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# The need to consider the service life of all components of a modern MSW landfill liner system

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ABSTRACT

The long-term performance of a geosynthetic clay liner (GCL) above a drainage layer and a geocomposite drain (GCD) are investigated. Full-scale tests are used to: (i) assess the integrity of GCL and GCD in a double composite liner below a defect in the primary geomembrane with ageing, and (ii) establish the head at which there was internal erosion in GCL without a carrier geotextile (GTX) such that the bentonite is in direct contact with the underlying gravel drainage. Six years after contact with simulated landfill leachate at 85 °C through an intentional defect on the geomembrane, the GCL resting on the GCD had failed due to degradation of the GTX between the bentonite and the core of the GCD and subsequent erosion of the bentonite into the core structure of the GCD was observed. In addition to complete degradation of its GTX at some locations, the GCD had also experienced extensive stress cracking and rib rollover. The second test demonstrates that if a suitable gravel drainage layer had been used instead of the GCD, the GTX component of the GCL would not have been required for acceptable long-term performance under normal design conditions and indeed could withstand a head of up to 15 m before problems became evident. The findings serve as a warning landfill designers and regulators that more attention must be paid to the service life of all components of double liner systems used in Municipal Solid Waste (MSW) landfills.

## 1. Introduction

Modern municipal solid waste (MSW) landfills commonly have a primary composite liner comprised of a geomembrane (GMB) over a geosynthetic clay liner (GCL; typically, a layer of bentonite clay sandwiched between two GTXs and needle-punched together). Single-lined systems have often proven effective in containing last century's contaminants of concern. However, the presence of contaminants of emerging concern such as per- and polyfluoroalkyl substances (PFAS) and increasingly stringent regulatory requirements for many of these compounds have raised questions regarding the effectiveness of single-lined systems for the containment of this century's contaminants of concern (Rowe and Barakat 2021; Rowe and Jefferis 2022). Double-lined systems with a leak detection layer in the secondary liner have been required for hazardous waste landfills, and in some jurisdictions (e.g., New York State USA, Ontario Canada) have been required for large municipal solid waste landfills for the last few decades. The need to contain compounds like PFAS is increasing the interest in using double-lined systems for better containment of leachate and the contaminants therein.

Double-lined systems have been used for decades. Weeks and Schubert (1986) describe the use of a geonet (GNT) as a drainage layer between two geomembranes (GMBs) for the containment of hazardous waste [GMB + GNT + GMB]. Giroud et al. (1997) describe a double liner comprised of a GMB over a GCL overlying a layer of gravel used as the leak detection and secondary leachate collection system over a secondary geomembrane [GMB + GCL + Gravel + GMB]. In a review of five bioreactor/recirculation landfills, Benson et al. (2007) describe a liner configuration with a primary composite liner, a geocomposite drain (GCD) as a leak detection and secondary leachate collection layer, overlying a secondary geomembrane [GMB + GCL + GCD + GMB]. Koerner and Koerner (2019) describe the uncovering of the edges of the

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*Abbreviations:* ASTM, American Society for Testing and Materials; GCD, Geocomposite drain; GCL, Geosynthetic clay liner; GMB, Geomembrane; GNT, Geonet; GTX, Geotextile; HDPE, High density polyethylene; MSW, Municipal solid waste; OIT, Oxidative induction time; $t_{NF}$, Time to nominal failure.

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liner system of an existing landfill cell to allow the connection of the liner for a new cell. The original cell liner, constructed in 1993 and exhumed in 2016, comprised a layer of sand, a geotextile (GTX), a geonet, another geotextile, a primary geomembrane, a GCL, a GCD (GCD = GTX + GNT + GTX), over secondary geomembrane over a secondary GCL, over the silty subgrade with the essential components of the double liner system being [GMB + GCL + GCD + GMB + GCL]. Jaisv et al (2006) describe the design of a MSW landfill liner in Thailand comprised of a geomembrane and GCL as the primary composite liner over a GCD as the leak detection and secondary leachate collection system over a secondary composite liner [GMB + GCL + GTX + GNT + GMB + CCL].

These liner systems have served well for the past 40 years. However, the question that is increasingly being asked is how long they will continue to do so? One element that all of the systems above have in common is the GMB. There has been more than 25 years of research into the long-term performance of high-density polyethylene (HDPE) GMBs (e.g., Viebke et al., 1994; Hsuan and Koerner, 1998; Müller and Jakob, 2002; Rowe and Sangam, 2002; Rowe and Rimal, 2008a,b; Scheirs, 2009; Rowe et al., 2009, 2010, 2013, 2019, 2020; Abdelaal et al., 2014; Abdelaal and Rowe, 2015, 2019; Ewais and Rowe, 2014a,b,c; Ewais et al., 2018). It is known that the time to nominal failure (i.e., when the GMB has lost 50 % of some critical physical property) is highly dependent on the resin, the antioxidants and stabilizers added to the resin to provide it with protection against thermo-oxidative degradation, the chemistry of the leachate in contact with the geomembrane, and the geomembrane temperature. For example, Rowe (2020a) quotes research indicating that a high-quality HDPE GMB produced in 1997 and tested for 17 years had an expected time to nominal failure ranging between 720 years at 30 °C, to 470 years at 40 °C, to 150 years at 50 °C, and only 54 years at 60 °C. Unfortunately, this level of research has only been conducted for HDPE GMBs.

There is a paucity of research relating to the long-term implications associated with ensuring that there is a suitable means of supporting the bentonite in the GCL and preventing unacceptable intrusion or erosion into the underlying drainage layer (i.e., to the extent it prevents the GCL or GCD, GNT, or gravel from performing as assumed in the design) as well as the long-term performance of the GNT or any other components of the GCD. Pioneering work by Legge and Davies (2002) examined the short-term intrusion of a GCL into GCDs as a function of temperature and pressure and showed that this intrusion could substantially reduce the transmissivity of the GCD even in the short term due to the mechanical interaction between lining and drainage components. However, no previous study has examined the implications of ageing of the GCL and GCD geotextile components on the long-term field performance. Thus, the primary objective of this paper is to prevent a case that should draw the attention of landfill designers to the need to pay attention to the long-term performance of GCLs above a drainage layer and to that of GCDs.

## 2. Service life of GCLs

The majority of GCLs on the market comprise a layer of bentonite sandwiched between two GTXs and needle-punched together. They typically have an advertised hydraulic conductivity, *k*, as established by a standard test (e.g., ASTM D5887). However, the description is deceptively simple. The Canadian GCL manufacturer produces 50 different GCLs that meet this basic definition, but all have different characteristics in the field. The factors affecting the short- and ultimately the long-term performance of the GCL include (Rowe 2020b):

(a) the type and granularity of the bentonite,
(b) the mass of bentonite per unit area,
(c) the mass of the nonwoven needle-punched cover (upper during manufacture) GTX,
(d) the type and mass of the carrier (lower during manufacture) GTX,
(e) the amount of needle-punching,
(f) whether the needle-punched fibers are thermally bonded to the carrier GTX,
(g) whether there has been a plastic layer and, if so,
(h) whether the coating was applied in a molten state so that it is impregnated into and onto carrier GTX (known as a coated GCL), or was it produced separately and glued to the carrier GTX (a laminated GCL),
(i) the polymer used for the coated/laminated layer, and.
(j) the mass per unit area of the coated/laminated layer.

The needle-punched structure of these GCLs serves three potential purposes:

i. keeping the bentonite contained between the GTXs following GCL manufacture through and after its installation,
ii. providing restraint to the GCL during hydration at low stress levels, thereby reducing the swelling and improving the hydraulic characteristics of the GCL at low effective stress,
iii. providing internal shear strength; the needle-punched fibers increase the apparent friction angle from an average of 6 ± 2.5° for hydrated bentonite alone to a higher average value of 13 ± 5° (McCartney et al. 2002). The magnitude of the increased friction angle and apparent cohesion will depend upon the amount of needle-punching and how the needle-punched fibers are anchored to the carrier GTX.

A coating or laminate applied to GCL reduces the hydraulic conductivity by about an order of magnitude from less than $5 \times 10^{-11}$ m/s as per ASTM D5887 to typically less than $5 \times 10^{-12}$ m/s as per ASTM D5887 for multicomponent GCLs with either a coating or laminated plastic layer. In addition to reducing the hydraulic conductivity, the coating can also protect the GCL from hydrating or losing moisture in a manner that could impact its ultimate performance.

Although GCLs have typical index hydraulic conductivities as stated in the previous paragraph, the actual hydraulic conductivity in the field can vary from an order of magnitude lower than that indicated above to 4 to 5 orders of magnitude higher depending on the factors listed above together with the exposure conditions. A discussion of how these factors affect the field performance is beyond the scope of this paper and interested reader is referred to Rowe (2020b) for a recent discussion of these factors.

### 2.1. *Factors affecting the service life of a GCL*

The following discussion of GCL service life is primarily based on Rowe (1998) and Section 12.10.2 of Rowe et al. (2004) but has been updated for this paper. The primary active component of a GCL is bentonite. Bentonite is a naturally occurring swelling clay formed by the deposition of volcanic ash that consolidated into shale/mudstone. The bentonite used in GCLs is obtained by mining the rock and grinding it into either coarse grained (coarse sand size), fine-grained (medium to fine sand size), or powdered form (silt size).

The minerals in bentonite (predominantly montmorillonite) have been around for millennia and are likely to remain for millennia under typical field applications. However, its hydraulic conductivity can be affected by many factors, particularly the chemistry of the water with which it is hydrated and permeated and the field effective stress. Thus, consideration must be given to the operative hydraulic conductivity under the expected field conditions in selecting a hydraulic conductivity for use in design. As noted above, this hydraulic conductivity will depend on the details of the GCL manufacturer itself and the exposure conditions. Within this context, the bentonite in the GCL may be expected to have a very long service life (thousands of years) provided that:

(a) there is no significant loss of bentonite during the installation of the liner,
(b) there is no significant lateral movement (thinning) of bentonite or gaps/holes post-installation,
(c) there is no significant internal erosion,
(d) either there is no change in macrostructure due to wet-dry or freeze–thaw cycles, or that this is accounted for in the design hydraulic conductivity,
(e) the hydraulic conductivity was selected based on a realistic assessment of the field conditions (chemistry of fluid to be contained, pore fluid adjacent to the GCL, effective stress)
(f) it is installed with appropriate seams.

It follows from the preceding that the service life of a GCL will also be of the order of millennia, provided the six factors above have been addressed in design and construction, and provided that the long-term performance of the GCLs is not contingent on the service life of the geosynthetic components. A study by Rowe and Orsini (2003) reported that all the GCLs they tested over a GNT retained the bentonite while the carrier GTX was present at low heads but that the woven or nonwoven carrier GTX are prone to internal erosion (migration of the bentonite through the GTX pores into the underlying material) at high heads. The GCLs with a scrim reinforced nonwoven carrier could sustain heads exceeding 30 m, meeting criteria (c) above by approximately two orders of magnitude for the low (0.3 m) heads anticipated in landfill applications, provided that the GTX is present.

This paper focuses on Rowe's (1998) statement that acceptable long-term performance may be expected "provided that the GCLs long-term performance is not contingent on the service life of the geosynthetic components." In particular, whether the bentonite would be retained if the GTX between the GCL and the GNT in the core of the GCD degrades or whether the bentonite erodes into the drain.

## 3. Service life of GCDs

Geocomposite drains typically are comprised of two constituents: the core and the GTX that is intended to minimize the intrusion of the adjacent soil (e.g., bentonite in a GCL) into the core. The core is often manufactured from HDPE, while the GTXs are often manufactured from either polypropylene or polyethylene or, in some cases polyester. Polypropylene and polyethylene are both polyolefins with the base resin, antioxidants, and stabilizers to protect the resin from thermo-oxidative degradation and, in some cases, carbon black to protect against ultraviolet light.

The time to nominal failure, and hence service life, of polyolefins can be subdivided into three stages (Hsuan and Koerner 1998; Rowe and Sangam 2002). During Stage I, the protective antioxidants and stabilizers deplete until the effective chemical is no longer present. Stage II is a lag period after the antioxidants are depleted and before there is a measurable degradation in the polymer. During Stage III, the physical properties begin to degrade due to thermo-oxidative degradation. The time to nominal failure of the geosynthetic is reached when a critical physical property decreases to below 50 % of the specified value, and the service life is reached when it decreases below the threshold at which it can no longer sustain the tensile stresses/strains to which it is subjected (Rowe 2020a). Thus, the service life of the polyolefin can be increased by:

(i) using a high-quality resin,
(ii) using a good antioxidant/stabilizer package that substantially delays the depletion of antioxidants/stabilizers in a given chemical and thermal environment, and
(iii) designing to minimize tensile stresses/strains that must be sustained by the product (an engineered solution).

For geomembranes, all three approaches are adopted if a long service life is required. However, relatively little attention has been devoted to the long-term performance of the GCD's core, or the GTX component. For example, the level of antioxidants present in a particular polyolefin geosynthetic product can be correlated to an index test (e.g., ASTM D3895) for the oxidative induction time (OIT). The values obtained for the GTX and GNT core from a common GCD were 4 min and 48 min respectively. To put this in context, the minimum value for a geomembrane is 100 min and two GMBs tested by the authors manufactured in 1997 and 2017 had values of 134 min and 285 min, respectively. Thus, the values obtained for the GTX and GNT were less than 3 % and 36 % of the GMB with the lowest values. However, the GTX must sustain tension arching over the ribs of the GNT, and the GNT must sustain compression and tension induced by the overlying system. This raises the question of how well the system is likely to perform under long-term field conditions.

## 4. A six-year geosynthetic liner longevity simulator (GLLS) test on a double composite liner system

It is rarely practicable to exhume a liner system from below a substantial mass of waste in the field. Most exhumations, such as that described by Koerner and Koerner (2019), have been performed at the edges of facilities where the liner is not subjected to stress, elevated temperature and chemical exposure below the main mass of waste. Furthermore, it is known that municipal solid waste landfills containing organic waste will typically reach a temperature of around 35 to 40 °C, and this can be sustained for many decades (Rowe 2005, 2012; Islam and Rowe 2009). Indeed, even higher temperatures have been reported, including landfills in the 45 to 60 °C range (e.g., some bioreactors; Rowe, 2012), and landfills at 85 °C to over 100 °C have also been reported (e.g., Stark et al. 2012; Jafari et al. 2014; Benson 2017). Hence, two questions need to be answered: (1) What is the effect of stress? (2) What is the effect of temperature? A practical means of answering these questions is to construct a liner system in a geosynthetic liner longevity simulator (GLLS; Fig. 1) designed to allow the circulation of leachate above the geomembrane in the leachate collection system and maintain a prescribed constant temperature within 0.5 °C at stress levels up to 1000 kPa.

A double composite liner system was constructed in a heavy steel cylinder with 60 cm-diameter and 47 cm internal height. From the bottom up (Fig. 1), the liner system comprised.

i. a layer of foundation soil (silica sand) compacted at a moisture content of 10 %,
ii. a secondary GCL with a 200 g/m$^2$ scrim reinforced nonwoven carrier GTX in contact with the sand and a 200 g/m$^2$ needle-punched nonwoven cover GTX in contact with
iii. a secondary 2 mm-thick HDPE GMB,
iv. a GCD, with a 6.3 mm thick biplanar HDPE GNT core and 335 g/m$^2$ needle-punched nonwoven polypropylene top (cover) and bottom (carrier) GTXs, heat bonded to the GNT core,
v. a primary GCL with a 105 g/m$^2$ woven polypropylene carrier GTX resting on the underlying GCD and a 200 g/m$^2$ nonwoven cover GTX in contact with
vi. a 1.5 mm thick HDPE GMB.
vii. a 570 g/m$^2$ needle-punched nonwoven GTX protection layer, and
viii. a layer of 39 mm nominal gravel typically used in leachate collection systems in the province of Ontario and elsewhere.

Both GCLs had a minimum average roll value (MARV) of 3660 g/m$^2$ (dry) of fine granular bentonite, and both had been thermally treated to bond the needle-punched fibers to the carrier GTX.

To simulate a leakage through a defect in the primary liner, a 1 cm-wide and 50 cm-long section was cut out of the center of the primary GMB and the center of the nonwoven cover GTX of the primary GCL, before they were placed in the cell. The defect simulated here is similar

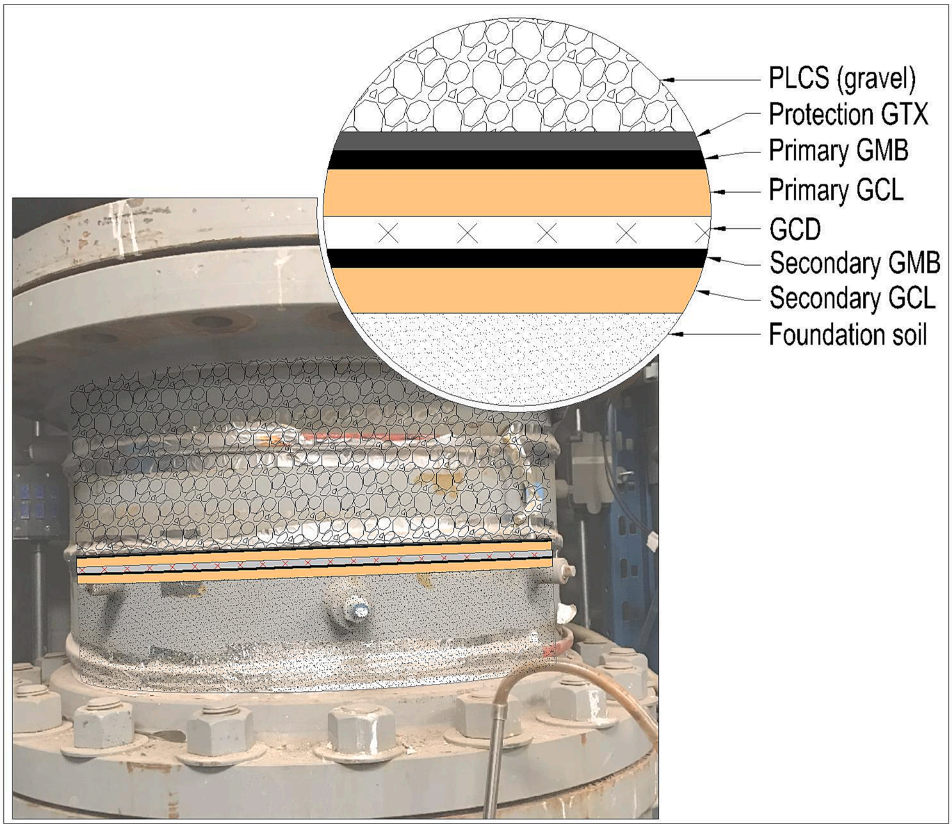

**Fig. 1.** Photograph of the geosynthetic liner longevity simulator (GLLS) with schematic of a double composite liner system reported in this paper superimposed on the photograph and indicating the various constituents.

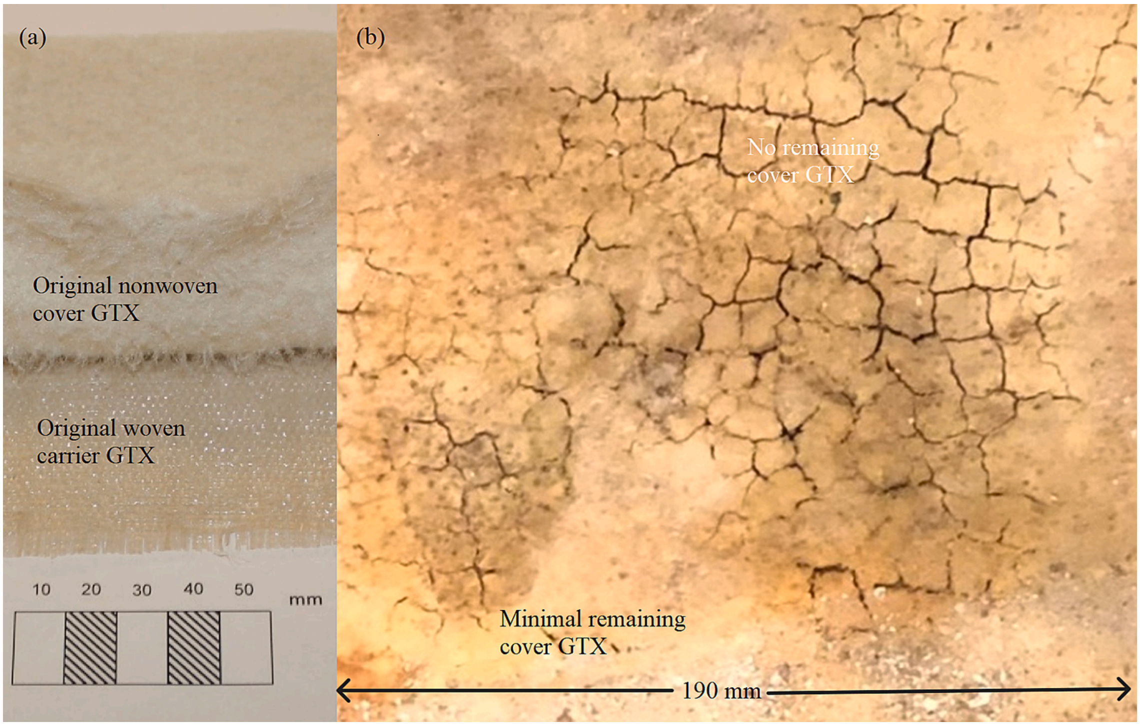

**Fig. 2.** (a) Original 200 g/m$^2$ nonwoven upper (cover) GTX (b) Top of portion of GCL after removal of the geomembrane showing an area where the upper GTX has mostly disappeared.

to severe defects identified by Gilson-Beck (2019) in electrical leak location surveys and could go undetected during construction in the many projects that do not have an electrical leak location survey.

To simulate real-world situations, synthetic MSW leachate (see Rowe et al. 2008; Abdelaal et al. 2014 for details) was put in the primary leachate collection system (gravel) with a bath-circulating system. The recirculating system is located only in the primary leachate collection system (PLCS, gravel), not in direct contact with the liner barrier, simulating the pumping of the leachate in the field. The flow induced by the recirculation is lateral and at a rate of 0.22 L/min, reproducing a gradient of 1 % in the base of the landfill, thus it is not expected to create any significant erosive force in the liner that the liner was covered by a GTX protection liner that served to protect not only the geomembrane but also the GCL below the geomembrane. To represent an average of about 25 m of solid waste, a normal vertical pressure of 250 kPa was applied on top of the PLCS, and, the cell was maintained at 85 °C throughout the testing period, to accelerate the ageing process.

After 76 months (6.3 years), the test was terminated, and the liner system was exhumed. From top to bottom and it was found that:

a. The protection GTX layer showed various indentations from the gravel and had partially disappeared (~7 % of the total area).
b. The primary GMB had several deep indentations with high strains, but no detectable cracks.
c. In the primary GCL, the 200 g/m$^2$ needle-punched nonwoven cover GTX had mostly disintegrated (~95 % of the total area, Fig. 2), but in some sections, the bentonite was partially to entirely eroded at the location where the 105 g/m$^2$ woven polypropylene carrier GTX was also partially or entirely degraded (Figs. 3 & 4). GTXs immersed in MSW synthetic leachate at 85 °C show a fast degradation, significantly decreasing their puncture properties between 3 and 6 months and their tensile properties even earlier (Reinert and Rowe, 2020). Degradation and loss of function of the GTX likely allowed the subsequent erosion of the bentonite into the GNT. The fact that the GTX below the GMB was far more degraded than the GTX above the GMB highlights the importance of having adequate antioxidant stabilization of these GTX and shows that one product can perform better than another in terms of aging
d. Fig. 3 shows an area more than 200 mm long and up to 190 mm wide from the top portion of the primary GCL after the removal of the primary GMB. Most of the cover and carrier GTX had disintegrated, and the bentonite had eroded with some remnants remaining. In the bottom left of Fig. 3, the circled area is less eroded, but the bentonite is already breaking up, and it is surrounded by an area where the cover GTX had disintegrated but bentonite remains (like that in Fig. 2). With extended ageing time, it is expected that the bentonite would erode (wash away) from the small, circled area, and the lower GTX would undergo additional degradation until it too became a hole like the 40 mm long and 20 mm wide hole (area 800 mm$^2$, depth ~ 7 mm) shown in Fig. 4 that was located 75 mm away from the defect in the GMB and was not directly related to the defect in the GMB although its formation was likely a result of leachate leaking

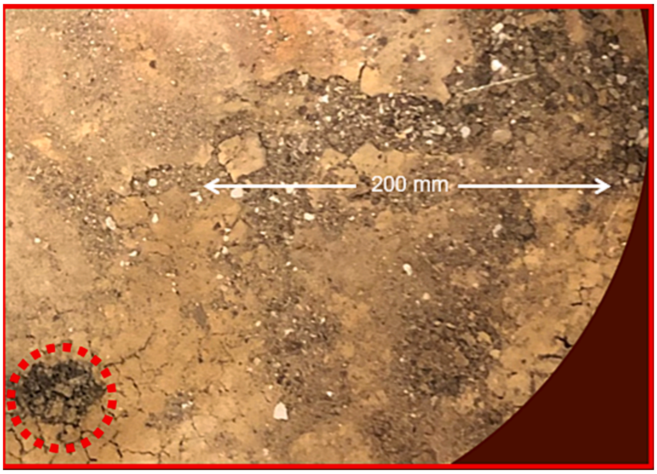

**Fig. 3.** Top of portion of the GCL after removal of geomembrane showing an area more than 200 mm long and up to 190 mm wide where most of the upper GTX, the bentonite, and lower GTX have gone with some remnants remaining. Circled area less eroded but breaking up surrounded by an area where to (cover) GTX has gone but bentonite remains (like that in Fig. 2).

**Fig. 4.** Top of GCL showing partly degraded upper cover GTX around and over a bentonite hole 40 mm long and 20 mm wide.

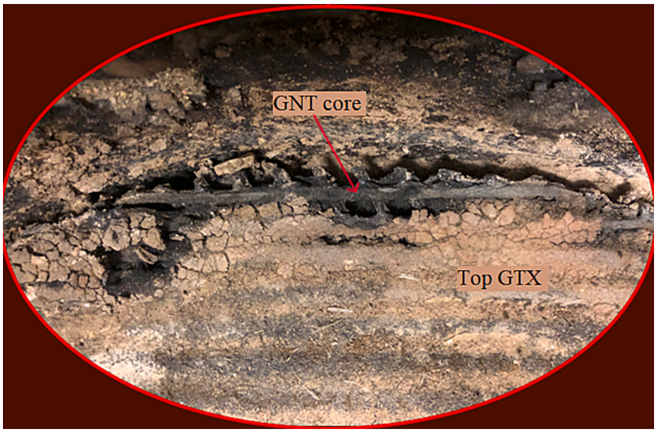

**Fig. 5.** Location where the GCL is completely disintegrated as has the top GTX on the GCD and the bentonite has eroded into the GNT.

through the defect in the GMB. One such hole in the area of the test corresponds to over 35,000 such holes per hectare.

e. Fig. 5 shows the worst area where the primary GCL had disintegrated entirely, as had the top GTX on the GCD, exposing the GNT and allowing bentonite erosion into the GNT leaving a gap of about 100 $mm^2$ (Fig. 5). This defect was located about 200 mm away from the defect in the primary geomembrane is leachate reaching the location to the interface transmissivity of the interface between the geomembrane and GCL. The purpose of the GCL is to minimize leakage through holes in the GMB. The purpose of the GCD is to collect any leachate that leaks through a hole in the GMB. Therefore, it is important that the GCL remain effective. That is not the case in Figs. 4 and 5. In both cases the GTX has degraded the point that it can no longer support the bentonite under the applied stress and a gradient. The primary purpose of the GTX between the bentonite and the GNT core of the GCD is provide physical support for the bentonite between the ribs of the GNT. In the absence of such support the applied pressure and gradient could be expected to cause intrusion of the bentonite into the core of the GCD. Thus, the loss of bentonite is likely the result of a combination of physical intrusion of the bentonite together with some erosion under the hydraulic gradient. The severe defects in the GCL, such as those in Figs. 4 and 5, were located 100 to 200 mm from the location of the defect in the GMB and except for the fact that they were in the wetted zone where leachate could reach the GCL from the GMB defect were not directly related to the location of the defect. The location is likely due to the statistical variation in the antioxidants and properties of the GTX. Since the GMB defect only represents 1.8 % of the area of the material tested it is to be expected (probability greater than 98 %) that the locations where the GTX is most poorly stabilized and/or least robust will be at a location away from the defect in the GMB. This test shows that as long as the more poorly stabilized GTX is within the wetted radius of the defect (typically about 500 mm with 0.2 m head in the leachate collection system), then degradation of the GTX component of the GCL and GCD can result in significant defects in the GCL.

f. The GCL component of the primary liner had a 200 $g/m^2$ nonwoven cover GTX (95 % of which has degraded) and a 105 $g/m^2$ woven polypropylene carrier GTX (30 % of which had degraded). GCL are available with 200 $g/m^2$ or 300 $g/m^2$ carrier GTX and these may perform better than the 105 $g/m^2$ woven used in this test. However, with a substantially without a substantial increase in stabilizers is far from certain that just using a heavier GTX will resolve the issue; particularly given that the 200 $g/m^2$ nonwoven cover GTX had disintegrated in the 6 years of the test.

g. After the careful removal of the remains of the primary GCL, the GCD was examined, and it was found that: (i) where the top GTX was still present it was effortless to peel it off with the heat bonding being no longer effective, (ii) there was bentonite inside the GNT that had eroded from the GCL, (iii) the GNT had a significant number of cracks and experienced rollover of the ribs, decreasing its thickness, and thus the flow rate of the GCD.

h. The secondary liner did not show any visible degradation. The secondary GMB had some indentations but no visible cracks, and the secondary GCL was still hydrated with no visible cracks or indentations.

i. The foundation soil was intact and compacted.

In summary, after 6 years in a double composite liner system at 85 °C, the GCL primary liner and the leak detection system provided by the GCD reached the end of their service life and were no longer functioning as intended in the design.

## 5. The need to evaluate dependence on the geosynthetic component

In the test described in the previous section, the GTX component of the GCL and the GCD were critical to the long-term effectiveness of the system. However, this may not always be the case. The tension that must be sustained by the GTX is related to the applied stress and the distance that the GTX must span to prevent the bentonite escaping into the GNT (i.e., the distance between the ribs). For the GNT tested, the opening in the GNT that must be spanned was approximately 10 mm. The fact that the GTX had degraded sufficiently in 6 years at 85 °C to allow bentonite to erode into the GNT under a head not exceeding 0.3 m indicates that the GTX was a critical component of the system, and thus the service life of the GTX component of the GCL used in this test (a GCL commonly used in North America) and of the GCD drainage system.

Conceptually, there are only two ways in which to know whether the service life of the GTX components of the GCL or the GCD are adequate for the design, namely:

(i) Have information that can be used to calculate the likely time to nominal failure and service life of the GTX components of the GCL and the GCD under the anticipated exposure conditions and establish that they exceed the design life of the facility. At present this information is not available.
(ii) Perform a test to ascertain the head at which internal bentonite erosion will occur if there were no GTX and the hydrated bentonite was resting directly on the drainage layer. (One would expect the GCL to normally be hydrated prior to failure of the GTX in the GCL).

For example, if the GCD in the previous case were replaced by a gravel drainage layer with 100 % finer than 10 mm ($D_{100}$ less than 10 mm), 50 % finer than 7 mm ($D_{50} = 7$ mm), 10 % finer than 5 mm ($D_{10} = 5$ mm), the average pore size would be 33 % of 7 mm or 2.3 mm, and maximum pore size that the bentonite would have to span without the GTX would be less than 3 mm. A GLLS test was performed to ascertain the dependence of the GCL on the GTX component over the gravel. A specimen of the same GCL from the same roll was hydrated with leachate to about 100 % gravimetric water content under 2 kPa stress. The carrier GTX was carefully removed by cutting the needle-punched fibres with a sharp knife and exposing the bentonite (Fig. 6a). The bentonite was then placed directly over the gravel previously described (Fig. 6b). A sand cushion (used to protect a GMB when a GMB is present) was placed over the cover GTX of the GCL, the cell was sealed, and the stress increased to 250 kPa (the same as in the test described in the

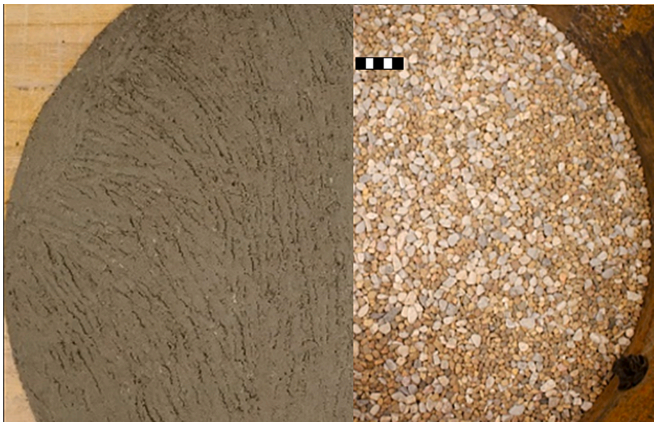

**Fig. 6.** (a) Hydrated (to a water content of about 100 %) bentonite after removal of the carrier GTX and before placement on the (b) gravel drainage layer. Note: each square in the black and white scale bar is 1 $cm^2$ and the bar itself is 5 cm long.

previous section). The GMB was removed to simulate worst-case conditions with a large (~600 mm diameter) hole in the geomembrane. A typical leachate design head of 0.3 m was applied for 21 days. There was no evidence of erosion, and the measured permittivity was $6 \times 10^{-10}$ $s^{-1}$, with a corresponding hydraulic conductivity of $1 \times 10^{-11}$ m/s (1/5 of the typical design value of $5 \times 10^{-11}$ m/s).

Without any problem under design conditions, the head was gradually increased to 15 m, and the permittivity and hydraulic conductivity remained at $6 \times 10^{-10}$ $s^{-1}$ and $1 \times 10^{-11}$ m/s, respectively. When an attempt was made to further increase the head to 20 m, local erosion at one location in the GCL occurred at a head of 15.5 m. The leakage was such that the head could no longer be increased as the bulk permittivity and hydraulic conductivity increased four orders of magnitude to $7 \times 10^{-6}$ $s^{-1}$ and $1 \times 10^{-7}$ m/s, respectively. Blue dye was added to the permeating fluid to identify the location of the erosion. When the GCL was removed, the upper layer of gravel had been impregnated with bentonite and had effectively become a part of the GCL (Fig. 7). The failure was identified at one small location surrounded by a dashed red circle in the photograph, where presumably there had been less bentonite or a larger pore but ultimately erosion began.

It was possible to induce an erosion failure of the GCL with dry bentonite MARV of 3660 g/m$^2$; the fact that it did not occur until a head of 15.5 m and 250 kPa applied vertical stress (more than 50-fold greater than the design head of 0.3 m) effectively demonstrated that the GTX component of the GCL was not essential for its effective long-term performance as part of the primary composite liner if this gravel size and graduation had been used as the drainage layer in a landfill with a design head of 0.3 m and a stress of 250 kPa.

## 6. Discussion and practical implications

Although the average temperature expected in the liner is 35–40 °C (Yoshida and Rowe 2003; Rowe 2005, 2012; Islam and Rowe 2009), there are historical cases of MSW landfills with measured temperatures as high as 150 °C (Calder and Timothy, 2010; Stark et al., 2012; Martin et al., 2013). A GLLS test was conducted with the GCL resting on the GCD at 85 °C and 250 kPa applied stress. Although elevated, 85 °C is within the range in landfills and hence is directly relevant to those situations. The fact that the GTX component of the GCL and GCD failed in 6 years should serve as a warning to landfill designers and regulators that as much attention needs to be paid to the service life that can be expected of the GTX component of a GCL and the geosynthetic components of GCDs as to the GMB when considering their use in MSW landfill double liner systems. This is especially true at elevated temperatures although it is also applicable to the more traditional 35 to 40 °C of MSW landfills. The service life of geosynthetics at these temperatures is currently under investigation by the authors. Although the service life is not yet known, it is known that the GTX generally not well stabilized compared to the GMB and consequently it can be confidently predicted that the service life of the GTX component will be less than that of the GMB. Given that, as this test demonstrated, problems are likely to occur at the most critical locations where the GCL and GCD are needed: at the location in the wetted zone near defects in the GMB at all temperatures during the contaminating lifespan of the landfill. Consequently, either the quality of the GTXs used must be very stand substantially improved to give an adequate service life or design that is not dependent on the long-term performance of the GTX should be adopted (e.g., Priyanto et al. 2019; Rowe et al., 2020).

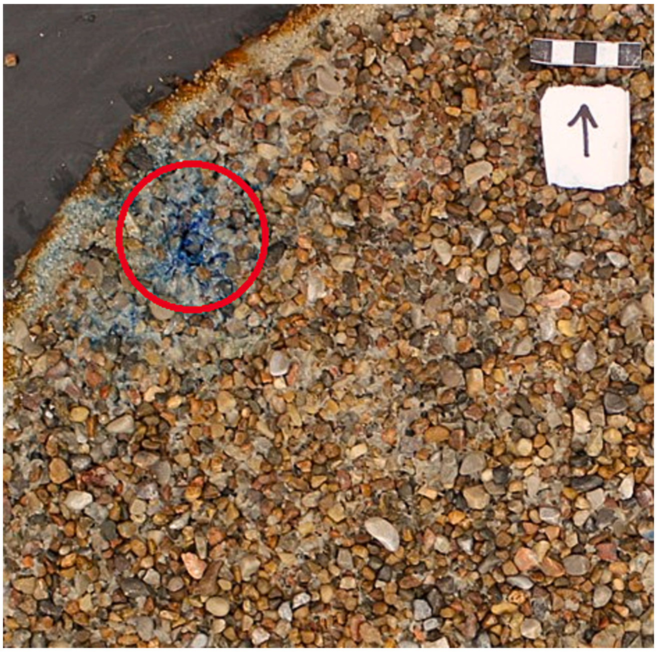

**Fig. 7.** Gravel adhering to bentonite which has party intruded into the upper layer of gravel and location (red dotted circle) where the GCL ultimately failed to sustain an increase in head to 15.5 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The secondary GCL that was resting on the sand subgrade had been covered by a fully intact secondary GMB without contact with the leachate. This secondary GCL was still in good condition, demonstrating that the problems with the primary GCL related to interaction with the simulated MSW leachate under a head of 0.3 m. Also, even if the secondary GCL had been subjected to a head of leachate, it would not have required the GTX for long-term performance since the sand can be expected to perform as an adequate filter for the GCL bentonite (Rowe and Orsini 2003).

The second test reported demonstrates that, with the specific and straightforward change in design where a suitable gravel drainage layer was used instead of the GCD, the GTX component of the primary GCL was not required for good long-term performance under normal design conditions and indeed could withstand a head of up to 15 m before problems became evident.

It has been previously demonstrated with respect to GMB service life (ibid.) that temperature significantly affects the service life of polyolefin geosynthetics. Thus, the 6 years at 85 °C can be expected to translate into a longer period at lower temperatures. It is not yet possible to predict how much longer. Studies are ongoing to try and resolve this question, but the answer will take several more years of continued testing.

## 7. Conclusions

Two large-scale tests in geosynthetic liner longevity simulators have been described. It was shown that a defect in the GMB that allows leachate contact to an underlying GCL can cause degradation of the GTX component of the GCL and an underlying GCD leading to the formation other defect in the GCL within the wetted distance from the defect. Similar effects should be expected in the field under similar conditions. For the materials and experimental conditions examined in these tests, the following conclusions can be reached.

1. A six year test at 85 °C with simulated MSW leachate at a nominal 0.3 m head in the leachate collection system above a protection GTX, primary GMB with a prescribed rectangular defect, GCL, GCD, intact secondary GMB, GCL, and sand layer revealed that under these conditions much of the GTX component of the GCL and upper GTX on the GCL had disintegrated into microplastics. With the loss of support from the GTX at one location of a defect, bentonite had eroded into the GNT drainage layer. Thus, in this design, the GTX component of the GCL was critical to the long-term performance of both the GCL and the drainage layer and its service life was inadequate.

2. The GNT component of the GCD had also experienced extensive stress cracking and rollover of the ribs, reducing its functionality even if it were not for the bentonite intrusion and erosion into its structure. Research is required into the long-term performance of GCDs if they will be used as leak detection and secondary leachate collection layers in MSW landfills.
3. Engineers need to pay more attention to the long-term performance of components of the double-lined barrier system and, in particular, to the GTX component of GCLs and GCDs. Until such time that these components of the system can be given a design life that exceeds the contaminating lifespan of the facility, engineer should be avoided designs where failure of the GTX component of the GCL and GCD represents a critical failure mode.
4. With proper design, the service life of the GTX component for preventing internal erosion under design conditions can be neglected. The test conducted with no GTX between the underlying gravel ($D_{50} = 7$ mm, $D_{100} < 10$ mm) drainage layer and the bentonite showed no evidence of internal erosion under a typical 0.3 m design head and exhibited low ($1 \times 10^{-11}$ m/s) hydraulic conductivity and the applied stress of 250 kPa. This test demonstrated that the GTX was not essential in the long-term for the effective and adequate performance of the system. However, the grain size distribution of the drainage layer is a critical consideration in reaching this conclusion which cannot be generalized (e.g., to gravel with a larger particle size or a GCL with less bentonite).

Although the study has shown the failure of the GCL and GCD system after only 6 years at 85 °C and 250 kPa applied stress, this does not imply imminent failure for landfills with liner temperatures of 35–40 °C (or lower) since the time to failure will increase with decreasing temperature. However, it does raise questions about the effectiveness of any similar design used in hot landfills at temperatures exceeding 60 °C and does indicate the need for research to address the question of the long-term performance of GCDs together with design that does not rely on the long-term performance of the GTX component of GCLs. One of the tests reported in this paper illustrates that such a design is feasible.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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