Geomembrane puncture and strains from tire derived aggregate for use in landfill applications

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ABSTRACT: Tire derived aggregate (TDA) is currently being used as landfill leachate collection systems in landfills as a cost effective solution to gravel. TDA is composed of light vehicle tires that have been shredded into pieces. However, the particles often contain protruding wires and may puncture the geomembrane that the TDA is placed above. Furthermore, as the geomembrane is placed above a compacted clay subgrade, high pressures may result in tensile strain developing in the geomembrane. It has been well established that where sustained loading results in tensile strain greater than about 6%, stress cracking is likely to occur. This paper presents data for preliminary research of puncture protection for TDA over geomembranes of different thicknesses and overlying protection layers. A comparison of strains for gravel and TDA is also presented. Preliminary results indicate that TDA may be suitable as a drainage layer, but further research into protection layers is required as puncture occurred with different protection layers at each load tested.

Keywords: geomembrane, tire derived aggregate, compacted clay, strains, liner, landfill, geotextile

1 INTRODUCTION

Composite liners consist of a geomembrane placed above a compacted clay liner (CCL) or geosynthetic clay liner, and work in unison to prevent the movement of contaminants to the environment (Rowe, 2005). The geomembrane is placed directly on the clay liner to reduce transmissive flow along the interface (Nosko and Touze-Foltz 2000). A coarse aggregate drainage layer is placed above the geomembrane to reduce the hydraulic head on the liner. Large aggregate is required as clogging of the collection system is a function of surface area of the drainage material (Fleming et al, 1999; Fleming and Rowe 2004). The disadvantage of the coarse aggregate is the high contact pressure and point loading that results on the geomembrane, which can be 100 times larger than the applied pressure of the waste above (Brachman and Gudina 2008).

The point loading of the geomembrane may result in deformation and high localised strain in the geomembrane. Over time, areas of high strain (> 6%) can result in stress cracking in aged geomembranes, particularly under elevated temperatures (Abdelaal et al, 2014) A strain limit of 3% has been proposed by Seeger and Müller (2003) as a conservative limit to ensure at least 100 years of service life. A strain limit of 6-8% has also been proposed by Peggs et al. (2005) for geomembranes depending on the resin used in manufacturing the geomembrane.

1.1 *Strain calculations*

Localised “dimple” areas of high strain in geomembranes have been measured through scanning the surface of an underlying lead sheet to acquire a profile (i.e. Tognon et al. 2000; Brachman and Sabir 2013; Brachman and Gudina 2008, Hornsey and Wishaw 2012). A method developed by Tognon et al. (2000) used kinematic deformations to assess the membrane strain, assuming zero shear strain, i.e. that any point on the geomembrane experiences only vertical deformations to result in the dimpled deformed surface that results from point loading. Using a uniform point spacing, the membrane strain can be approximated by:

$$\varepsilon_M = \sqrt{\left[1 + \left(\frac{1}{2\Delta x}\left[z_{i+\Delta x} - z_{i-\Delta x}\right]\right)\right]} - 1 \tag{1}$$

Where $z_{i+\Delta x}$ and $z_{i-\Delta x}$ are the vertical displacements at point i+Δx and i-Δx, and Δx is the grid spacing. In addition to the membrane strain, there is an additional bending strain component that considers differences in strain through the thickness of the geomembrane (Tognon 1999; Brachman & Eastman, 2012). It may be represented by a second-order finite difference approximation:

$$\varepsilon_B = \frac{m}{(\Delta x)^2}\left[z_{i+\Delta x} - 2z_i + z_{i-\Delta x}\right] \tag{2}$$

Where m is the distance from the middle of the geomembrane. Therefore, the membrane strain will be a maximum at the surface of the geomembrane and zero at the centre. The total strain is the sum of the membrane and bending strain (Tognon et al. 2000):

$$\varepsilon_T = \varepsilon_M + \varepsilon_B \tag{3}$$

Hornsey and Wishaw (2012) identified that manual selection of dimples may not properly assess damage to geomembranes and suggested a grid scanning method. Each grid elevation point used has four orthogonal neighbors and four diagonal neighbors. Strain is calculated for each neighboring cell, and the highest calculated strain was then assigned to the array of strains. However, the method by Hornsey and Wishaw (2012) only considered membrane strain (Eq. 1). Strain in the geomembrane was then assessed on a percentage of the total area above a given strain as opposed to simply the maximum strain.

2 MATERIALS AND METHODS

2.1 *Materials used for testing*

Gravel and TDA, as shown in Figure 1, were used during testing. TDA is manufactured from shredding light vehicles tires. The shape and size of TDA varies by the manufacturing process. Grain size analysis is completed by hand and is shown in Figure 2. Pieces vary in size between 40-500mm in length.

Figure 1: Sample of TDA and gravel used in testing program

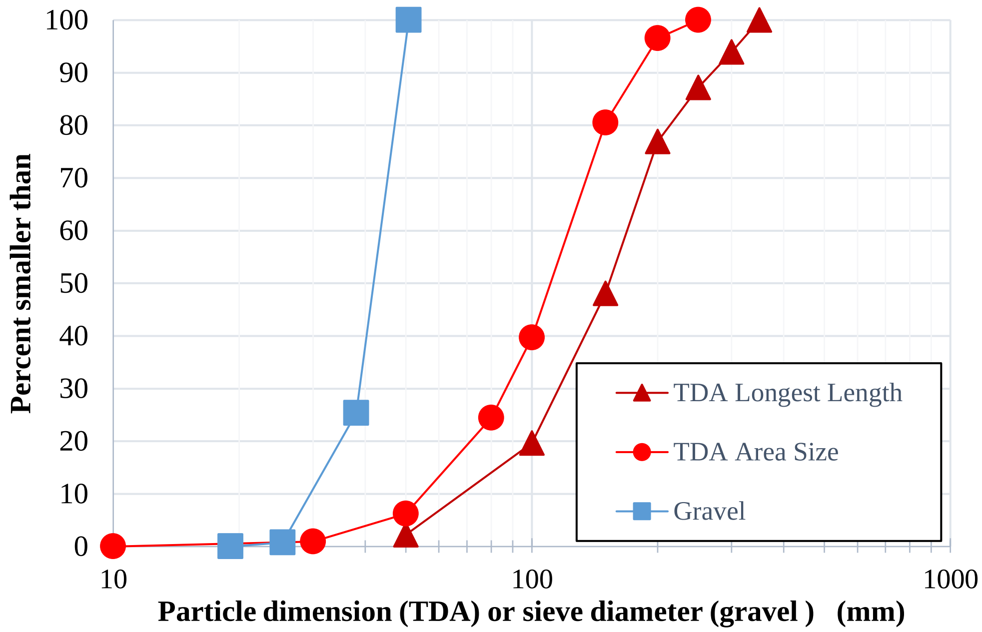

Figure 2: Particle size distribution of TDA and gravel used in testing

The TDA was classified based on the longest length measured as well as an area size distribution. The area size was calculated by the square root of the area of the two largest dimensions (assuming all pieces have relatively constant thickness).

The TDA has numerous protruding wires of different lengths. Wire lengths for the TDA sample grain size shown in Figure 2 are given in Table 1.

Table 1: Percentage of tires containing different sizes of protruding wires

Length of Wire (mm)	0 - 5	5- 10	10 - 15	15 - 20	20 - 25	25 - 30	30 - 35	35- 40	40 - 45	45 - 50	>50
% of parti-	54.1	38.4	26.8	16.1	11.6	7.3	4.1	1.3	1.5	1.3	4.3

A commercial pottery clay was used to represent the compacted clay seepage layer under the geomembrane, as it is highly reproducible and serves as an index material for future testing with natural soils. The pottery clay was used to compare TDA strains with gravel. A second soil, referred to as Floral Till (extensively tested and reported e.g. Sauer et al, 1993) was also used in the puncture testing with TDA only. Standard soil index testing was completed as given in Table 2.

Table 2. Properties of clay materials used in large scale testing

Soil	USCS	LL (%)	PL (%)	Activity	OMC (%)	ρ_{Dmax} (kg/m^3)	Sand (%)	Silt (%)	Clay (%)
Pottery Clay	CL	46	19	0.64	20.0	1690	5.5	52.2	42.2
Floral Till	CL	43	21	0.55	21.5	1620	9.2	50.8	40.0

* LL – liquid limit; PL – plastic limit; PI – plasticity index; OMC – optimum moisture content using Standard Proctor compaction; ρ_{Dmax} – maximum dry density using Standard Proctor compaction

Both soils were dried, crushed and gravel particles greater than 9.5 mm were removed. The soil was then mixed with distilled water to a water content between 2-4% wet of standard proctor optimum, as this is the upper range of placement in the field (Benson and Daniel 1990, 1994).

2.2 *Apparatus used for testing*

Due to the large size of TDA, a large testing apparatus had to be commissioned to evaluate strains. The device was designed and built at the University of Saskatchewan (Marcotte and Fleming 2017). It consists of a metal ring measuring 900 mm in diameter and 350 mm in height to hold the clay and TDA. Pneumatic cylinders with a long (6 inch) stroke applied a constant load, up to approximately 700 kPa, as significant compression of the TDA occurs.

2.3 *Testing procedure*

The clay was compacted in 3 lifts using equivalent energy to standard Proctor compaction using a large steel compaction rammer. In the large-scale tests on the Pottery Clay, lead sheets were used to capture deformations similar to others (e.g., Tognon et al. 2000; Gudina and Brachman 2006; Brachman and Eastman 2013, Abdelaal et al. 2014). The lead sheet was placed directly on the clay and a geomembrane placed above. For the tests performed on the Floral Till, the clay was directly scanned. A geotextile protection layer was placed above the geomembrane in some tests, and the selected aggregate was placed above.

To evaluate whether TDA had the potential to puncture the geomembrane, 11 TDA pieces were selected based on having rigid protruding wires of different sizes, as shown in Figure 3.

Figure 3: TDA pieces selected for specific placement during puncture analysis

Each of the 11 pieces was placed in approximately the same position and orientation for each of the TDA puncture tests. Once the pieces were specifically placed, the load cylinder was filled randomly with TDA. The sample of TDA selected to be used was hand-picked to represent the “worst-case” sample that contained numerous wire. Approximately 35 kg of “worst-case” TDA was hand selected from a 185 kg sample to be used in testing.

Load was applied in approximately 50-100 kPa increments in 10-15 minutes until the desired pressure was reached. The final load was held constant for 22 hours.

The TDA was removed carefully and the geomembrane was inspected for puncture. The TDA piece for each puncture was identified for each test, although sometimes disturbance of the TDA made this impractical. The geomembrane was then removed and further inspected for holes.

A photogrammetry procedure (see Marcotte and Fleming 2017) was used to reproduce the deformations virtually. Once on the computer, strains could be calculated using the equations as described by Tognon (1999) on a grid basis.

3 RESULTS AND DISCUSSION

3.1 *Puncture results*

A total of 15 TDA puncture tests were completed, and the results are given in Table 3. Three different geomembrane thicknesses, varying pressure, and different protection layers were used.

Table 3: Summary of puncture tests completed

Test	Geomembrane Thickness	Protection Layer	Pressure	# Of Punctures	TDA #
1	1.5 mm	None	200	5	**1**(2),**2,3,4**
2		340 g/m^2	300	3	**1,5**(2)
3		340 g/m^2	400	5	**1**(2),**?**(3)
4		340 g/m^2	200	4	**1**(3),**?**
5		340 g/m^2	500	3	**5**(2),**8**
6		540 g/m^2	550	1	**8**
7		PDG	550	4	**1**(2),**?**(2)
8	2 mm	None	500	4	**?**(4)
9		None	350	4	**1,5**(2),**9**
10		PDG	350	1	**1**
11		PDG	500	1	**?**
12		340 g/m^2	350	0	
13		400 g/m^2	500	3	**1**(2),**10**
14		2 X 340 g/m^2	550	5	**1,9**(2),**11**(2)
15	3 mm	None	500	0	

PDG – Planar Drainage Geocomposite

The TDA # represents which TDA piece punctured the geomembrane, followed by the number of punctures caused by that piece (in brackets). For example, for Test 1, the geomembrane had 5 punctures: 2 of these punctures came from piece #1, and the other three came from TDA pieces #2, #3, and #4. Unknown pieces are denoted with a “?” mark.

Some interesting comparisons can be drawn from the puncture data, although no concrete conclusions about appropriate protection can be reached. For example, when comparing the 1.5 mm geomembrane tests, a reduction in the number of punctures occurred with a 540 g/m^2 geotextile protection. However, during the tests completed on a 2 mm geomembrane, the highest number of punctures occurred through the doubled-up 2X 340 g/m^2 geotextile, protection layers. No punctures occurred at 500 kPa with a 3 mm geomembrane.

Comparing tests with the same protection layer, but different applied loads demonstrates that pressure does not appear to influence the rate of puncture, for the relatively high loads applied (>200 kPa). Figure 4 shows the results from different applied pressures above a 1.5 mm geomembrane with 340 g/m^2 protection layer.

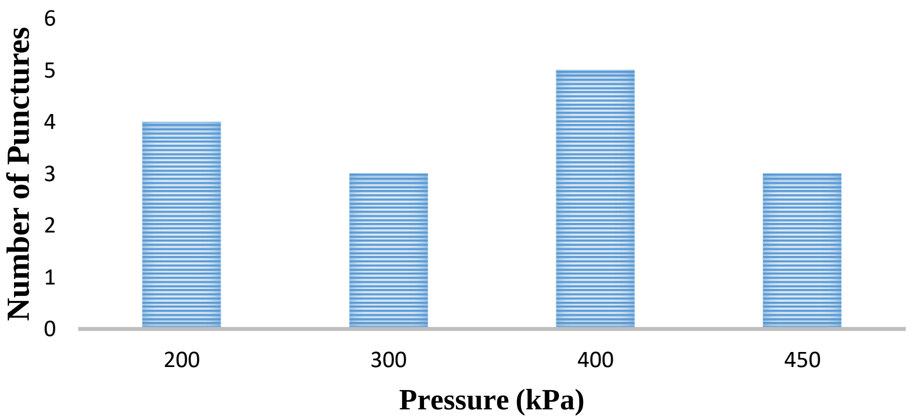

Figure 4: Number of punctures for a 60 mil geomembrane with a 10 oz/yd protection layer at different applied loads

It must be emphasized that the testing procedure followed was not “random” as specific pieces were placed on the geomembrane with the goal of achieving puncture. The TDA used in testing was selected as the ‘worst-case’ from a larger sample of TDA (35kg from 185 kg) as described previously. About 75% (32/43) punctures in all the tests completed were caused by TDA pieces selectively placed on the geomembrane. Numerous punctures occurred from TDA piece #1, as given with other punctures in Figure 5.

Figure 5: Examples of puncture of geomembrane from TDA (top left = TDA #1; top right = TDA #4; bottom left = unknown; bottom right = TDA #3)

The puncture of the geomembrane from TDA poses significant risk to the longevity of landfill liners if not properly protected. To date, no punctures have been observed in the current testing program using gravel. High pressure testing of geomembranes above compacted clay by Rowe et al. (2013) indicated that no punctures occurred even at pressures of 200 kPa.

3.2 *Strain results*

Strain was calculated using the equations developed by Tognon (1999) and the grid method as described by Hornsey and Wishaw (2012). The maximum bending and membrane strain was calculated for each cell based on the neighboring eight cells. The maximum bending strain was calculated for both the top and the bottom of the geomembrane, and the higher of the two values was added to the maximum bending strain, and the result was compiled in a strain array. A 500 mm diameter selection from middle of the 900 mm sample was selected, and the maximum strain area was plotted as a contour map as given in Figure 6.

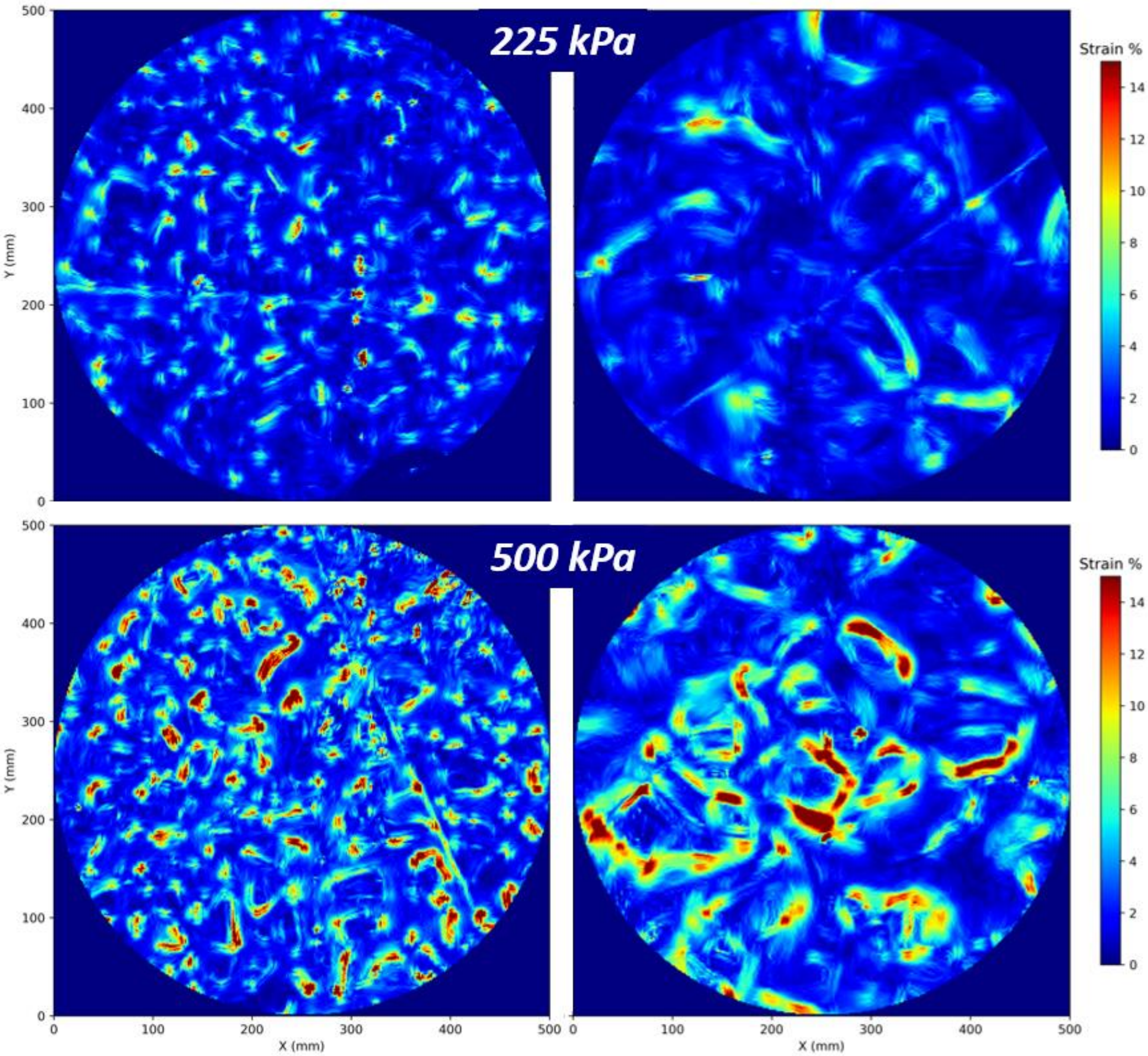

Figure 6: Contour map of Tognon (1999) strain in a 2 mm geomembrane with gravel and TDA placed immediately over the geomembrane with no protection layer

A total of four tests are presented using an 80 mil geomembrane at two different applied loads. The gravel has multiple indentations of high strain spaced closely together when compared to the TDA with large indentations spaced further apart. With both gravel and TDA, increasing the applied load increases the degree of geomembrane strain. All geomembranes had areas greater than the proposed strain limit of 6-8% as given by Peggs et al (2015).

4 CONCLUSION

This paper presents a methodology and data for the evaluation of geomembrane puncture and strains resulting from point loading by coarse drainage media consisting of tire derived aggregate (TDA) and gravel. The following preliminary conclusions have been made based on the results provided:

- Geomembranes were punctured by TDA at high and low pressures tested, and the rate of puncture did not relate to the applied pressure.
- Geomembranes were punctured by TDA with all protection layers used in the current study.
- Geomembranes were found to develop strains with both TDA and gravel. An increase in strain occurred with an increase in applied pressure for both aggregates.
- Geomembrane strain mapping using calculations developed by Tognon (1999) showed promise in the evaluation and comparison of geomembrane strains between gravel and TDA.

5 FUTURE WORK

Since puncture testing was completed with a selective "worst case" sample, and a majority of the punctures occurred from hand-placed TDA pieces (with the goal of maximizing puncture potential), further research is required to quantify the rate of puncture of geomembranes when TDA is used. The strain testing completed in this study is in the early stages. Additional research is required to quantify the long-term strain damage to geomembranes when TDA is used and compared to gravel.

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