Service life of some HDPE geomembranes

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Abstract. This study evaluated nine exhumed high-density polyethylene (HDPE) geomembranes from different Brazilian civil construction facilities under several exposure times, from two to fifteen years in service. Physical and thermal analyses were performed to understand the behavior of the geomembranes' samples in the final condition after the environmental exposure and, in some cases, also after contact with residues. The analyses showed the vulnerability of the geomembranes investigated and demonstrated, in general, the short-term durability of the products tested. Finally, this research showed the need to standardize the resins and additives types of the

geomembranes to guarantee their long-term durability, avoiding detrimental environmental impacts and associated financial costs.

Keywords: geomembrane; HDPE; durability; final condition; service life

1 Introduction

Geomembranes are applied in environmental, geotechnical and transportation facilities. High-density polyethylene (HDPE) geomembranes are the most widely used liner elements in the world. In facilities such as water ponds, waste liquid ponds, leachate ponds, farm ponds, canals and artificial beaches, the aging mechanisms act on the whole geomembrane's service life, at least for the slope crest part above the water table (Rollin and Rigo 1991; Vertematti 2015; Palmeira 2018; Koerner 2005).

The service life of HDPE geomembranes can reach more than a century or less than a decade. It depends on the material composition and the field's boundary conditions. Many factors command the material's long-term performance, such as field temperature, mechanical stresses during construction, local stress concentration, covered or protected conditions, contact with residues, resin quality and product formulation (Rowe and Sangam 2002; Zhang et al. 2018; Peggs and Zanzinger 2018).

Lifetime is usually defined as the time to reduce a given material's property to 50 % of its virgin value. However, this is an arbitrary method to determine the product's lifetime. The end of life is when the geomembrane can no longer perform the fluid containment function. For the end-of-life prediction, the designer needs experience, extrapolation of the measured properties, or laboratory testing to simulate and accelerate the field conditions (Peggs and Zanzinger 2018; Rowe 2012; Rowe 2020).

According to Rowe (2012), when the geomembrane can no longer be considered effective in working as a barrier element, the leakage is controlled by the liner layer under the geomembrane. In this condition, the material reached its service life and the stress cracking commands the process, culminating in a considerable increase of defects in the geomembrane.

The decrease in the geomembrane's service life can happen due to the exposure to high temperatures, accelerating the oxidative degradation and, consequently, causing losses in stress crack resistance. For HDPE geomembranes, manufacturers do not recommend exposure to temperatures higher than 57 °C (Rowe and Rimal 2009; Rowe et al. 2010).

Jafari et al. (2014) reported monitoring the landfill temperature in six cell composite liners. The authors could predict the HDPE geomembrane service life through a three-stage degradation model. They used stress crack resistance, tensile break resistance and tensile break elongation as parameters for the study. However, the authors considered stress crack resistance as the determinant for end of life. The service life results presented a range of between 960 years to 20 years, depending on the measured temperature in the cells.

Gulec et al. (2004) estimated the antioxidant depletion of a 1.5 mm-thick HDPE geomembrane after exposure to synthetic acidic mine drainage for 22 months at 60 °C, 40 °C and 20 °C. The antioxidant depletion estimation was 426 years to 46 years. The melt flow index (MFI) results demonstrated an increasing trend.

Rowe et al. (2009) analyzed an HDPE geomembrane with 2.0 mm of nominal thickness for 10 years immersed in synthetic leachate, water and air at different temperatures. According to the authors, using a three-stage degradation model, the sample in contact with the leachate had a service life of more than 50 years at 50 °C.

The service life of an HDPE geomembrane applied in a double liner landfill was evaluated by Rowe and Hoor (2009). Considering a liner configuration of a primary HDPE geomembrane, a geosynthetic clay liner (GCL), 1 m of soil foundation or compacted clay liner (CCL) and a secondary HDPE geomembrane, the service life of the secondary geomembrane was estimated in 75 years at 50 °C.

This work evaluated the service life of nine high-density polyethylene smooth geomembranes exhumed from different Brazilian civil construction facilities subjected to different exposure times. Physical and thermal analyses were performed to understand the behavior of the geomembranes' samples in the final condition after the environmental exposure and, in some cases, also after contact with residues.

2 Material and Methods

2.1 Materials

The HDPE geomembrane samples collected in the field and evaluated in this work are described in Table 1. The samples were exhumed from different Brazilian construction works in many applications. Lavoie (2021) analyzed the final condition of these samples using physical and thermal analyses. The samples' characterization was described by Lavoie et al. (2020; 2020-1; 2021; 2021-1; 2022).

The samples were collected directly from the sites. Geomembrane samples MIN, MIN2, LDO, CAM, CAM1 and CAM2 were stored in a covered place without contamination right after the collection until the transportation to the laboratory. Otherwise, the CLIQ and LCH samples were left uncovered in the field for 2 months before transportation to the laboratory. Finally, the sample LTE was left for 1 week uncovered in the field before being transported to the laboratory.

2.2 Performed Laboratory Tests

2.2.1 Melt Flow Index (MFI) Test

The melt flow index (MFI) test (ASTM D 1238, 2020) was carried out using a plastometer manufactured by Instron at Norwood, USA, model CEAST MF20. The material was extruded through a smooth bore (2.095 ± 0.005 mm in diameter and 8000 ± 0.025 mm long) at 190 ± 0.08 °C with a 5.0 ± 0.01 kg of deadweight. After 10 min (with precision of 1 s) of the sample extrusion, the material mass was measured using an analytical balance with 0.0001 g of precision.

2.2.2 Tensile Properties

The tensile test (ASTM D 6693, 2020) was performed using a universal machine manufactured by EMIC in São José dos Pinhais, Brazil, model DL 3000, with a 2-kN load cell, conducted with a test speed of 50 ± 1 mm min^{-1} and the type IV dog bone specimen. The tensile strength and tensile elongation were recorded for the material's machine direction.

2.2.3 Stress Crack Resistance (SCR) Test

The stress crack resistance (SCR) was determined using a deadweight load of 30 % of the yield tensile strength of the samples (precision of 10 g) and a notch of 20 % of the specimen thickness (precision of 0.001 mm). The test (ASTM D 5397, 2020) was performed using equipment manufactured by WT Indústria at São Carlos, Brazil. The specimens were immersed in a solution with 10 ± 0.1 % of Igepal CO 630 and 90 ± 0.1 % of water at a constant temperature of 50 ± 1 °C. The results were reported using the mean rupture time of 5 specimens with a precision of 1 s.

2.2.4 Oxidative-Induction Time (OIT) Tests

This study utilized two tests to determine the oxidative-induction time (OIT) of the HDPE geomembrane samples. The standard OIT (Std. OIT) (ASTM D 3895, 2019) and the high-pressure OIT (HP OIT) (ASTM D 5885, 2020) tests were performed. Both tests can search for the different antioxidants in the material's blend. DSC (differential scanning calorimetry) equipment was used to perform the tests, model Q20, manufactured by TA Instruments in New Castle, USA, using a sample mass of 5 ± 0.5 mg inside an aluminum crucible. The standard OIT test was performed at 200 ± 2 °C with an oxygen constant pressure of 140 ± 5 kPa, a heating rate of 20 ± 1 °C min^{-1} and a flow rate of 50 ± 5 mL min^{-1}. The high-pressure OIT test was conducted at 150 ± 0.5 °C with an oxygen constant pressure of 3.4 ± 0.06 MPa and a heating rate of 20 ± 1 °C min^{-1}.

3 Results and Discussion

3.1 MFI Test Results

The MFI is an excellent parameter to compare virgin with exposed samples. The increase or decrease in this index can explain possible polymer degradation (Telles et al. 1984). Table 2 presents the MFI test results and the standard deviations (SD) for the analyzed exhumed samples. Figure 1 shows the exhumed samples' MFI results versus exposure time (log scale), including the tendency line of the results. The oldest samples (LDO, MIN2, CAM, and CAM1) presented the highest MFI values (near or higher than 1.0 g 10 min^{-1}). The highlight was the CAM1 sample, which was exhumed from the Shrimp Farming Pond's slope liner and continuously exposed to environmental agents, which presented the highest MFI value and needed to be tested at a lower temperature (160 °C) due to its atypical behavior, showing the highest standard deviation among the tested samples. The tendency line indicates the MFI's increase with the exposure time. The Coefficient of Determination (R^2) of the tendency line was 0.1049, which demonstrated a high data variation.

3.2 Tensile Test Results

Tables 3 and 4 present, respectively, the tensile resistance and elongation at break test results, including the standard deviations (SD) for the analyzed exhumed samples.

Figures 2 and 3 show, respectively, the tensile resistance versus exposure time (log scale) and the tensile elongation versus exposure time for the exhumed samples, including the tendency lines of the results. In Figure 2, the 100 % value represents the minimum value required according to GRI-GM13 (2021) for each thickness. Only the LCH and LTE samples presented higher tensile resistance than the minimum tensile resistance value prescribed by the American standard. The tendency line presents an almost constant behavior close to 90 % of the retained tensile resistance. The Coefficient of Determination (R^2) of the tendency line was 0.0001, which demonstrated a high data variation. For the tensile elongation results (Figure 3), only the LCH sample presented a value of elongation at break higher than 700 %. It is important to note that the LCH sample was the thickest exhumed sample, presenting the best mechanical behavior. The CLIQ, MIN, MIN2, LDO, and CAM2 samples exhibited brittle behavior for some test specimens tested. Three samples (CAM2, MIN, and LDO) presented average tensile elongation values lower than 350 %, which corresponds to less than 50 % of the minimum required value according to GRI-GM13 (2021). The worst tensile behavior was verified for the LDO sample, which is the oldest analyzed sample. A high standard deviation was noted for the CLIQ, MIN, MIN2, LDO and CAM2 samples, demonstrating that polymer changes are occurring. The tendency line indicates the tensile elongation's decrease along the exposure time. The Coefficient of Determination (R^2) of the tendency line was 0.0455, which also demonstrates a high data variation.

3.3 Stress Crack Resistance Test Results

Table 5 presents the stress crack resistance (SCR) test results, including the standard deviations (SD) for the analyzed exhumed samples. Figure 4 shows the stress crack resistance results versus exposure time (log scale) for the exhumed samples, including the tendency line of the results. The minimum SCR value required by GRI-GM13 (2021) is 500 h. The CAM, CLIQ, and LCH samples presented SCR values higher than the minimum value prescribed by the American standard. The other samples showed SCR values lower than 100 h, especially LDO and CAM1, the oldest analyzed samples, which exhibited very low SCR values, and this can affect their liner performance. The CAM and CAM1 samples, although exhumed from the same shrimp farming pond, showed opposite SCR results due to the environmental exposure experienced by the CAM1 sample. The tendency line indicates the stress crack resistance's decrease along the exposure time, reaching less than 200 h for 15 years of exposure. A high standard deviation was noted for the CLIQ, LCH and CAM samples, particularly for LCH. The Coefficient of Determination (R^2) of the tendency line was 0.0323, revealing a high data variation.

3.4 Oxidative-Induction Time (OIT) Test Results

Tables 6 and 7 present Std. OIT and HP OIT test results, respectively, including the standard deviations (SD) for the analyzed exhumed samples. Figures 5 and 6 show, respectively, the Std. OIT and HP OIT test results versus exposure time (log scale) for the exhumed samples, including the tendency line for the results.

The minimum Std. OIT value required by GRI-GM13 (2021) is 100 min. The LCH sample was the only exhumed geomembrane that presented a Std. OIT value higher than 100 min. The CAM2, LTE, and CLIQ samples presented Std. OIT values higher than 50 min (50 % of the minimum required value by the American standard). The LDO, CAM, CAM1 and MIN2 samples, the oldest samples, presented near or lower Std. OIT values than 10 min (10 % of the minimum required value by the American standard). The tendency line indicates the Std. OIT's decrease along the exposure time, almost reaching the total antioxidant consumption after 15 years. A high standard deviation was noted for the CLIQ sample. The Coefficient of Determination (R^2) of the tendency line was 0.4503, also revealing a high data variation.

The minimum HP OIT value required by GRI-GM13 (2021) is 400 min. None of the tested samples presented OIT-HP values equal to or higher than 400 min. The presence of HALS (Hindered Amine Light Stabilizer) in the additive package increases the OIT-HP results. As this test is performed at 150 ºC, probably none of the virgin samples presented HALS in their additive package. The best performance was that of the thicker sample (LCH). The CLIQ, LTE, and CAM2 samples presented HP OIT values higher than 150 min (37.5 % of the minimum required value by the American standard). The MIN, MIN2, and LDO samples presented HP OIT values higher than 100 min (25 % of the minimum required value by the American standard). The CAM and CAM1 samples, from the same shrimp farming pond liner, presented different results. The CAM1 sample, which was exhumed from the slope liner, presented oxidation immediately after the oxidation process started in the test, that is, the antioxidant content was completely depleted. This result is due to the type of exposure of the CAM1 sample, which was submitted to weather exposure for 8.25 years. The tendency line indicates the HP OIT's decrease with the exposure time, reaching less than 100 min after 15 years. A high standard deviation was noted for the MIN2 and CAM2 samples. The Coefficient of Determination (R^2) of the tendency line was 0.03395, which demonstrated a high data variation.

3.5 Behavior of the Exhumed Samples

Table 8 shows the behavior of the samples from the analysis of their property's values, including the thermal analyses performed by Lavoie (2020; 2020-1; 2021; 2021-1; 2022). It was observed that the antioxidant depletion is related to the geomembrane's thickness, that is, the thicker sample, LCH, presented the highest Std. OIT value. Otherwise, the CAM, CAM1, LDO, MIN2 samples presented the lowest Std. OIT values.

Some exhumed samples showed different changes in thermal behavior due to the environmental agents and the contact with the residues along the exposure time. The LCH sample, which was in contact with leachate, was the sample that presented the greatest thermal changes. Other samples also presented significant changes in the thermal behavior, such as the LDO, CAM2, CLIQ and LTE samples.

High MFI values (low viscosity) were noted for the MIN2, LDO, CAM and CAM1 samples. On the other hand, the CLIQ, LCH, LTE, MIN and CAM2 samples presented low MFI values.

Some exhumed samples showed brittle behavior (MIN, LDO and CAM2 samples), and the CLIQ and MIN2 samples presented some tendency to brittle behavior. The loss of ductility has a high impact on the geomembrane's performance.

The SCR results demonstrated low values for the exhumed samples compared to the GRI-GM13 (2021) requirements. The LTE, MIN, MIN2, LDO, CAM1 and CAM2 samples presented the tendency to brittle failure. Only the CLIQ, LCH and CAM samples demonstrated high SCR results.

4 Conclusions

This work aimed to understand the final conditions of nine exhumed HDPE smooth geomembranes applied in some geotechnical and environmental Brazilian facilities.

The analyzed exhumed geomembranes showed several changes in their properties, except for the LCH sample, the thicker one, which presented good performance in the physical properties, but some changes in thermal decomposition. The LTE sample changes its physical properties over time and could yield to a liner rupture in the near future. The MIN, MIN2, LDO, and CAM2 samples showed brittle tensile behavior, low SCR values, low Std. OIT values and could culminate in a system failure. The CAM1 sample presented an atypical viscosity, low SCR result, unprotection from the additives against the oxidative degradation, certainly having reached its lifetime. The CLIQ and CAM samples changed their physical and thermal behavior and may cause liner rupture in the short-term. The evaluated tendency lines demonstrated high variations, which limits the extrapolation of results.

The exhumed samples analyses showed the vulnerability of the HDPE geomembranes tested and demonstrated, in general, the short-term durability of the products tested. Finally, this research showed the need for a standardization of resins and additives of the HDPE geomembranes to guarantee products with long-term durability, avoiding losses in terms of environmental impacts and financial costs. Better quality control practices of geosynthetic products must be required by designers and enforced by regulatory agencies to avoid using inadequate products regarding their service lives and required engineering properties.

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Table Captions:

Table 1: HDPE geomembrane exhumed samples used in this research

Table 2: MFI test results of the exhumed samples

Table 3: Tensile resistance at break test results of the exhumed samples

Table 4: Tensile elongation at break test results of the exhumed samples

Table 5: SCR test results of the exhumed samples

Table 6: Std. OIT test results of the exhumed samples

Table 7: HP OIT test results of the exhumed samples

Table 8: Exhumed samples' behavior

Figure Captions:

Figure 1: MFI results versus exposure time for the exhumed samples

Figure 2: Retained tensile resistance at break results versus exposure time for the exhumed samples

Figure 3: Tensile elongation at break results versus exposure time for the exhumed samples

Figure 4: SCR results versus exposure time for the exhumed samples

Figure 5: Std. OIT results versus exposure time for the exhumed samples

Figure 6: HP OIT results versus exposure time for the exhumed samples

Table 1. HDPE geomembrane exhumed samples used in this research

Sample	Nominal Thickness (mm)	Application	Exposure Time (years)
CLIQ [15]	1.0	Industrial Water Pond	2.25
LTE [16]	1.0	Sewage Treatment Aeration Pond	2.75
LCH [16]	2.0	Municipal Landfill Leachate Pond	5.17
MIN [17]	1.0	Pond for Water Use for the Iron Ore Process	7.92
MIN2 [17]	1.0	Spillway Channel of a Ferronickel Tailing Dam	10.08
LDO [18]	0.8	Biodegradable Waste Pond	15.17
CAM [19]	0.8	Shrimp Farming Pond – Bottom Liner	8.25
CAM1 [19]	0.8	Shrimp Farming Pond – Slope Liner	8.25
CAM2 [19]	0.8	Another Shrimp Farming Pond	3.0

Table 2. MFI test results of the exhumed samples

Sample	Exposure Time (years)	MFI (g 10 min^{-1})	SD (g 10 min^{-1})
CLIQ	2.25	0.4256	0.0079
LTE	2.75	0.4555	0.0061
LCH	5.17	0.5008	0.0072
MIN	7.92	0.4016	0.0052
MIN2	10.08	0.8635	0.0229
LDO	15.17	0.7375	0.0225
CAM	8.25	1.4191	0.0325
CAM1	8.25	3.9939	0.2188
CAM2	3.0	0.5831	0.1380

Table 3. Tensile resistance at break test results of the exhumed samples

Sample	Exposure Time (years)	Tensile Resistance (kN m^{-1})	SD (kN m^{-1})
CLIQ	2.25	21.98	6.82
LTE	2.75	27.12	1.30
LCH	5.17	60.40	7.66
MIN	7.92	22.11	4.05
MIN2	10.08	24.14	4.30
LDO	15.17	20.35	0.98
CAM	8.25	19.23	3.11
CAM1	8.25	16.12	2.09
CAM2	3.0	16.37	2.15

Table 4. Tensile elongation at break test results of the exhumed samples

Sample	Exposure Time (years)	Tensile Elongation (%)	SD (%)
CLIQ	2.25	482.63	329.65
LTE	2.75	679.33	27.53
LCH	5.17	752.60	81.38
MIN	7.92	301.15	397.19
MIN2	10.08	495.52	445.38
LDO	15.17	259.24	342.71
CAM	8.25	684.63	96.46
CAM1	8.25	627.07	63.27
CAM2	3.0	312.74	335.42

Table 5. SCR test results of the exhumed samples

Sample	Exposure Time (years)	SCR (h)	SD (h)
CLIQ	2.25	709.45	78.63
LTE	2.75	30.89	12.31
LCH	5.17	542.15	508.17
MIN	7.92	45.25	34.13
MIN2	10.08	20.22	7.04
LDO	15.17	8.89	4.12
CAM	8.25	1151.98	44.64
CAM1	8.25	4.25	1.52
CAM2	3.0	90.41	17.01

Table 6. Std. OIT test results of the exhumed samples

Sample	Exposure Time (years)	Std. OIT (min)	SD (min)
CLIQ	2.25	53.27	10.86
LTE	2.75	60.69	0.21
LCH	5.17	110.70	1.56
MIN	7.92	29.55	4.70
MIN2	10.08	10.86	5.60
LDO	15.17	6.94	1.04
CAM	8.25	6.36	0.52
CAM1	8.25	9.65	0.70
CAM2	3.0	67.61	5.13

Table 7. HP OIT test results of the exhumed samples

Sample	Exposure Time (years)	HP OIT (min)	SD (min)
CLIQ	2.25	162.55	7.42
LTE	2.75	180.00	1.41
LCH	5.17	231.50	2.12
MIN	7.92	110.45	5.87
MIN2	10.08	113.25	12.37
LDO	15.17	106.45	5.87
CAM	8.25	60.60	4.81
CAM1	8.25	0	0
CAM2	3.0	166.05	15.06

Table 8. Exhumed samples' behavior

Sample	Viscosity	SCR Behavior	Tensile Behavior	Antioxidant Depletion	Thermal Behavior
CLIQ	High	High	TBB	High	CB; OVL
LCH	High	High	Ductile	Low	CTD; CB; INT
LTE	High	TBF	Ductile	Low	INT
MIN	High	TBF	BB	High	Normal
MIN2	Low	TBF	TBB	ATAC	Normal
LDO	Low	TBF	BB	ATAC	OVL; INT
CAM	Low	High	Ductile	ATAC	BCE
CAM1	Low	TBF	Ductile	ATAC	BCE
CAM2	High	TBF	BB	Low	BCE; CTD

ATAC – Almost total antioxidant consumption

BB – Brittle behavior

BCE – Baseline change event

CB – Combustion

CTD – Changes in thermal decomposition

INT – Interaction between the polymer and the solution

OVL – Overlapped reactions

TBB – Tendency to brittle behavior

TBF – Tendency to brittle failure

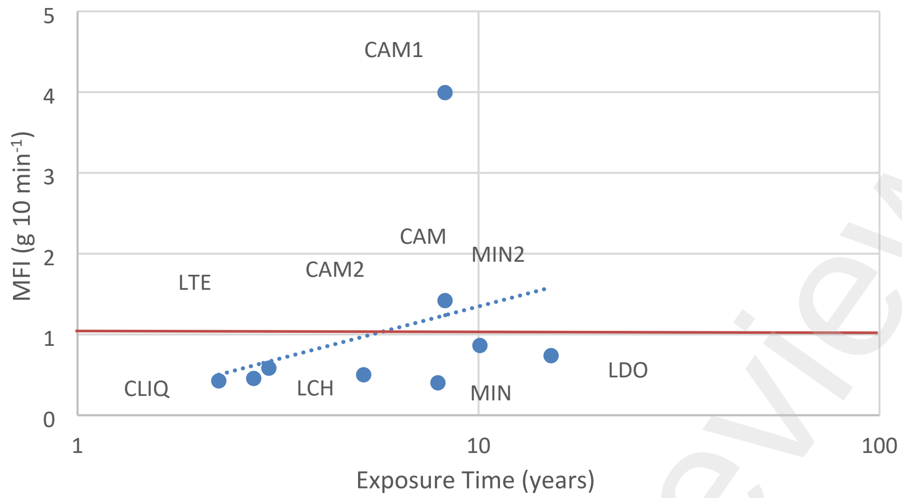

Figure 1. MFI results versus exposure time for the exhumed samples

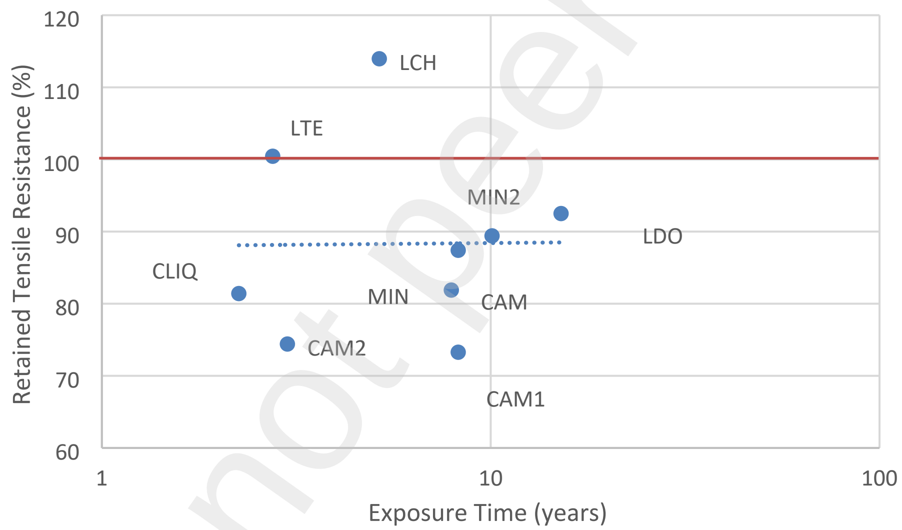

Figure 2. Retained tensile resistance at break results versus exposure time for the exhumed samples

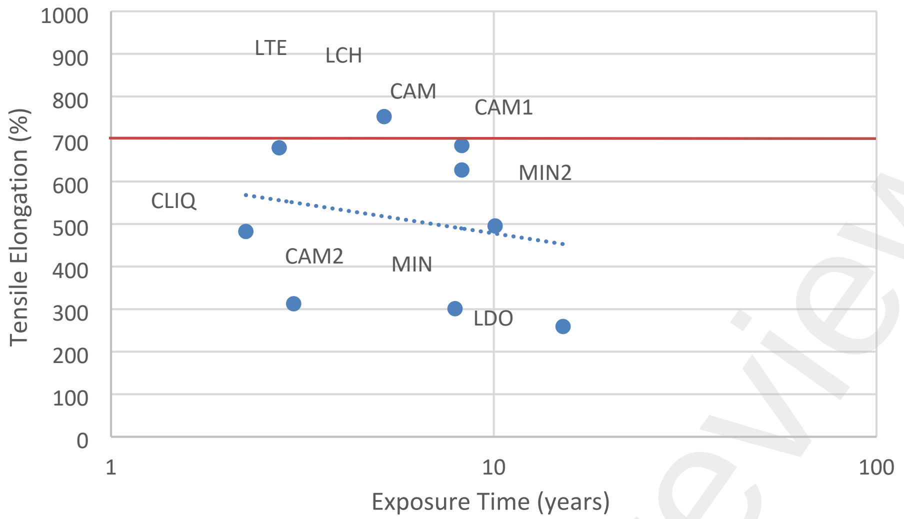

Figure 3. Tensile elongation at break results versus exposure time for the exhumed samples

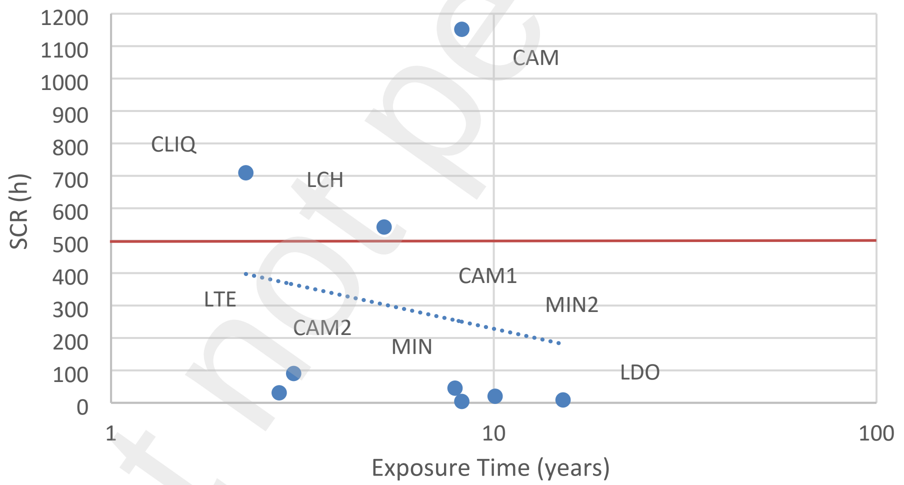

Figure 4. SCR results versus exposure time for the exhumed samples

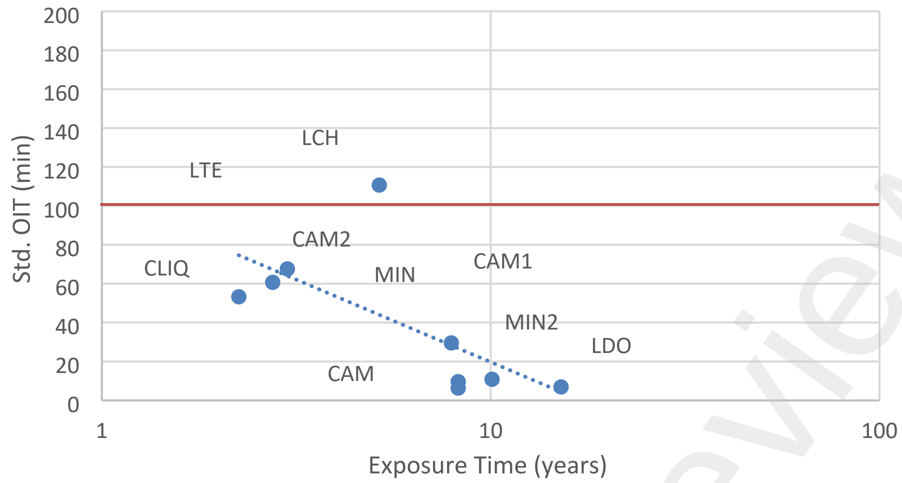

Figure 5. Std. OIT results versus exposure time for the exhumed samples

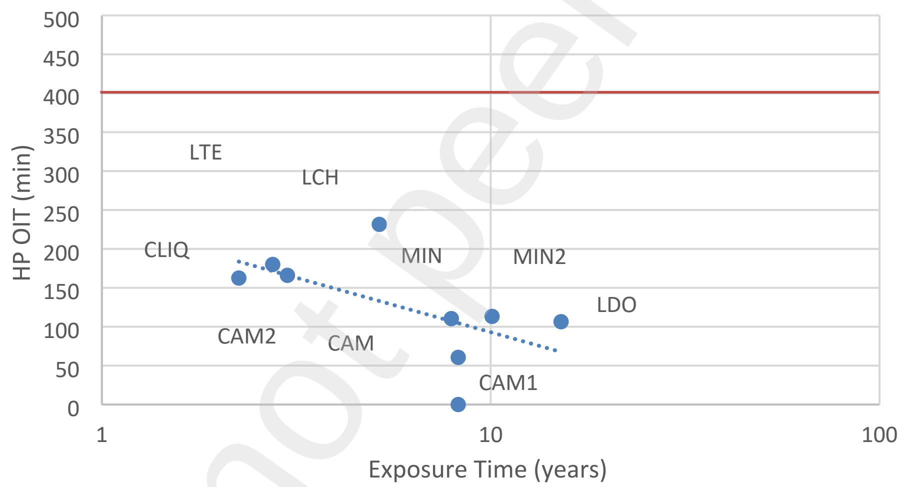

Figure 6. HP OIT results versus exposure time for the exhumed samples