Multiple Linear Regression Analysis of Degradation Phenomena of HDPE Geomembrane Using Machine Learning

V. Nikhila Bhavani and S. Sangeetha

Abstract Leachates generated from municipal solid waste landfills, acid mine tailings etc., are toxic and hazardous which are being released into the environment. These leachates when released into the soil highly alter the geo-environmental properties of soil which are becoming biggest alarm in recent days. To avoid these problems, HDPE geomembrane is used as a barrier between soil and landfill waste but due to continuous exposure to leachates, life expectancy of geomembrane will be reduced which has to be analyzed. Oxidative induction time test is the most versatile test being used to estimate the life expectancy of geomembrane. The present study is an attempt to analyze the data digitized from previous research works and to develop a model by considering the combined effect of medium of exposure, thickness, temperature and time on depletion of antioxidants from geomembrane using machine learning.

Keywords HDPE geomembrane · OIT · Machine learning · Multiple linear regression analysis

1 Introduction

High Density Polyethylene (HDPE) geomembranes are most widely used liners for different types of landfills like MSW landfills, mine tailings, heavy leach ponds etc., (Rowe et al. 2008a, b) because of the stupendous physical and chemical resistance. Degradation of HDPE geomembrane is enormous, due to long-effect of above-mentioned contaminants. Hence, verifying the effectiveness of geomembrane is becoming the most important concern in present days. In general, intact geomembrane experiences degradation with ageing due to the physico-chemical effects during its service period (Husan and Koerner 1998). Practically, estimating the service life of geomembrane in field is not feasible for a longer duration. So, accelerated laboratory tests are performed to know the degradation pattern of geomembrane (Rowe et al.

V. Nikhila Bhavani (✉) · S. Sangeetha
Department of Civil Engineering, VNRVJIET, Hyderabad, Telangana 500090, India

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2008a, b). But accelerated tests are also required to be performed for a minimum period of 2 years.

Degradation of geomembrane is defined as depletion of material properties in a slow and irreversible manner under adverse environmental conditions. Due to ageing, geomembrane undergoes adverse effects like loss of additives, plasticizers, change in molecular weight, formation of free radicals and become brittle as well (Kulshershtha 1992). Usually several degradation mechanisms such as ultraviolent degradation, chemical degradation, biological degradation, degradation by swelling, degradation by extraction, oxidative degradation and thermal degradation can take place based on exposure condition (Haxo and Nelson 1984; Koerner et al. 1990).

Effect of these degradations can be in any combinations, of which oxidative degradation is the most destructing phenomenon for HDPE geomembrane (Hawkins 1984). Oxidative degradation leads to formation of free-radicals by development of oxidative chain reactions in geomembrane (Kelen 1983). Due to these chains, HDPE polymer breaks down and leads to decrease in molecular weight of geomembrane; in succession, geomembrane eventually becomes brittle and is vulnerable to environmental stress cracking.

Oxidative degradation of HDPE geomembrane is divided into three stages—stage (I): Depletion time of antioxidants, stage (II): Incubation time, stage (III): Property reduction due to degradation of polymer (Husan and Koerner 1998). During manufacturing of geomembrane, the basic polymeric properties may vary. In order to avert these effects, antioxidants are added to geomembrane. Antioxidants prevents oxidative reactions to occur which usually happen in stage I. Antioxidants get depleted with the ageing process and this depletion depends on type of anti-oxidants, amount of antioxidants, combination of antioxidants used during manufacturing. It also depends on temperature, type of exposure medium to which geomembrane is subjected during testing (Fay and king 1994; Hsuan and Koerner 1998).

2 Problem Statement

In previous studies (Rowe et al. 2008a, b, 2010a, b; Gulec et al. 2004; Abdelaal et al. 2011) depletion of antioxidants is measured in terms of Oxidative Induction Time (OIT). Using the computed OIT values the life expectancy of geomembrane is estimated through Arrhenius Equation. The present research included collection of data from various journals and developed a model using Machine Learning after pooling the digitized data that accounted the combined effect of exposure condition, thickness, temperature and time of exposure.

3 Oxidative Induction Time Test

Degradation of geomembrane is generally measured using stress crack resistance test, oxidative induction test, melt flow index test, crystallinity test, and tensile test. The present study has focused on Oxidative Induction Time tests that were previously performed by various researchers in the past as per ASTM D3895. These tests give a detailed data regarding the presence of antioxidants in geomembrane. OIT can be performed in two ways such as Standard Oxidative Induction Time and High-Pressure Oxidative Induction Time. Standard OIT test is conducted using TA instrument Q-100 series differential scanning calorimeter which is provided with auto sampler. Samples of 6–10 g are heated to temperature of 200 °C at a rate of 20 °C/min and maintaining a pressure of 35 kPa in the presence of nitrogen environment, when the temperature reaches to 200 °C flow of nitrogen gas is stopped and maintained for 5 min, later the gas flow is changed to oxygen with the same pressure of 35 kPa. Using Differential Scanning Calorimeter, the level of antioxidant depletion is measured. The procedure for high pressure OIT test is same as standard OIT test but the temperature of 150 °C and pressure of 3500 kPa is maintained. To carry out this test, at least five samples are to be collected and tested; finally, it is concluded with average results and standard deviation.

4 Methodology

4.1 Collecting, Digitizing, Segregating the Data

In the present study multiple linear regression analysis has been performed for the data collected. Data are digitized for different test results given below which are collected from different literatures and weightage for exposure medium is found out based on the obtained OIT values in terms of air. Weightage of exposure medium varies with the different exposed condition like air, water, DI water, acid water, acid mine drainage and leachate. Initially weightage of exposure condition is determined when exposed to air, water, and leachate for testing data 1 in terms of air. Further, weightage of exposure condition for different leachates are determined in terms of air.

The study focusses on developing an inter-relation between independent and dependent variables where independent variables are weightage for exposure medium, thickness, time and temperature and dependent variables are oxidative induction time respectively. Data consist of four independent variables and one dependent variable, between these variables relationship is developed, and statistical measure has been computed for validating the relations. Such type of analysis is called as multiple linear regression analysis. In traditional methods, laboratory tests are conducted to predict the OIT of geomembrane at given conditions but this research aims at predicting the OIT value without going through those tedious and time-consuming processes if considerable research data are combined in a single program which are available in the literatures. The main purpose of performing this type of analysis is to develop a model such that it predicts the OIT value based on the combined effect of thickness of geomembrane, any given exposure conditions, temperature to which geomembrane is exposed and time period to which geomembrane gets exposed.

4.2 Machine Learning

Machine learning is a language which is used to build a mathematical model and to predict the results based on available data referred as training data. In present research, analysis has been carried out in python language as it is easy, user-friendly, expressive, object oriented, high-level programming language which is widely being used in present days for writing scripts and complex computation program.

In order to perform the analysis, testing data were digitized from seven different studies i.e., Rowe et al. (2002b, 2008a, b, 2010a, b), Gulec et al. (2004), Abdelaal et al. (2011) and all the data were amalgamated. Following are the tables representing the data digitized from above mentioned studies. As data is huge only two digitized data are mentioned in Tables 1 and 2.

4.3 Development of Program Using Machine Learning

The flow chart representing the processing of individual and amalgamated data on Python platform is depicted in Fig. 1.

Initially analysis has been carried out based on the above procedure for individual test data and further all the data are pooled together to evaluate the R square value.

5 Results and Discussions

Multiple Linear Regression Analysis has been carried out for the digitized data and the following equations were developed.

Rowe et al. (2002b):

$$\mathrm{Y} = -0.0477(\mathrm{X}_1) - 9.02 \times 10^{-17}(\mathrm{X}_2) - 0.0576(\mathrm{X}_3) - 0.0119(\mathrm{X}_4) + 9.73,\quad \mathrm{R}^2 = 75\% \tag{1}$$

Gulec et al. (2004):

Table 1 Variation of ln (OIT) with varying exposure condition, thickness, temperature and time (Rowe et al. 2002b)

Weightage for exposure medium	Thickness (mm)	Temperature (°C)	Time (months)	ln (OIT) (min)
1	2	55	0	4.9
1	2	55	2	4.8
1	2	55	8	4.7
1	2	55	14	4.6
1	2	55	23	4.3
1	2	55	33	4.1
2	2	55	0	4.9
2	2	55	1	4.8
2	2	55	8	4.5
2	2	55	14	4.2
2	2	55	23	3.8
2	2	55	33	3.3
4	2	55	0	4.9
4	2	55	2	4.2
4	2	55	5	3.8
4	2	55	8	3.7
4	2	55	13	2.7
4	2	55	30	0.23
1	2	85	0	4.8
1	2	85	2	4.7
1	2	85	8	3.6
1	2	85	14	2.8
1	2	85	23	2
1	2	85	33	0.71
2	2	85	0	4.9
2	2	85	2	4.5
2	2	85	8	3.1
2	2	85	14	1.9
2	2	85	23	−1.7
2	2	85	33	−2.6
4	2	85	0	4.9
4	2	85	2	3.5
4	2	85	5	2.8
4	2	85	8	0.8

Table 2 Variation of ln (OIT) with varying exposure condition, thickness, temperature and time (Gulec et al. 2004)

Weightage for exposure medium	Thickness (mm)	Temperature (°C)	Time (months)	ln (OIT) (min)
0.99	1.5	20	0	6
0.99	1.5	20	3	6
0.99	1.5	20	6	6
0.99	1.5	20	9	5
0.99	1.5	20	12	5
0.99	1.5	20	15	5
0.99	1.5	20	18	5
0.99	1.5	20	21	5
1.05	1.5	40	0	5
1.05	1.5	40	3	5
1.05	1.5	40	6	5
1.05	1.5	40	9	5
1.05	1.5	40	12	5
1.05	1.5	40	15	5
1.05	1.5	40	18	5
1.05	1.5	40	21	5
1.05	1.5	60	0	6
1.05	1.5	60	9	5
1.05	1.5	60	12	4
1.05	1.5	60	15	4
1.05	1.5	60	18	4
1.05	1.5	60	21	4
1.09	1.5	80	0	5
1.09	1.5	80	1	5
1.09	1.5	80	2	4
1	1.5	60	0	5.6
1	1.5	60	3	5.5
1	1.5	60	9	5.2
1	1.5	60	12	5
1	1.5	60	15	4.7
1	1.5	60	18	4.7
1	1.5	60	21	4.6
1.05	1.5	60	0	5.6
1.05	1.5	60	3	5.5
1.05	1.5	60	6	5.2

(continued)

Table 2 (continued)

Weightage for exposure medium	Thickness (mm)	Temperature (°C)	Time (months)	ln (OIT) (min)
1.05	1.5	60	9	4.8
1.05	1.5	60	12	4.6
1.05	1.5	60	15	4.5
1.05	1.5	60	18	4.2

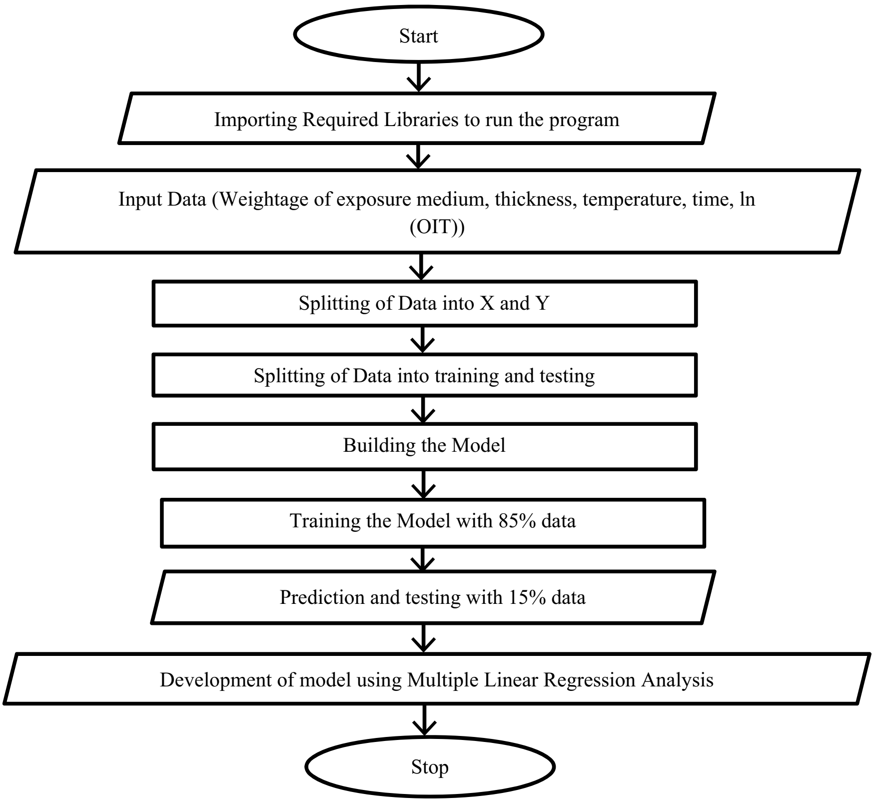

Fig. 1 Workflow in python

$$Y = -5.7(X_1) - 1.27 \times 10^{-13}(X_2) - 0.09(X_3) - 0.054(X_4) + 11.87,\ R^2 = 78\% \quad (2)$$

Rowe et al. (2008a, b):

$$Y = -0.002(X_1) - 8.32 \times 10^{-17}(X_2) - 0.054(X_3) - 0.077(X_4) + 7.4,\ R^2 = 77\% \quad (3)$$

Rowe et al. (2008a, b):

$$Y = -1.21(X_1) + 3.9 \times 10^{-14}(X_2) - 0.042(X_3) - 0.078(X_4) + 8.38, R^2 = 66\% \quad (4)$$

Rowe et al. (2010a, b):

$$Y = -1.95(X_1) + 3.5 \times 10^{-14}(X_2) - 0.09(X_3) - 0.14(X_4) + 12.8, R^2 = 75\% \quad (5)$$

Abdelaal et al. (2011):

$$Y = -0.157(X_1) - 1.24 \times 10^{-16}(X_2) - 0.002(X_3) - 0.021(X_4) + 6.2, R^2 = 83\% \quad (6)$$

Combined data

$$Y = -0.13(X_1) + 0.24(X_2) - 0.04(X_3) - 0.09(X_4) + 7.1, R^2 = 83\% \quad (7)$$

where X_1 = Weightage of exposure condition, X_2 = Thickness (mm), X_3 = Temperature (°C), X_4 = Time (months), Y = ln (OIT) (min).

Using above developed equations oxidative induction time of geomembrane can be determined.

Figures 2 and 3 represents the time versus ln (OIT) plot for the data digitized from Rowe et al. (2002b). Time taken for complete loss of antioxidants from geomembrane when exposed to air, water, and leachate at 55 °C is 583, 624, and 573 months and at 85 °C is 433, 474 and 498 months. It is noticed that the consumption of antioxidants from geomembrane takes place at faster rate at 85 °C when compared with the other as shown in the plots. Rate of depletion of antioxidants is dependent on various factors like physical, chemical, mechanical i.e., diffusion, volatilization, reaction with oxygen, free radicals and it is observed that time taken for antioxidant depletion is fast when geomembrane exposed to leachates as there is a extraction of antioxidants

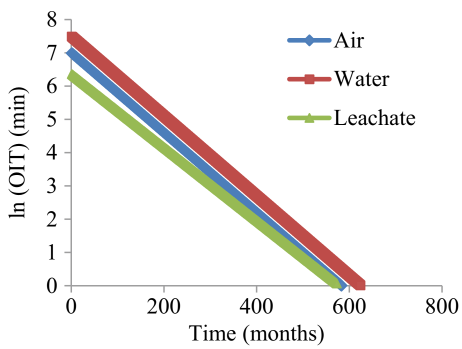

Fig. 2 Estimated OIT of geomembrane at 55 °C in air, water and leachate (Rowe et al. 2002b)

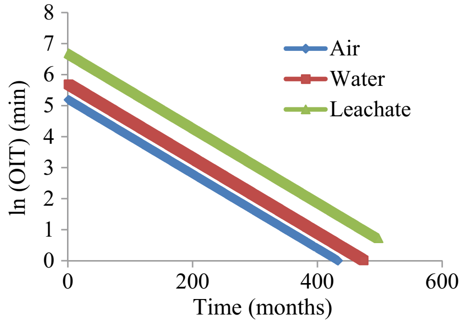

Fig. 3 Estimated OIT of geomembrane at 85 °C in air, water and leachate (Rowe et al. 2002b)

which leads to faster rate of loss of antioxidants at 55 °C when compared to air, water. But the pattern is reverse when geomembrane exposed to 85 °C this may be due to effect of polymerization of chains in geomembrane (Rowe et al. 2008a, b) which lead to increase in time for loss of antioxidants in MSW leachate.

Figure 4 represents variation of estimated OIT of geomembrane at different temperatures for the data digitized from Gulec et al. (2004). Acid mine drainage (AMD) is used as an exposure medium in this study. Based on equation obtained from multiple linear regression analysis for the digitized data OIT is determined. It is observed that effect of increase in temperature on loss of antioxidants is predominant. Time taken for reduction in antioxidants from geomembrane at 20, 40, 60, 80 °C is 111, 101, 98, 90 months. As temperature increases the consumption of antioxidants increases where the pattern followed in loss of antioxidants for this study is same as the previous study, but AMD has higher effect on loss of antioxidants when compared to MSW leachate.

Figure 5 represents plot for ln (OIT) with the time digitized from Rowe et al. (2008a, b) which shows linear response curve. It shows that the consumption of antioxidants is more at higher temperature when compared to lesser temperature. Estimated time taken for loss of antioxidants at different temperatures i.e., 26, 55,

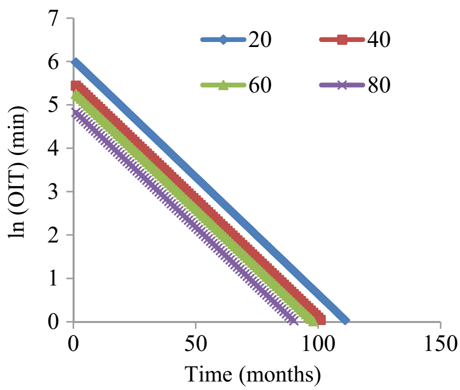

Fig. 4 Estimated OIT of geomembrane at 20, 40, 60 and 80 °C in leachate (Gulec et al. 2004)

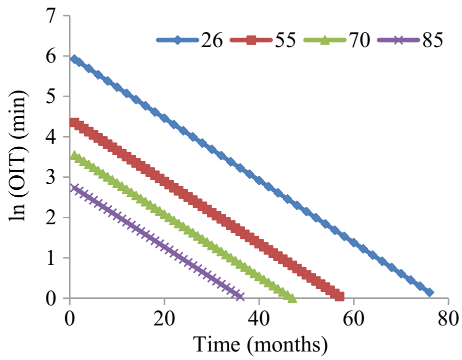

Fig. 5 Estimated OIT of geomembrane at 26, 55, 70 and 80 °C in leachate (Rowe et al. 2008a, b)

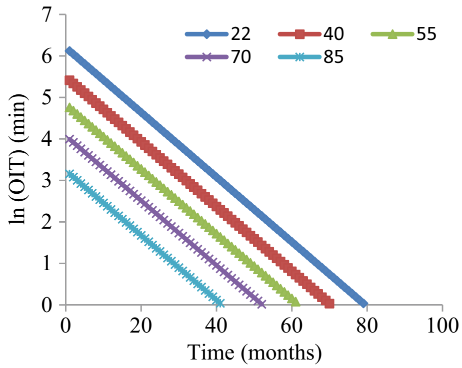

Fig. 6 Estimated OIT of geomembrane at 22, 40, 55, 70 and 80 °C in leachate (Rowe et al. 2008a, b)

70, 85 °C is 76, 57, 47, 36 months. Presence of surfactant in leachate is major source of loss of antioxidant from geomembrane and the effect of consumption increases with increase in temperature.

Variation of estimated OIT of geomembrane for data digitized from Rowe et al. (2008a, b) is shown in Fig. 6. In the present study geomembrane is exposed to four leachates and the above plot represents estimated OIT for leachate 1. It is seemed that the loss of antioxidants is increasing with the increase in temperature alike the other studies and time taken for consumption of antioxidants from geomembrane when immersed in leachate 1 at 22, 40, 55, 70, 85 °C is 79, 70, 61, 52, 41 months whereas in case of leachate 2 at 22, 40, 55, 70, 85 °C is 79, 69, 60, 49, 38 months; leachate 3 at 22, 40, 55, 70, 85 °C is 78, 70, 61, 49, 40 months; leachate 4 at 22, 40, 55, 70, 85 °C is 78, 70, 61, 51, 39 months. Based on above results it is examined that there is not much difference in consumption of antioxidants from geomembrane when exposed to four different types of leachates with varying composition at four different temperatures only the temperature effect is prevailing factor for loss of antioxidants.

Plot shown in Fig. 7 digitized from Rowe et al. (2010a, b) for leachate 1 reveals that pattern followed for consumption of antioxidants from geomembrane is same

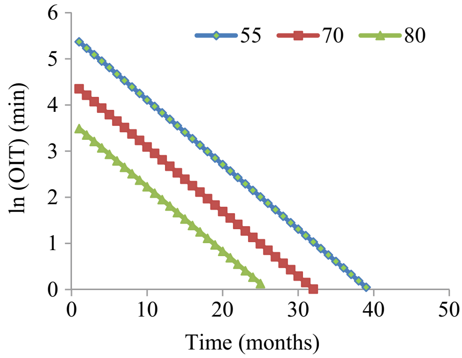

Fig. 7 Estimated OIT of geomembrane at 55, 70 and 80 °C in leachate (Rowe et al. 2010a, b)

as the other studies whereas the effect of temperature is a dominant factor in loss of antioxidants from geomembrane. Based on the developed from multiple linear regression analysis OIT is estimated at different temperatures it is examined that the time taken for complete loss of antioxidants from geomembrane in leachate 1 at 55, 70, 85 °C is 39, 32, 25 months and for leachate 2 at 55, 70, 85 °C is 41, 31, 25 months. It is also noticed that there is no much difference in loss of antioxidants from geomembrane when exposed to both leachates and pattern followed is same for both the leachates and alike other studies where temperature has major effect on depletion of antioxidant from geomembrane.

Multiple linear regression analysis has been carried out for the data digitized from Abdelaal et al. (2011) and estimated OIT is mentioned in the plot given in Fig. 8 which shows that there is an increment in depletion of antioxidants with increase in temperature which follows the same trend alike other studies. Time consumed for the complete loss of antioxidants from geomembrane at 75, 85, 95 °C is 292, 295, 294 months. It is witnessed that for loss of antioxidants, temperature has no effect as there is no much difference in time taken for complete depletion at the three different temperatures considered.

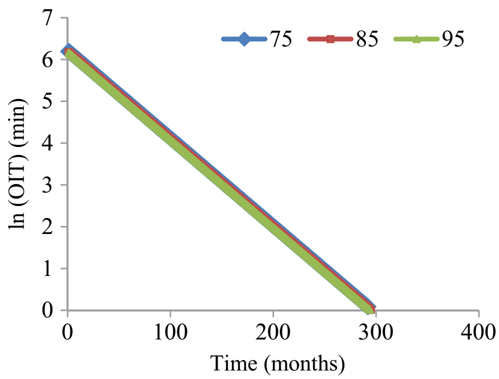

Fig. 8 Estimated OIT geomembrane at 75, 85 and 95 °C in leachate (Abdelaal et al. 2011)

5.1 Extrapolation of Half-Life of Geomembrane for the Above Digitized Data

From the estimated OIT, half-life of geomembrane is extrapolated for all testing data using time- temperature superposition model. Half-life of geomembrane is extrapolated for field temperature is given below.

5.1.1 Testing Data 1

Initially time taken for retention of 50% of OIT is tabulated for air, water, leachate at 55, 85 °C using multiple linear regression analysis for Rowe et al. (2002b) in Table 3. According to time–temperature superposition model a plot is made between temperature (K^{-1}) and time ($month^{-1}$) as shown in Fig. 9 and extrapolated half-life of geomembrane at field temperature of 33 °C using Eqs. 8, 9 and 10 in air, water, leachate is 43, 65, 88 years given in Table 4.

$$\text{In water} \quad Y = -5.1506X + 0.0181, R^2 = 1 \tag{8}$$

Table 3 Estimated half-life of geomembrane at 55 and 85 °C in air, water and leachate

Exposure medium	Temperature (°C)	Time (t) (month)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Air	55	379	328.15	0.0030	0.0026
	85	229	358.15	0.0028	0.0044
Water	55	421	328.15	0.0030	0.0024
	85	271	358.15	0.0028	0.0037
Leachate	55	356	328.15	0.0030	0.0028
	85	354	358.15	0.0028	0.0028

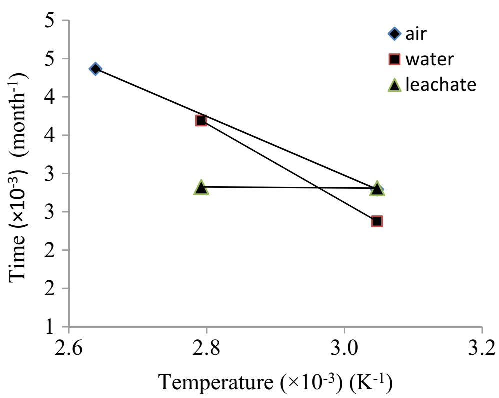

Fig. 9 Variation of half-life of geomembrane at 55 and 85 °C in air, water and leachate

Table 4 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Air	33	43
Water	33	65
Leachate	33	88

$$\text{In air} \quad Y = -3.8514X + 0.0145, R^2 = 1 \tag{9}$$

$$\text{In leachate} \quad Y = -8.6819X + 0.0293, R^2 = 1 \tag{10}$$

5.1.2 Testing Data 2

Table 5 represents the estimated half-life of geomembrane at 20, 40, 60, 80 °C and a plot is made between temperature (K^{-1}) and time ($month^{-1}$) according to time–temperature superposition model for the estimated half-life of geomembrane using multiple linear regression analysis for Gulec et al. (2004) shown in Fig. 10 and half-life of geomembrane is extrapolated at field temperature of 33 °C using Eq. 11 which is of 4.1 years when exposed to leachate as shown in Table 6.

Table 5 Estimated half-life of geomembrane at 20, 40, 60, 80 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (month)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate	20	56	293.15	0.0034	0.0179
	40	46	313.15	0.0032	0.0217
	60	42	333.15	0.0030	0.0238
	80	30	353.15	0.0028	0.0333

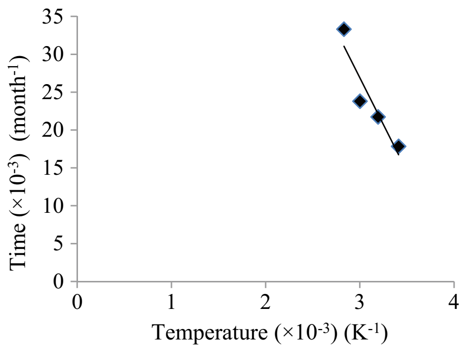

Fig. 10 Variation of Half-life of geomembrane at 20, 40, 60 and 80 °C in leachate

Table 6 Prediction of half-life of geomembrane at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate	33	4.1

$$y = -24.696X + 0.101, R^2 = 0.8778 \quad (11)$$

5.1.3 Testing Data 3

A time–temperature plot is made shown in Fig. 11 to extrapolate the half-life of geomembrane at field temperature of 33 °C using estimated half-life of geomembrane at temperatures 26, 55, 70, 85 °C for Rowe et al. (2008a, b) given in Table 7 and using Eq. 12 the half-life of geomembrane is and extrapolated at 33 °C is 3.3 years depicted in Table 8.

$$Y = -40.695X + 0.1585, R^2 = 0.7582 \quad (12)$$

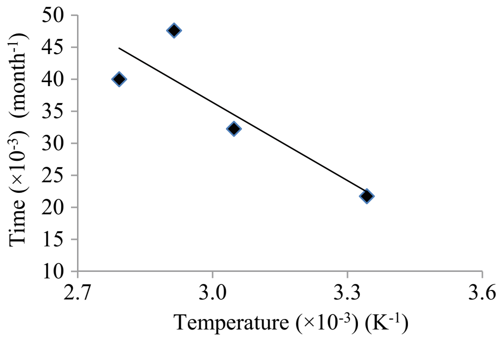

Fig. 11 Variation of half-life of geomembrane at 26, 55, 70 and 80 °C in leachate (Rowe et al. 2008a, b)

Table 7 Estimated half-life of geomembrane at 26, 55, 70, 85 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t (month $^{-1}$)
Leachate	26	46	299.15	0.00334	0.021
	55	31	328.15	0.00304	0.032
	70	21	343.15	0.00291	0.047
	85	25	358.15	0.00279	0.04

Table 8 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate	33	3.3

5.1.4 Testing Data 4

Half-life of geomembrane is estimated at 22, 40, 55, 70, 85 °C for leachate 1 using multiple linear regression analysis to data digitized from Rowe et al. (2008a, b) which is mentioned in Table 9 and plot is developed shown in Fig. 12 based time–temperature superposition to extrapolate the half-life of geomembrane at field temperature of 33 °C using Eq. 13 and is 3.7 years shown in Table 10 and at the same field temperature extrapolated half-life for other leachates is 4.3, 3.7, 4.1 years. It is observed that there is no huge difference in extrapolated half-life for four leachates. So, in present study variation in composition of leachate has no effect on half-life of geomembrane

$$Y = -149.7X + 0.5113, R^2 = 0.6821 \quad (13)$$

Table 9 Estimated half-life of geomembrane at 22, 40, 55, 70, 85 °C in leachate 1

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate 1	22	46	295.15	0.0034	0.022
	40	37	313.15	0.0032	0.027
	55	29	328.15	0.0030	0.034
	70	19	343.15	0.0029	0.053
	85	8	358.15	0.0028	0.125

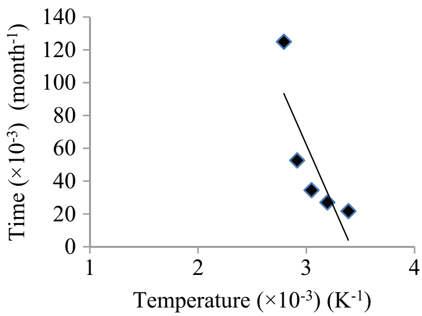

Fig. 12 Variation of half-life of geomembrane at 22, 40, 55, 70 and 80 °C in leachate 1

Table 10 Prediction of half-life of geomembrane at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate 1	33	3.7

5.1.5 Testing Data 5

Estimated half-life of geomembrane for leachate 1 and 2 at temperatures 55, 70, 85 °C from Rowe et al. (2010a, b) is tabulated in Table 11 and a time–temperature plot is made shown in Fig. 13 to extrapolate the half-life of geomembrane using Eqs. 14 and 15 at field temperature of 33 °C and the half-life for leachate 1 and 2 is 3.5, 2.6 years shown in Table 12.

$$Y = -325.52X + 1.031, R^2 = 0.9871 \tag{14}$$

$$Y = -301.25X + 0.9604, R^2 = 0.9418 \tag{15}$$

Table 11 Estimated half-life of geomembrane at 55, 75 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate 1	55	21	328.15	0.0030	0.048
	70	14	343.15	0.0029	0.071
	85	8	358.15	0.0028	0.125
Leachate 2	55	24	328.15	0.0030	0.042
	70	13	343.15	0.0029	0.077
	85	8	358.15	0.0028	0.125

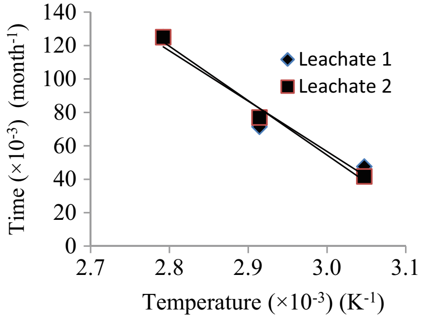

Fig. 13 Variation of half-life of geomembrane at 26, 55, 70 and 80 °C in leachate (Rowe et al. 2010a, b)

Table 12 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate 1	33	3.5
Leachate 2	33	2.6

Table 13 Estimated half-life of geomembrane at 75, 85, 95 °C

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate	75	186	348.15	0.0029	0.00538
	85	185	358.15	0.0028	0.00541
	95	184	368.15	0.0027	0.00543

Fig. 14 Variation of half-life of geomembrane at 22, 40, 55, 70 and 80 °C in leachate

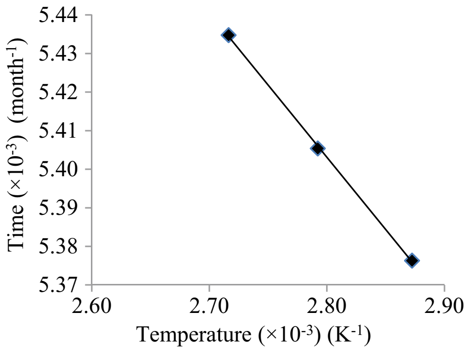

Table 14 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate	33	16

5.1.6 Testing Data 6

Table 13 represents estimated half-life of geomembrane at 75, 85, 95 °C when exposed to leachate digitized from Abdelaal et al. (2011). A time–temperature superposition plot is made for the estimated data shown in Fig. 14 and at field temperature of 33 °C extrapolated half-life of geomembrane is 16 years using Eq. 16 shown in Table 14.

$$Y = -0.3744X + 0.0065, R^2 = 0.9996 \quad (16)$$

5.1.7 Testing Data 7 (Pooled Data)

Multiple linear regression analysis is also performed for pooled data taken from Rowe et al. (2002b, 2008a, b, 2010a, b), Gulec et al. (2004) and Abdelaal et al. (2011). Procedure followed for Half-life estimation for all the data and procedure followed for extrapolation of half-life at field temperature of 33 °C is same as the individual data.

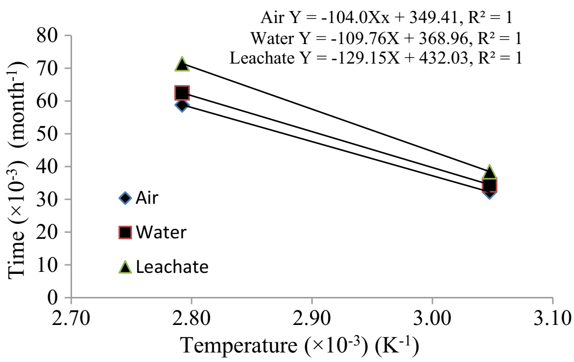

Fig. 15 Variation of half-life of geomembrane at 55 and 80 °C in air, water and leachate

Table 15 Estimated half-life of geomembrane at 55, 85 °C in air, water and leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Air	55	31	328.15	0.0030	0.0323
	85	17	358.15	0.0028	0.0588
Water	55	29	328.15	0.0030	0.0345
	85	16	358.15	0.0028	0.0625
Leachate	55	26	328.15	0.0030	0.0385
	85	14	358.15	0.0028	0.0714

Table 16 Prediction of half-life of geomembrane at field data temperature for at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Air	33	8.8
Water	33	7.95
Leachate	33	8.21

For Rowe et al. (2002b)

See Fig. 15 and Tables 15, 16.

For Gulec et al. (2004)

See Fig. 16 and Tables 17, 18.

For Rowe et al. (2008a, b)

See Fig. 17 and Table 19, 20.

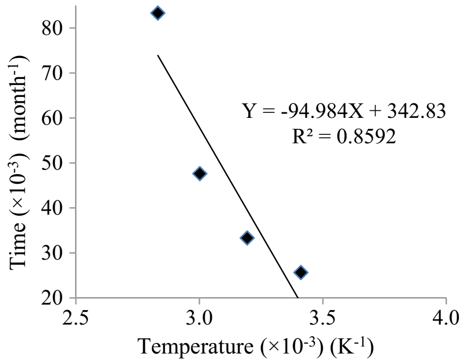

Fig. 16 Variation of half-life of geomembrane at 20, 40, 60 and 80 °C in leachate

Table 17 Estimated half-life of geomembrane at 20, 40, 60, 80 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate	20	39	293.15	0.0034	0.0256
	40	30	313.15	0.0032	0.0333
	60	21	333.15	0.0030	0.0476
	80	12	353.15	0.0028	0.0833

Table 18 Prediction of half-life of geomembrane at room temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate	33	2.56

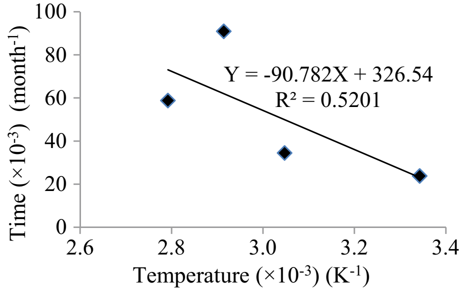

Fig. 17 Variation of half-life of geomembrane at 26, 55, 70 and 85°C in leachate

Table 19 Estimated half-life of geomembrane at 26, 55, 70, 85 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate	26	42	299.15	0.0033	0.0238
	55	29	328.15	0.0030	0.0345
	70	11	343.15	0.0029	0.0909
	85	17	358.15	0.0028	0.0588

Table 20 Prediction of Half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate 1	33	2.8

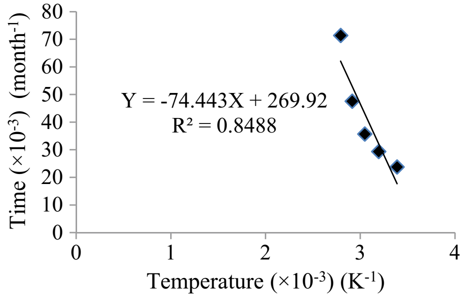

Fig. 18 Variation of half-life of geomembrane at 20, 40, 55, 70 and 85 °C in leachate

Table 21 Estimated half-life of geomembrane at 22, 40, 55, 70, 85 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate 1	22	42	295.15	0.0034	0.0238
	40	34	313.15	0.0032	0.0294
	55	28	328.15	0.0030	0.0357
	70	21	343.15	0.0029	0.0476
	85	14	358.15	0.0028	0.0714

Table 22 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate 1	33	3.1

For Rowe et al. (2008a, b)

See Fig. 18 and Tables 21, 22.

For Rowe et al. (2010a, b)

See Fig. 19 and Tables 23, 24.

For Abdelaal et al. (2011)

See Fig. 20 and Tables 25, 26.

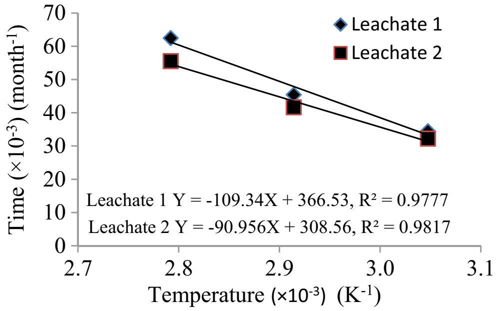

Fig. 19 Variation of half-life of geomembrane at 55, 70 and 85 °C in leachate

Table 23 Estimated half-life of geomembrane at 55, 70, 85 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate 1	55	29	328.15	0.0030	0.0345
	70	22	343.15	0.0029	0.0455
	85	16	358.15	0.0028	0.0625
Leachate 2	55	31	328.15	0.0030	0.0323
	70	24	343.15	0.0029	0.0417
	85	18	358.15	0.0028	0.0556

Table 24 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate 1	33	9
Leachate 2	33	7

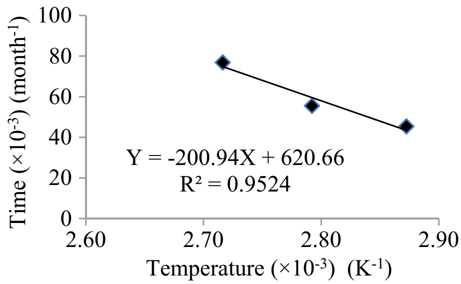

Fig. 20 Variation of half-life of geomembrane at 55, 70 and 85°C in leachate

Table 25 Estimated half-life of geomembrane at 75, 85, 95 °C in leachate

Exposure medium	Temperature (°C)	Time (t) (months)	Temperature (T) (K)	1/T (K^{-1})	1/t ($month^{-1}$)
Leachate	75	22	348.15	0.0029	0.0455
	85	18	358.15	0.0028	0.0556
	95	13	368.15	0.0027	0.0769

Table 26 Prediction of half-life of geomembrane at field temperature at 33 °C

Exposure medium	Temperature (°C)	Half-life (years)
Leachate	33	2.34

Table 27 Extrapolated half-life of geomembrane at field temperature of 33°C for all testing data

S. No.	Testing data source	Medium of exposure	Extrapolated half-life of geomembrane at field temperature of 33 °C (Years)		% variation of individual and pooled data
			Individual data	Pooled data	
1	Rowe et al. (2002)	Air	43	8.8	80
		water	65	7.92	87.7
		Leachate	68	8.21	88
2	Gulec et al. (2004)	Acid mine Drainage	4.1	2.56	38
3	Rowe et al. (2008a, b)	Leachate	3.3	2.8	15
4	Rowe et al. (2008a, b)	Leachate 1	3.7	3.1	16
		Leachate 2	4.3	3.1	28
		Leachate 3	3.7	3.2	14
		Leachate 4	4.1	3.2	22
5	Rowe et al. (2010a, b)	Leachate 1	3.5	9	61
		Leachate 2	2.6	7	63
6	Abdelaal et al. (2011)	Leachate	16	2.34	85

OIT obtained by validating the digitized data is almost same when compared with the actual data which was obtained by conducting accelerated laboratory tests. Table 27 gives half-life calculated using individual data, pooled data and percentage variation between them. The main advantage of this type of study is, one can estimate the Oxidative induction time easily as this procedure does not require any kind of laboratory testing and it is possible to estimate the time taken for the complete loss of antioxidants from geomembrane using this method. As the conventional laboratory method is time consuming, one could ignore the degradation study while harnessing geomembrane for field applications.

6 Conclusions

From the above computation, it has been witnessed that half-life of geomembrane estimated from pooled testing data is almost in line with individual data for all the literatures considered except for the testing data 1, 5, 6 this may be due to non-linearity when data is pooled. As 50% of the obtained results are inline with each other, half-life obtained from both the individual and pooled data are satisfactory. Hence, this procedure can be used to estimate the antioxidant depletion time of geomembrane by performing multiple linear regression analysis for the digitized and amalgamated data sets without any laboratory testing. As this is a new technique to estimate the antioxidant depletion time and is also a preliminary study there is a need to do more research to obtain accurate results by collecting large number of data sets which are required to estimate life of geomembrane.

Scope

Antioxidant depletion rate can be determined by developing a software using machine learning technique so that we can avoid tedious laboratory process which would be generally ignored before field implementation and can save time.

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