Forensic Investigation Of Geomembrane Liner Cracking: Premature Failure Or End-Of-Life?

Ian D. Peggs
I-CORP INTERNATIONAL INC., Ocean Ridge, FL, USA, icorp@geosynthetic.com

Keywords: geomembrane, lifetime, durability, stress cracking, oxidation

ABSTRACT: A single HDPE geomembrane liner manufactured and installed in 1993 in the mid-west USA cracked vertically on slopes (not at welds), at subgrade stone protrusions, and along both fusion and extrusion welds, in 2008. Of course, this was claimed to be a premature failure and that there should have been much more service life available in the geomembrane. All index mechanical and physical properties met original specifications. The cracks were stress cracks and had been initiated on the exposed surface where there was a critical combination of tensile stress and oxidation. The test data show that this was not a premature failure but was, in fact a "mature" end-of-life (EOL) failure. While no failure is ever expected an unavoidable EOL failure is far different to an avoidable premature failure.

1 INTRODUCTION

A single 0.75 mm thick high density polyethylene (HDPE) geomembrane was installed in an animal farm wastewater treatment pond in the mid-west USA in 1993. The farm was sold in 2007. In January 2008 the new owner complained that the original owner had sold a defective pond because the liner was cracking in the low December/January temperatures. Litigation was threatened. Both parties had the cause of cracking investigated. This paper presents the original owner's argument.

The key question was, was this a "premature" (unexpected) failure or was it a "mature" end-of-lifetime (EOL) failure? While no failure is ever expected an unavoidable end-of-life (EOL) failure is far different to an avoidable premature failure.

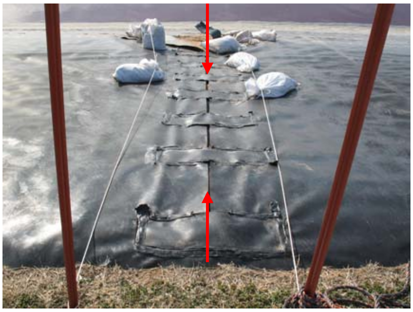

Figure 1 Cracking (arrowed) up side slope

Figure 2 Small crack (circled) at subgrade stone protrusion

2 OBSERVATIONS

Discrete vertical splits, about 10 m long, had occurred on two side slopes of the pond from the water level up to the crest of the slope (Figure 1). The crack opening displacement was about 450 mm. Attempts had been made to "strap" the sides of the cracks together to prevent further wind-induced damage. Cracks were also found at subgrade stone protrusions at the crest of the slope (Figures 2 and 3) and along the edges of both fusion (Figure 4) and extrusion (Figure 5) welds – more on extrusion welds. At the time of the investigation the temperature was just above freezing and the liner was reasonably taut (Figure 6).

Figure 3 Long and short cracks on extrusion die lines at subgrade stone protrusion

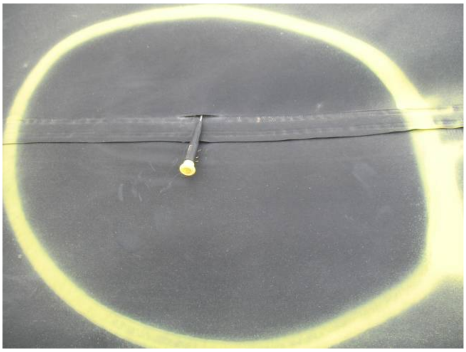

Figure 4 Cracking along edge of fusion weld

Figure 5 Stress cracks along extrusion weld

Close examination of the long splits revealed that they had occurred along the longitudinal manufacturing folds resulting from the round extrusion die (blown film) manufacturing process. At the top of the cooling tower the extruded bubble (tube) is flattened as it passes over rollers, then it is cut in the middle of one side and opened up leaving two slight folds at the one-quarter and three-quarter roll width positions (Figure 7). Conformance testing performed in the early 1980s showed these fold marks not to seriously affect the index properties of the material.

Figure 6 Taut liner at time of visit – temperature ~1°C.

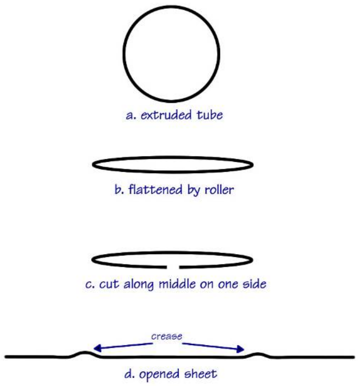

Figure 7 Cause of folds during manufacturing process

When all of the panels on the slopes were examined it was found that there was some degree of splitting/cracking in only a few of them, but that cracking only occurred in panels placed with the apex of the fold pointing down. There was no apparent cracking in any of the 72 of 90 panels placed with the apex pointing up. At one location (Figure 8) there were apex-up folds parallel to, and about 250 mm from, a central apex-down fold, but only the apex-down fold was cracked. It was also noted that the long splits were made up of many small cracks linked together (Figure 9).

Figure 8 Cracked apex-down fold between two un-cracked apex-up folds (inside arrows).

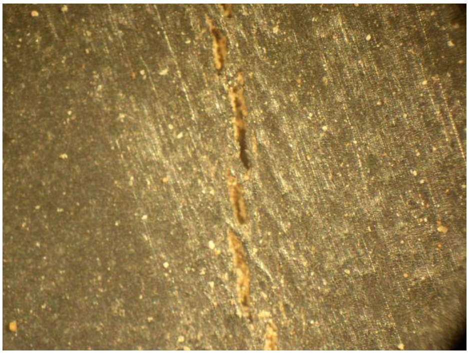

Figure 9 Long crack in fold made up of many small cracks

At the subgrade stone protrusions at the crest of the slope there were several straight cracks that had been initiated on the top surface of the geomembrane at faint extrusion die lines (Figure 3). These cracks were extremely sharp, brittle, and well-defined. They had propagated from the exposed surface down to the underside surface where the final ligament had failed in a ductile manner. These were perfect examples of stress cracks; slowly-propagating cracks at constant or cyclic stresses lower than the yield or break stress of the HDPE. The cracks along the welds were also stress cracks.

Appropriate samples were removed for more detailed microscope examination in the laboratory and for conformance testing.

3 TEST RESULTS AND DISCUSSION

Since most geomembrane manufacturers discard retained samples after 5 years there was no archive material available for baseline as-manufactured conformance testing. Because of this potential problem, samples had been taken from both high up and deep down in the anchor trench. These samples, and samples of exposed liner, were tested and compared to the specifications of National Sanitation Foundation International Standard 54 that was in effect in 1993, and with which the manufacturer would have complied. The results are shown in Table 1.

Table 1 Conformance test data

Test Parameter	NSF-54 (1993)		Sample Location			
	Method	Spec	Method	AT High	AT Low	Exposed
Break Strength MD (ppi)	ASTM D638	>114	ASTM D638	97	118 -	127
TD		>114	GRI.GM13	108		
Break Elongation MD (%)	ASTM D638	>560	ASTM D638	530	555	69
TD		>560	GRI.GM13	657		7
Puncture Resistance (lb)	FTMS 101C	>36	FTMS 101C	42	-	51
Tear Resistance (ppi)	ASTM D1004	>20	ASTM D1004	26	-	29
S-OIT (min)	ASTM D3895	(>75)	ASTM D3895	-	40	-
HP-OIT (min)		-	ASTM D5885	-	302	148
SCR (hr)	ASTM D1693	>1500	ASTM D5397 (plaque)	>110*	>200	-

* Two of five specimens >200 hr   AT – anchor trench

Allowing for surface scratches on anchor trench samples it can be seen that break stress and elongation, puncture resistance, and tear resistance all meet the NSF specifications. In fact, the exposed samples also still meet the NSF 54 specification, so had apparently not degraded or weathered significantly. The SCR of the material from low in the anchor trench met the specification (>200 hr) of the Geosynthetic Research Institute GM13 standard introduced about 3 years later. However, the sample from high in the anchor trench, that might have been a little more oxidized, did not meet that specification. There were no requirements for oxidative induction times in 1993. Therefore, the material, when manufactured, met all then-existing specifications. It cannot be faulted.

Measurements of HP-OIT on the exposed surface layer of the geomembrane showed a significant reduction to 148 min from 302 min in the anchor trench. Therefore, although there had been a reduction in HP-OIT there still appeared to be ample remaining stabilizer to provide adequate oxidation protection. However, it must be remembered that oxidation is initiated on the surface and that it is quite possible for all stabilizer to be consumed on the surface while much still remains in the body of the geomembrane. And if oxidation occurs on the surface, stress cracks can be initiated that will propagate more easily into and through the geomembrane thickness as observed at the subgrade stone protrusions.

Therefore, the exposed surface of the geomembrane is more oxidized than the underside surface. When a subgrade stone protrudes against the geomembrane the exposed surface is placed in tension. The die lines concentrate the stress until a critical combination of tensile stress and oxidation initiates the stress cracking. As lower temperatures cause the geomembrane to contract the oxidation/stress situation at the manufacturing folds is shown in Table 2. Only the apex-down folds have the required combination of tensile stress and oxidation to initiate cracks, so they crack first.

Cracks occur at welds due to both the stress concentrating notch geometries and the added oxidation that occurs during welding. Extrusion welds are more susceptible due to the presence of grinding gouges and in those locations where multiple weld beads are placed. In extrusion welds cracking invariably occurs at the edge of the bead in the lower sheet (Peggs, 2009A). This is due to the extra oxidation in the adjacent geomembrane, the notch geometry, and the internal microstructural transition "flaw" at the boundary of the heat affected zone and the melted and solidified weld zone. The weld zone is unoriented while the heat affected zone is still oriented (Figure10). The sharper that transition band the easier it is for cracks to propagate into the geomembrane.

Therefore, the installed material met its original specification. Failure was not caused by any abnormal events or liner mistreatment, nor was it caused by poor welding or subgrade preparation. The majority of HDPE geomembranes contain the manufacturing folds which typically do not cause problems. And many exposed geomembranes are subject to wider ranges of temperature and the related expansion and contraction stresses and do not fail. That leaves inadequate oxidation and stress cracking resistances as the primary cause of failure. Resistance to thermal and photo (UV) oxidation is provided by an additive formulation that is proprietary to HDPE resin and geomembrane manufacturers. Therefore, HDPE geomembranes have a range of resistances to oxidation. A material that lasts a long time in the Arctic will have a shorter lifetime in the Sahara desert.

Table 2. Surface conditions at low temperature

FOLD PERFORMANCE				
Fold Orientation	**Surface**	**Oxidized**	**Stress**	**Cracked**
Apex down	*Exposed*	*Yes*	*Tension*	*Yes*
	Un-exposed	*No*	*Compression*	*No*
Apex up	*Exposed*	*Yes*	*Compression*	*No*
	Un-exposed	*No*	*Tension*	*No*

Stress cracking resistance is a function of the HDPE resin used and the co-monomers used to counter its susceptibility to stress cracking. Figure 11 shows the stress rupture curves of five different HDPE geomembranes in the early 1990s (Hsuan 1992). The knee in the curve is the transition from ductile breaks to brittle stress cracking breaks. There is a factor of about 500 difference in the time to the "knee" in these curves. Therefore, all HDPEs do not have the same stress cracking resistance. Thus, they do not have the same long term mechanical durability. There is, in fact, a third stage in the stress rupture curve (Figure 12), a vertical line indicative of when fracture occurs, at any applied tensile stress, as a result of complete oxidation of the material (Koch et al., 1987).

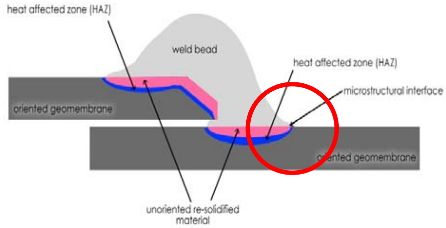

Figure 10 Microstructure at stress cracking at edge of extrusion weld (circled).

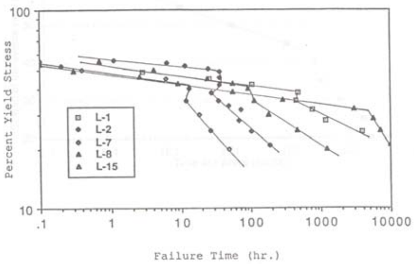

Figure 11 Stress rupture curves for five HDPE geomembranes (Hsuan et al, 1992)

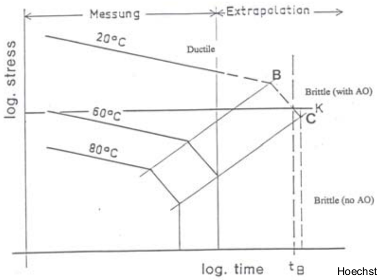

Figure 12 Stress rupture curve showing third stage oxidation region. (Koch et al., 1987)

4 SUMMARY

It was concluded that the liner material had oxidized on the exposed surface in the natural environment, and that, where there was a critical combination of oxidation and tensile stress, cracking had occurred. These stresses were normal service contraction stresses in that environment. The material itself met specifications when it was manufactured and still met those specifications when it failed. With no rogue agencies acting on the geomembrane it was concluded that the failure of the liner was not premature, but simply EOL for that specific HDPE resin, with that specific stabilizer formulation, in that specific application, in that specific environment. In another environment that specific material could have had a longer lifetime. Another HDPE material in that specific environment might still be functioning satisfactorily.

Since 1993 the SCR of HDPE geomembranes has increased significantly, and by specifying HP-OIT values we can better ensure long lifetime installations. In fact, with these data, it is possible to predict the remaining lifetime of exposed geomembrane liners such that we may avoid failures, whether they be premature or mature (Peggs 2009B).

5 CONCLUSION

The lifetime of an exposed HDPE geomembrane is a function of the resin used to manufacture the liner, the stabilizer package formulation, the quality of installation, and the service environment. All HDPEs will not have the same lifetime in the same application

In this specific project the liner had reached the end of its life after only 15 years. As such it was not a premature failure due to some material or environmental problem. It was, in fact, a mature EOL failure.

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