Short Course on

GEOMEMBRANES AND COMPOSITE LINERS IN LANDFILLS AND MINING: MOVING FORWARD

Sunday 17 Sept. 2023

4. Emerging contaminants (PFAS) and composite liner performance

R. Kerry Rowe OC, FRS, FREng, NAE

Barrington Batchelor Distinguished University Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering

The Geo-Engineering Centre at Queen's-RMC

Queen's University
Kingston
Canada
www.geoeng.ca

Queen's University

1

PFAS is everywhere!

Source: Australian Department of Defence

Source: Melbourne Age

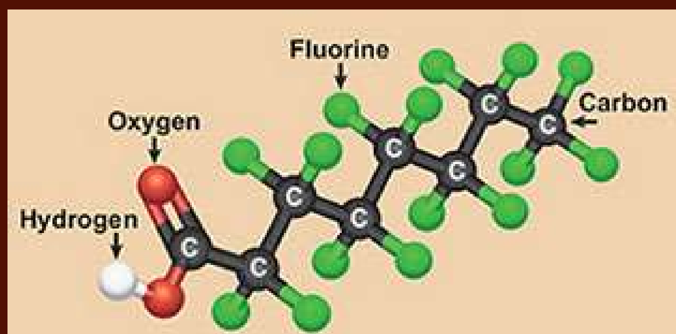
US EPA proposed safe levels of PFOA and PFOS in drinking water is 4 nanograms per liter (0.000004 mg/L).

2

PFAS: What are they?

Per- and PolyFluoroAlkyl Substances

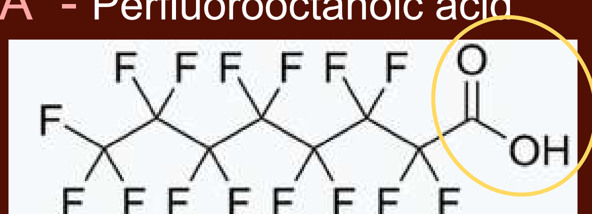
Let's start with an example:
Perfluorooctanoic Acid (PFOA)



3

Common PFAS of Concern

- PFOA - Perfluorooctanoic acid



- PFOS - Perfluorooctane sulfonate

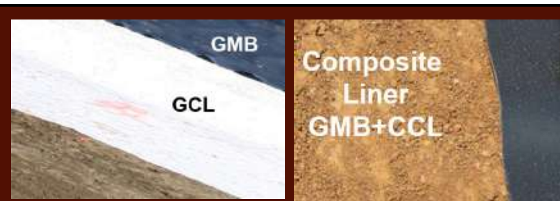
Hydrophobic (lipophilic)

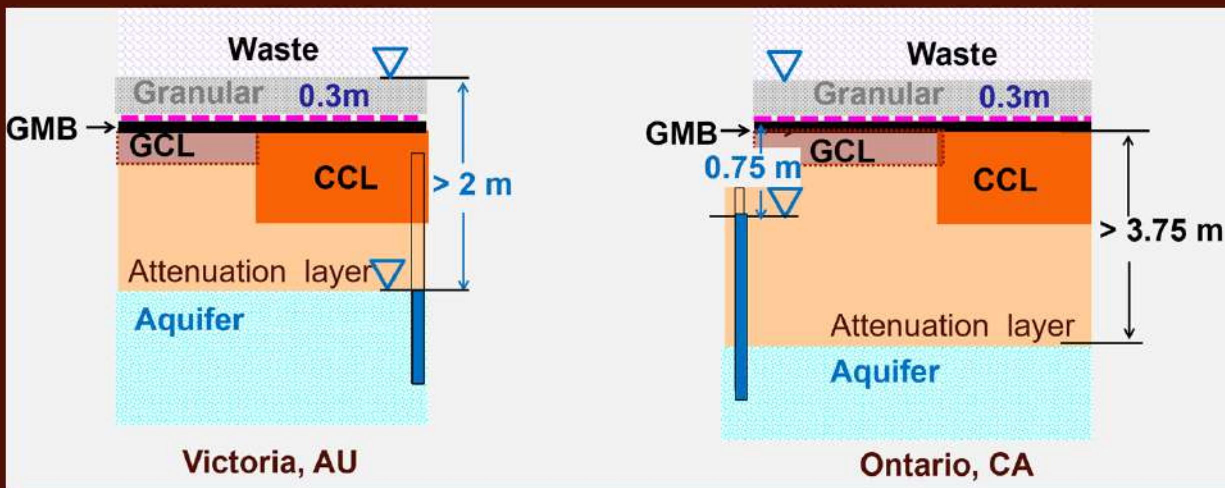
Hydrophilic

Structure of typical PFAS – these are surfactants

4

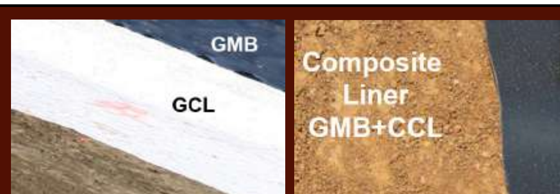
Composite liners





5

Composite liners



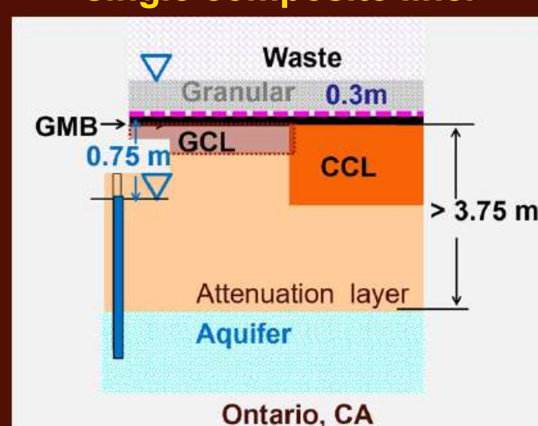
Current knowledge

- Good understanding of leakage through single composite liners

Current challenge:

- PFAS are hard to contain at levels acceptable in ground and surface water
  - Diffusion $f = P_g \cdot (\Delta c/H) = S_{gf} \cdot D_g \cdot (\Delta c/H)$

Barrier system with a single composite liner

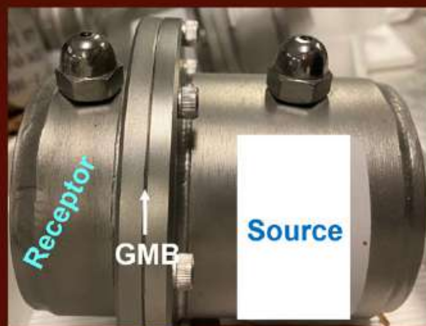


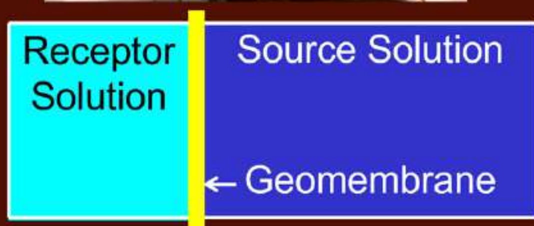
6

Diffusion through a GMB

PFAS examined

PFOA
PFOS
PFBS
6:2 FTS
GenX
7:3 FTCA





Stainless steel cells used for PFAS

Tests series include a control to check for losses and

a blank (DI water) cell to check for any lab contamination.

$$f = -P_g$$

7

Effect of Uncertainty re S_{gf} on PFOA Concentration in Aquifer

Rowe et al. (2023)

Thermoplastic polyurethane (TPU)

GMB	T (°C)	P_g (m²/s)	D_g (m²/s)	S_{gf} (-)	c_p (ng/l)	t_p (yr)
TPU	50	3.2×10^{-14}	3.2×10^{-11}	0.001	3.1	280
TPU	50	3.2×10^{-14}	3.2×10^{-12}	0.01	3.1	280
TPU	50	3.2×10^{-14}	3.2×10^{-13}	0.1	3.1	280
TPU	50	3.3×10^{-14}	3.3×10^{-14}	1	3.2	280

c_o= 750 ng/L; q_o= 0.15 m/yr
EPA drinking water limits for PFOA is now 4 ng/L

$$P_g = S_{gf} \cdot D_g$$

8

Effect of Temperature on PFOA Concentration in Aquifer

Thermoplastic polyurethane (TPU)

Rowe et al. (2023)

GMB	T (°C)	P_g (m²/s)	D_g (m²/s)	S_{gf} (-)	c_p (ng/l)	t_p (yr)
TPU	50	3.3×10^{-14}	3.3×10^{-14}	1	3.2	280
TPU	40	1.6×10^{-14}	1.6×10^{-14}	1	1.7	300
TPU	35	1.1×10^{-14}	1.1×10^{-14}	1	1.2	300
TPU	30	0.8×10^{-14}	0.8×10^{-14}	1	0.9	300

c_o= 750 ng/L; q_o= 0.15 m/yr
EPA drinking water limits for PFOA is now 4 ng/L

$$P_g = S_{gf} \cdot D_g$$

9

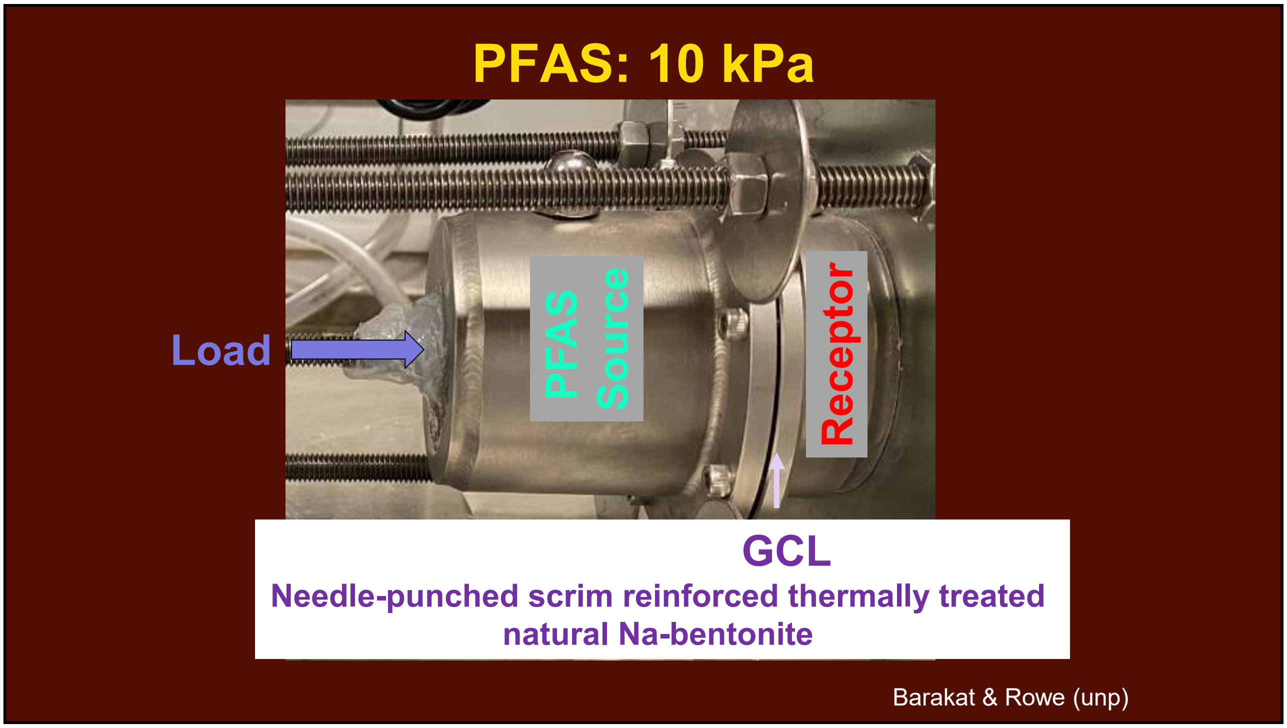
PFOA and PFOS best estimate S_{gf} and P_g Literature values for other chemicals 23°C

Not good diffusion barriers			Excellent diffusion barriers		
Contaminant	S_{gf} (-)	P_g (m²/s)	Contaminant	S_{gf} (-)	P_g (m²/s)
PCE (0.75mm LLDPE)[1]	1250	2.5×10^{-10}	PFOA (0.29mm EIA1)	1	$\leq 1.8\times10^{-16}$
PCE (1.5mm TPU)[1]	900	1.6×10^{-10}	PFOS (0.29mm EIA1)	1	$\leq 1.3\times10^{-16}$
PCE (1.5mm HDPE)[1]	850	1.0×10^{-10}	PFOA (0.26mm EIA3)	1	$\leq 1.2\times10^{-16}$
Toluene (LLDPE)[2]	350	7.7×10^{-11}	PFOS (0.26mm EIA3)	1	$\leq 1.1\times10^{-16}$
Benzene (LLDPE)[2]	200	4.4×10^{-11}	PFOS(0.1mm LLDPE)	4	$\leq 3.3\times10^{-17}$
PFOS (0.3mm TPU)	1	7.6×10^{-14}	PFOA (0.1mm EVOH)	1	$\leq 1.3\times10^{-17}$
Phenol (HDPE)[3]	3.5	5.9×10^{-14}	PFOS(0.1mm EVOH)	1	$\leq 1.1\times10^{-17}$
PFOA (0.3mm TPU)	1	5.6×10^{-15}	PFOA(0.1mm LLDPE)	1.2	$\leq 1.0\times10^{-17}$

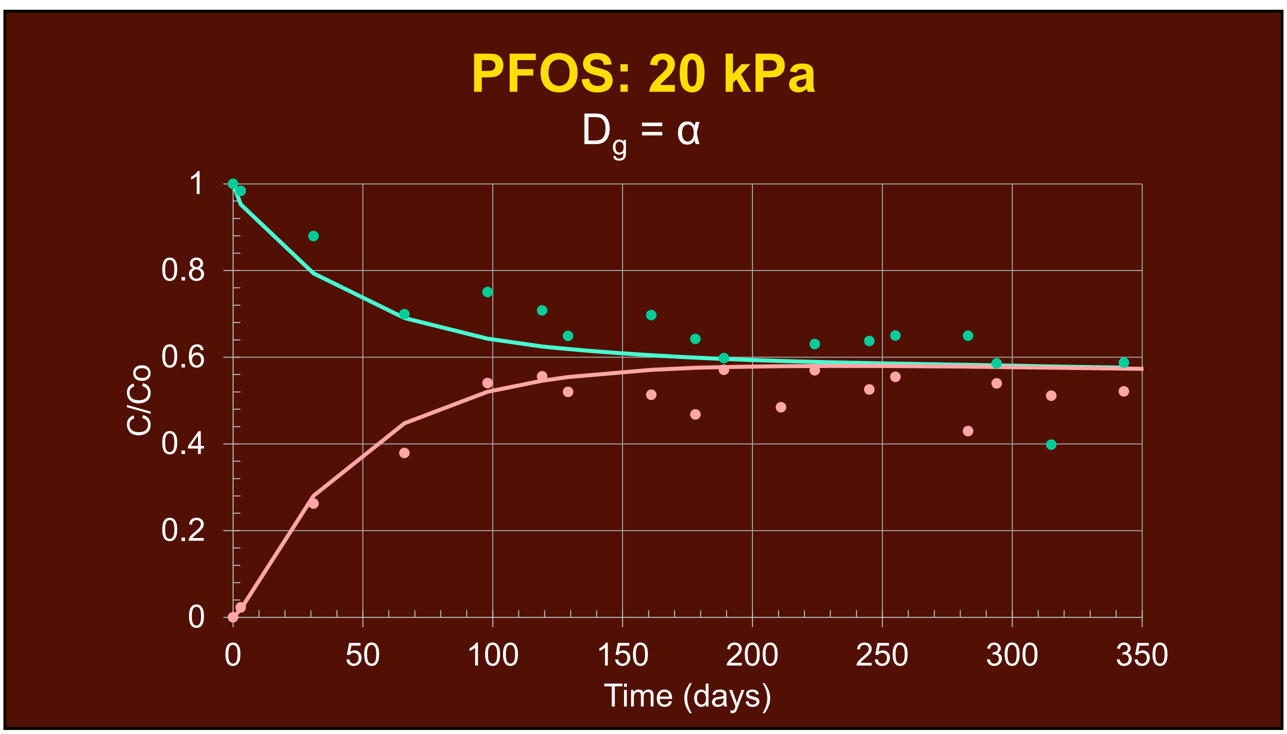
[1]Di Battista and Rowe 2020a, [2]Di Battista and Rowe 2020b, [3] Saheli et al. 2016.

$$P_g = S_{gf} \cdot D_g$$

10


PFAS: 10 kPa
Load
PFAS Source
Receptor
GCL
Needle-punched scrim reinforced thermally treated natural Na-bentonite
Barakat & Rowe (unp)

11


PFOS: 20 kPa
$D_g = \alpha$
C/Co
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
Time (days)

12

GCL Permeation - Applied Stress

Applied stress (kPa)	PFOS P_g	PFOA P_g
20	α	γ
60	0.8 α	0.75 γ
150	0.5 α	0.5 γ

Preliminary: subject to change with more data

13

Relative Diffusive Resistance

Contaminant	Applied stress (kPa)	D_g / D_{ref}
Chloride	22	1.0
PFOA	20	0.11
PFOS	20	0.11
Chloride	145	0.45
PFOA	150	0.05
PFOS	150	0.05

Preliminary: subject to change with more data

14

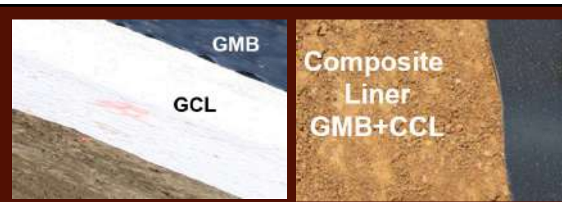
Composite liners

Current knowledge

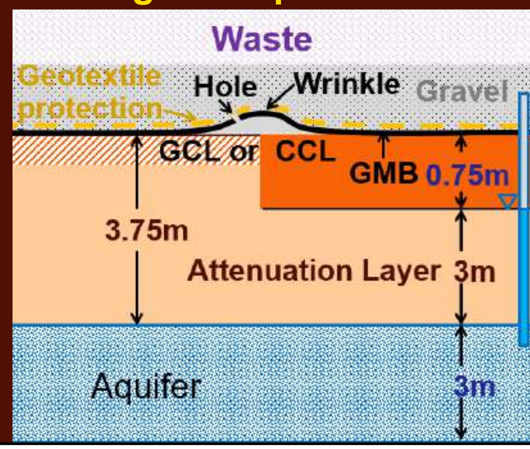
- Good understanding of leakage through single composite liners

Current challenge:

- PFAS are hard to contain at levels acceptable in ground and surface water
  - Diffusion $f = P_g \cdot (\Delta c/H) = S_{gf} \cdot D_g \cdot (\Delta c/H)$
  - Advection (leakage)

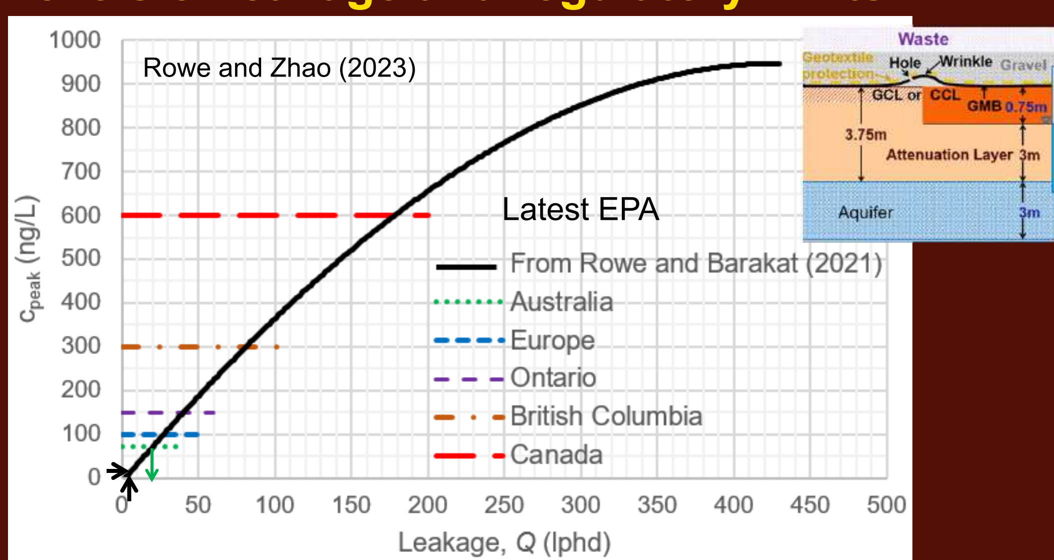


Barrier system with a single composite liner



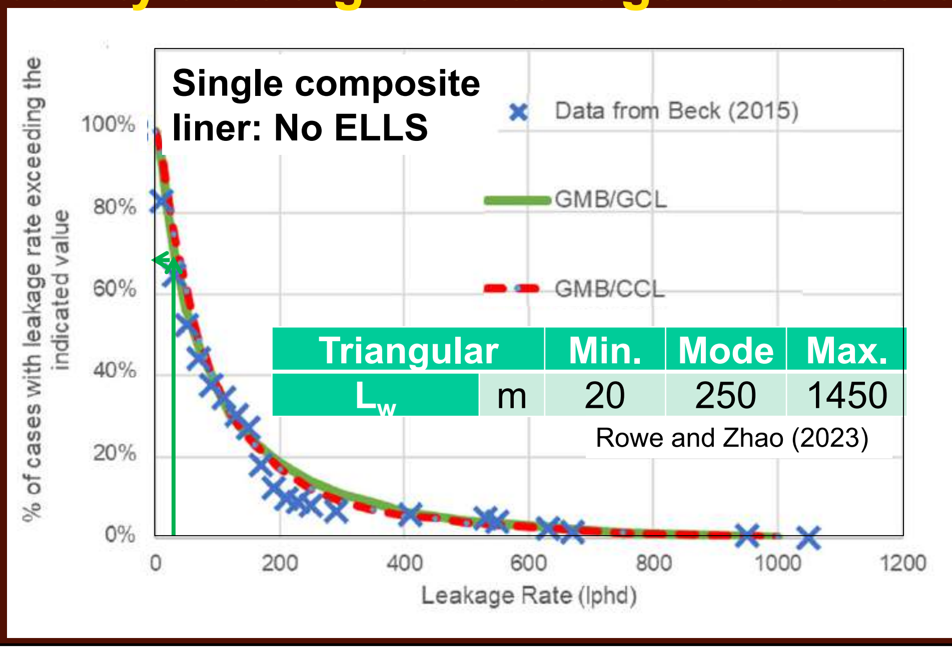
15

Peak PFOS impact in the aquifer for different levels of leakage and regulatory limits.



16

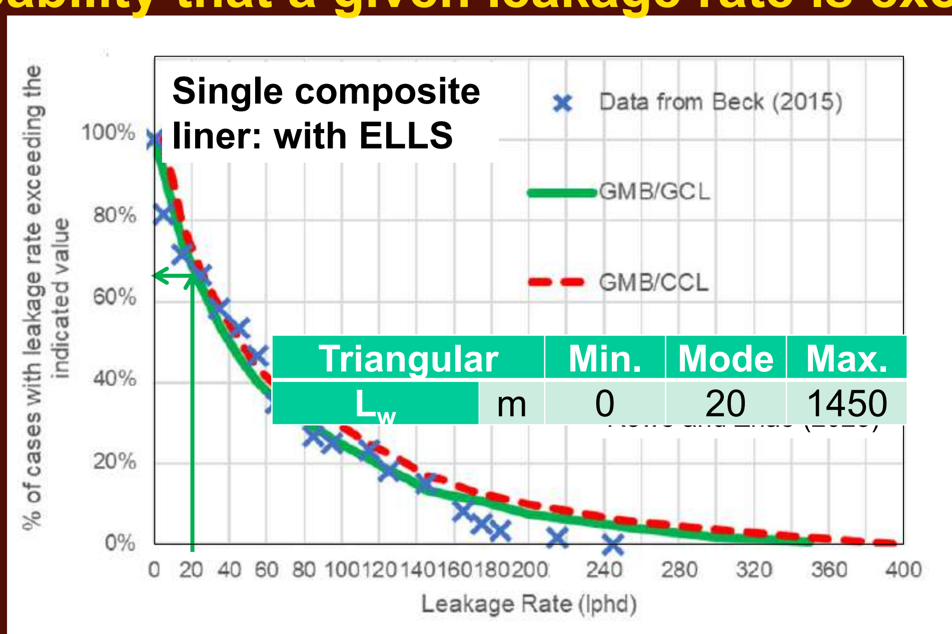
Probability that a given leakage rate is exceeded



Triangular		Min.	Mode	Max.
L_w	m	20	250	1450

17

Probability that a given leakage rate is exceeded



Triangular		Min.	Mode	Max.
L_w	m	0	20	1450

18

Double composite liner

Secondary liner below GMB	ELLS	CQA	GM (lphd)	Median (lphd)
GCL+1.75m AL	No	Good	33	35
	Yes	Good	21	24
	Yes	Excellent	4	5
CCL+1 m AL	No	Good	35	37
	Yes	Good	23	26
	Yes	Excellent	5	5
GCL+CCL+1 m AL	No	Good	13	13
	Yes	Good	8	9
	Yes	Excellent	2	2

Rowe and Zhao (2023)

19

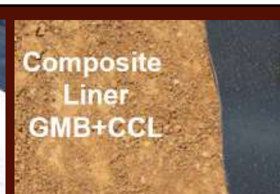
Composite liners

Advance:

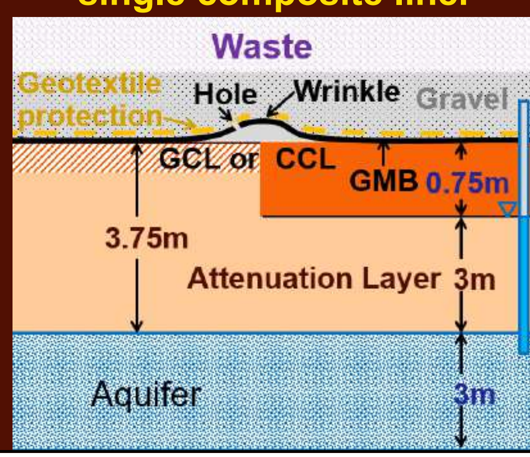
- Good understanding of leakage through single composite liners

Challenge:

- PFAS are hard to contain at levels acceptable in ground and surface water
  - Diffusion $f = P_g \cdot (\Delta c/H) = S_{gf} \cdot D_g \cdot (\Delta c/H)$
  - Advection (leakage)
  - Service life

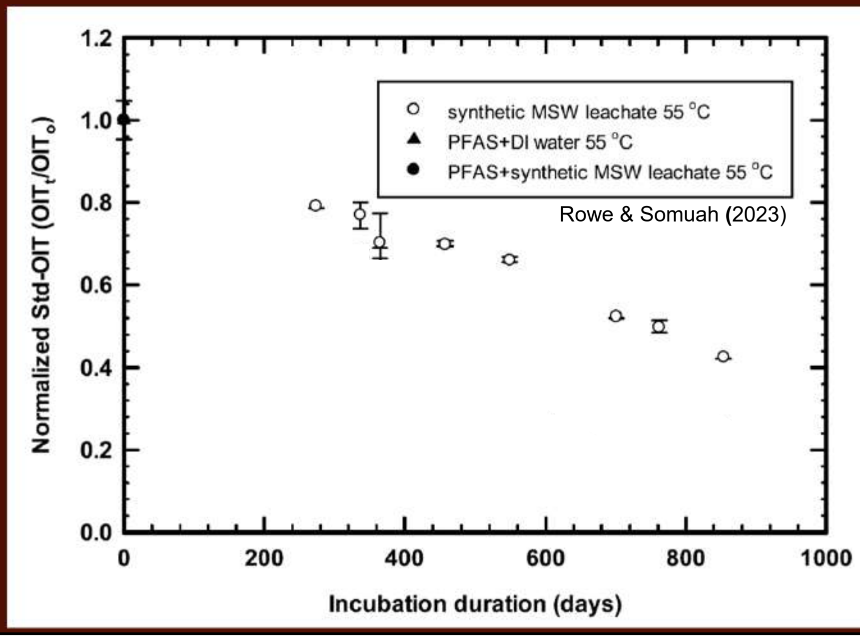


Barrier system with a single composite liner



20

Stage I: antioxidant depletion



21

	Predicted Depletion Time (years)					
	Immersed in Leachate			In Composite Liner		
Temp. (ºC)	MSW leachate	PFAS + DI water	PFAS + MSW leachate	MSW leachate	PFAS + DI water	PFAS + MSW leachate
40	50	27	18	170	90	63
35	90	45	30	310	150	98
30	170	78	46	580	270	160
25	330	140	74	1100	460	250
20	640	240	120	> 2000	830	410

Caution: Numbers for 1 GMB and high (20 ppm) PFAS.

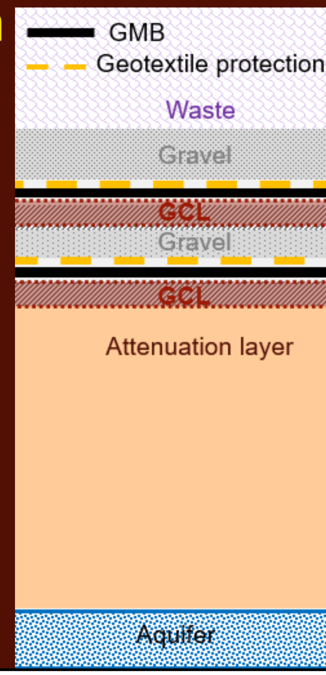
Current studies examining different GMBs & effect of concentration.

Rowe & Somuah (2023)

22

Contaminants of emerging concern

- To have less than low probability of unacceptable impact requires 3 or more of the following:
  - an appropriate electrical leak location survey before and after the GMB is/was covered,
  - a high-level of hydrogeologic protection and attenuation, and/or
  - excellent CQA, and/or
  - an extra level of engineering in the form of a secondary leachate collection/ leak detection and double composite liners



23

Take home messages

- What we have been doing, in general, with landfill design may not have been adequate for PFAS (more investigation is needed).
- Future design & construction needs more considerations of:
  - Diffusion
  - Leakage
  - CQA with leak location
  - Service life of the system

  than has been common in the past

24

"The basics"

Books

- Rowe, R.K. (2001). Geotechnical and Geoenvironmental Engineering Handbook, Kluwer Academic Publishing, Norwell, USA, (Editor) 1088p.

- Rowe, R.K., Quigley, R.M., Brachman, R.W.I. and Booker, J.R. (2004). Barrier Systems for Waste Disposal Facilities, E & FN Spon, Taylor & Francis Books Ltd, London, 587

25

"Must read papers"

Overarching

- Rowe, R.K. 1998. Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste, Keynote paper, Proceedings of 6th International Conference on Geosynthetics, Atlanta, **1**: 27-103.
- Rowe, R.K. 2005. Long-term performance of contaminant barrier systems, 45th Rankine Lecture. Geotechnique, 55(9):631-678.

GCLs

- Rowe, R.K. (2020) "Geosynthetic clay liners: perceptions and misconceptions", *Geotext. Geomembr.*, **48**(2):137-156, https://doi.org/10.1016/j.geotexmem.2019.11.012

26

"Must read papers"

Geomembranes – leakage and service-life

- Rowe, R.K (2012). "Short and long-term leakage through composite liners", The 7th Arthur Casagrande Lecture", *Can. Geotech. J.* **49**(2): 141-169.
- Rowe, R.K. (2020) "Protecting the environment with geosynthetics - The 53rd Karl Terzaghi Lecture", ASCE J Geotech. Geoenviron., 146(9):04020081, 10.1061/(ASCE)GT.1943-5606.0002239
- Rowe, R.K., Abdelaal, F.B., Zafari, M. Morsy, M.S. and Priyanto, D.G. (2020). "An approach to geomembrane selection for challenging design requirements", Can. Geotech. J. , 57(10):1550–1565, doi:10.1139/cgj-2019-0572

Geomembrane strains

- Rowe, R.K and Yu, Y. (2019) "Magnitude and significance of tensile strains in geomembrane landfill liners", Geotext. Geomembr., 47(3):429-458.

27

Queen's U. PFAS Papers

Diffusion

- DiBattista, V., Rowe. R.K., Patch, D. and Weber, K. (2020) "PFOA and PFOS Diffusion through Geomembranes at Multiple Temperatures", Waste Management, 117: 93-103, DOI: 10.1016/j.wasman.2020.07.036
- Rowe. R.K., Barakat, F.B, Patch, D. and Weber, K. (2023) "Diffusion and partitioning of different PFAS compounds through thermoplastic polyurethane and three different PVC-EIA liners." STOTEN-D-23-00804 (in review)

Leakage

- Rowe, R.K. and Barakat, F.B. (2021) "Modelling the transport of PFOS from single lined municipal solid waste landfill", *Computers and Geotechnics*, **137**(9):104280-1 104280-11. https://doi.org/10.1016/j.compgeo.2021.104280
- Rowe, R.K. and Zhao, L-X. (2023) "Implications of double composite liner behaviour for PFAS containment", Proceedings of the 9ICEG 9th International Congress on Environmental Geotechnics, June, Chania, Greece, 10p.

Service-life

- Rowe, R.K and Somuah, M. (2022) "Effects of Perfluoroalkyl Substances (PFAS) on Antioxidant Depletion from a High-Density Polyethylene Geomembrane." J. Environmental Management 328,116979, https://doi.org/10.1016/j.jenvman.2022.116979

28

Other useful reading (+ papers listed for tailings)

- Rowe, R.K. and Islam, M.Z. 2009. Impact on landfill liner time-temperature history on the service-life of HDPE geomembranes. Waste Management, 29: 2689-2699.
- Rowe, R.K., Rimal, S. and Sangam, H.P. (2009). "Ageing of HDPE geomembrane exposed to air, water and leachate at different temperatures", Geotext. Geomembr. , 27(2):131-151.
- Rowe, R.K., Islam, M.Z., Brachman, R.W.I., Arnepalli, D.N. and Ewais, A. (2010). "Antioxidant depletion from an HDPE geomembrane under simulated landfill conditions", ASCE J Geotech. Geoenviron., ASCE, 136:(7): 930-939.
- Sangam, H.P. and Rowe, R.K 2002. Effects of exposure conditions on the depletion of antioxidants from HDPE geomembranes. CGJ, 39(6):1221-1230.
- Rowe, R.K. (2011). "Systems engineering the design and operations of municipal solid waste landfills to minimize leakage of contaminants to groundwater", Geosynthetics International, 16(6): 391-404.
- Rowe, R.K. (2014) "Performance of GCLs in liners for landfill and mining applications", J. of Environmental Geotechnics, 1(1): 3-21; http://dx.doi.org/10.1680/envgeo.13.00031

29

Topics of Papers on GMBs in TSF

GMB

1. Joshi, P., Rowe, R.K. and Brachman, R.W.I (2017) "Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings", Geosynth. Int., 24(1):82-94,
2. Rowe, R.K., Joshi, P., Brachman, R.W.I and McLeod, H. (2017) "Leakage through holes in geomembranes below saturated tailings", ASCE *J Geotech. Geoenviron.*, 143(2):4016099
3. Chou, Y-C., Rowe, R.K. and Brachman, R.W.I. (2018) "Erosion of Silty Sand Tailings through a Geomembrane Defect under Filter Incompatible Conditions", *Can. Geotech. J.* 55(11):1564-1576.

30

Topics of Papers on GMBs in TSF

GMB

4. Rowe, R.K. and Fan, J.-Y. (2021) "Effect of Geomembrane Hole Geometry on Leakage Overlain by Saturated Tailings", Geotextiles and Geomembranes, 49(6):1506-1518
5. Fan, J.-Y. and Rowe, R.K. (2022) "Seepage through a Circular Geomembrane Hole when covered by Fine-Grained Tailings under Filter Incompatible Conditions" Can. Geotech. J., 59(3): 410-423.
6. Chou, Y-C, Brachman, R.W.I and Rowe, R.K. (2022) "Leakage through a hole in a geomembrane beneath a fine-grained tailings", Canadian Geotechnical Journal, Published Online: 26 May 2021 https://doi.org/10.1139/cgj-2020-0289
7. Fan, J-Y and Rowe, R.K., (2022) "Piping of silty sand tailings through a circular geomembrane hole". Geotext. Geomembr. 50(1), 183-196. https://doi.org/10.1016/j.geotexmem.2021.10.003

31

Topics of Papers on GMBs in TSF

GMB

9. Rowe, R.K. and Fan, J., 2022. A general solution for leakage through geomembrane defects overlain by saturated tailings and underlain by highly permeable subgrade. Geotext. Geomembr., 50(4), pp.694-707.
10. Fan, J-Y, Rowe, R.K., and Brachman, R.W.I. (2022) "Compressibility and Permeability of Sand-Silt Tailings' Mixtures", Can. Geotech. J., 59(8), 1348-1357.
11. Fan, J-Y and Rowe, R.K. (2022) "Effect of Subgrade on Tensile Strains in a Geomembrane for Tailings Storage Applications", Can. Geotech. J, https://doi.org/10.1139/cgj-2022-0019
12. Fan, J-Y and Rowe, R.K. (2022) "Effect of Subgrade on Leakage through a Defective Geomembrane Seam below Saturated Tailings" Geotext. Geomembr.,

32