Short Course on

GEOMEMBRANES AND COMPOSITE LINERS IN LANDFILLS AND MINING: MOVING FORWARD

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3. Geomembranes and their Service Life

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Most common types of GMBs

- **High density polyethylene (HDPE)**
- **Linear low density polyethylene (LLDPE)**
- Polypropylene (PP)
- Polyvinyl chloride (PVC)
- Ethylene interpolymer alloy (PVC-EIA)
- Bituminous geomembranes (BGM)
- Ethylene vinyl alcohol (EVOH)
- Chlorosulfinated polyethylene (CSPE)
- and others

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What defines a PE Geomembrane?

- Both LLDPE and HDPE are polyolefins (C_nH_{2n}) with a polyethylene backbone:

- C – H - C – H - C – H - C – H - C – H - C – H - ...

ASTM D833:

- HDPE has a density $\rho \geq 0.941$ g/cm^3
- MDPE has a $0.926 \leq \rho \leq 0.940$ g/cm^3
- LLDPE has a density of $0.919 \leq \rho \leq 0.925$ g/cm^3
- LDPE has a density $\rho < 0.919$ g/cm^3

- GMB density is very blunt instrument

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Basis Constituents

LLDPE	HDPE
• 94-97% PE resin • 2-3% carbon black • 0.25-2% antioxidants	• 95-98% PE resin • 2-3% carbon black • 0.25-1% antioxidants

- Vary in crystallinity
- Carbon black provides protection against UV
- Antioxidants/stabilizers protect against oxidation and UV

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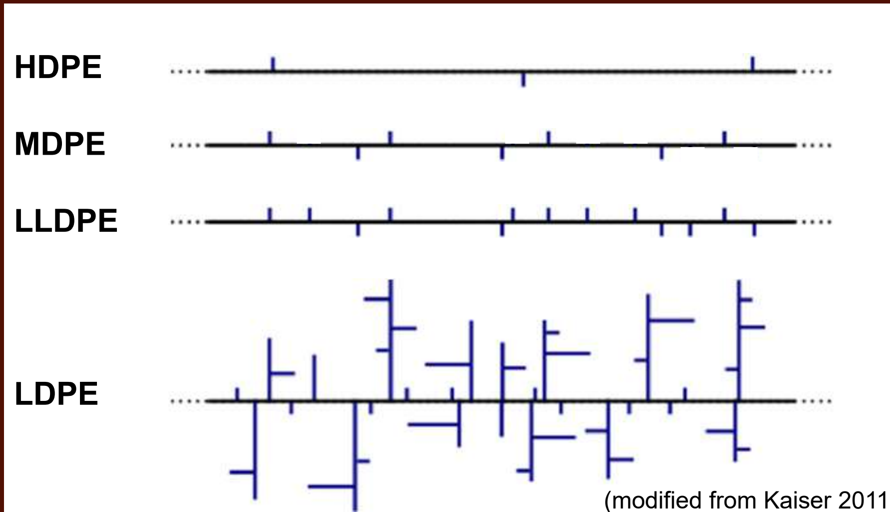
Resin: So what is the difference? Branching off the backbone



(modified from Kaiser 2011)

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Resin: What does branching affect

- Resin density
- GMB Crystallinity
- Resistance to chemicals
- Stress crack resistance (SCR)
- Mechanical properties

True HDPE with HDPE resin had:

- High crystallinity, high chemical resistance but low SCR (~ 200 - 300 hours or less)
- Relatively little used since the late 1990's

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Resin: Modern HDPE

- Mostly is medium density resin (suspect that in some cases LLDPE may have been blended in)
- Lower GMB crystallinity
- Initial stress crack resistance (SCR_o) much higher than for old HDPE
- SCR_o > 500 hours, often > 1000 hours, sometimes > 10,000 hours
- Equilibrium SCR_m maybe much less than SCR_o

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Specifications for HDPE and LLDPE GMBs

Property	Specification	
	LLDPE	HDPE
GMB Density	≤ 0.939 g/cm³	> 0.94 g/cm³
Resin Density	≤ 0.926 g/cm³	> 0.932 g/cm³
Carbon black content	2-3%	2-3%
Stress crack resistance	Not specified (high)	> 500 hours
	GRI-GM 17	GRI-GM 13

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The Additive Package

Masterbatch for PE geomembrane generally comprises:

- a resin carrier (usually MDPE or LLDPE);
- a processing stabilizer such as a hindered phosphite;
- a thermal stabilizer which comprises a primary antioxidant such as a hindered phenolic antioxidant;
- an ultra-violet radiation, UV, stabilizer (e.g., hindered amine stabilizer (HAS, formerly HALS) also thought to be a long-term thermal stabilizer);

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Antioxidant and stabilizer (AOS) packages

Hindered phenolic antioxidant
[processing, welding and medium–term heat stability]

Hindered phosphite antioxidant
[processing, welding and medium–term heat stability]

Thiosynergists (Thioester) Sulfur-based secondary AOs combined with phenolic antioxidants [elevated temperatures]

Hindered amine stabilizer
(LMW - low molecular weight HAS) [heat and UV stability]

Hindered amine stabilizer
(HMW - high molecular weight HAS) [heat and UV stability]

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Antioxidant and stabilizer (AOS) packages

What you really need to know:

- Some of these compounds will diffuse out or be consumed faster than others.
- It is not just the compounds but, in some cases, the relative proportions of compounds that affect long-term performance(more to come on this).
- There is a limit to how much a geomembrane can accommodate – once this limit is exceeded excess AOS will exsolve and can be manifest by rapid OIT depletion and poor weldability of the material.
- Effect of high molecular weight HAS may decrease with GMB thickness (more to come on this).
- Initial OIT values may be useful for CQC/CQA but do not tell you much about long-term performance.

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The Additive Package

Masterbatch for PE geomembrane generally comprises:

- a resin carrier (usually MDPE or LLDPE);
- a processing stabilizer such as a hindered phosphite;
- a thermal stabilizer which comprises a primary antioxidant such as a hindered phenolic antioxidant;
- an ultra-violet radiation, UV, stabilizer (e.g., hindered amine stabilizer (HAS, formerly HALS) also thought to be a long-term thermal stabilizer);
- a carbon black pigment;

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Carbon black

The choice of carbon black matters!

- 60 nm N660 carbon black is too coarse for optimum UV screening (leading to failures from UV-related degradation).
- Smaller carbon black particle size
  - improves UV resistance
  - increase specific surface area,
  - **requires more antioxidants/stabilizers** to be added to the resin to compensate for the proportion of additives adsorbed by carbon black particles' high surface area.
- N330 grade is most used for geomembranes but is also prone to agglomeration
- extruder must provide good dispersive and distributive mixing

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The Additive Package

Masterbatch for PE geomembrane generally comprises:

- a resin carrier (usually MDPE or LLDPE);
- a processing stabilizer such as a hindered phosphite;
- a thermal stabilizer which comprises a primary antioxidant such as a hindered phenolic antioxidant;
- an ultra-violet radiation, UV, stabilizer (e.g., hindered amine stabilizer (HAS, formerly HALS) also thought to be a long-term thermal stabilizer);
- a carbon black pigment;
- a titanium dioxide pigment (for white geomembranes);
- an acid neutralizer (to scavenge acidic residues from the PE catalyst); and
- a polymer processing aid (PPA) such as a fluorinated elastomer.

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Questions

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Preliminary Selection - (GRI-GM13)

Properties	Test Method	Test Value 0.75 mm	1.00 mm	1.25 mm	1.50 mm	2.00 mm	2.50 mm	3.00 mm
Thickness - (min. ave.) - mm • lowest individual of 10 values - %	D5199	nom. -10	nom. -10	nom. -10	nom. -10	nom. -10	nom. -10	nom. -10
Formulated Density (min. ave.) - g/cc	D 1505/D 792	0.940	0.940	0.940	0.940	0.940	0.940	0.940
Tensile Properties *(1)* (min. ave.) • yield strength - kN/m • break strength - kN/m • yield elongation - % • break elongation - %	D 6693 Type IV	11 20 12 700	15 27 12 700	18 33 12 700	22 40 12 700	29 53 12 700	37 67 12 700	44 80 12 700
Tear Resistance (min. ave.) - N	D 1004	93	125	156	187	249	311	374
Puncture Resistance (min. ave.) - N	D 4833	240	320	400	480	640	800	960
Stress Crack Resistance *(2)* - hr.	D 5397 (App.)	500	500	500	500	500	500	500
Carbon Black Content (range) - %	D 4218 *(3)*	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0	2.0-3.0
Carbon Black Dispersion	D 5596	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*
Oxidative Induction Time (OIT) (min. ave.) *(5)* (a) Standard OIT - min. — or — (b) High Pressure OIT - min.	D 8117 D 5885	100 400	100 400	100 400	100 400	100 400	100 400	100 400
Oven Aging at 85°C *(5), (6)* (a) Standard OIT (min. ave.) - % retained after 90 days — or — (b) High Pressure OIT (min. ave.) - % retained after 90 days	D 5721 D 8117 D 5885	55 80	55 80	55 80	55 80	55 80	55 80	55 80
UV Resistance *(7)* (a) Standard OIT (min. ave.) — or — (b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(9)*	D 7238 D 8117 D 5885	N. R. *(8)* 50	N.R. *(8)* 50	N.R. *(8)* 50	N.R. *(8)* 50	N.R. *(8)* 50	N.R. *(8)* 50	N.R. *(8)* 50

GRI-GM13 Mar. 2021

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Properties	Test Value
	1.50 mm
Thickness - mils (min. ave.)	nom. (mil)
• lowest individual of 10 values	-10%
Density (min.)	0.940 g/cc
Tensile Properties *(1)* (min. ave.)	
• yield strength	22 kN/m
• break strength	40 kN/m
• yield elongation	12%
• break elongation	700%
Tear Resistance (min. ave.)	187 N
Puncture Resistance (min. ave.)	480 N
Stress Crack Resistance *(2)*	500 hr.
Carbon Black Content - %	2.0-3.0%
Carbon Black Dispersion	note *(4)*
Oxidative Induction Time (OIT) (min. ave.) *(5)*	
(a) Standard OIT	100 min.
— or —	
(b) High Pressure OIT	400 min.
Oven Aging at 85°C *(5), (6)*	
(a) Standard OIT (min. ave.) - % retained after 90 days	55%
— or —	
(b) High Pressure OIT (min. ave.) - % retained after 90 days	80%
UV Resistance *(7)*	
(a) Standard OIT (min. ave.)	N.R. *(8)*
— or —	
(b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(9)*	50%

Revised from 200 hrs to 300 hrs in 2003 and to 500 hrs in Nov. 2014

Has not changed since GRI-GM13 Issued in June 1997

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Preliminary Selection - (GRI-GM13)

Property		Value	Indication for
1a. Std-OIT (min)	AND	>100	Amount of antioxidant
% retained after 90 days at 85°C in air		55%	Antioxidant stability
OR			
1b. HP-OIT (min)	AND	>400	Amount of antioxidant
% retained after 90 days at 85°C in air		80%	Antioxidant stability

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Std-OIT Vs HP-OIT

	Std-OIT	HP-OIT
Temperature	200°c	150°c
Pressure	35 kPa	3500 kPa

- Std-OIT method faster than HP-OIT.
- Some antioxidant are volatilized at high temperatures and can not be detected by Std-OIT.

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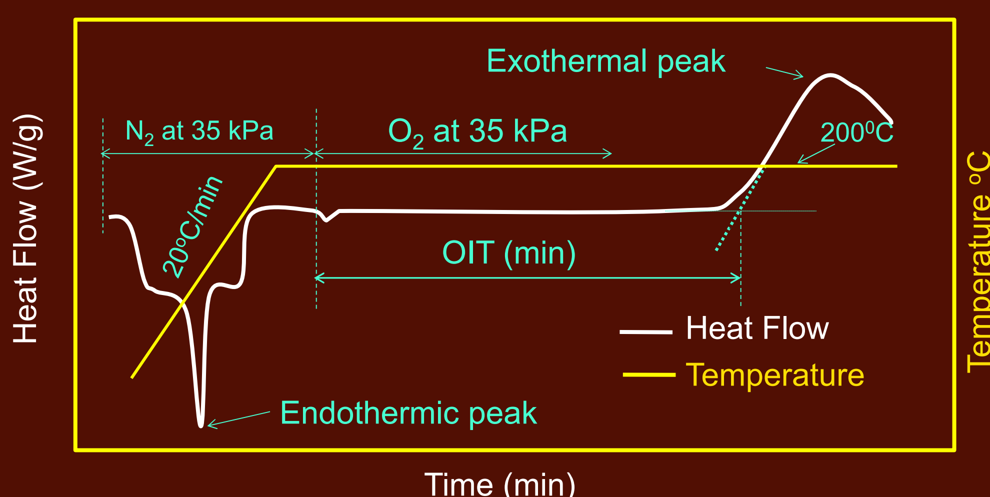
Laboratory Testing

Standard Oxidative time (Std-OIT, ASTM D3895)



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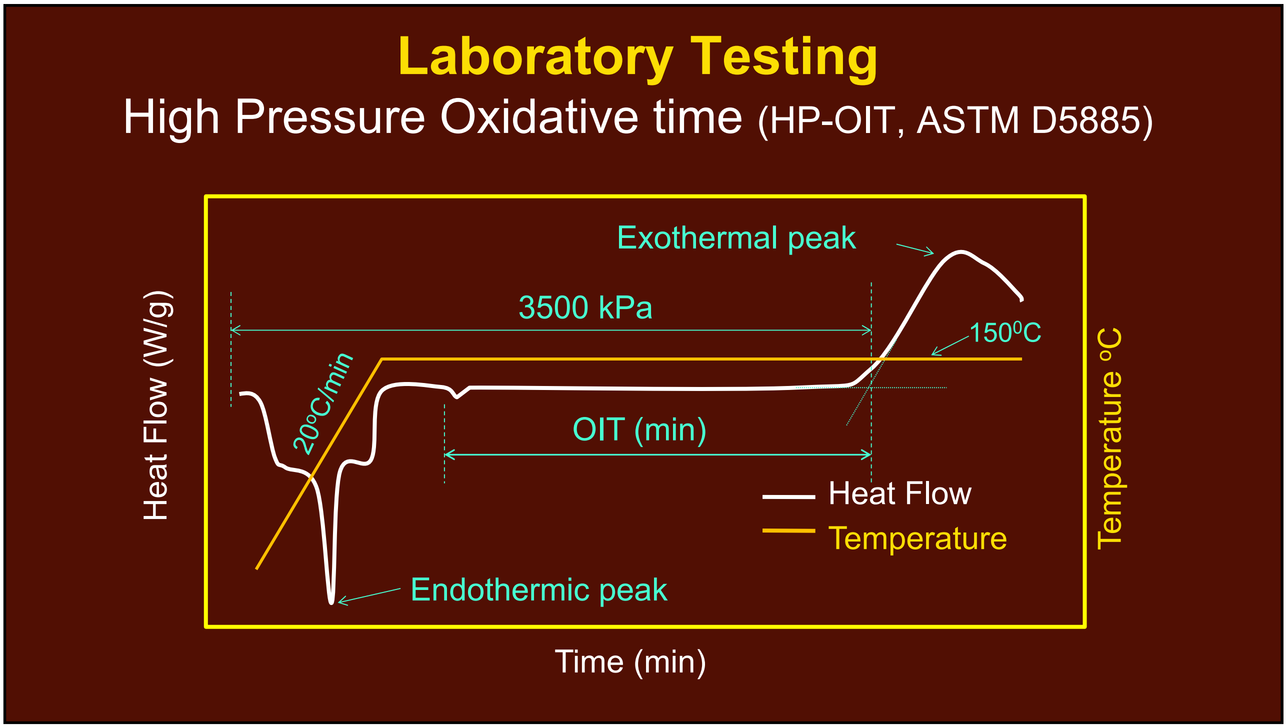
Laboratory Testing
High Pressure Oxidative time (HP-OIT, ASTM D5885)
Exothermal peak
3500 kPa
150⁰C
20⁰C/min
OIT (min)
Heat Flow
Temperature
Endothermic peak
Heat Flow (W/g)
Temperature ⁰C
Time (min)

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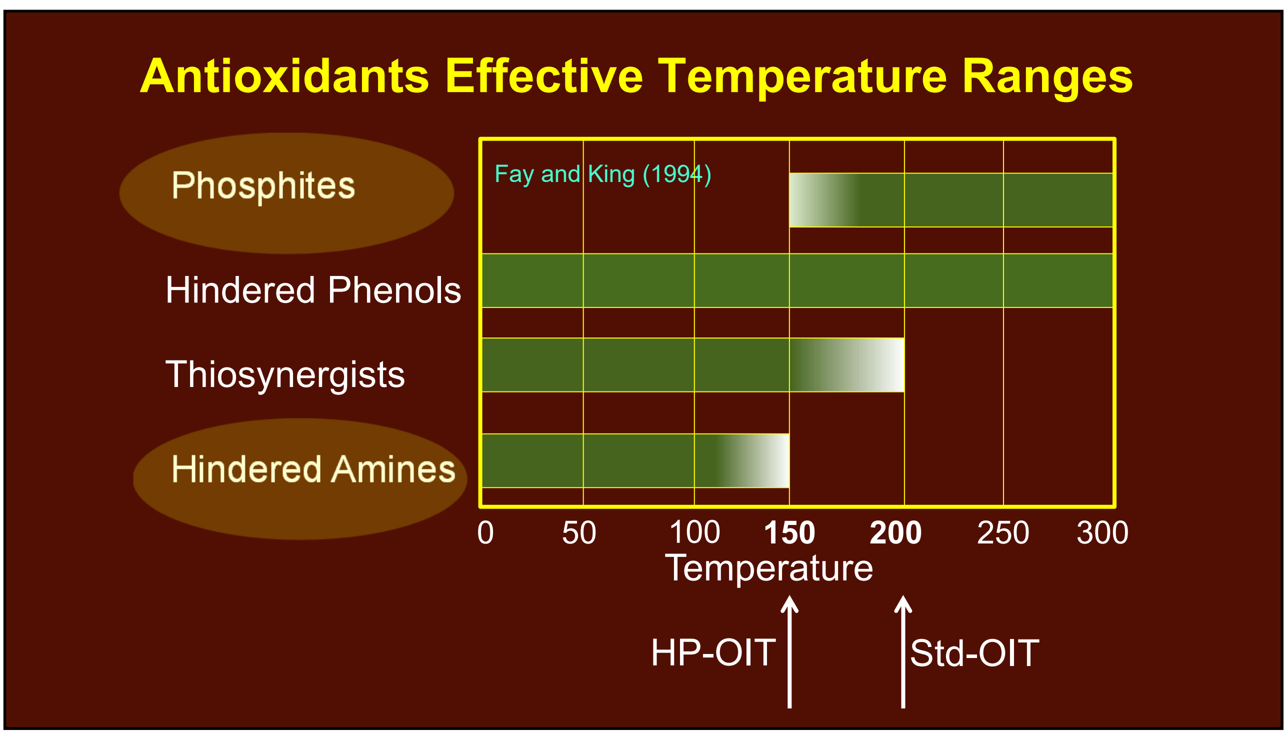
Antioxidants Effective Temperature Ranges
Fay and King (1994)
Phosphites
Hindered Phenols
Thiosynergists
Hindered Amines
0
50
100
150
200
250
300
Temperature
HP-OIT
Std-OIT

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Preliminary Selection - (GRI-GM13)

Property		Value	Indication for
1a. Std-OIT (min)	AND	>100	Amount of antioxidant
% retained after 90 days at 85°C in air		55%	Antioxidant stability
OR			
1b. HP-OIT (min)	AND	>400	Amount of antioxidant
% retained after 90 days at 85°C in air		80%	Antioxidant stability
AND			
2. SCR (hours)	AND	>500	Mechanical resitance

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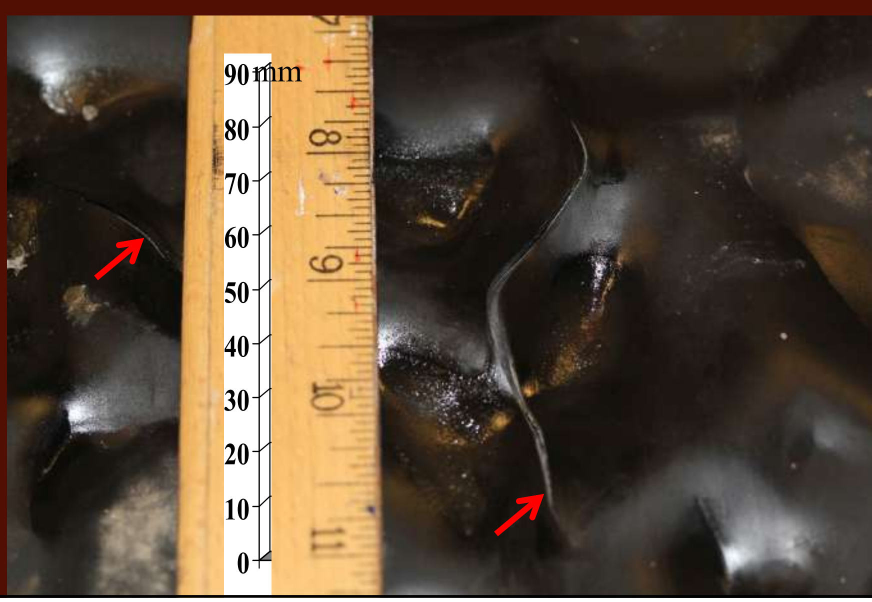
Stress cracking with ageing (250kPa)



MxA

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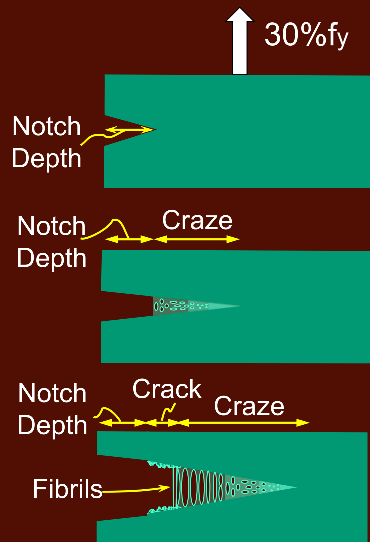
Stress Crack resistance (SCR) by Single point notched constant tensile load (SP-NCTL; ASTM D5397- appendix) test



(Photos: Dr. A. Ewais)

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Preliminary Selection - (GRI-GM13)

Property		Value	Indication for
1a. Std-OIT (min)	AND	>100	Amount of antioxidant
% retained after 90 days at 85°C in air		55%	Antioxidant stability
OR			
1b. HP-OIT (min)	AND	>400	Amount of antioxidant
% retained after 90 days at 85°C in air		80%	Antioxidant stability
AND			
2. SCR (hours)	AND	>500	Mechanical resistance
3. Break Elongation (%)		>700	CQC

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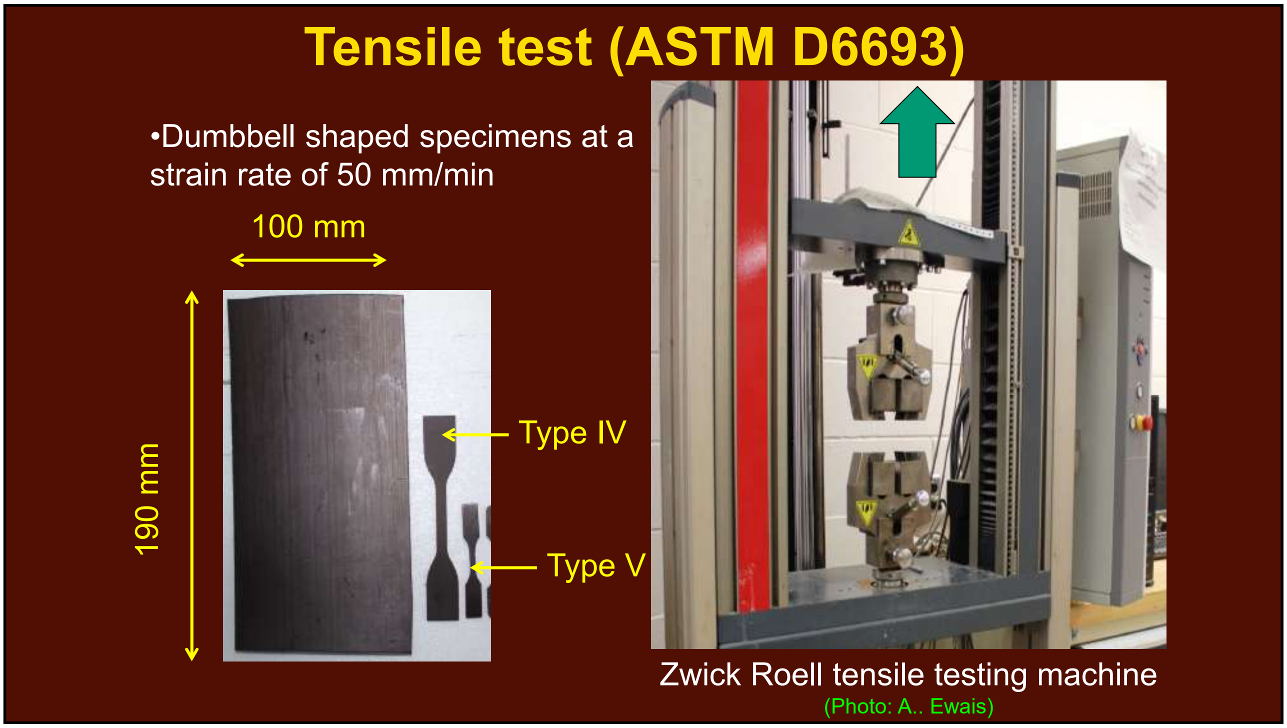
Tensile test (ASTM D6693)
•Dumbbell shaped specimens at a strain rate of 50 mm/min
100 mm
190 mm
Type IV
Type V
Zwick Roell tensile testing machine
(Photo: A.. Ewais)

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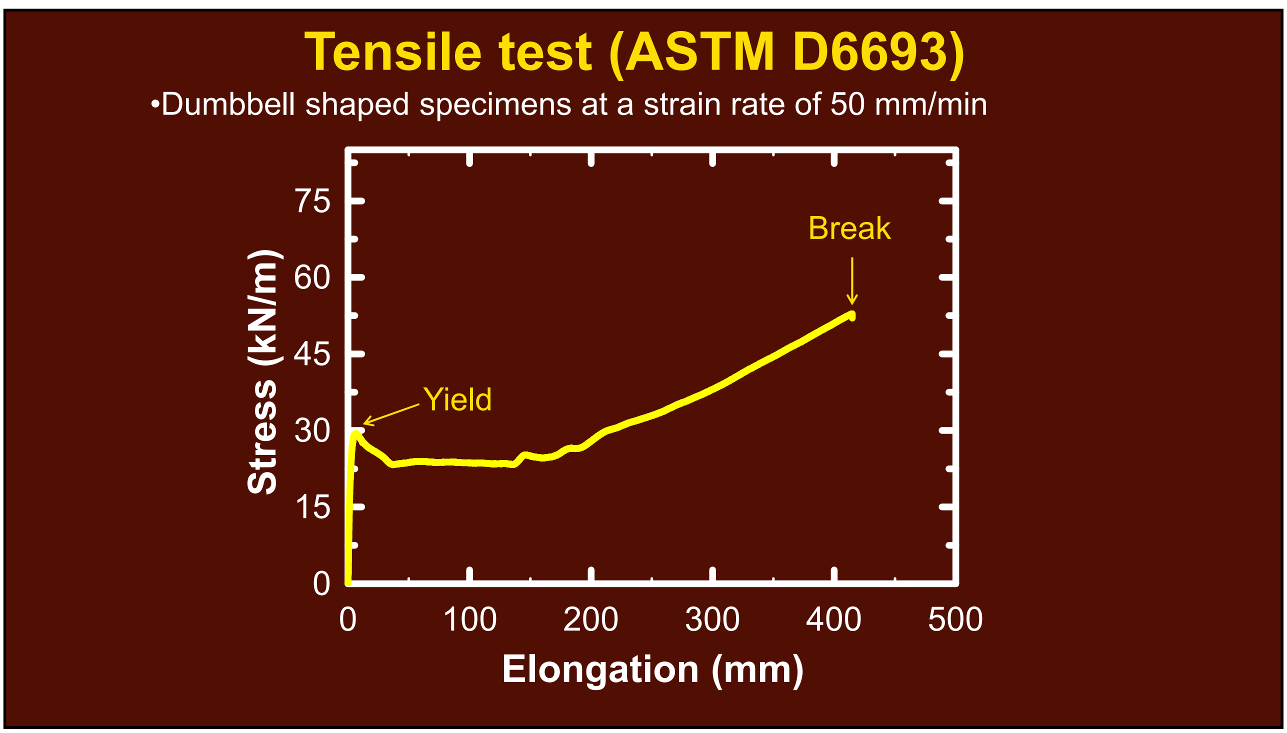
Tensile test (ASTM D6693)
•Dumbbell shaped specimens at a strain rate of 50 mm/min
Stress (kN/m)
0
15
30
45
60
75
Elongation (mm)
0
100
200
300
400
500
Yield
Break

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Specifications for HDPE and LLDPE GMBs

Property (2 mm thick)		Specification	
		LLDPE	HDPE
Break strength (kN/m)	Smooth	53	53
	Textured	21	26
Break elongation (%)	Smooth	800	700
	Textured	250	100

These parameters have no direct relationship with field performance.

* After 90 days oven ageing at 85°C	GRI-GM 17	GRI-GM 13

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Specifications for HDPE and LLDPE GMBs

Property (2 mm thick)		Specification	
		LLDPE	HDPE
Break strength (kN/m)	Smooth	53	53
	Textured	21	26
Break elongation (%)	Smooth	800	700
	Textured	250	100
Standard OIT (min)	(*)	100 (35%)	100 (55%)
	(or)		
High pressure OIT (min) (*)		400 (60%)	400 (80%)

* After 90 days oven ageing at 85°C	GRI-GM 17	GRI-GM 13

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Single Layer
Black Core
Black smooth
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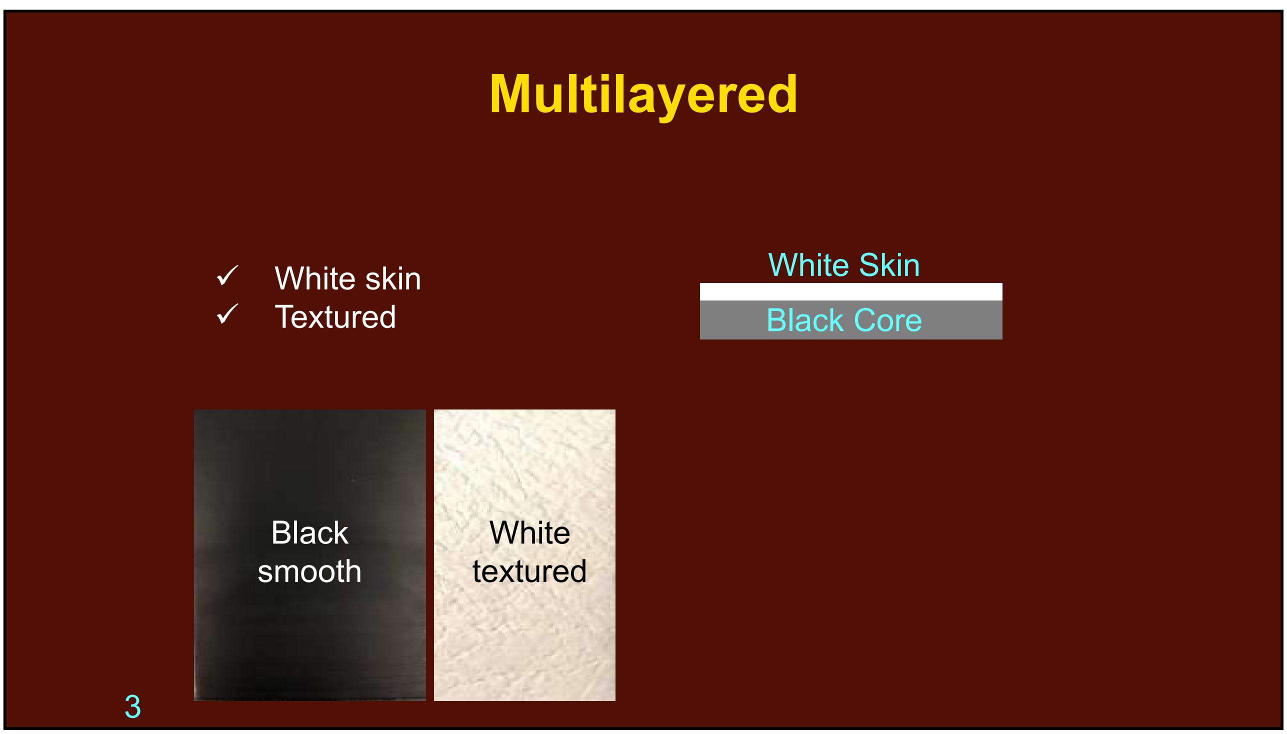
Multilayered
✓ White skin
✓ Textured
White Skin
Black Core
Black smooth
White textured
3

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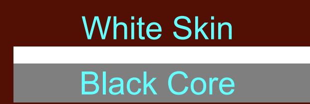
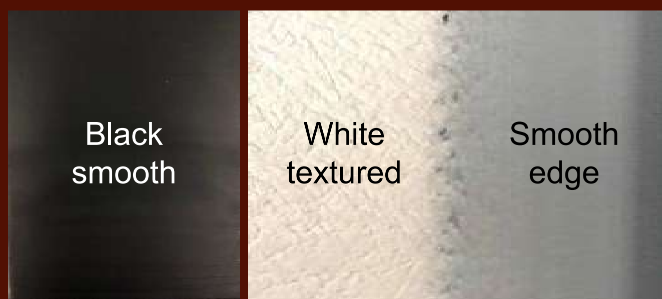
Multilayered

- ✓ White skin
- ✓ Textured





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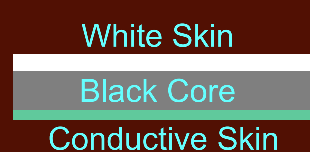
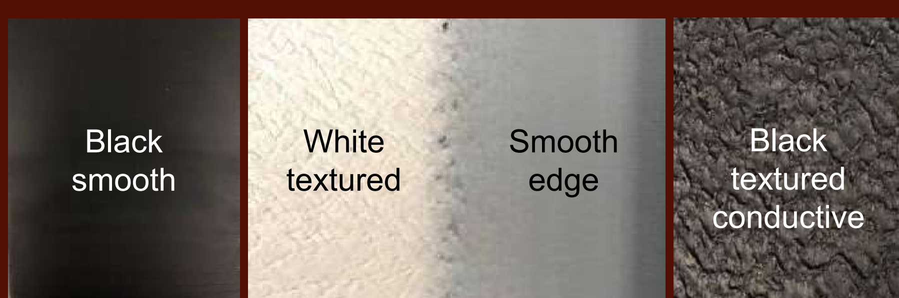
Multilayered

- ✓ White skin
- ✓ Textured
- ✓ Conductive





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Is a GMB that meets requirements of GRI-GM13 suitable for my landfill or mining application?

- Maybe, maybe NOT
- Generally, want Std-OIT > 150 -160 min
- Want SCR_m (after 90 days ageing at 55°C) ≥ 500 hours
- If you need more than 150-year service-life (SL), you need a GMB that has been shown through immersion testing in a simulated MSW leachate to have projected SL > required SL

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Melt Index

•Melt index (MI), aka melt flow index: After a specified preheating time, MI is the mass of molten thermoplastic extruded through a die with a specified length and orifice diameter under prescribed conditions of temperature (e.g., 190°C) and load (e.g., 2.16 kg).

- Melt index increases → molecular weight decreases
- Melt index increases → SCR decreases
- Chain scission → Melt index increases
- Cross-linking → Melt index decreases

- HLMI = high load melt index obtained with a load of 21.6 kg.
- High molecular weight resins have HLMI < 15 g/10 min.
- Blown film 12 ≤ HLMI ≤ 16 g/10 min
- Flat die 18 ≤ HLMI ≤ 24 g/10 min

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Questions

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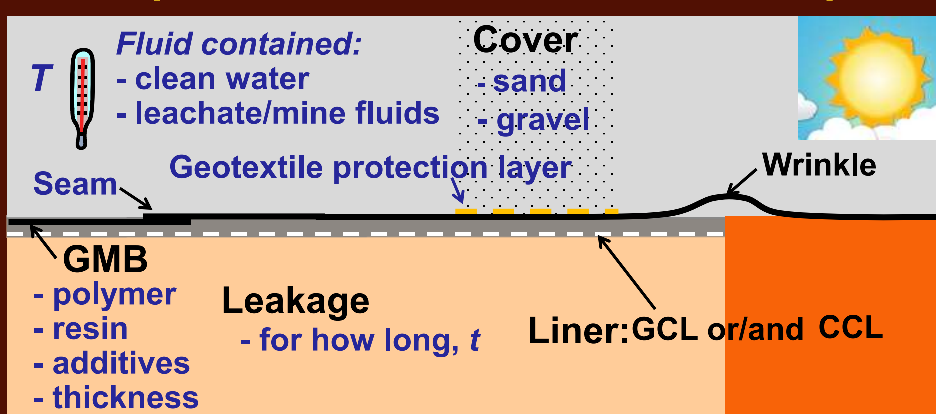
How long will the GMB last (what is its service-life)



T = temperature; *t* = time

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Modes of long-term degradation for PE geomembranes

- Biological degradation
- **Ultraviolet (UV) degradation**

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Ultraviolet (UV) degradation

- Field exposure (Queen's University, Kingston)
- Laboratory accelerated ageing studies

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Ultraviolet (UV) degradation

- Some have reported that antioxidants deplete faster from stabilized LLDPE GMBs than stabilized HDPE GMBs HOWEVER our tests have faster depletion from some HDPE than some LLDPE
- Difficult to generalize about UV degradation of LLDPE vs HDPE since it depends on the specific antioxidant/stabilizer package, carbon black, and resin
- Loss of strength and elongation in Koerner et al. (2008) laboratory study faster for 1mm LLDPE than 1.5mm HDPE for GMBs tested but it was inferred that the service life of exposed LLDPE (1 mm) and HDPE (1.5 mm) GMBs is greater than 28 years for Texas weather conditions.

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Ultraviolet (UV) degradation

- Properly stabilized LLDPE and HDPE GMBs have shown to perform their intended function for more than 8 - 16 years in the field.
- Given the limited research relating to this important topic, more research is required.

[0]

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Modes of long-term degradation for HDPE geomembranes

- Biological degradation
- Ultraviolet (UV) degradation
- **Extraction (e.g., antioxidants)**
- **Oxidation**

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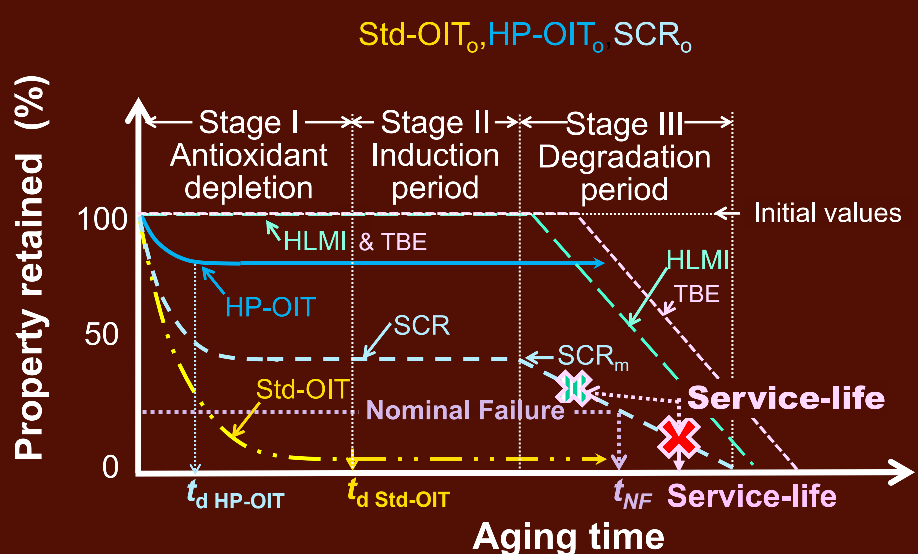
Oxidative degradation



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Symptoms of degradation

The following mechanical property changes are generally observed with geomembrane degradation (often in order shown)

- A decrease in stress crack resistance below SCR_m.
- A change in high load melt index (HLMI) this may be an increase or decrease.
- A decrease in % elongation at failure.
- (Sometimes an increase and then) A decrease in strength at failure (i.e., tensile stress at break).I
- An increase in brittleness (i.e., general loss of ductility).

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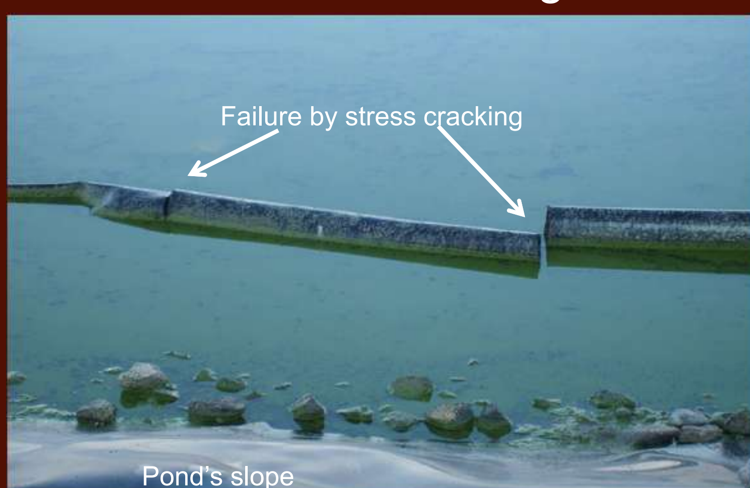
Concerns - HDPE GMBs

Stress Cracking



GMB stress cracking at wrinkle at the base of water pond
(Peggs et al. 2014)

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What is end of life (service-life) for a geomembrane (GMB)?

When it no longer serves its original design function: i.e., when it has sufficient number/size of holes (ruptures) to allow excessive fluid loss

61 holes in 0.6m dia.
2.2 million holes/ha

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Some Recently Studied GMBs

Generic Name	MxTB W20	MxTD WC20	MzTA W20	MyTA WC20	MyTB W20	MyI WC20	MyJ W20
Meets GRI-GM13?	✓	✓	✓	✓	✓	✓	✓
Std-OIT (minutes)	285	220	185	165	165	165	165
% Std-OIT retained @90 days	56% ✓	53% ✗	38% ✗	57% ✓	42% ✗	58% ✓	53% ✗
HP-OIT (minutes)	960	705	1920	800	915	780	1490
% HP-OIT retained @90 days	66% ✗	85% ✓	95% ✓	92% ✓	94% ✓	94% ✓	86% ✓

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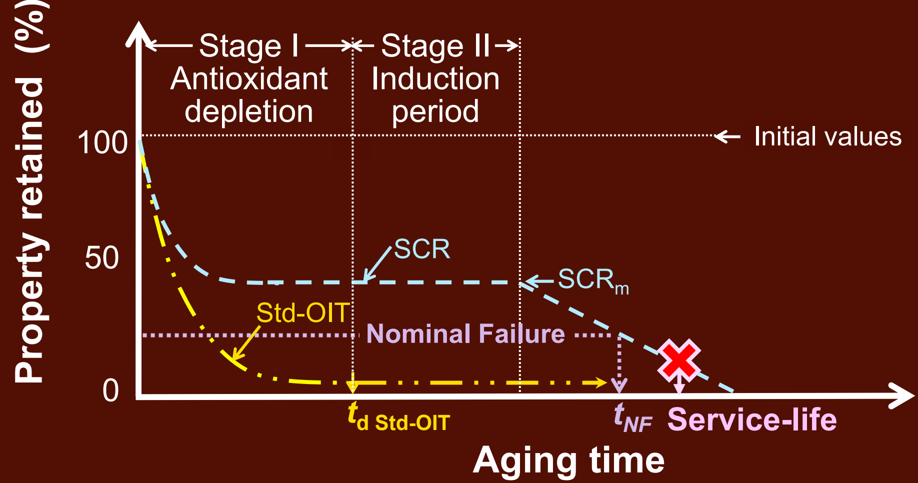
Oxidative degradation

Std-OIT$_o$, HP-OIT$_o$, SCR$_o$



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Evolving formulations and multilayered GMBs

Stress crack resistance (SCR)

- a critical design parameter for HDPE GMBs
- initial value: SCR$_o$
  - not representative of the true stress crack resistance

Reduction at 22°C in laboratory

Year	SCR (hours)	
2005	1430	SCR$_o$
2008	910	
2011	720	
2017	530	
SCR$_m$	390	aged at 55°C for 3 months

This decrease in SCR is the GMB tending to this stable natural state with the stress crack resistance SCR$_m$ and does not represent degradation.

SCR$_m$ /SCR$_o$ = 0.27

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Estimate of Stress Crack Resistance after morphological change (SCR_m)

	MxTB W20	MxTD WC20	MzTA W20	MyI WC20	MyJ W20
SCR_o (hrs)	1600	>11000	670	1600	350
SCR_m (hrs)	**500**	**5400**	330	**900**	260
SCR_m/SCR_o	~30%	~50%	~50%	~60%	~70%

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Estimate of Stress Crack Resistance after morphological change (SCR_m)

	HDPE						LLDPE
	MyA 20	MxA 20	MxA 15	MyC 15	MxC 15	MxC 20	LxD 15
SCR_o (hrs)	5,200	1,300	1,400	1,000	800	950	19,000
SCR_m (hrs)	**2,000**	**600**	400	**1,000**	390	340	**6,000**
SCR_m/SCR_o	38%	~50%	~30%	~100%	~50%	~35%	~32%

Some LLDPE have a yield some do not

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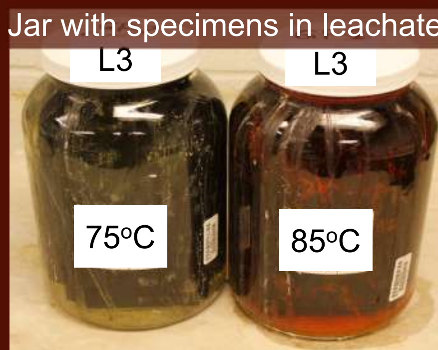
How long will the GMB last?

Immersion in leachate @ different temperatures: exposure - both sides



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How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)

Time to nominal failure, t_{NF},
1.5mm HDPE in simulated MSW leachate at 85°C

GMB	t_{NF} (months)	Relative t_{NF} (-)
MxA	14	1.0
MxB	19	1.4
MyC	31	2.2

Abdelaal & Rowe (2015)

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How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
    - Elements (UV; variable temperature; damage)
    - Chemical composition of fluid in contact with GMB
    - Temperature
    - Tensile strains induced in the GMB

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Chemical characteristics that can affect PE aging

- Surfactant (in MSW leachate and some heap leach solutions) on OIT depletion
- Salts (not on OIT but on later degradation)
- pH (effect depends on antioxidant package)
- Chlorine (e.g., in treated water)

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Effect of fluid on time to nominal failure, t_{NF}, at 30°C

Leachate		Stage I (years)	t_{NF} (years)	t_{NF} Ratio (-)
MSW-L3	Full-VFAs	24	53	1.0
MSW-L1	Full MSW	28	59	1.1
MSW-L2	Surfactant only	21	83	1.6

Surfactant and high pH accelerates antioxidant depletion (shortens Stage 1) but salts affect Stages II and III and hence t_{NF}

GMB with best resistance in one fluid may not be best in another fluid

Abdelaal, Rowe & Islam (2014)

1.5 mm thick HDPE GMB MxC15

57

Effect of fluid on time to AO depletion, t_d, at 30°C (Stage I)

Leachate	xTD	xTB	zTA	yTB
LLW-L7	280	1100	550	700
LLW-L9	280	1000	540	630
MSW-L3	70	370	200	320

Rounded to 2 significant figures

Zafari et a.l (2023)

2 mm thick HDPE

58

HDPE or LLDPE?

Test data on 4 GMBs

GMB/Property	MxA15	MxC15	LxD15	LxE15
Resin	HDPE	HDPE	LLDPE	LLDPE
Std-OIT (min)	100	**160**	190	**155**
HP-OIT (min)	260	**960**	350	**890**
SCR_o (Hours)	720	800	19,000	18,500
Break strength (kN/m)	47	51	55	53
Break Strain (%)	874	857	980	980

59

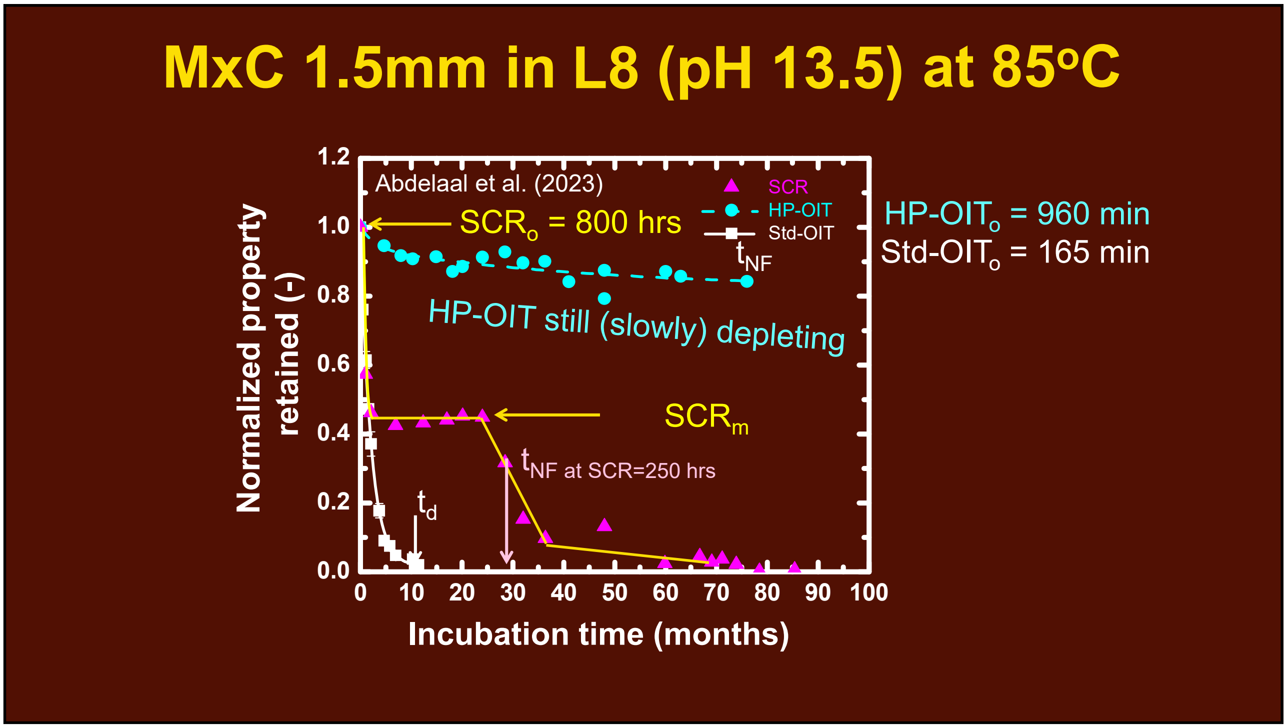
HDPE or LLDPE?

Test data on 4 GMBs

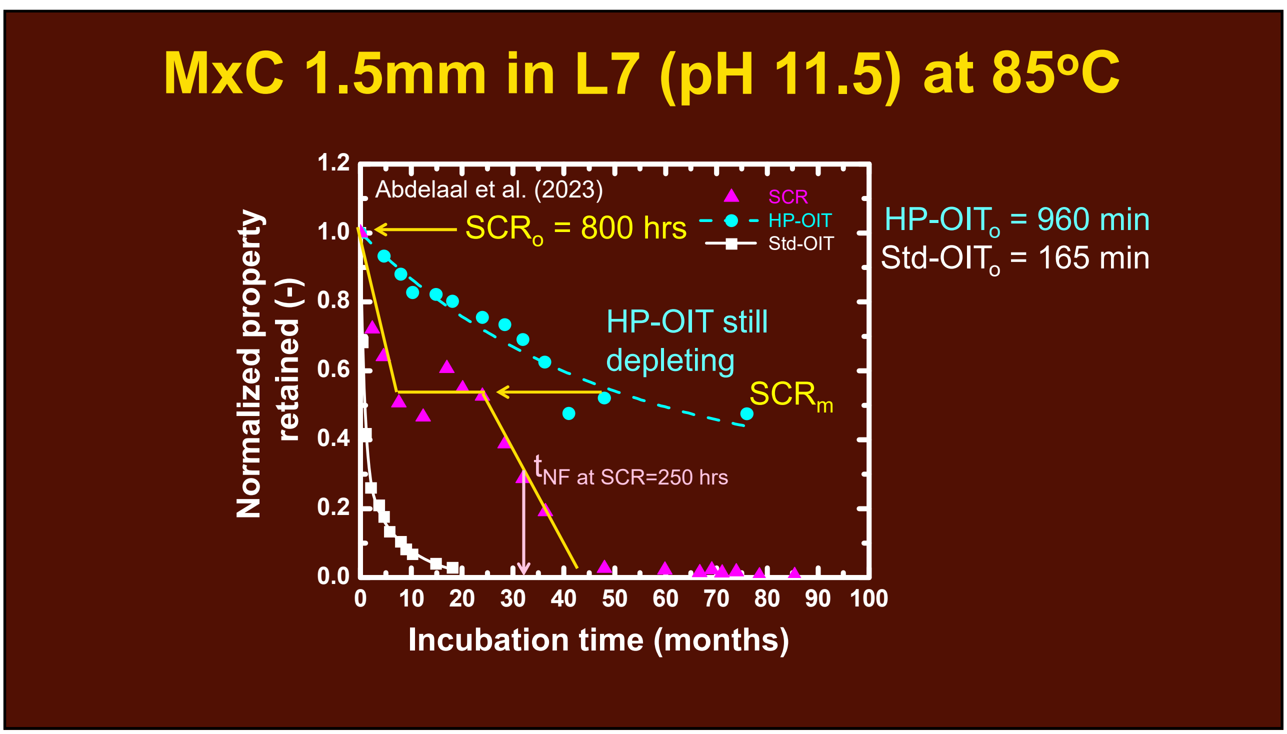
GMB/Property	MxA15	MxC15	[illegible]	[illegible]
Resin	HDPE	[illegible]	[illegible]	LLDPE
Std-OIT (min)	[illegible]	[illegible]	[illegible]	**155**
HP-OIT (min)	[illegible]	[illegible]	350	**890**
[illegible]	[illegible]	800	19,000	18,500
[illegible]	47	51	55	53
Break Strain (%)	874	857	980	980

How can you tell which is going to be adequate,
let alone best from this information?
Answer: you can not!

60

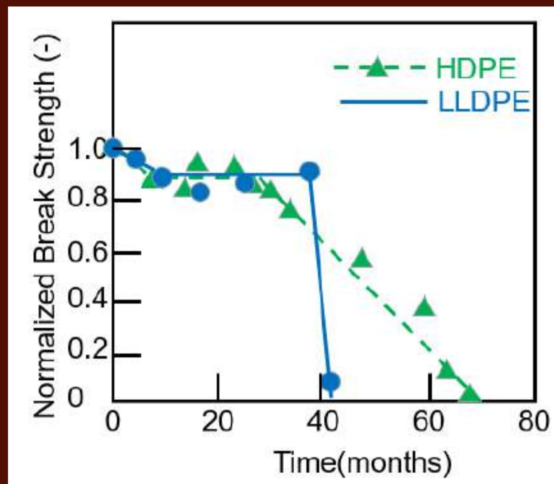

MxC 1.5mm in L8 (pH 13.5) at 85°C
Abdelaal et al. (2023)
SCR
HP-OIT
Std-OIT
SCRo = 800 hrs
HP-OITo = 960 min
Std-OITo = 165 min
tNF
HP-OIT still (slowly) depleting
SCRm
tNF at SCR=250 hrs
td
Normalized property retained (-)
Incubation time (months)

61


MxC 1.5mm in L7 (pH 11.5) at 85°C
Abdelaal et al. (2023)
SCR
HP-OIT
Std-OIT
SCRo = 800 hrs
HP-OITo = 960 min
Std-OITo = 165 min
HP-OIT still depleting
SCRm
tNF at SCR=250 hrs
Normalized property retained (-)
Incubation time (months)

62

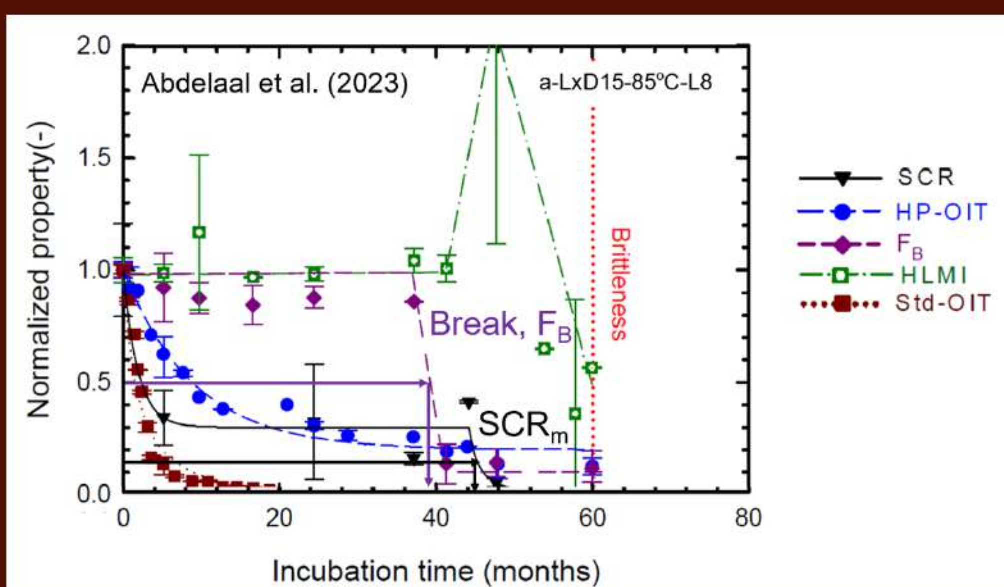
HDPE or LLDPE?



Variation in geomembrane normalized break strength with time after ageing in high pH heap leach solution at 85°C
(Rowe and Jefferis 2022)

63

LLDPE can also stress crack



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Geomembranes for LLRW

- HDPE degradation by high energy irradiation can be similar to degradation by UV radiation (Needham et al. 2004)
- Mechanical properties change due to irradiation degradation by chain scission at a total dose greater than 1 to 10 Mrad (Phillips 1988)

65

Geomembranes for LLRW

- Impact of irradiation is determined primarily by the total absorbed dose and the presence or absence of oxygen (Phifer 2005).
- At high absorbed doses PE becomes very hard and brittle (Sangster 1993)
- With air (oxygen) available, irradiation can provide the activation energy for oxidation to occur. (Schnabel 1981; Sangster 1993; Sun et al. 1996; Badu-Tweneboah et al. 1999)
- Need to watch pH of the fluid in contact with GMB (for high pH need to select GMB carefully)

[0]

66

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
    - Elements (UV; rapid changes in temperature)
    - Chemical composition of fluid in contact with GMB
    - Temperature

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Liner temperature

- - 40 to 70^{o}C exposed to "sun" in Canada
- 30 to 40^{o}C normal MSW landfill
- 40 to 60^{o}C with extra moisture
- 65 to 70^{o}C in ashfills (also high pH)
- 70 to 80^{o}C some heap leach pads
- > 85^{o}C unusual landfills
- 40 to 95^{o}C brine ponds and solar ponds

68

Effect of temperature on time to nominal failure, t_{NF}

Immersed in MSW-L1 (an aggressive solution)

Geomembrane:	MyC 1.5mm	MyA 2.0mm
Temperature °C	t_{NF} (years)	
60	9	13
50	15	36
40	30	120
30	60	430

Could be shorter or longer for other GMBs and exposure conditions

MyC: 9 years data, Abdelaal, Rowe & Islam (2014)
MyA: 17 years data, Ewais & Rowe (unpublished)

69

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure

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Concerns - HDPE GMBs

Stress Cracking

GMB stress cracking of a 1.5 mm thick HDPE geomembrane in a tailings storage facility, China in 2009 (Peggs et al .2014)

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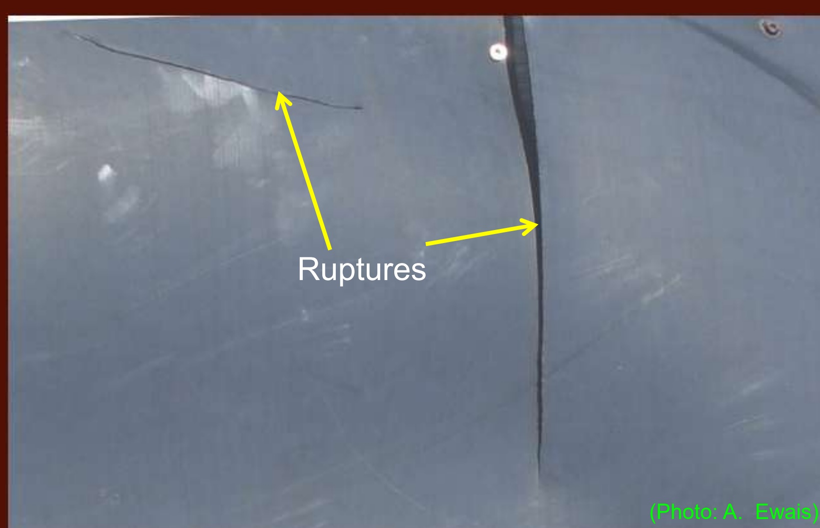
Concerns - HDPE GMBs

Stress Cracking



72

How long will the GMB last?

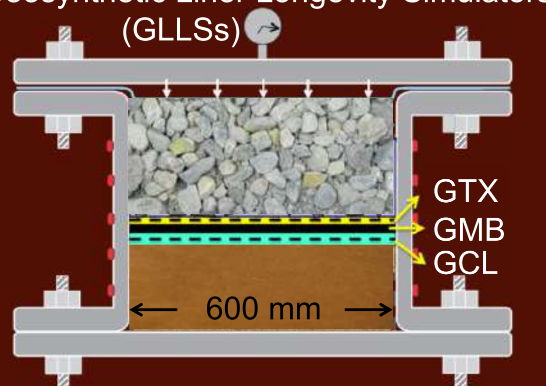
Depends on

- Nature of the exposure to leachate

Immersion tests (Jar)

Leachate exposure: Both sides

Geosynthetic Liner Longevity Simulators (GLLSs)

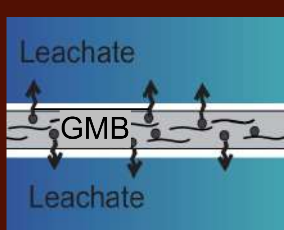


Upper side only

73

How long will the GMB last?

Immersed time to OITdepletion: JAR



MxA 1.5mm

Rowe et al. (2010 & 2013)

GLLS/Jar = 2.1

GLLS/Jar = 3.0

Ratio may vary with GMB, leachate, liner configuration & stage

OIT depletion takes 2-4 times longer in composite liner

74

How long will the GMB sheet last?

Based on 17 years of test data at accelerated temperatures in simulated MSW landfill leachate

Temperature °C	Immersed t_{NF} (years)	Composite liner t_{NF} (years)
60	13	50
35	220	880

Assumes: Good construction, covered, and **negligible tensile strain**

Will be different for other GMBs, leachates, and liner configurations

Ewais et al. (2017); Rowe et al, (2020)

2 mm thick HDPE MyA

75

How long will the GMB lasts

Depends on

- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
    - Elements (UV; rapid changes in temperature)
    - Chemical composition of fluid in contact with GMB
    - Temperature
    - Nature of exposure
    - **Sustained tensile strains in GMB**

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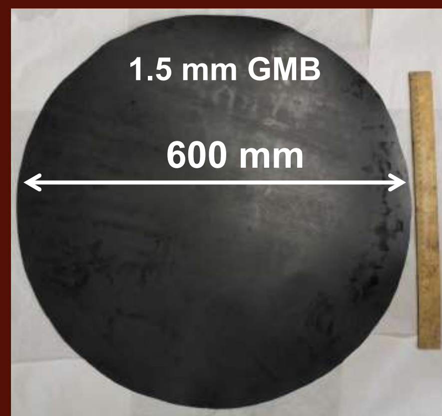
Service-life of a HDPE GMB under simulated landfill conditions

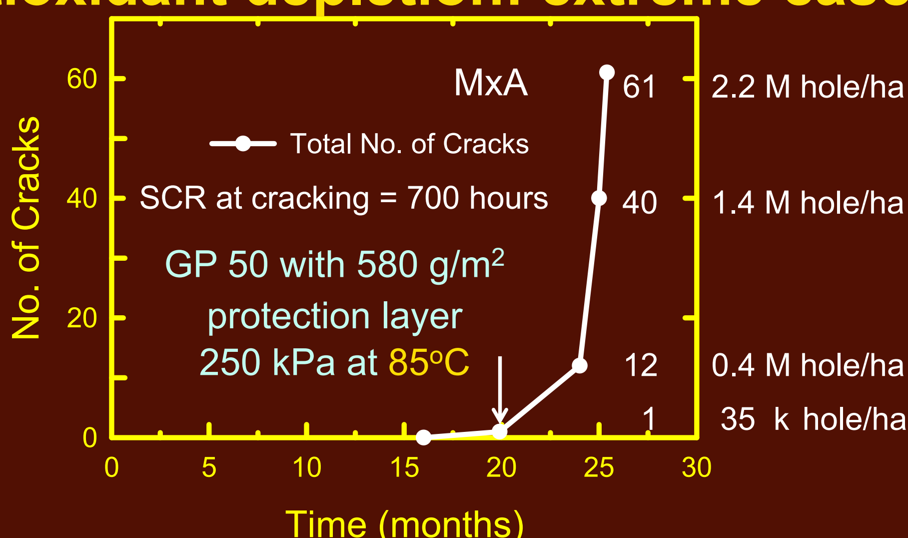
(Rowe et al. 2010b, Ewais et al. 2014, + papers in progress)

GLLS



77

Time to brittle rupture after antioxidant depletion: extreme case

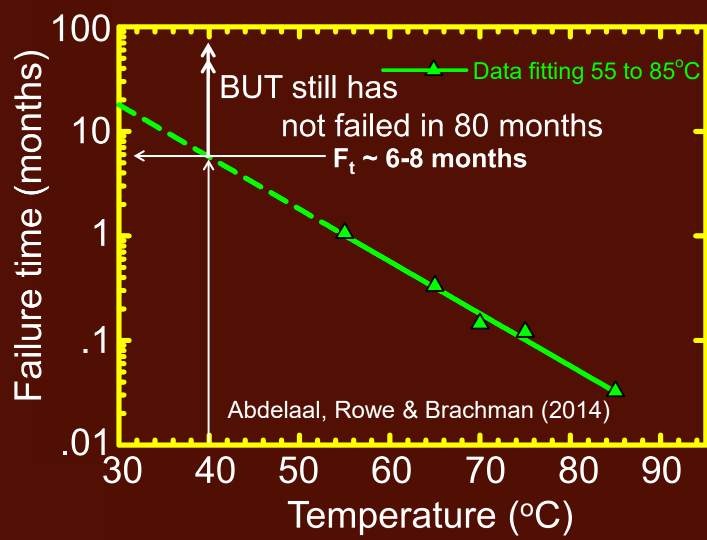


Ewais, Rowe, Brachman & Arnepalli (2014)

78

Temperature effect

GMB pre-aged to low resistance



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GMB Strains

Indentations at 250 kPa and 85°C

GTX 580g/m^2

Strains up to 15%

Ruptured in < 3 years

Sand Protection layer

Minimal strains (< 1%)

Ewais, Rowe & Brachman (2014)

Rowe, Abdelaal & Brachman (2013)

80

Smooth Black 1.5-mm HDPE GMBs

Property	GMB1	GMB2	GMB3	GMB4
SCR_o (hours)	7,600	8,100	6,500	2,800
SCR_m (hours)	2070	1370	1010	646
Std-OIT (min)	179	206	209	254
HP-OIT (min)	1,220	950	1,260	1,410
t_{NF} (field) @ 30°C	350-510	280-750	280-750	310-580
t_{NF} (field) @ 40°C	130-140	100-180	90-180	120-180

Clinton and Rowe (unp)

All GMBs contain HALS
All GMBs produced from same manufacturer

81

Estimated time to nominal failure (years) in a composite liner in MSW leachate

(rounded to 2 significant digits; Zafari et al. 2023)

Temp. (°C)	Comparator GMB: yA20 immersed in MSW leachate (Ewais et al. 2018)							
	xTB		xTD	zTA		yTA		yTB
	Min.	Exp.	Exp.	Min.	Exp.	Min.	Exp.	Exp.
20	2600	6400	1100	1600	3500	1800	5500	4000
30	790	1500	370	520	900	600	1300	970
35	**450**	750	230	300	470	**350**	660	500
40	260	**390**	140	180	250	220	**350**	260
45	150	200	92	110	140	130	180	140
50	92	110	61	69	79	83	100	77

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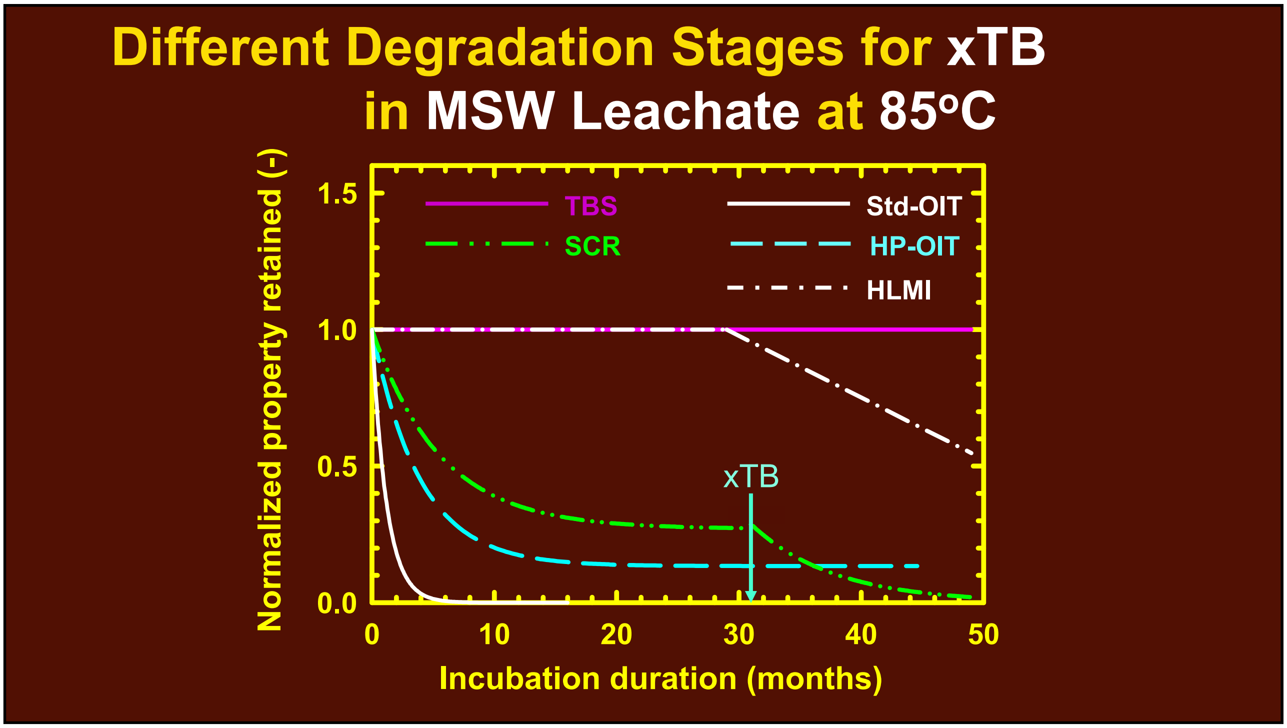
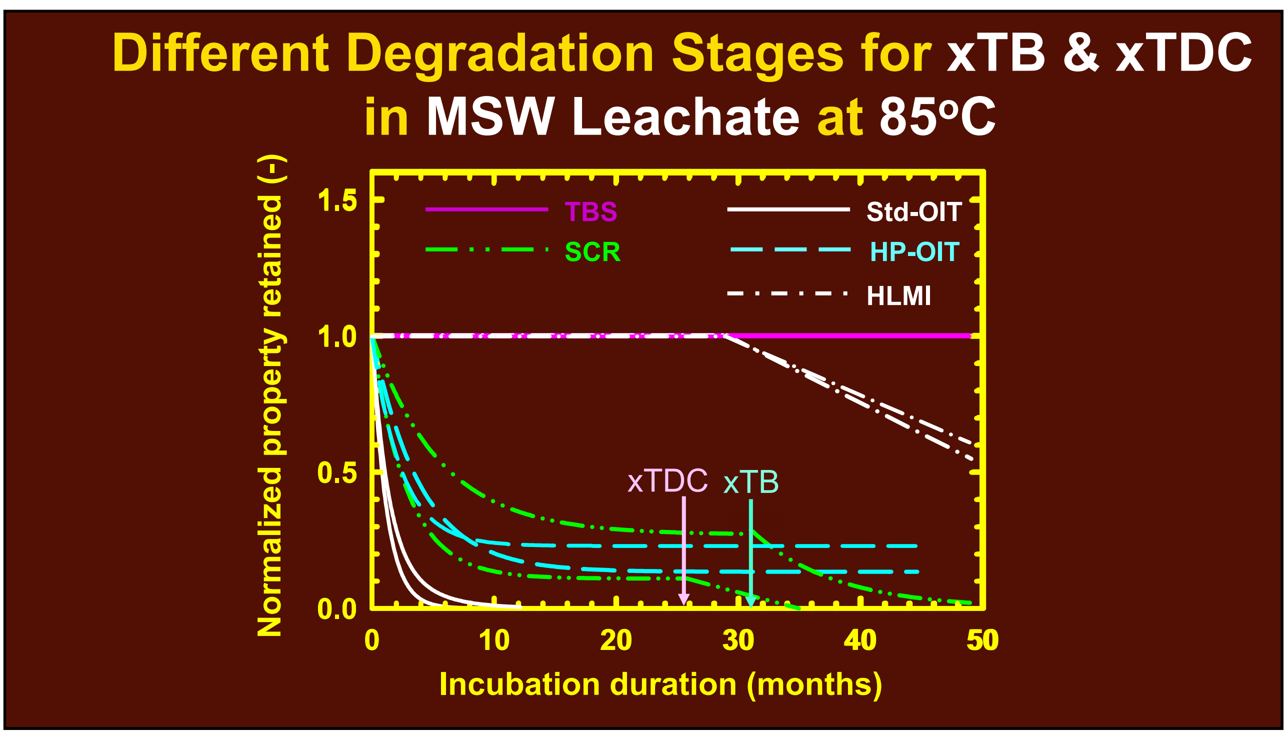
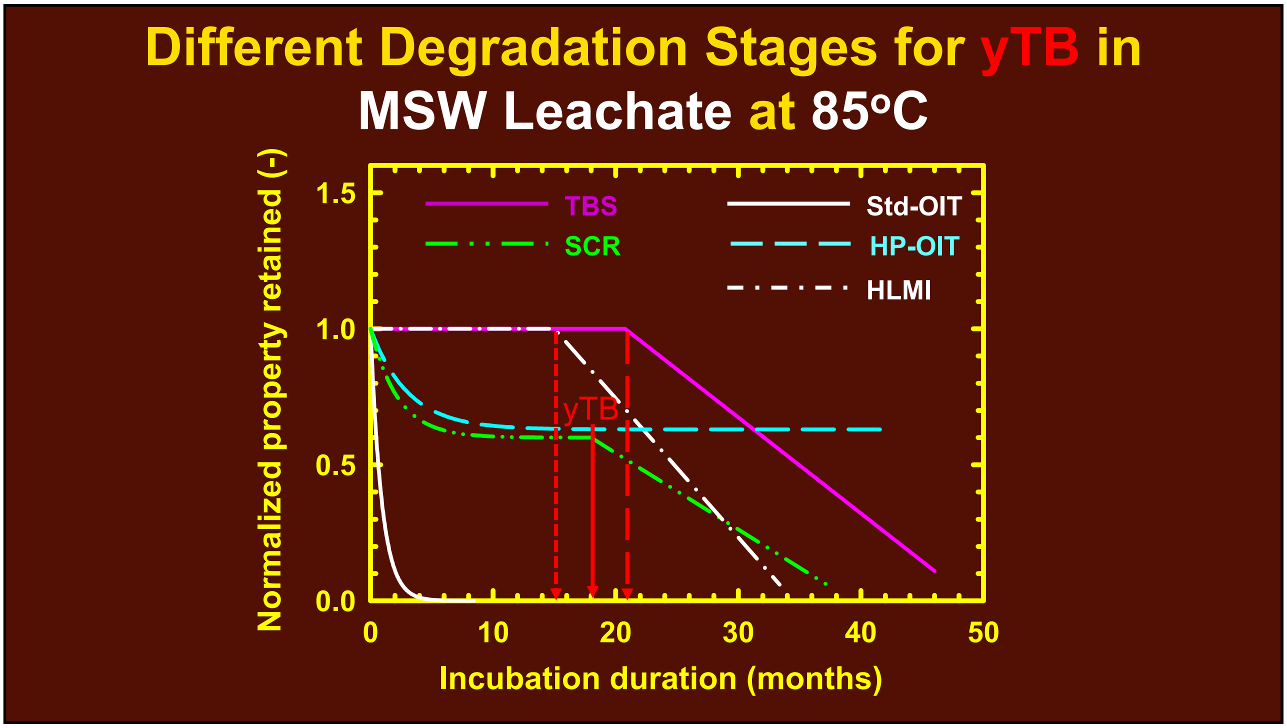

Different Degradation Stages for xTB
in MSW Leachate at 85°C
Normalized property retained (-)
1.5
1.0
0.5
0.0
TBS
SCR
Std-OIT
HP-OIT
HLMI
xTB
0
10
20
30
40
50
Incubation duration (months)

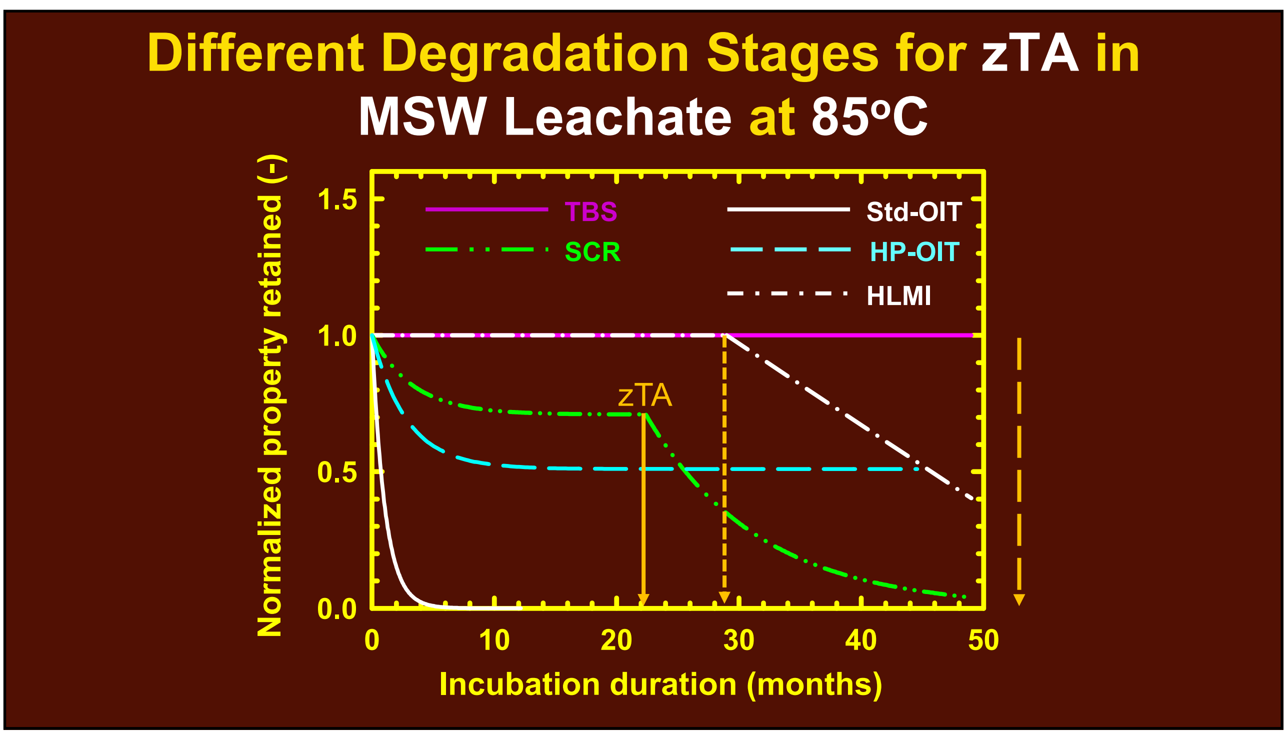
83


Different Degradation Stages for xTB & xTDC
in MSW Leachate at 85°C
Normalized property retained (-)
1.5
1.0
0.5
0.0
TBS
SCR
Std-OIT
HP-OIT
HLMI
xTDC
xTB
0
10
20
30
40
50
Incubation duration (months)

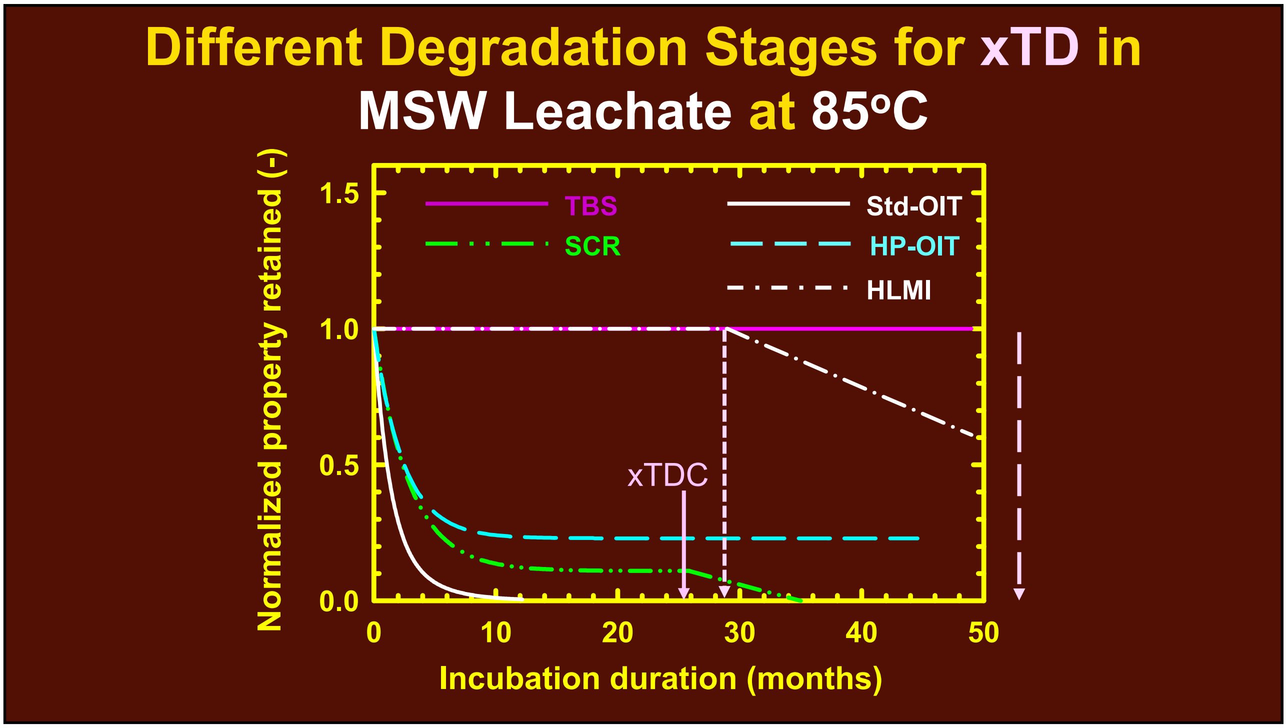
84


Different Degradation Stages for yTB in
MSW Leachate at 85oC
Normalized property retained (-)
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Incubation duration (months)
TBS
SCR
Std-OIT
HP-OIT
HLMI
yTB

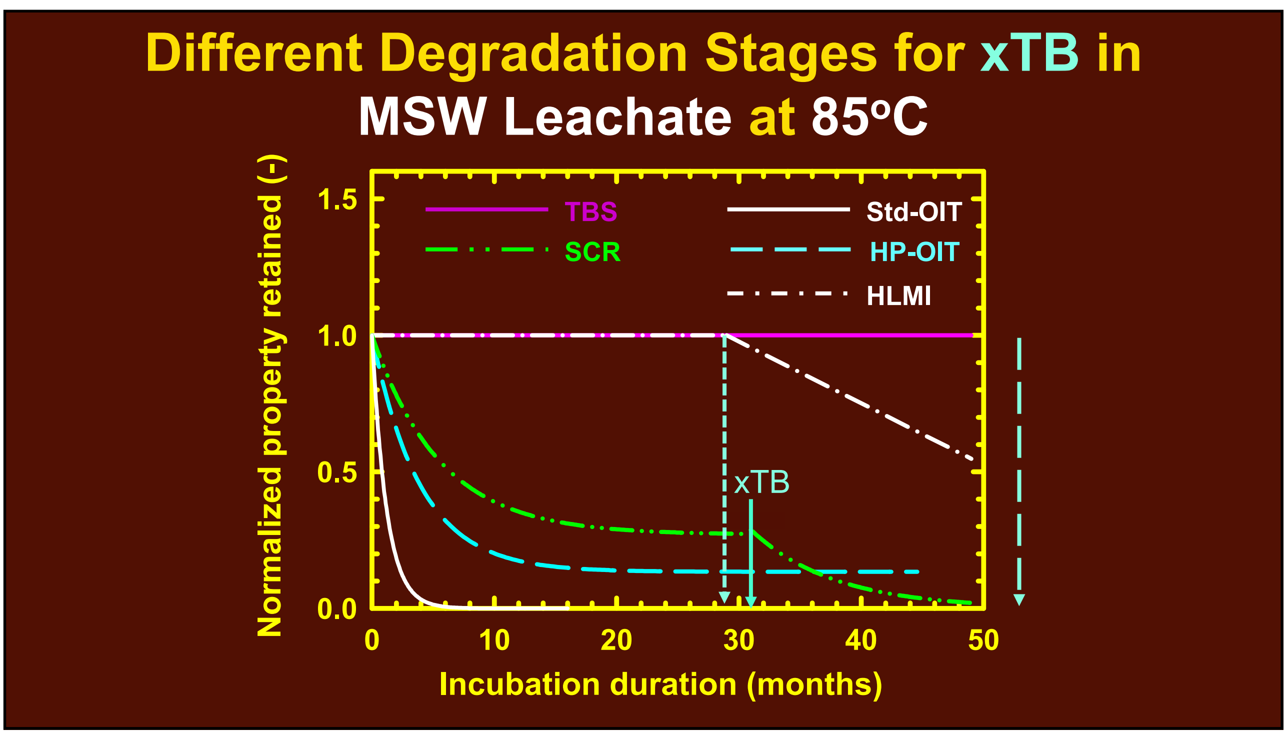
85


Different Degradation Stages for zTA in
MSW Leachate at 85oC
Normalized property retained (-)
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Incubation duration (months)
TBS
SCR
Std-OIT
HP-OIT
HLMI
zTA

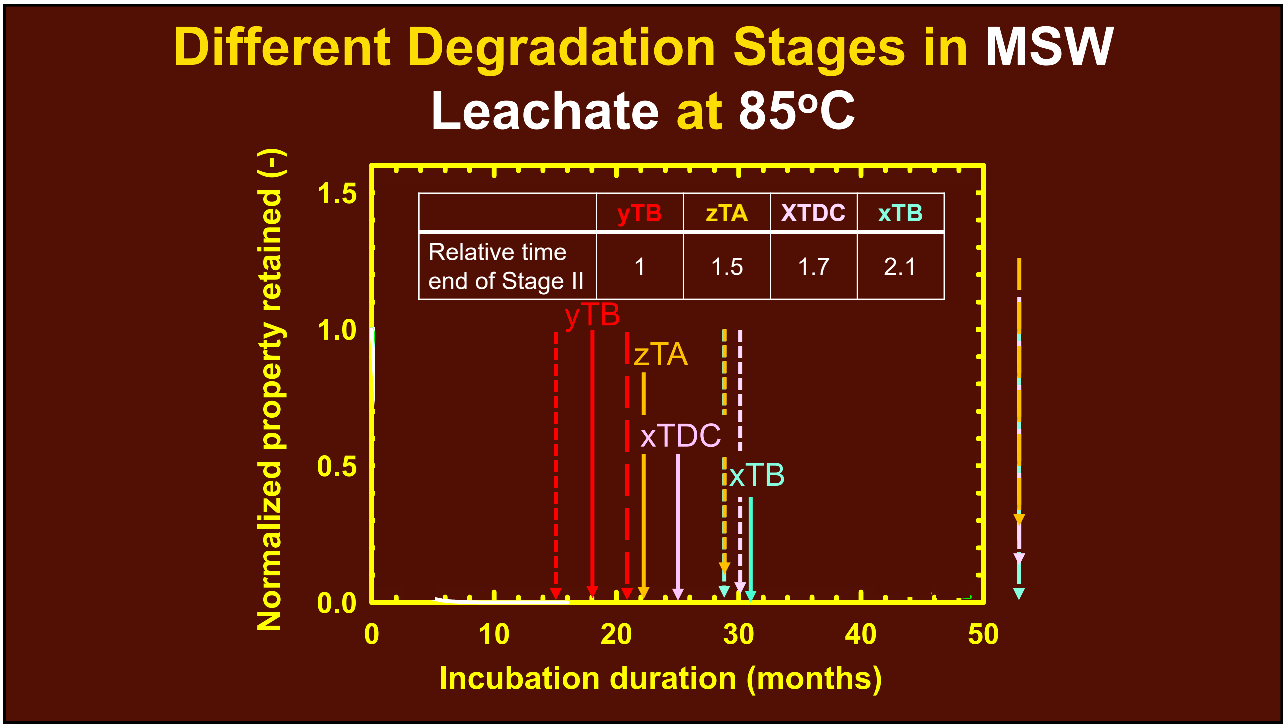
86


Different Degradation Stages for xTD in MSW Leachate at 85°C
Normalized property retained (-)
Incubation duration (months)
TBS
SCR
Std-OIT
HP-OIT
HLMI
xTDC
0.0
0.5
1.0
1.5
0
10
20
30
40
50

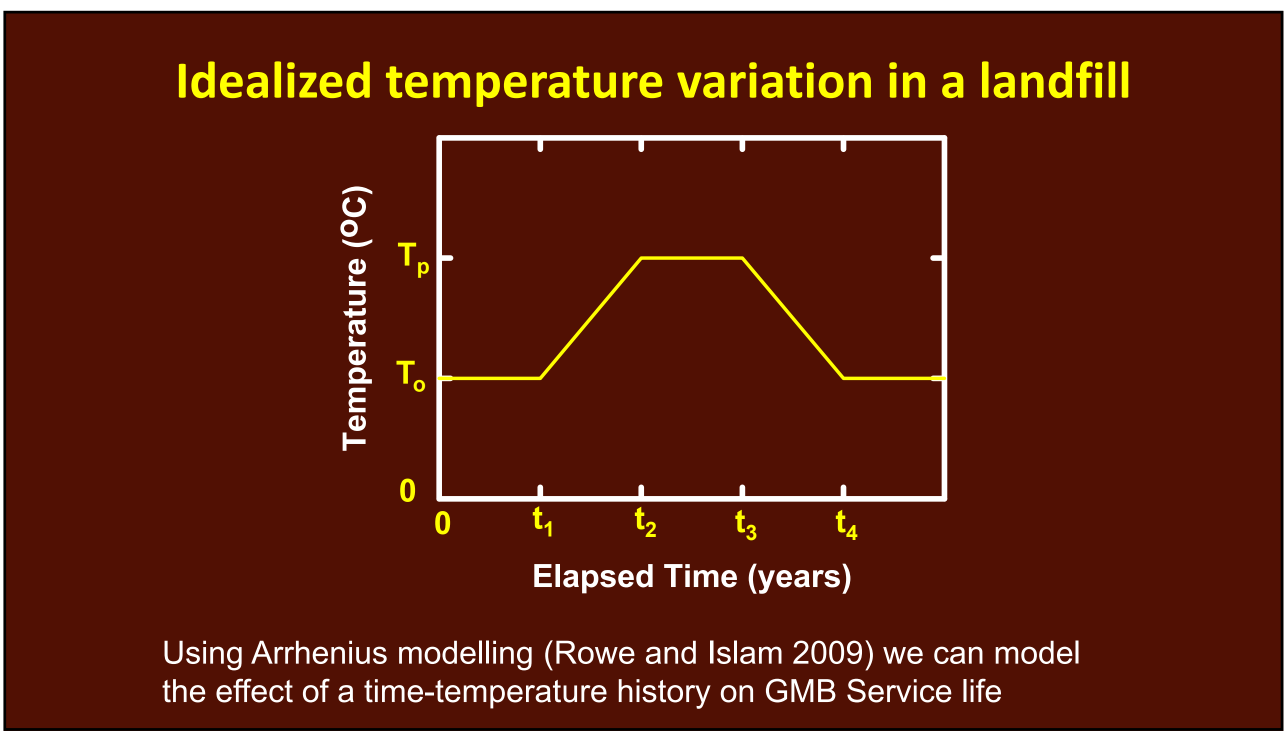
87


Different Degradation Stages for xTB in MSW Leachate at 85°C
Normalized property retained (-)
Incubation duration (months)
TBS
SCR
Std-OIT
HP-OIT
HLMI
xTB
0.0
0.5
1.0
1.5
0
10
20
30
40
50

88


Different Degradation Stages in MSW Leachate at 85°C
Normalized property retained (-)
Incubation duration (months)
yTB
zTA
XTDC
xTB
Relative time end of Stage II
1
1.5
1.7
2.1
yTB
zTA
xTDC
xTB
1.5
1.0
0.5
0.0
0
10
20
30
40
50

89


Idealized temperature variation in a landfill
Temperature (°C)
Tp
To
0
0
t1
t2
t3
t4
Elapsed Time (years)
Using Arrhenius modelling (Rowe and Islam 2009) we can model
the effect of a time-temperature history on GMB Service life

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How long will the GMB lasts

Depends on

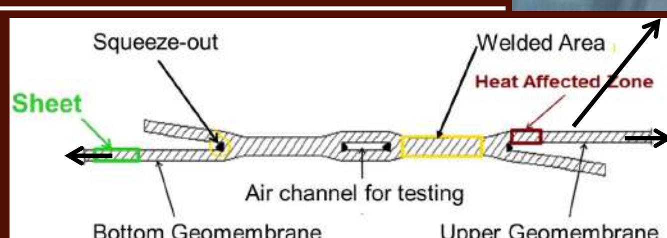
- GMB used – (polymer and antioxidant/stabilizers)
- The exposure conditions
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure
  - Sustained tensile strains in GMB
  - **Seams (welds)**

91

Ratio of time to nominal failure, t_{NF} of sheet to weld

Immersion fluid	Ratio $t_{NF\ (GMB)}/t_{NF\ (weld)}$	$t_{NF\ (weld)}=$
Brine	1.5	$0.67 \times t_{NF\ (GMB)}$
MSW leachate	2.2	$0.45 \times t_{NF\ (GMB)}$

MyE 1.5 mm based on 3 years data



Rowe & Shoaib (2017)

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Weld summary

- Typically > 1500 m of weld/ha
- Welds are a critical location with respect to GMB service-life
- Time to failure needs more investigation but is known to depend on GMB, leachate, and temperature
- Potential for further increased leakage reduced by
  - minimizing covered wrinkles/waves
  - using composite liner with GCL

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Questions

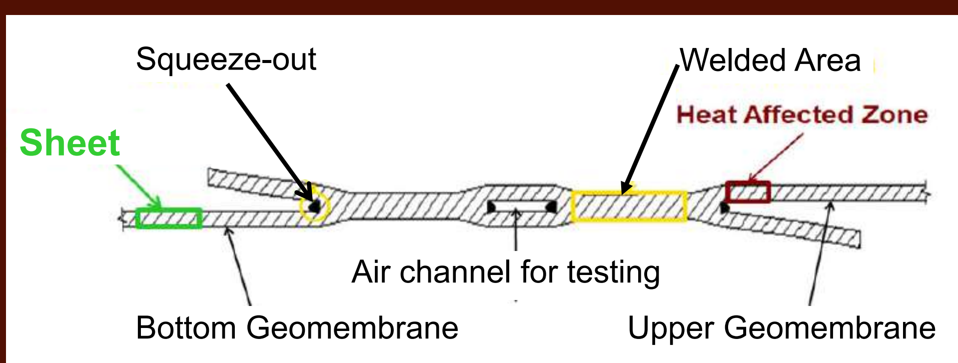
94

Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,

95

Anatomy of a duel wedge weld



- 6.8 m wide rolls need > 1500 m of weld per ha
- 50 ha facility will have > 80 km of dual wedge welds

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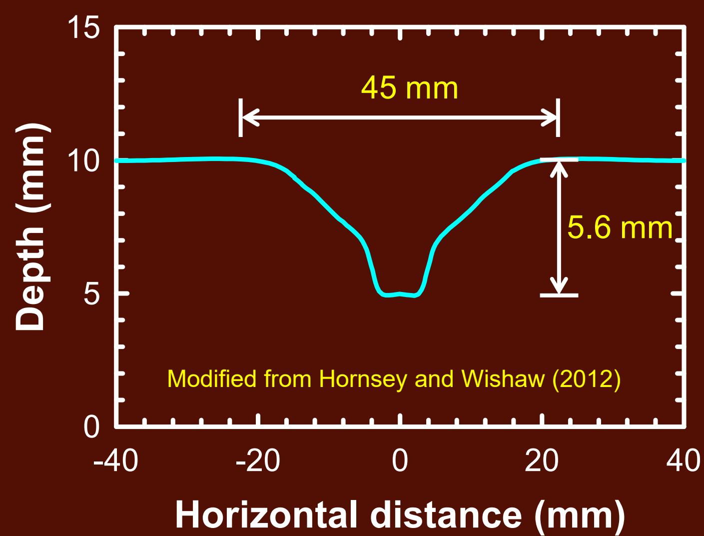
GMB Indentation Profile



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Calculated Maximum GMB Strains

Strain calculation method	Max. GMB strain
ASTM arch elongation method	0.016% (wrong)
BAM arch elongation method	4.1%
LFE-2 incremental strain (3 mm)	13%
LFE-2 incremental strain (1 mm)	42%
Tognon et al. (2000) (1 mm)	75%

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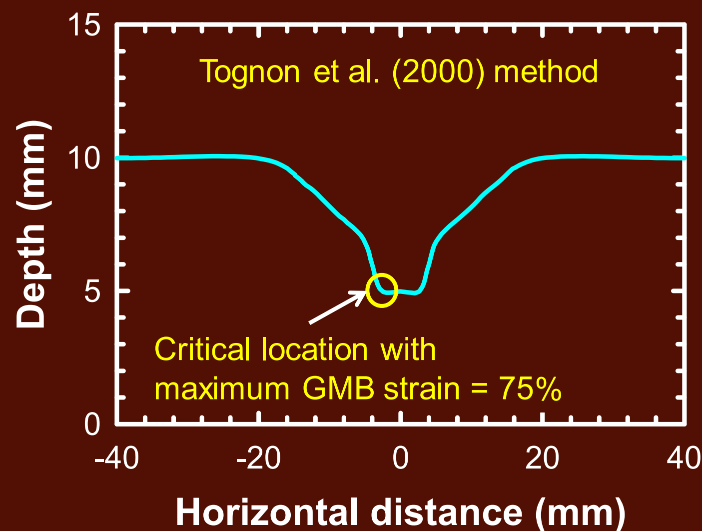
Location of Maximum GMB Strain



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Calculating Maximum GMB Strain

How one calculates strain matters

- Some methods give wrong results
- Some methods give misleading results
- Current best available method - Tognon et al. (2000) (but to the extent it errs in underestimates strain)

[:0]

100

How much strain is too much?

Our test have ruptures at 5% (unp.)

Recommended maximum strain
for low level radioactive waste landfill:
Base 3%, Side slope 4%, Cover 5%
(Rowe et al. 2019)

101

Alternate geosynthetics

GT4 NW-HB 250 g/m^2 | GT3 NW-NP 2000 g/m^2 | GC1 Geo-composite

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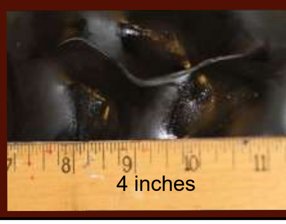
A Cracked GMB @ 85°C after 34.5 months

- Nonwoven needle punched GTX (MA=580g/m²)
- 61 Cracks/sample
(>2.0 million holes/ha)
- Crack length can reach 10 cm



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Maximum Strain: GMB / CCL

Gravel	Protection layer	Maximum strain
25 mm	None	16%
50 mm	None	32%
25 mm	570 g/m² GTX	13%
50 mm	540 g/m² GTX	15%
25 mm	2240 g/m² GTX	4.5%
50 mm	2200 g/m² GTX	8.2%

1.5 mm HDPE GMB on a compacted clay liner at 250 kPa; Temperature = 21°C; Period of sustained loading = 10 hrs

Data from Brachman & Gudina (2008a)

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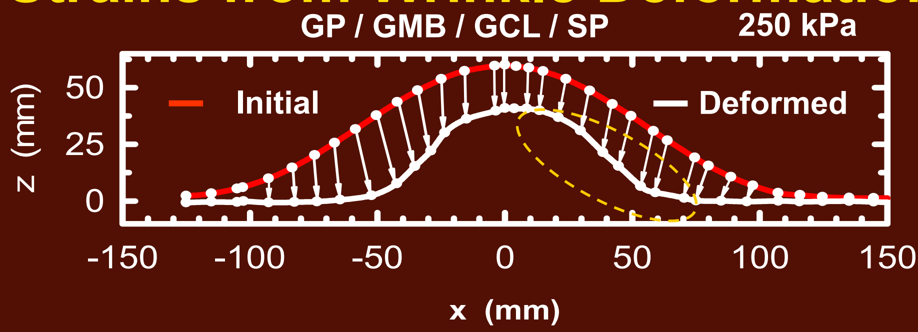
Strains from Wrinkle Deformation



Brachman and Gudina (2008)

105

Maximum GMB Strains

GP / GMB / GCL / SP at 250 kPa

Protection	Tensile Strain (%)	
	No Wrinkle	With Wrinkle
None	17	18
GTX1 (390 g/m^2)	10	-
GTX2 (1200 g/m^2)	7.7	10
GTX3 (2000 g/m^2)	5.5	7.5
150-mm Sand	**0.2**	**0.3**

ε_{max}: 6% (Peggs et al. 2005); 3% (Seeger and Müller 2003; Rowe et al. 2019)

w_{GCL}=113-148

Brachman and Gudina (2008)

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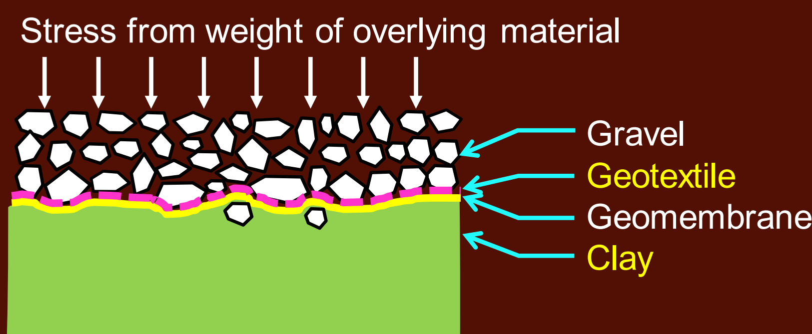
Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,
ii. gravel in an underlying layer (e.g., compacted clay liner),



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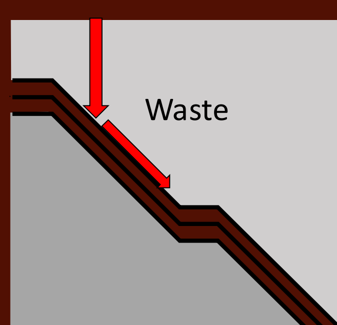
Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,
ii. gravel in an underlying layer (e.g., compacted clay liner),
iii. down-drag forces on side slopes both on initial loading and with subsequent consolidation and settlement of the waste,



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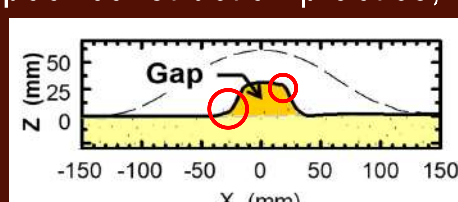
Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,
ii. gravel in an underlying layer (e.g., compacted clay liner),
iii. down-drag forces on side slopes both on initial loading and with subsequent consolidation and settlement of the waste,
iv. "trampolining" or tensile membrane strains/stresses induced by poor construction practice,

109

Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,
ii. gravel in an underlying layer (e.g., compacted clay liner),
iii. down-drag forces on side slopes both on initial loading and with subsequent consolidation and settlement of the waste,
iv. "trampolining" or tensile membrane strains/stresses induced by poor construction practice,
v. wrinkles,



110

Sources of Tensile Strain (Stress) in Buried GMB Liner

i. gravel in an overlying drainage layer,
ii. gravel in an underlying layer (e.g., compacted clay liner),
iii. down-drag forces on side slopes both on initial loading and with subsequent consolidation and settlement of the waste,
iv. "trampolining" or tensile membrane strains/stresses induced by poor construction practice,
v. wrinkles,
vi. differential settlement of subgrade/waste with time, and
vii. any permanent strains induced by seismic events

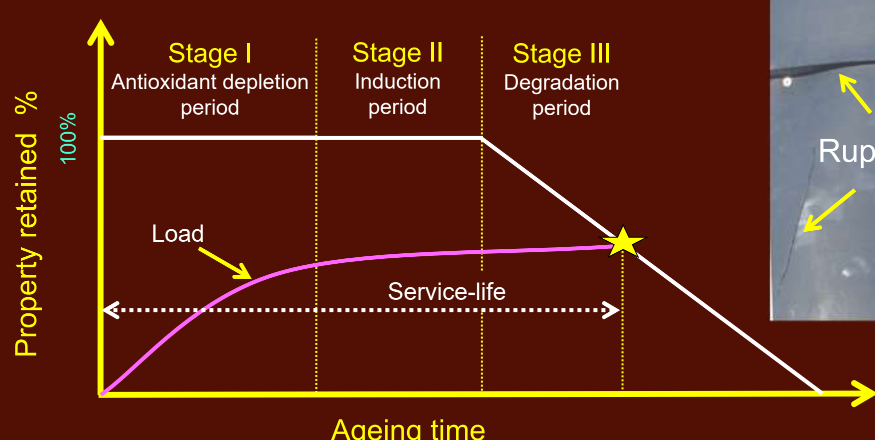
Design

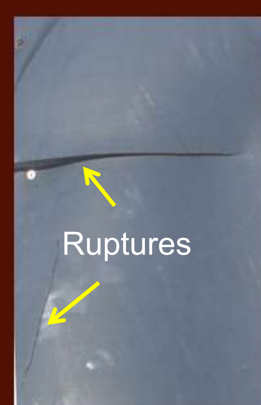
Construction

Design

111

Service-life of GMB in Field





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GMB service-life depends on

- GMB used — Manufacture & design
- The exposure conditions — Design, construction & operations
  - Elements (UV; rapid changes in temperature)
  - Chemical composition of fluid in contact with GMB
  - Temperature
  - Nature of exposure
  - Sustained tensile strains in GMB
  - Seams/Welds

Ranges from years to many centuries

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Take home message

Not all HDPE geomembranes are the same

- Index properties are good for CQA but not for design
- A GMB's formulation is a recipe - change any one component (resin, antioxidants or stabilizers, carbon black, or other additives) and you can significantly change the product
- Good design requires a minimum of 3 months testing and 12 months if it is a very important project

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