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Brittle Stress Cracking of HDPE Geomembrane caused by Localized Over-Heating of Fusion Wedge Welds

A. L. Marta, Red Earth Engineering, Brisbane, Queensland, Australia
C.J. Armstrong, Red Earth Engineering, Brisbane, Queensland, Australia

ABSTRACT
This paper presents the results of an investigation carried out on a geomembrane lined pond in Australia which was temporarily decommissioned due to elevated leakage rates and observed development of geomembrane 'whales', after it was in service for only 4 years. The investigation identified a number of geomembrane cracks (or splits) in the vicinity of the whales. The cracks were orientated parallel to the outside edges of fusion wedge weld tracks where adjoining geomembrane panels were seamed. A 400 mm long crack was exhumed and analysed in the laboratory. The testing confirmed the heat affected zone adjacent to the crack was more susceptible to brittle stress cracking compared a control sample, and exhibited raised crystallinity which is indicative of higher than industry standard welding temperatures and slower cooling. It is hypothesized that failure of the geomembrane occurred at the edges of fusion wedge weld tracks due to the combined effects of 1) raised crystallinity from unacceptably high welding temperatures; 2) geometric stress concentrating features along the weld profile, and 3) variations in ambient temperatures causing whales to 'breath', inducing a flexing action on the edge of welds. The geomembrane cracks were repaired in situ and the impact on leakage rates was assessed after the pond was recommissioned. The lessons learnt from the investigation are presented in this paper.

1. INTRODUCTION

It can be said that a geomembrane liner system is only as strong as its weakest weld. This statement is particularly true for geosynthetic lined ponds, which require a large number of discrete geomembrane panels to be joined together to create a low permeable barrier. In recent years pond owners have recognized the importance of answering the question "how long is the service life of the geomembrane?" This is reflected by their readiness to invest in testing a variety of different types of geomembranes to examine properties related to durability and degradation; an exercise required to ensure suitable materials are procured for the project-specific application. However, premature failure of the geosynthetic lining system can also arise from weak elements which are built into the system during construction.

This paper presents the results of an investigation carried out on a geomembrane lined pond in Australia which was temporarily decommissioned due to elevated leakage rates (in excess of 10,000 lpd) and observed development of geomembrane 'whales', after it was in service for only 4 years. The surface area of the installed geomembrane is approximately 9.3 hectares and the operational fluid head is 6.7 m, which provides 290 ML of storage volume for treated water produced from coal seam gas extraction. The lining systems consists of 2.0 mm HDPE geomembrane underlain by 150 mm thickness compacted clay.

A number of geomembrane cracks (or splits) were identified in the vicinity of the whales. The cracks were orientated parallel to the outside edges of fusion wedge weld tracks where adjoining geomembrane panels were seamed. The heat affected zone of a weld adjacent to a 400 mm long crack was analysed in the laboratory to assess the causes of the geomembrane cracks. The geomembrane cracks were repaired in situ and the impact on leakage rates was assessed after the pond was recommissioned. The lessons learnt from the investigation are presented in this paper. This paper also demonstrates that the use of Action Leakage Rates (ALRs) are an effective tool for pond operators to assess the performance of the geosynthetic lining system, by comparing the monitored leakage rates with the calculated ALR, which then informs appropriate remedial actions to be taken in the event of the ALR being exceeded.

2. GEOMEMBRANE HOLES AND DEFECTS

A list of holes and defects identified in the geomembrane is provided in Table 1. The word 'hole' is used to describe a passageway of any shape and size (such as a puncture, tear, crack or gap) through the geomembrane which allows liquid to migrate from the containment side of the geomembrane to the bottom side. The word 'defect' is used to describe damage and imperfections present in the geomembrane. Defects can result from damage during installation, or can be formed during the manufacturing process of the geomembrane sheet. Many types of defects do not constitute a passageway for liquid flow (i.e. not all defects are holes), hence the terms ‘hole’ and ‘defect’ are established to avoid possible confusion between the two terms. This terminology was presented by Giroud (2016).

Table 1. List of Holes and Defects Identified on Pond Floor in the Geomembrane.

ID	Description	Photographs
Defect 1	50 mm long dent. Possible tool mark. Does not penetrate full thickness of geomembrane	
Defect 2	200 mm long extrusion weld on fusion weld seam. The extrusion weld penetrated the full thickness of geomembrane	
Hole 1	400 mm long split concealed beneath the overlap of fusion welded panels	Figure 1
Hole 2	60 mm long split concealed beneath failed extrusion weld	Figure 2
Hole 3	>500 mm long split concealed beneath the overlap of fusion welded panels	Figure 3

Figure 1. Photograph of Hole 1: a) top side; b) bottom side

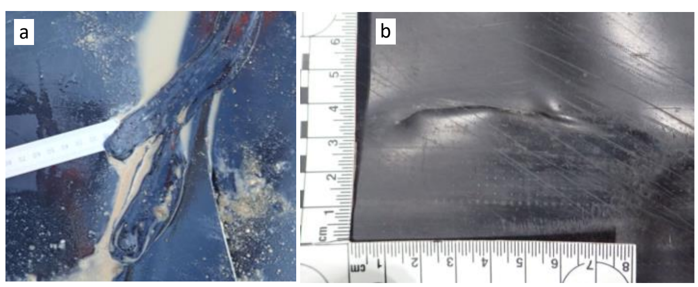

Figure 2. Photograph of Hole 2: a) top side; b) bottom side

Figure 3. Photograph of Hole 3

3. CONDITION OF GEOMEMBRANE SUBGRADE

Observations of the subgrade characteristics were inferred based on visual inspection of the shape of the overlying geomembrane, tactile assessment involving deformation/strength of the subgrade using boot pressure on top of the geomembrane, and direct inspection and sampling of the subgrade through large holes purposely cut in the geomembrane.

A list of relevant observations related to the geomembrane subgrade is provided in the following:

1. Some areas of the pond floor are not suitably graded towards the leakage discharge pipe; hence water was observed to be trapped beneath the geomembrane and the subgrade
2. Some areas of the upstream batters had water trapped beneath the geomembrane, as the ballast tubes positioned at the toe of the batters appeared to be preventing the water from flowing freely to the pond floor
3. The subgrade is generally undulating with localised depressions and raised mounds
4. The subgrade has been saturated and softened at localized areas due to leakage through the geomembrane holes

Photographs showing the condition of the subgrade at the locations of Hole 1 and Hole 2 are presented in Figure 4. Dynamic Cone Penetration testing suggests the wetting front of the leakage water penetrated the subgrade up to 0.5 m depth.

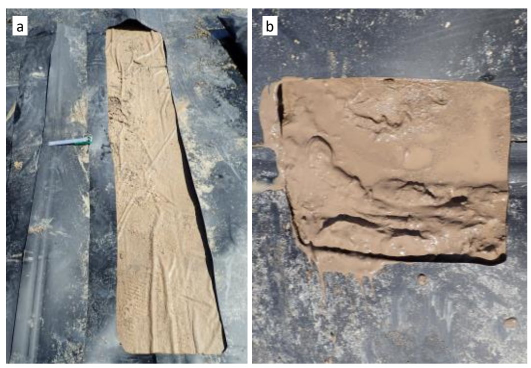

Figure 4. Inspection of subgrade at locations: a) Hole 1; and b) Hole 2.

4. GEOMEMBRANE REPAIRS AND QUALITY CONTROL

4.1 Trial Welds

Prior to undertaking geomembrane repairs, trial welds were performed on site using scrap pieces of geomembrane for quality control purposes (i.e. to establish weld machine settings of temperature, pressure and travel rate under actual site conditions, as well as establishing procedures to be followed by the welding technician). Coupons of 25 mm width were extracted from the trial welds and were subjected to peel and shear strength testing on site using a tensiometer, in accordance with the requirements of GRI GM19. Photographs of the trial weld coupons and the field testing are shown in 5.

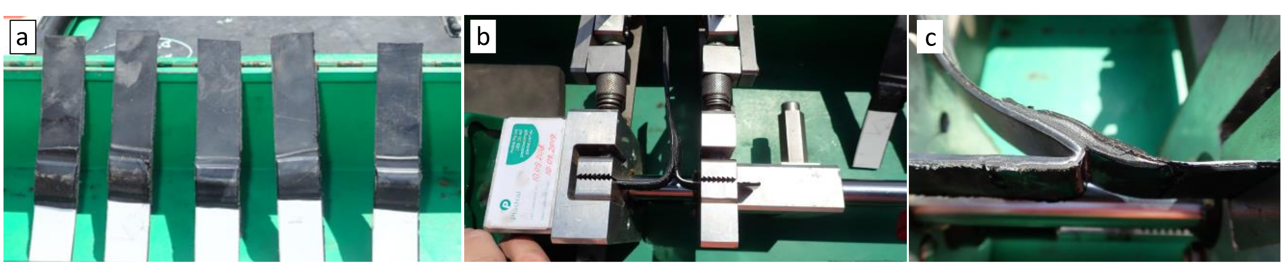

Figure 5. Photographs of trail weld field testing: a) prepared test coupons; b) peel test in the tensiometer; c) close up view

4.2 Extrusion Welds

All repairs were undertaken using extrusion weld patches. The patches comprised 2 mm white high-performance HDPE geomembrane manufactured from the same resin type as the installed geomembrane. The white geomembrane was selected for the repairs to provide a visual contrast from the black geomembrane, making their locations easy to identify for future monitoring and inspections. The general procedure for undertaking the patch repairs involved the following:

1) The defect or hole was cut out from the geomembrane. The cuts extended a minimum 150 mm past the edges of the defect or hole. Corners of the cuts were rounded with a smooth radius to minimize points of potential stress concentrations
2) The surface of the geomembrane was thoroughly cleaned using dry rags
3) The patch was temporarily bonded to the existing geomembrane using a heat gun and hand-rolling tool (see Figure 6a)
4) The perimeter of the patch (i.e. the area of geomembrane to be covered by the extrusion weld) was ground using an abrasive tool (i.e. angle grinder) to roughen the surface and remove potential contaminants (see Figure 6b)
5) The patch was bonded to the existing geomembrane using an extrusion fillet (see Figure 6c).

Figure 6. Photographs showing the sequence of patching: a) temporarily heat bonding; b) grinding; c) extrusion welding

4.3 Vacuum Box Testing

The extrusion welds for repair patches were visually inspected to assess the quality of the weld. This included observations of the weld width, thickness and geometry of the track marks. The extrusion welds were also subjected to vacuum box testing over the entire length of the seam (see Figure 7). The procedure for the vacuum box testing is as follows:

1) A soapy solution was applied over the seam
2) The vacuum chamber was placed on top of the seam and firmly held in position to ensure a perimeter seal
3) A negative (suction pressure) was applied to the chamber and held for a minimum of 10 seconds. During the suction, the seam was visually inspected through the clear walls of the vacuum chamber to assess whether air is flowing through the seam.

Figure 7. Photograph of vacuum box test

5. GEOMEMBRANE WHALES

Geomembrane whales developed on the pond floor while the pond was in service. Whales are bubbles of air (or other types of gas in some cases) that develop under the geomembrane, and appear as 'whale backs' above the surface of the water, exerting out-of-plane stresses in the geomembrane. Once initial geomembrane deformation occurs, the air tends to concentrate in localized areas beneath the geomembrane, causing the whale to grow over time. It is possible for whales to cause bursting failure of the geomembrane. A photograph of a typical whale in the pond is shown in Figure 8 and Figure 9. There are many possible causes of whales, including:

1) Trapped air during construction which has not been expelled
2) Air is potentially entering at geomembrane hole locations
3) A lower possibility could be leakage through geomembrane, which has infiltrated the underlying subgrade, expelling the pore air in the soil. The expelled pore air has migrated to the surface of the subgrade, and has become trapped beneath the geomembrane.

The whales were 'walked out' towards the batters where air vents are located. Ballast tubes installed at the toe of the batter were also removed at selected locations to allow the whales to be transmitted to the air vents.

Figure 8. Photograph of typical geomembrane whale in pond

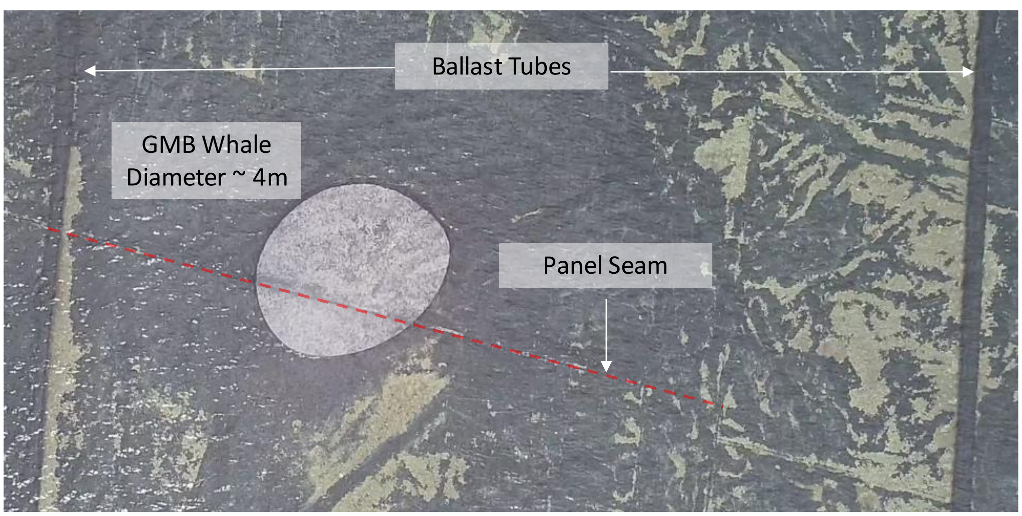

Figure 9. Aerial photograph showing location of whale relative to ballast tubes and geomembrane panel seam

6. LEAKAGE RATES

6.1 Monitored Leakage Rates

Leakage rates have been monitored prior to and after undertaking the geomembrane repairs. A graph of leakage rate plotted against time is shown in Figure 10. The pond water level (in terms of gauge board reading) is shown on the secondary vertical axis on the same plot.

During the first three days of monitoring, the leakage rate was approximately 10,000 lpd. The water level in the pond was then reduced by nearly 4 m following the three days of monitoring. Counterintuitively, the leakage rate rapidly increased from 10,000 lpd to over 100,000 lpd as the water level was lowered. According to leakage theory, the leakage rate is expected to reduce when the water head on the geomembrane is reduced. After the leakage rate peaked at over 100,000 lpd when the pond was emptied, it steadily reduced to less than 1,000 lpd. The fact that the leakage rate did not approach zero when the pond was empty indicates that not all the water trapped beneath the geomembrane was released before the pond was re-filled.

The observed increase in leakage rate that occurred during the lowering of the water level may be explained by the combination of water trapped beneath the geomembrane and the loss of what is referred to as 'intimate contact'. The term intimate contact is associated with a composite liner system comprising two complementary components: the geomembrane and layer of low permeability soil (or in some cases, a bentonite geocomposite). When the two components of the lining system are in intimate contact, leakage through a hole in the geomembrane is reduced due to the presence of the low permeability layer beneath the geomembrane. In liquid containment facilities, intimate contact between the geomembrane and the underlying soil is improved when the weight of the contained liquid applies a pressure above the geomembrane. In other words, a composite liner should always be loaded to achieve composite action.

Giroud and Bonaparte (1989) pointed out that composite liners must be used with caution in liquid containment facilitates, because leakage tends to accumulate between the geomembrane and low permeability soil, since the submerged portion of the geomembrane is easily uplifted. Then, if the pond is emptied rapidly, the geomembrane may be subjected to severe tensile stresses because the pressure of the entrapped water is no longer balanced with the pressure of the contained liquid. A large volume of water was likely trapped beneath the geomembrane due to holes in the geomembrane, and when the pond was rapidly emptied, the trapped water was no longer balanced with the pressure of the contained liquid, and was forced to evacuate via the discharge pipe.

When filling commenced, a clear hydraulic connection between the impounded water and the discharge pipe is observed for approximately 2.5 months, which is indicative of large holes in the geomembrane. The leakage rate responds almost immediately with only a very small time-lag with respect to changes in water level. That is, an increase in water level corresponds to an increase in leakage rate; while a decrease in water level corresponds to a decrease in leakage rate.

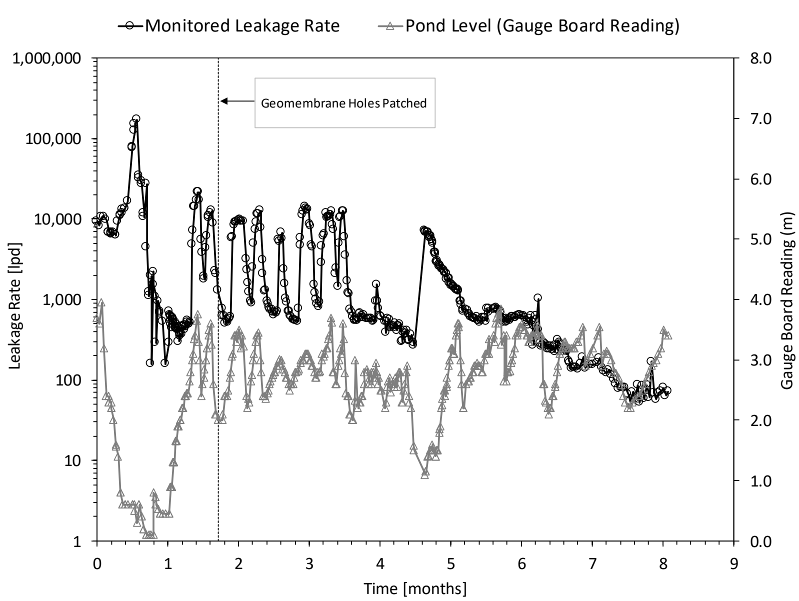

Figure 10. Plot of leakage rates and pond level against time

6.2 Action Leakage Rate

The term 'action leakage rate' is used to quantify the limit between acceptable and unacceptable leakage rates. As adapted from Giroud (1984) and cited by Giroud (2016), leakage from a geomembrane-lined pond can be acceptable if the following five requirements are met:

1) the loss of liquid remains small enough to be economically acceptable
2) the leaking liquid does not cause unacceptable pollution of the ground or the ground water
3) the leakage is not perceived by the public as unacceptable
4) the leaking liquid does not cause a degradation of the soil or the structure supporting the geomembrane
5) the leaking liquid does not uplift the geomembrane liner or otherwise damage the liner.

Action leakage rates were calculated based on theoretical leakage equations (Giroud, 1997) and published data relating to the frequency and size of holes in HDPE geomembranes which are installed with strict construction quality assurance and electric liner integrity surveys (Giroud, 2016). The graph of action leakage rate (as a function of hydraulic head) plotted against time is provided in Figure 11. Included on the same figure is the monitored leakage rate for direct comparison with the action leakage rate.

After the geomembrane holes were patched and the pond was returned to service, it took approximately 3 months before the monitored leakage rate dropped continuously below the action leakage rate. This lag time may be attributed to the fact that the leakage rate did not approach zero when the pond was empty, which indicates the flow of trapped water beneath the geomembrane was contributing the leakage rate after the geomembrane was repaired.

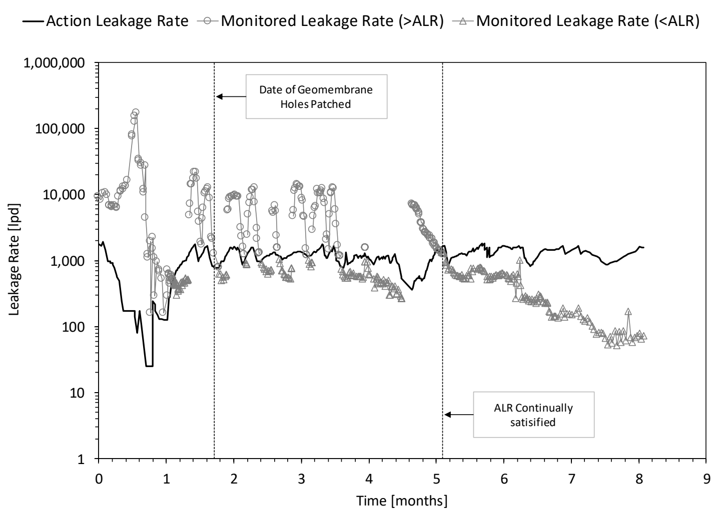

Figure 11. Plot of action leakage rate and monitoring data against time

7. FAILURE ANALYSIS OF GEOMEMBRANE CRACK

7.1 Specimen Preparation

Geomembrane specimens were prepared from the 'Hole 1' geomembrane sample as shown in Figure 12.

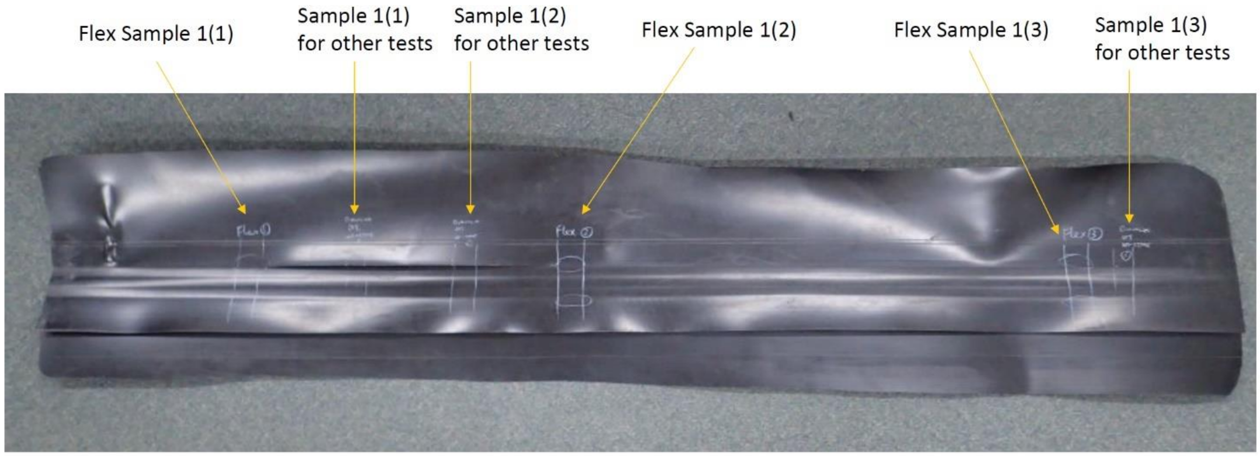

Figure 12. Photograph of ‘Hole 1’ sample outlining specimen locations

7.2 Weld Profile Dimensional Change

The weld profile of each specimen was measured using calibrated digital Vernier calipers. The results of the measurements are summarized in Table 2, and shows there is a thick-thin transition that occurs across the weld profile (a pronounced geometric effect leading to a stress concentration). A photograph of a weld profile is shown in Figure 13.

Table 2. Weld profile dimensions.

Dimension (mm)	1(1)	1(2)	1(3)
Thickness of liners	3.93	3.91	3.93
Thickness of seam	3.54	3.49	3.55
Seam reduction thickness	0.39	0.42	0.38
Air channel width	8.72	8.37	8.96
Weld width	11.8	11.8	12.2
Width of squeeze out bead	4.81	4.88	4.98

Figure 13. Photograph of weld profile (specimen 1(3) shown).

7.3 Standard Oxidative Induction Time

The standard oxidative induction time (Std-OIT) was measured for each specimen in accordance with ASTM D3895 and the results are summarized in Table 3.

Table 3. Summary of standard oxidative induction times

Test Location	1(1)	1(2)	1(3)
Crack surface (mins)	126	129	-
Weld bead on crack (mins)	66	69	-
Weld bead away from crack (mins)	-	-	133

7.4 Flexural Cycle Testing

The primary and secondary seams of specimen were subjected to flexural cycle testing using an accelerated flex-life apparatus. The results are shown in Figure 14
, which indicates the weld track located closest to the crack is more susceptible to brittle stress cracking than the weld track located further away from the crack. The weld track closest to the crack fails with far less flex cycles, and fails directly on the edge of the weld track as was the case in the field failure. The weld track further from the crack fails with ductile behavior, and the failure occurs several centimeters away from the edge of the weld track.

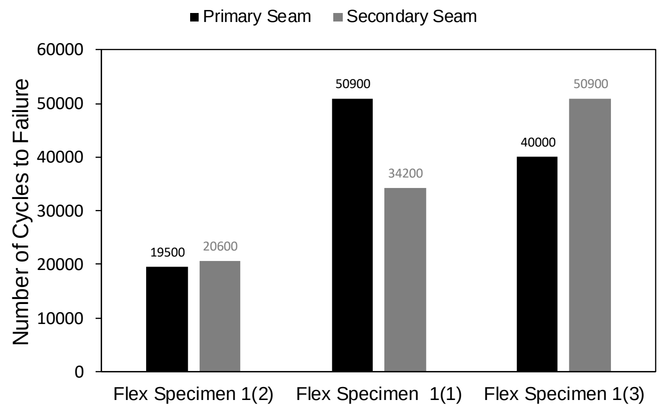

Figure 14. Results of flexural cycle testing

7.5 Weld Interface Light Transmission Microscopy Examination

The weld interfaces of specimens 1(1) and 1(2) were examined using light transmission microscopy, shown in Figure 15.
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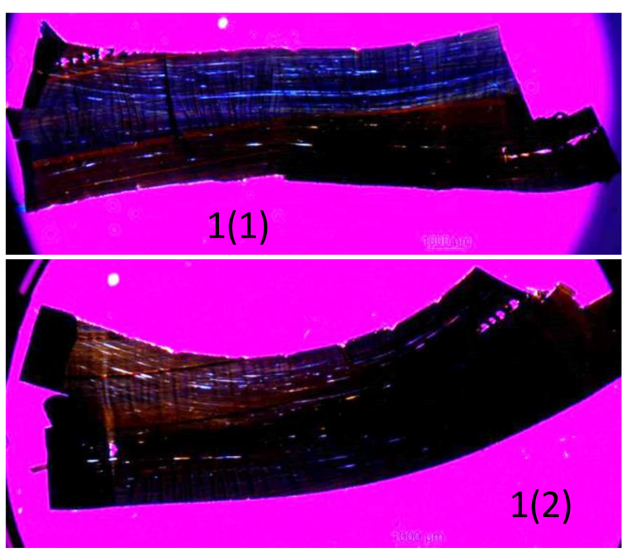

Figure 15. Weld interface light transmission microscopy examinations polarized with lambda plate

8. CONCLUSIONS

The hypothesis following observations on site is the fusion weld at 'Hole 1' was overheated during welding and subsequently stressed sufficiently during service to cause brittle cracking failure. The source of stresses during service are likely to have been whales, which can impose cyclic flexing as the whale 'breathes' (i.e. growing and shrinking over time as temperature and water levels change). This flexing is likely to have been exacerbated by the fact that the whales were locked in by the ballast tubes installed across the floor of the pond. Additionally, the irregular surface of the subgrade may have created a topographic environment where whales were unable to move laterally to upstream batters, where they can be vented.

Laboratory flex testing using the accelerated flex life apparatus has confirmed that the fusion weld at 'Hole 1' is more susceptible to stress cracking than the weld located 400 mm further away from the edge of the hole, where the failure mode is more ductile.

The other factors that have contributed to the observed brittle failure of 'Hole 1' are raised crystallinity on the edge of the weld (in the heat affected zone) - usually due to slow cooling - and also the thick-thin transition that occurs across the weld profile (a geometric effect). When all three factors occur in the field, namely; the raised crystallinity, the geometric stress concentrating feature (which is inevitable with fusion welds) and the cyclic stresses imposed by whales, brittle cracking is likely to occur directly at the edge of the weld track.

REFERENCES

Giroud, J.P. (1984). Geomembrane Liners: Accidents and Preventive Measures, *Proceedings of the Second* International Symposium on Plastic and Rubber Waterproofing in Civil Engineering, Vol. 1, Session 4, Liege, Belgium, June 1984, pp. 4.2.1-4.2.6.

Giroud, J.P. & Bonaparte, R. (1989). Leakage through Liners Constructed with Geomembranes, Part I: Geomembrane Liners, *Geotextiles & Geomembranes*, Vol. 8, No. 1, pp. 27-67.

Giroud, J.P. (1997). Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects, Geosynthetics International, Special Issue on Liquid Migration Control Using *Geosynthetic Liner Systems*, Vol. 4, Nos. 3-4, pp. 335-348.

Giroud, J. P. (2016). Leakage Control using Geomembrane Liners. *The fifth Victor de Mello Lecture*. Soils and rocks, Sau Paulo.

GRI-GM19a (2017). Seam Strength and Related Properties of Thermally Bonded Homogeneous Polyolefin Geomembranes/Barriers. *Geosynthetic Institute*, 475 Kedron Avenue, Folsom, PA 19033-1208 USA.