipe. In: *Pipelines 2013*, Fort Worth, Texas, pp 161–170. <https://doi.org/10.1061/9780784413012.014>
- Rubeiz CG (2004) Case studies on the use of HDPE pipe for municipal and industrial projects in North America. In: *Pipeline engineering and construction*, San Diego, California, pp. 1–10. [https://doi.org/10.1061/40745\(146\)22](https://doi.org/10.1061/40745(146)22)
- Ortega R, Klopfenstein C, Morris A (2004) HDPE, an alternative with limitations; Houston's experience. In: *Pipeline engineering and construction*, San Diego, California, pp 1–10. [https://doi.org/10.1061/40745\(146\)39](https://doi.org/10.1061/40745(146)39)
- Nguyen KQ, Mwiseneza C, Mohamed K, Cousin P, Robert M, Benmokrane B (2021) Long-term testing methods for HDPE pipe - advantages and disadvantages: a review. *Eng Fract Mech* 246:107629. <https://doi.org/10.1016/j.engfracmech.2021.107629>
- Qureshi FS, Hamid SH, Maadhah AG, Amin MB (1989) Weather-induced degradation of plastic pipes. *Polym-Plast Technol Eng* 28(7–8):663–670. <https://doi.org/10.1080/03602558908049821>
- Stuart S (2011) Evaluation of HDPE and PVC pipes used for cross-drains in highway construction, PhD Thesis, Auburn University
- Zhao JQ, Kuraoka S, Baker THW, Gu P, Masson J-F, Boudreau S, Brousseau RJ (1998) Durability and performance of gravity pipes: state-of-the-art literature review, Institute for Research in Construction, <https://nrc-publications.canada.ca/eng/view/accepted/?id=3f56015a-909e-45fb-9b8a-c8e536b96d54>
- H. PPI (2008) Second edition handbook of PE pipe | HDPE handbook. <https://plasticpipe.org/publications/pe-handbook.html>
- Rabek JF (1995) "Physical aspects of the photodegradation of polymers", in *Polymer Photodegradation*. Springer, Dordrecht
- Becerra AFC, d'Almeida JRM (2017) UV effects on the tensile and creep behaviour of HDPE. *Polym Polym Compos* 25(5):327–332. <https://doi.org/10.1177/096739111702500502>
- Roy PK, Surekha P, Raman R, Rajagopal C (2009) Investigating the role of metal oxidation state on the degradation behaviour of LDPE. *Polym Degrad Stab* 94(7):1033–1039. <https://doi.org/10.1016/j.polymdegradstab.2009.04.025>

14. Koutny M, Lemaire J, Delort A-M (2006) Biodegradation of polyethylene films with prooxidant additives. *Chemosphere* 64(8):1243–1252. <https://doi.org/10.1016/j.chemosphere.2005.12.060>
15. BNQ 3624-120 (2016) Tuyaux à profil ouvert et à paroi intérieure lisse en polyéthylène (PE) et raccords en polyéthylène (PE) pour les égouts pluviaux, les ponceaux et le drainage des sols,” Bureau de Normalisation du Québec
16. ASTM D4218 (2015) Standard test method for determination of carbon black content in polyethylene compounds by the muffle-furnace technique, ASTM International, West Conshohocken
17. Attwood J, Philip M, Hulme A, Williams G, Shipton P (2006) The effects of ageing by ultraviolet degradation of recycled polyolefin blends. *Polym Degrad Stab* 91(12):3407–3415. <https://doi.org/10.1016/j.polymdegradstab.2006.04.025>
18. Maria R et al (2011) Monitoring the influence of different weathering conditions on polyethylene pipes by IR-microscopy. *Polym Degrad Stab* 96(10):1901–1910. <https://doi.org/10.1016/j.polymdegradstab.2011.07.004>
19. Jassim KA, Jassim WH, Mahdi SH (2017) The effect of sunlight on medium density polyethylene water pipes. *Energy Procedia* 119:650–655. <https://doi.org/10.1016/j.egypro.2017.07.091>
20. Jiang T, Qi Y, Wu Y, Zhang J (2019) Application of antioxidant and ultraviolet absorber into HDPE: enhanced resistance to UV irradiation. *e-Polymers* 19(1):499–510. <https://doi.org/10.1515/epoly-2019-0053>
21. Thomas RW (2011) Performance of corrugated pipe manufactured with recycled polyethylene content, vol. 696. Transportation Research Board
22. Pluimer M, Sprague J, Thomas R, McCarthy L, Welker A, Sargand S, White K (2018) Field performance of corrugated pipe manufactured with recycled polyethylene content
23. Pluimer ML (2016) Evaluation of corrugated HDPE pipes manufactured with recycled content in commuter rail applications, Villanova University
24. Shaheen ET (2018) Long term performance of corrugated HDPE pipes produced with post-consumer recycled materials under constant deflection, Ohio University
25. Dormer A, Finn DP, Ward P, Cullen J (2013) Carbon footprint analysis in plastics manufacturing. *J Clean Prod* 51:133–141. <https://doi.org/10.1016/j.jclepro.2013.01.014>
26. Korhonen MR, Dahlbo H (2007) Reducing greenhouse gas emissions by recycling plastics and textiles into products. Finnish Environment Institute, Helsinki
27. Nguyen KQ, Cousin P, Mohamed K, Robert M, Benmokrane B (2022) Comparing short-term performance of corrugated HDPE pipe made with or without recycled resins for transportation infrastructure applications. *J Mater Civil Eng* 34(2):402–1427. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004067](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004067)
28. ASTM D792 (2013) Standard test methods for density and specific gravity (relative density) of plastics by displacement, ASTM International, West Conshohocken
29. ASTM D1238 (2013) Standard test method for melt flow rates of thermoplastics by extrusion plastometer, ASTM International, West Conshohocken
30. ASTM D5805-00 (2019) Standard test methods for rubber - determination of carbon black in masterbatches, ASTM International, West Conshohocken
31. ASTM E2550 (2017) Standard test methods for thermal stability by thermogravimetry, ASTM International, West Conshohocken
32. ASTM D638 (2014) Standard test methods for tensile properties of plastics, ASTM International, West Conshohocken
33. ASTM D4329 (2013) Standard practice for fluorescent ultraviolet (UV) lamp apparatus exposure of plastics, ASTM International, West Conshohocken
34. Hitachi High-Tech (1986) Application note: thermal analysis-DSC measurement of polyethylene_no_26. Hitachi High-Tech Science Corporation. https://www.hitachi-hightech.com/file/global/pdf/products/science/appli/ana/thermal/application_TA_026e.pdf
35. ASTM D3895 (2019) Standard test method for oxidative-induction time of polyolefins by differential scanning calorimetry. ASTM International West Conshohocken
36. ASTM D2240, “Standard Test Method for Rubber Property—Durometer Hardness,” ASTM International, West Conshohocken, PA, USA, 2015.
37. Khan SM, Gull N, Munawar MA, Islam A, Zia S, Shafiq M (2016) 2D Carbon fiber reinforced high density polyethylene multi-layered laminated composite panels: structural, mechanical, thermal, and morphological profile. *J Mater Sci Technol* 32(10):1077–1082. <https://doi.org/10.1016/j.jmst.2016.06.011>
38. Jung MR, Horgen FD, Orski SV, Rodriguez V, Beers KL, Balazs GH et al (2018) Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. *Mar Pollut Bull* 127:704–716. <https://doi.org/10.1016/j.marpolbul.2017.12.061>
39. Asensio RC, Moya MSA, de la Roja JM, Gómez M (2009) Analytical characterization of polymers used in conservation and restoration by ATR-FTIR spectroscopy. *Anal Bioanal Chem* 395(7):2081–2096. <https://doi.org/10.1007/s00216-009-3201-2>
40. Luongo JP (1960) Infrared study of oxygenated groups formed in polyethylene during oxidation. *J Polym Sci* 42(139):139–150. <https://doi.org/10.1002/pol.1960.1204213916>
41. JS, HELD University (2021) Fourier-transform infrared spectroscopy (FTIR) technology & analysis 1st edition. <https://assets.jsheld.com/uploads/Fourier-Transform-Infrared-FTIR-Technology-Analysis-PDF.pdf?mtime=20211006171616&focal=none>
42. Wong WK (2011) Evaluation of the oxidative degradation mechanism of corrugated high density polyethylene pipe and the pipe resin, Doctoral dissertation, Drexel University
43. Majewski K (2018) Morphology and mechanical properties of high-density polyethylene exposed to chlorinated water, Doctoral dissertation, University of Minnesota
44. Mouallif I, Latrach A, Chergui MH, et al. (2011) FTIR study of HDPE structural changes, moisture absorption and mechanical properties variation when exposed to sulphuric acid aging in various temperatures. In: CFM 2011–20ème Congrès Français de Mécanique. AFM, Maison de la Mécanique, 39/41 rue Louis Blanc-92400 Courbevoie
45. Wang S, Zhang J, Liu L, Yang F, Zhang Y (2015) Evaluation of cooling property of high density polyethylene (HDPE)/titanium dioxide (TiO₂) composites after accelerated ultraviolet (UV) irradiation. *Sol Energy Mater Sol Cells* 143:120–127. <https://doi.org/10.1016/j.solmat.2015.06.032>
46. Hoang EM, Lowe D (2008) Lifetime prediction of a blue PE100 water pipe. *Polym Degrad Stab* 93(8):1496–1503. <https://doi.org/10.1016/j.polymdegradstab.2008.05.008>
47. Hassinen J (2004) Deterioration of polyethylene pipes exposed to chlorinated water. *Polym Degrad Stab* 84(2):261–267. <https://doi.org/10.1016/j.polymdegradstab.2003.10.019>
48. Weon J-I (2010) Effects of thermal ageing on mechanical and thermal behaviors of linear low density polyethylene pipe. *Polym Degrad Stab* 95(1):14–20. <https://doi.org/10.1016/j.polymdegradstab.2009.10.016>
49. Nguyen KQ, Cousin P, Mohamed K, Robert M, Benmokrane B (2021) Influence of wall thickness on the thermo-mechanical properties of aging HDPE pipes under Freeze-thaw cycles in Quebec Province, Canada (No. 7000), 2021. EasyChair
50. Wong WK, Hsuan YG (2012) Interaction between carbon black and antioxidants in high-density polyethylene pipe resin. *Transp Res Rec* 2310(1):137–144. <https://doi.org/10.3141/2310-15>

51. Special Chem - The material selection platform, "OIT-Assessment of oxidative stability of polymeric material," <https://polymer-additives.specialchem.com/centers/antioxidants-to-prevent-polymer-oxidation/oxidation-induction-time>. Accessed 12 Jan 2022
52. Kadhim LF (2017) Mechanical properties of high-density polyethylene/chromium trioxide under ultraviolet rays. *Int J Appl Eng Res* 12(10):2517–2526
53. Hafiz E (2015) The 'carbon footprint' of sewer pipes: risks of inconsistency. In: *Proceedings of the institution of civil engineers-engineering sustainability*. Thomas Telford Ltd, pp 38–48. <https://doi.org/10.1680/ensu.14.00012>
54. Nguyen LK, Na S, Hsuan YG, Spataro S (2020) Uncertainty in the life cycle greenhouse gas emissions and costs of HDPE pipe alternatives. *Resour Conserv Recycl* 154:104602. <https://doi.org/10.1016/j.resconrec.2019.104602>
55. Javadi Y, Hosseini MS, Aghjeh MKR (2014) The effect of carbon black and HALS hybrid systems on the UV stability of high-density polyethylene (HDPE). *Iran Polym J* 23(10):793–799. <https://doi.org/10.1007/s13726-014-0275-2>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.