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ORIGINAL ARTICLE

The effects of using reprocessable material on the durability and mechanical properties of landfill leachate collection HDPE pipes

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Abstract This paper investigated the durability and mechanical properties of landfill leachate collection HDPE pipes which had been made of different weight percent amounts of virgin and reprocessable HDPE compounds (VC and RC). Durability is reported base on the chemical properties, obtained through oxidative induction time (OIT) and melt flow index (MFI) measurements, at the temperature of 50 °C and over a period of 12 months immersion in a synthetic leachate. Mechanical properties are also described according to tensile and pressure tests which had been conducted on the pipes samples. All of the factors were examined had been affected by the addition of RC, but for the special combination the antioxidant depletion was significantly affected by the experimental aging condition and no important changes had been observed in the other pipe properties. The results from OIT tests indicate that the rate of antioxidant depletion is reduced by an increase in the weight percent amounts of RC, during the experimental aging condition. This reduction is probably attributed to the extraction of antioxidants from RC in their recovery process. Finally, although these results are related to the particular HDPE compound, antioxidant formulation and condition examined, but it can be said that the use of clean own reprocessable material for the production of landfill leachate pipes shall be permitted without limitations.

Keywords Reprocessable material · Durability · Mechanical properties · HDPE · Leachate collection

Introduction

During the last few decades, the worldwide production of high density polyethylene (HDPE) resulted in a significant proportion of municipal solid waste (MSW) [1]. Therefore, attempts have been made to reprocess or recycle HDPE scraps to reduce environmental impacts [2–5]. For this purpose, the first approach is primary recycling which is referring to the "in-plant" reprocessing of the scrap material of the controlled history [6]. Also, it is worthy to mention that a greater use of recycled HDPE offers the prospect of lessening the waste disposal and the reduction of the product costs. For example, in reference [2] the possibility of using recycled HDPE in the production of AGL (Anti-Glare Lamellae) has been studied. It compares an AGL (Anti-Glare Lamellae) currently manufactured from virgin HDPE with an alternative one made with recycled HDPE. The obtained results show that there is a clear overall environmental and economic advantage in replacing virgin HDPE with recycled HDPE.

Despite relatively short history, polyethylene pipes have been successfully utilized for a variety of piping applications for over 50 years. HDPE leachate collection pipes are important components in the leachate collection system of modern solid waste landfills. These are designed to collect and convey the leachate out of the landfill for treatment or reinjection depending on the liquid management strategy [7]. These pipes may fail due to clogging, crushing, or

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faulty installation [8]. Because the contaminating lifespan of a modern landfill can exceed many decades, the long-term durability and structural response of leachate collection pipes is an issue that needs to be examined. Therefore, many laboratory testing and numerical analysis have been conducted on leachate collection pipes [9–14] and aging of HDPE geomembranes exposed to air, water and leachate at different temperatures [15–23].

According to ISO 4427 [24]; clean, reprocessable materials generated from a manufacturer's own production and works testing of products may be used if it is derived from the same compound as used for the relevant production. In addition, the application of reprocessable material obtained from external sources and recyclable material is not permitted to be used. Nevertheless, there is no valuable data about the effects of using reprocessable material on the durability and mechanical properties of landfill leachate collection HDPE pipes at this time. Therfore, to shed light on this subject, the efficiency of this idea was examined in the present investigation.

Theory

Oxidation and antioxidant depletion

Various aging and degradation mechanisms can take place in plastic pipes depending on the type of polymer and environmental exposure. Due to the degradation of the polymer, the following changes take place in the pipes: gain or reduction of molecular weight, formation of free radicals, brittleness, loss of additives and plasticizers [25]. Three major mechanisms which can adversely affect the durability of HDPE pipes are photodegradation, stress cracking, and oxidative degradation. Photodegradation is not an issue for leachate collection HDPE pipes because modern HDPE pipe resins include the carbon black to protect the pipe from the sun prior to burial. Stress cracking is an issue for internally pressurized pipes where tensile stresses exist through the entire wall of the pipe. Therefore, it is not an issue for leachate collection pipes which are subjected to gravity loads from burial that result in internal pipe stresses that are a combination of tension and compression through the thickness of the pipe. Consequently, major mechanism that can adversely affect the durability of HDPE pipes is oxidative degradation [10].

Oxidation in polymeric materials (HDPE pipes) is associated with the formation of free radicals or auto-oxidation chains mechanism which has two interacting cyclical processes (Fig. 1). In the first cycle (A), hydroperoxide (ROOH) and free radicals are formed due to alkyl/alkylperoxyl chain reactions whereas in the second cycle (B), hemolysis of hydroperoxide occurred and more free

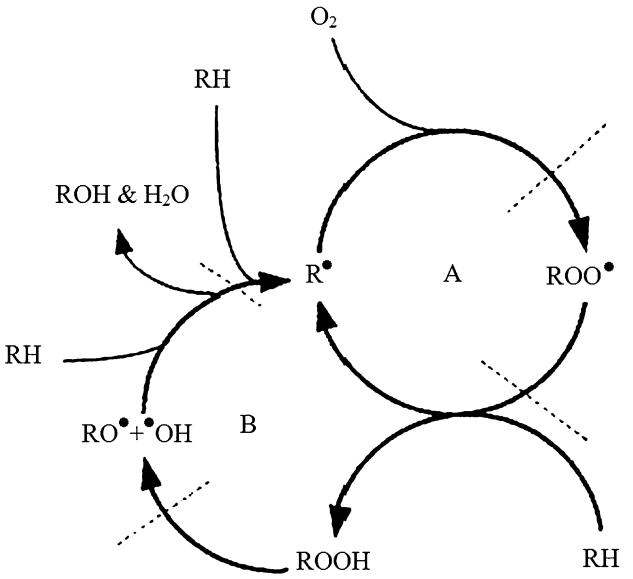

Fig. 1 Oxidation cycles in polyethylene

Table 1 Equations describing the oxidative degradation process in polymers [26]

Number	Equations
(1)	$RH \rightarrow R^{\cdot} + H^{\cdot}$
(2)	$R^{\cdot} + O_2 \rightarrow ROO^{\cdot}$
(3)	$ROO^{\cdot} + RH \rightarrow ROOH + R^{\cdot}$
(4)	$ROOH \rightarrow RO^{\cdot} + OH^{\cdot}$
(5)	$RO^{\cdot} + RH \rightarrow ROH + R^{\cdot}$
(6)	$OH^{\cdot} + RH \rightarrow H_2O + R^{\cdot}$
(7)	$ROOH + M^{n+} \rightarrow RO^{\cdot} + M^{(n+1)} + OH^{-}$
(8)	$ROOH + M^{(n+1)+} \rightarrow ROO^{\cdot} + M^{n} + H^{+}$

radicals are formed. Equations (1)–(8) which are describing the oxidative degradation process in polymers have been presented in Table 1 [26]. The oxidative reaction initiates by forming free radicals ($R^{\cdot}$) from the polymer chain (RH) under the influence of energy or catalyst residues in the polymer (Eq. 1). Once a free radical is formed, it reacts with oxygen and produces a peroxy radical ($ROO^{\cdot}$) (Eq. 2). A hydrogen atom from the surrounding polymer reacts with the peroxy radical ($ROO^{\cdot}$) and forms hydroperoxide (ROOH) and another free radical (Eq. 3). The breakdown of the hydroperoxide initiates when a significant concentration of ROOH accumulates (Eq. 4). More free radicals form due to the decomposition of ROOH which eventually attacks the polymer chain to form more free radicals and alcohol (ROH) (Eq. 5). Simultaneously, there are reactions between the $OH^{\cdot}$ radical and the polymer chain which yield free radicals and water (Eq. 6). Also, oxidative degradation is known to be accelerated by the presence of transition metals. More free radicals are

formed when metal ions react with hydroperoxide through redox reactions, according to the Eqs. 7 and 8.

Antioxidants are normally added to polymeric materials to retard the oxidative reactions by breaking the links in the auto-oxidation chains and to extend the induction period. Various factors affect the effectiveness of antioxidants, Including temperature, type of antioxidants, amount of antioxidants, and the combination of antioxidants used. There are four different antioxidants that are commonly used in the formation of PE pipes: hindered phenols, hindered amines, phosphites, and thiosynergists. Antioxidants can also be divided into two categories: primary (hindered amines and hindered phenol) and secondary antioxidants (phosphites, thiosynergists, and hindered amines). Primary antioxidants react with free radical either by accepting or donating an electron and form a stable polymer chain. Secondary antioxidants impede the formation of free radical by decomposing hydroperoxides into stable alcohols [15].

The amount of antioxidant in a HDPE pipe decreases as the pipe ages because of two mechanisms: chemical reactions and physical loss. Chemical reactions occur when the antioxidants react with oxygen, free radicals or alkyl peroxides. Physical loss occurs from diffusion, extraction or volatilization. Volatility and diffusion of antioxidants are a function of temperature. Increased temperatures result in increased volatilization of stabilizers from the pipe surfaces, and increased diffusion of stabilizers from the interior to the surfaces of the pipe. Volatility is also a function of the mobility of antioxidants in the amorphous phase of the polymer, as a greater concentration of antioxidants can be found in the amorphous phase [27]. The selection of antioxidants should be such that they can withstand the manufacturing temperature as well as service temperature. More than one antioxidant is generally used by the manufacturers to provide greater stability to the pipe.

Since no stabilization system will last forever, an eventual decrease in pipe properties arising from the oxidation is expected to occur [10]. It has been postulated by Hsuan and Koerner [27] that the durability of HDPE can be quantified using three distinct stages (Fig. 2): t_1, the time required to deplete antioxidants; t_2, the time required for the induction of the polymer degradation; and t_3, the time required for the engineering property of interest to degrade to the extent where it no longer performs its intended design function. Therefore, the aim of the present investigation is to quantify these three distinct stages by examination of durability and mechanical properties of PE pipes which had been made of different weight percent amounts of VC and RC, through experimental testing methods.

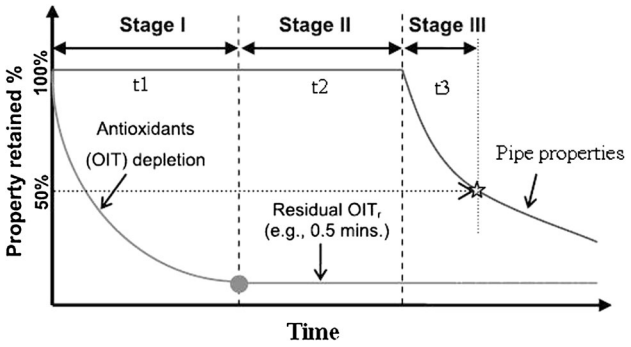

Fig. 2 Three conceptual stages in chemical aging of HDPE

Materials and procedure

Virgin HDPE compound (VC)

A virgin PE piping material consists of a polyethylene polymer resin (HMCRP 100 N) which had been added quantities of process stabilizers, antioxidants, lubricants (processing aid) and acid scavengers, produced by Jam petrochemical Co., Iran; and carbon black (masterbatch code: VB-MBC40) which is produced by Vizhegan Baspar Co., Iran, in order to protect the pipe from the sun prior to burial. Details of the virgin PE and carbon black resins which are used in the study have been compiled in Table 2.

Reprocessable HDPE compound (RC)

Reprocessable compound (RC) was produced from the same pipe resin [i.e., polymer resin (PE100), antioxidant/stabilizer package, and carbon-black batch], using the in-plant recycling of the scrap material of controlled history, according to ISO 4427. It should be noted that "in-plant recycling of the scrap material of controlled history" means wastes that have been produced by the production of different products of the factory at the time of using resins referred to in the section "Virgin HDPE compound (VC)". Also, the time of their production is completely clear. It should be noted that the given wastes have been kept in the stock and away from any process that leads to a decrease in antioxidants in these products from the production of the wastes until the production of reprocessable HDPE compound (RC) and the production of pipes used in this study. In addition, based on ISO 4427, before the production of RC, the polymer is separated from its associated contaminants, thoroughly washed with water, dried at 65 °C for 12 h, chopped into small components, reprocessed by melt extrusion and shaped into a granular form [28]. The measured properties of the recycled HDPE show MFI values about 0.348 g/10 min at 190 °C.

Table 2 Material properties of the virgin PE and carbon black resins used in this experiment

Test/composition	Value	Unit	Method
PE resin			
Density	0.948	g/cm^3	ISO 1183
Hydrostatic strength	5000 (4.5 N/mm^2)	h	ISO 1167
MFI 190 °C/21.6 kg	6.2	g/10 min	ISO 1133
MFI 190 °C/5 kg	0.22	g/10 min	ISO 1133
Notched impact (23 °C)	24	mJ/mm^2	ISO 179
Application	HDPE irrigation pipes, corrugated PE pipe		
	Value	Unit	Method
Carbon black resin/polyethylene based/code: VB-MBC40			
MFI 190 °C/5 kg	<0.3	g/10 min	ISO 1133
Density	1.13 ± 0.03	g/cm^3	ISO 1183
Carbon black content	40 ± 2	%	ISO 6964
Volatile content	<350	PPM	EN 12099
Pellet shape	Spherical	–	–

Pipes

All HDPE pipes samples had been produced through a conventional extrusion line (Fig. 3) by the same pipe supplier (Pooyashiraz Co., Iran) and were 110 mm nominal diameter (DN), dimension ratio (SDR) 21 and an average wall thickness of 5.5 mm when classified in accordance with ISO 4427, with a hydrostatic nominal pressure (PN) of 8 bar at 23 °C. SDR is the ratio of pipe outside diameter to pipe wall thickness. The pipe samples names and their raw material compositions are summarized in Table 3 base on the weight percent amounts of carbon black, VC and RC. It should be noted that the paper only involves plane-wall pipes (i.e., pipes with a solid and uniform wall thickness).

Synthetic leachate

The synthetic leachate used in this study was produced by mixing trace metals, surfactant, and reducing agent in distilled water as detailed in Table 4. This leachate was selected based on a study by Rowe et al. [22] which showed that it contained the components of a MSW leachate (i.e., trace metals and surfactant) that affect the aging of HDPE pipes. To simulate the possible scenario in a landfill where leachate is continuously collected through a leachate collection system, the leachate in this study was completely replaced with a newly prepared leachate every 2 weeks. The 2 weeks leachate renewal frequency adopted in this paper was based on a study that examined different leachate renewal frequencies on the antioxidant depletion [22]. The leachate in the pilot was continuously mixed between the 2 weeks refreshment periods using an external recirculation pump. Several mixing trials were conducted by changing port configuration and circulation flow rate to ensure a system that provided uniform mixing and avoided areas of stagnant flow of leachate within the pilot.

Exposure testing tank

Perforated pipes are placed in the exposure testing tank and immersed in the synthetic landfill leachate to simulate the landfill exposure condition. The exposure testing tank is schematically depicted in Fig. 4. This test cell is a 0.4 m high, 1.1 m long and 0.8 m wide. All frameworks and miscellaneous parts of the exposure testing tank were constructed by borosilicate glass and have been attached to

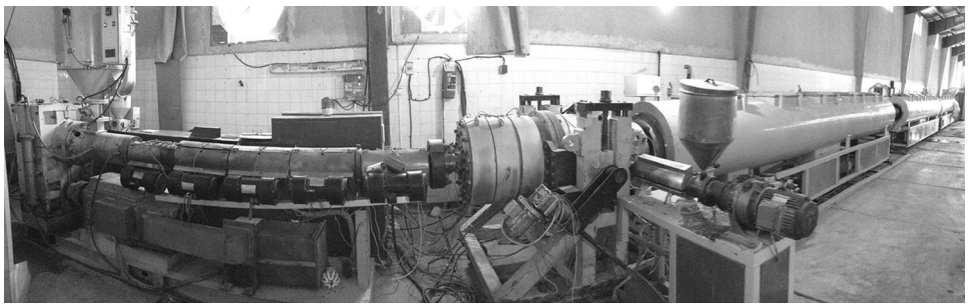

Fig. 3 Conventional HDPE pipe extrusion line used in the current investigation

Table 3 The pipe samples names and their raw material composition used in the study

Pipe samples names	Raw material composition (weight percent)		
	Virgin HDPE compound	Reprocessable HDPE compound	Carbon black
PE0	98	0	2
PE5	93	5	2
PE10	88	10	2
PE15	83	15	2
PE20	78	20	2
PE25	73	25	2
PE50	48	50	2

Table 4 Composition of synthetic leachate

Component		Concentration (mg/L) (except where noted)
Trace metal solution[a,b] (mL/L)		1
Surfactant, Igepal® CA720 (mL/L)		5
E_h (adjusted by $Na_2S{\cdot}9H_2O$) (mV)		~ -120
pH 6 [adjusted by NaOH (15 M)]		
Composition of trace metal solution		
Ferrous sulfate	$FeSO_4{\cdot}7H_2O$	2000
Boric acid	H_3BO_3	50
Zinc sulfate heptahydrate	$ZnSO_4{\cdot}7H_2O$	50
Cupric sulfate, pentahydrate	$CuSO_4{\cdot}5H_2O$	40
Manganous sulfate monohydrate	$MnSO_4{\cdot}H_2O$	500
Ammonium molybdate tetrahydrate	$(NH_4)_6Mo7O_{24}{\cdot}4H_2O$	50
Aluminum sulfate 16-hydrate	$Al_2(SO_4)_3{\cdot}16H_2O$	30
Cobaltous sulfate heptahydrate	$CoSO_4{\cdot}7H_2O$	150
Nickel (II) sulfate	$NiSO_4{\cdot}6H_2O$	500
Sulfuric acid	H_2SO_4 (mL/L)	1

[a] Composition of trace metal solution

[b] 1 mL of trace metal solution was added in 1 L of synthetic leachate

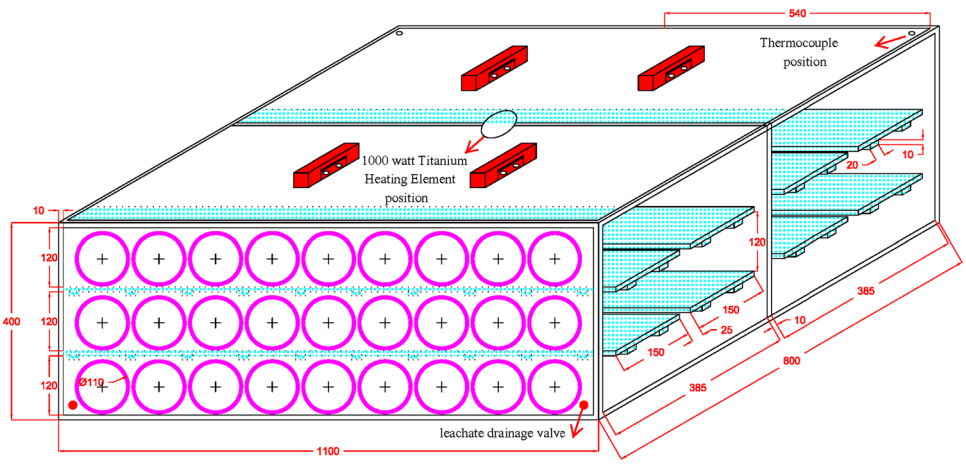

Fig. 4 Schematically view of the exposure testing tank. [To fully show the internal components of the tank (*glass shelves*), three-dimensional drawing of pipes have been avoided and only in the front plate of the tank, the place of pipes has been mapped as *circles* with specific thickness and the sign (+) indicates the center of these testing pipes]

each other by Fix ALL® High Tack sealant-glue. Also, roof and floors of the testing tank were movable and have been designed so that the first floor of the tank was placed after placing the lower pipes; second floor was placed after placing central pipes, and finally the roof was placed after placing the upper pipes to prevent the floatation and

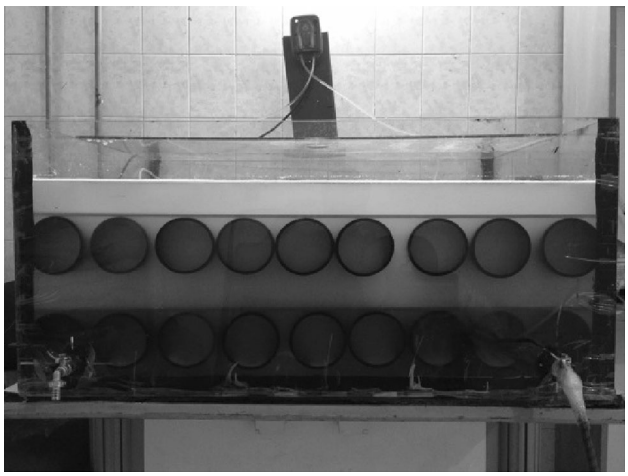

Fig. 5 The manner of placing pipes inside the exposure testing tank

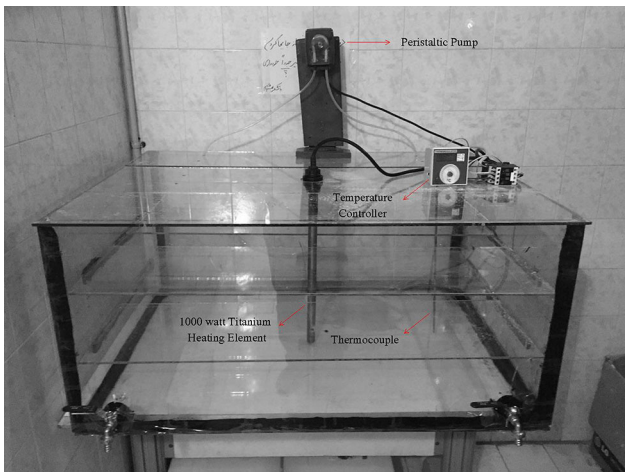

Fig. 6 Instrumentation of exposure testing tank

movement of the pipes while filling the tank with leachate. Figure 5 shows how testing pipes were placed inside the tank. It should be explained that in the given figure, the pipes of the upper floor were taken out of the tank to do the tests. Also, it should be noted that during the testing period the testing tank was completely filled with leachate, so that the leachate would float exactly at the top of the pipes and at the bottom of the tank roof.

Instrumentation

Elevated temperature was used to accelerate the antioxidant depletion. Therefore, the temperature was applied through the use of three numbers of 1000 W titanium heating elements at the beginning of the experiment. Afterward, when the temperature reached to the desired value, it was maintained constant through a process control loop. This intelligent system includes a temperature controller, thermocouple and one 1000 W titanium heating element (Fig. 6), which could hold the temperature with an accuracy of $\pm$ 2 °C. The temperature set point was located at the corner of the inside exposure testing tank.

When selecting the elevated temperature to use, it is important not to raise the temperature so high as to change the morphological structure of the material being examined. It is also important that the effective temperature range of the antioxidants which had been used in the pipe is not exceeded, or else the results from OIT tests could possibly be deceiving. In the current investigation, the tests were conducted at the temperature of 50 °C and were held within $\pm$ 2 °C. The adopted temperature is believed to be acceptable for use with the HDPE pipe, based on a review of the literature dealing with HDPE geomembranes and HDPE pipe elevated temperature tests [9, 17, 29].

Testing methods to evaluate durability and mechanical properties of PE pipe samples

Specimens cut from the pipes samples were subject to the standard OIT test [30]. In addition to monitoring the OIT of the pipes, melt flow index (MFI) [31] were measured to assess whether there was any durability changes of the polymer due to addition of RC and/or immersion in the elevated temperature synthetic leachate as the time went by. The mechanical tests consisted of uniaxial monotonic tensile and pressure tests [32, 33]. Tensile tests were performed on dumbbell specimens that had been cut from all aged and unaged pipes samples soaked in the elevated temperature synthetic leachate. In other hand, pressure tests were conducted only on the unaged specimens. The purpose of pressure tests at constant temperature were to establish a correlation between the outcome of the short-term tests (tensile, OIT, and MFI) and the true long-term creep behavior of the materials.

OIT test

The stage I of the service life of PE pipes is dependent on the rate of antioxidants depletion. During the stage I, the OIT value of the PE pipe decreases as antioxidants are depleted with time. Thus, the standard (Std-OIT) differential scanning calorimetry (DSC) tests were used to monitor the depletion of antioxidants from the PE pipes samples using TA Instruments DCS Q100, according to ISO 11357. The Std-OIT test is conducted at an isothermal temperature of 200 °C, inside a differential scanning calorimeter with inert atmosphere of N_2 and heating rate of 20 °C/min. When the set temperature was reached, the atmosphere inside the chamber was changed to oxygen under oxygen pressure of 35 kPa with a flow rate of 50 ml/

min; until the exothermic peak was detected. The 15 mg specimens have been punched out from the middle (55 mm from each end) of the pipes thickness and were used for OIT test. The time to the onset of exothermic peak resulting from oxidation, was taken as the OIT value. For any specific sampling, 6 samples were tested (3 from the pipe crown and others from the pipe springline) and the average is reported in the results section.

Melt flow index (MFI)

The oxidative degradation results in changes in the molecular weight of the polymer due to cross-linking or chain scission. Generally, cross-linking results in an increase in the molecular weight and chain scission decreases the molecular weight. The melt index is inversely correlated with the molecular weight. Therefore, MFI was used as a qualitative measure to infer the change in the polymeric structure due to oxidative degradation and to assess the variations in the molecular weight of the polymer due to addition of RC and/or immersion in the elevated temperature synthetic leachate with time. MFI is defined as the weight of the polymer (in grams) extruded in 10 min through a standard orifice of specified diameter at 190 °C under a constant load of 5 kg and the result is expressed in g/10 min. In the current investigation, the MFI tests were carried out using Dynisco LMI 4000 series melt indexer as per ISO 1133. For any specific sampling, 6 samples were tested (3 from the pipe crown and others from the pipe springline) and the average is reported in the results section.

Tensile properties

The tensile properties provide an index as to how PE pipes samples will respond to physical stress and is useful in evaluating the effects of using reprocessable material on the mechanical properties of landfill leachate collection HDPE pipes. As a consequence of oxidation that occurs during the 3rd stage of degradation, the tensile properties of HDPE pipes begin to decrease in stress and strain at break [10]. The decrease in tensile properties at break signifies the transition from a ductile to a brittle material as a result of degradation [20]. The tensile properties of the HDPE pipes specimens were tested in accordance with ISO 6259. The dumbbell shaped HDPE specimens (according to ISO 2818 [34]) were tested in Instron universal testing machine equipped with load cell, cross-head monitor and self-aligning wedge grips. The pipes specimens were stretched at the strain rate of 50 mm/min till rupture. For any specific sampling event, six samples were tested (three along the machine direction and other along the cross direction) and the average is reported in the results section.

Pressure test

As a further mechanical characterization, pressure tests at a constant temperature were performed on pipes samples. An unaged pipe sample (approximately 1 m long) from each of the raw material combinations was tested, according to ISO 1167. The pipes samples were subjected to an internal pressure that was generating a circumferential stress of 5 MPa in the pipe wall at a constant temperature of 80 °C. The 1000 h time period was examined in the current investigation.

Results and discussion

Std-OIT

It is interesting to compare the variation of OIT between VC, RC and unaged pipes specimens with different weight percent amounts of VC and RC, as this provides information on a consumption and/or extraction of antioxidants during HDPE recycling and pipe extrusion processes.

According to Fig. 7, the average OIT values of VC and unaged PE0 were about 73 and 70 min, respectively. These results indicated that the processes which are taking place during the pipe production from raw material extrusion had not significant effect on the depletion of antioxidants. But the results of experiments conducted on the RC showed the significant reduction on OIT value. The RC had the OIT value of 62 min which showed the effect of recycling process on the antioxidant reduction. Therefore, the addition of RC to the raw material compounds lead to lower OIT values in the final produced pipes.

Figure 8 is a plot showing the average results of OIT measurements versus time for the series of tests conducted on the pipes specimens with different weight percent amounts of VC and RC which had been soaked in synthetic leachate at 50 °C. From Fig. 8 it can be observed that despite the fact that PE0 had started with the highest OIT value, the results of all specimens were found to be equal at the end of storage time (about one-year immersion in the synthetic leachate at 50 °C). Overall, there appears to be no substantial difference in the antioxidant depletion after immersion about one year whether the pipe was consisted of RC or not. This behavior is probably caused by the rapid diffusion of unstable antioxidants during the beginning of the storage time which led to a certain amount of durable antioxidants in all the pipes specimens that had been equal in all different weight percent amounts of VC and RC at this experimental condition.

OIT depletion with respect to time has been expressed as an exponential function (Eq. 9) [27]:

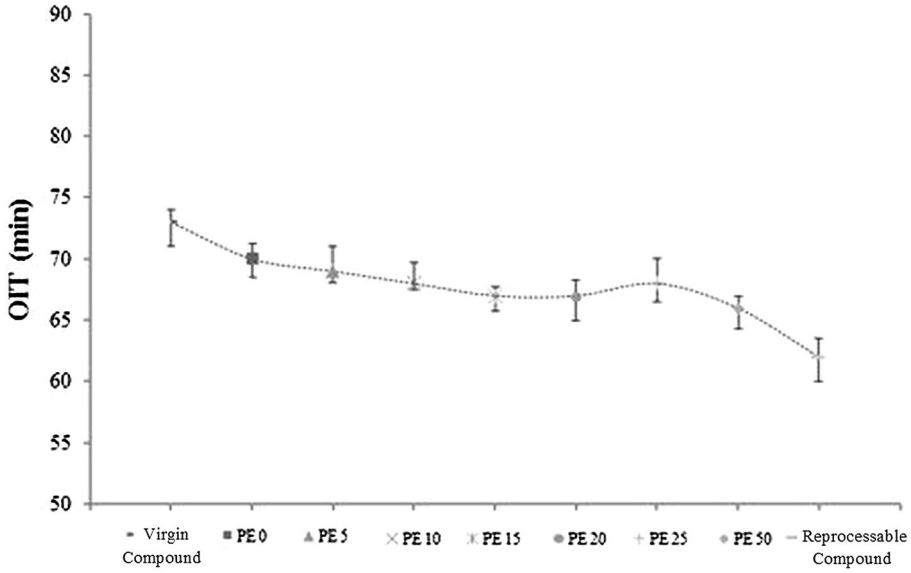

Fig. 7 OIT variation of VC, RC and unaged pipes specimens with different weight percent amounts of VC and RC (*Error bars* indicate the maximum and minimum variations)

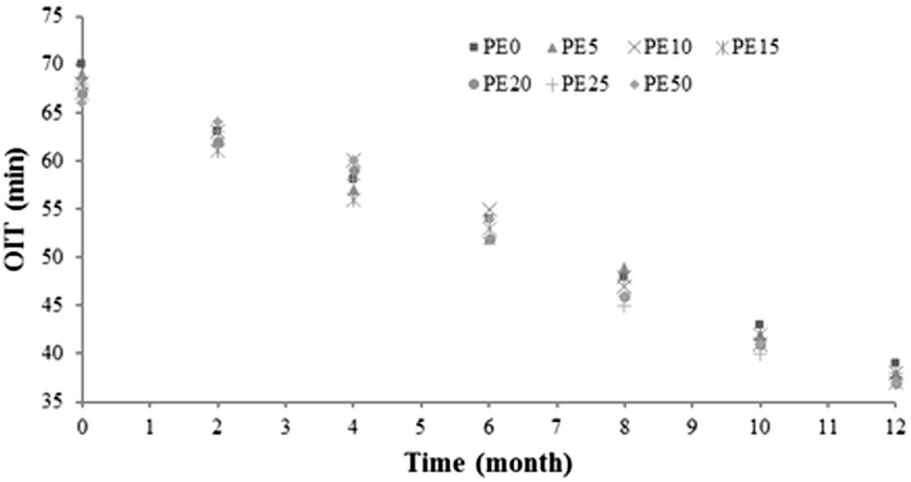

Fig. 8 The average results of OIT measurements versus time conducted on the pipes specimens with different weight percent amounts of VC and RC

$$OIT_t = OIT_0 e^{-st} \quad (9)$$

where OIT_t is the OIT value in minutes at time t in months, OIT_0 is the initial OIT value in minutes, and s is the rate of antioxidant degradation in 1/months. The data can be represented as a linear function of the natural logarithm of OIT against time, where the slope of the function is the rate of OIT degradation. Best-fit parameters from Eq. 9 using the method of least squares for the different weight percent amounts of VC and RC are presented in Table 5. Although there is no clear differentiation between OIT reduction rates among all specimens' formulations, but the rate of antioxidant depletion is reduced slightly by the addition of RC. This reduction is probably attributed to the extraction of unstable antioxidants from RC in their recovery process. Also, there is a good agreement between the current investigation results and the results have been mentioned by Krushelnitzky and Brachman [10].

Melt flow index (MFI)

Figure 9 is a plot of measured MFI for specimens of VC, RC, and unaged pipes specimens with the different weight percent amounts of VC and RC. The average of MFI tests is shown in the figure along with error bars indicating the maximum and minimum variations of tests results. Variability in the measurements can be a possible result of a heterogeneous distribution of reprocessable compound in the raw HDPE compounds and also as a result of manufacturing. According to Fig. 9, the addition of RC in the raw material led to increase in the MFI property because of probably decrease of molecular weight as a result of a chain scission which had been occurred during the recycling processes in the polymer. Almost certainly, as melt extrusion process to produce RC has already been used in the process of producing wastes, its reuse in the

Table 5 Antioxidant depletion rates

Exposure medium	Synthetic leachate (50 °C)						
Pipe sample specimen	PE0	PE5	PE10	PE15	PE20	PE25	PE50
Antioxidant depletion rate (1/month)	0.048	0.047	0.046	0.046	0.047	0.048	0.044

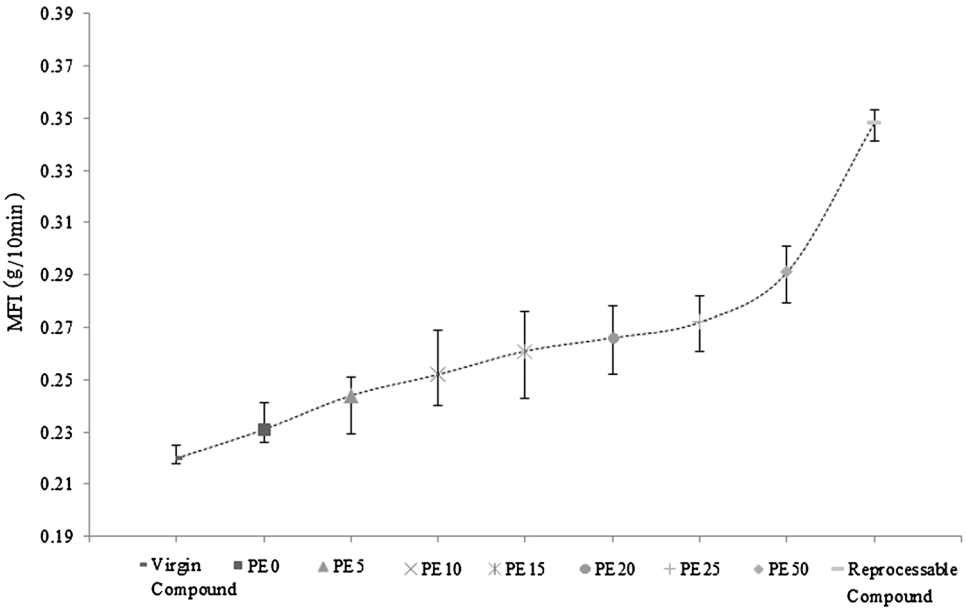

Fig. 9 MFI variation of VC, RC and unaged pipe specimens with different weight percent amounts of VC and RC (*Error bars* indicate the maximum and minimum variations)

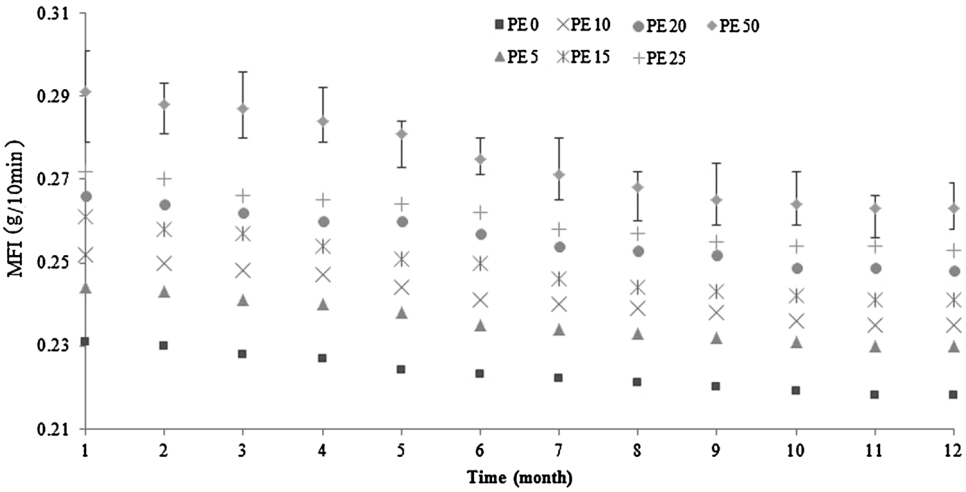

Fig. 10 The average results of MFI measurements with time conducted on the pipe specimens with different weight percent amounts of VC and RC (*Error bars* indicate the maximum and minimum variations of PE50)

production of RC may lead to chain scission due to the interference of the polymer resin, carbon black, antioxidants, etc.

Melt flow index (MFI), an inverse measure of molecular weight, also was measured as the pipes specimens aged. For all pipes samples, the measured MFI had been decreased but did not differ significantly from the initial MFI. Figure 10 shows the MFI values versus time for pipes specimens with different weight percent amounts of VC and RC. The results show that after aging the pipes samples for 1 year immersion in the synthetic leachate at temperatures of 50 °C, only the first stage of degradation was observed, based on no statistically significant change in the MFI property of the pipes.

Tensile properties

Tensile Properties of the HDPE pipe material were obtained from tension testing samples machined out of the pipes specimens' wall. Although tensile tests have been performed for all materials investigated, the presentation of data in the following will be limited to a few selected materials (PE0, PE25, and PE50) to exemplify the major of the RC addition. Results from tension testing are listed in Table 6. With addition of RC, the ultimate elongation value is seen to decrease, but there is no significant change in this property with time due to immersion in the synthetic leachate at 50 °C.

This finding apparently reflects the effect of density (an inverse measure of MFI) on the ultimate tensile elongation. According to Figs. 9 and 10, addition of RC in the raw material led into increase in MFI property and as a result the ultimate tensile elongation had been decreased. Also, immersion in synthetic leachate at 50 °C had slightly effect on the diminution of MFI and simultaneously growth on the ultimate tensile elongation.

Pressure tests

Table 7 summarizes the results of the pressure tests at a constant temperature of 80 °C. The tests were performed on three pipe samples from all of the raw material combinations, according to ISO 1167. In all the tests no failures were observed on the pipes samples at the end of the test period (1000 h).

Table 6 Ultimate tensile elongation (%) before and after aging HDPE pipe samples

Pipe samples	Ultimate tensile elongation (%)				
Time (month)	0	3	6	9	12
PE0	937	945	941	947	946
PE25	890	901	893	897	900
PE50	865	857	861	867	868

Table 7 Results of the pressure tests at a constant temperature of 80 °C on the pipes specimens

Pipe samples names	Time (h) 1000
PE0	Passed
PE5	Passed
PE10	Passed
PE15	Passed
PE20	Passed
PE25	Passed
PE50	Passed

Conclusions

To summarize, the addition of RC to the raw material and/or immersion in the elevated temperature synthetic leachate yielded the following results for the particular PE resin, antioxidants formulation and condition examined:

- The addition of RC to the raw material led to an increase in the MFI and simultaneously decreases in OIT value. Moreover, the addition of RC results slightly decreases in the ultimate tensile properties such as ultimate tensile elongation. The decrease in tensile properties at break signifies the transition from a ductile to a brittle material as a result of RC addition.
- The results of OIT tests indicated that the processes taking place during the pipe production from raw material extrusion had not significant effect on the depletion of antioxidants. But the results of experiments conducted on the RC showed the reduction effect of recycling process.
- The results of OIT values were found to be equal at the end of storage time (about one year immersion in the synthetic leachate at 50 °C). This behavior is probably caused by the rapid diffusion of unstable antioxidants during the beginning of the storage time which led to a certain amount of durable antioxidants in all the pipes specimens.
- Although there is no clear differentiation between OIT reduction rates among all specimens' formulations, but the rate of antioxidant depletion is reduced slightly by the addition of RC.
- The results of properties that were measured over time, including MFI and mechanical properties (Tensile properties and pressure test), showed that these properties did not change in any statistically significant manner during the one-year immersion in the synthetic leachate at the temperatures of 50 °C, which indicates that only the first stage of degradation (i.e., antioxidant depletion) had occurred during the test period.
- Finally, although these results are related to the particular HDPE compound, antioxidants formulation and condition examined, but it can be said that the use of clean own reprocessable material, up to 50 % by weight (according to the current investigation), meet the standard requirements [24] and shall be permitted without limitations for the production of landfill leachate pipes.

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