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STRESS CRACKING IN HDPE GEOMEMBRANES : WHAT IT IS AND HOW TO AVOID IT

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ABSTRACT

Stress cracking (SC) is a visually brittle failure that occurs at a constant stress lower than the yield stress of the material itself. It is a fundamental phenomenon to which all HDPE geomembranes are susceptible. Commercially available HDPE geomembranes show a range of stress cracking resistances that vary by a factor of 1000. In all other respects these HDPEs have very similar mechanical properties. This paper describes the stress cracking phenomenon and outlines those actions that can be taken during the design, specification, conformance testing, installation, seaming, testing, and facility operation phases to minimize the susceptibility of an HDPE geomembrane installation to stress cracking.

1 INTRODUCTION

Stress cracking is an apparent brittle cracking that occurs at a constant stress lower than the yield or break stress of a material. Many materials, metallic and nonmetallic, are subject to stress cracking. High density polyethylene (HDPE) as pipe, geomembrane, and geogrid, is one of these materials. Following the major stress cracking problems in natural gas distribution pipe in the late 1970s there were similar failures in several exposed HDPE geomembrane lined liquid impoundments in the 1980s (1). Research on resins has reduced the frequency of stress cracking failures but they have not been entirely eliminated. Provided the nature of stress cracking is understood, material specifications and installation, welding, and facility operating procedures can be introduced to minimize the potential for stress cracking failures. Most of the failures that have occurred to date have been repaired using HDPE.

Note that we are discussing "stress cracking" without any descriptor such as "environmental". Environmental stress cracking is just one component of the basic stress cracking phenomenon.

2 DESCRIPTION OF STRESS CRACKING

The high crystallinity that gives HDPE its excellent chemical resistance and strength characteristics is also responsible for its susceptibility to stress cracking. As in many materials, a gain in one performance characteristic is often countered by a loss in another.

The microstructure of an HDPE geomembrane is a series of lamellae (platelets) of folded molecules with side branches, molecule ends, and cilia (loose loops), dangling outside the lamellae and often entangled in the adjacent lamellae, as shown in Figure 1. As presented by Lustiger (2) when a high stress is applied to this structure (Figure 1) these linking chains remain frictionally entangled in the adjacent lamellae and break the lamellae into fragments that produce the common necking (yielding) and elongation characteristics of a conventional uniaxial tensile test. However, when a low stress is applied (Figure 2) the linking chains have time to slowly disentangle themselves so that separation of lamellae occurs, generating a smooth break in comparison to the previous yield/elongation ductile break.

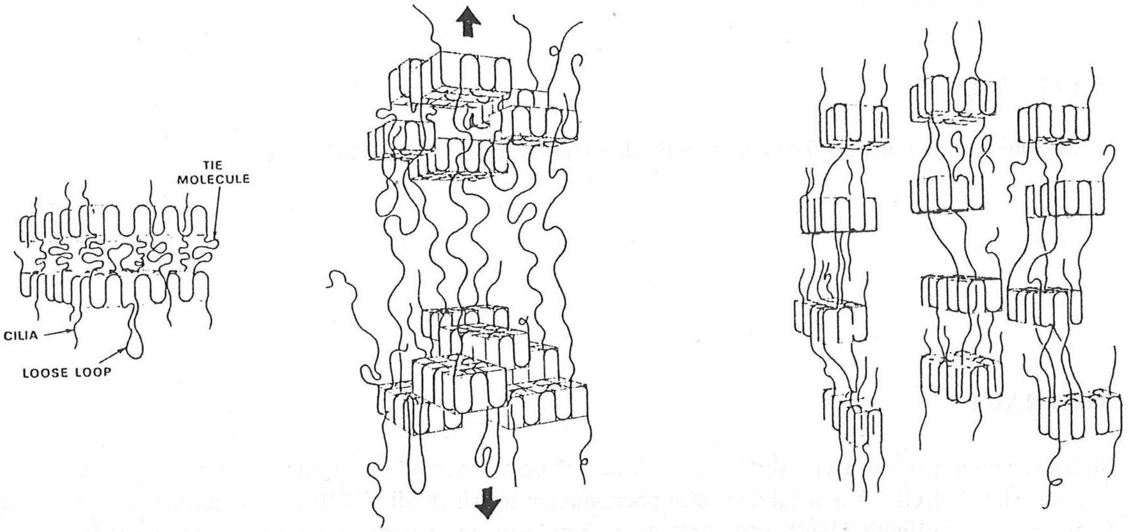

Figure 1 **Lamellar Structure Of HDPE And How It Yields** (2)

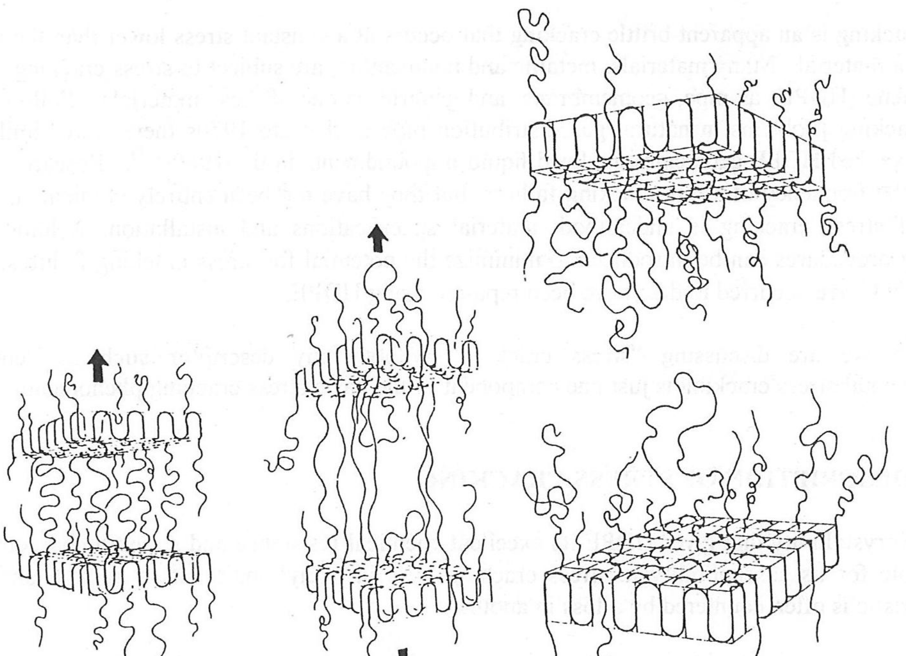

Figure 2 Stress Cracking At Low Applied Stress (2)

In the field, stress cracks typically occur along the edge of extrusion seams (Figure 3) in the lower sheet, along the peaks of wrinkles, or as "star" cracking at protruding stones. The cracks are usually quite short, perhaps up to 50 mm long. Long cracks on wrinkles and such as that shown in Figure 3 are often made up of many individual short cracks that link together to form the long one. The single unbranched cracks grow slowly by "slow crack growth (SCG)". When the cracks become of a critical size and reach a critical growth rate they can propagate very rapidly and branch many times to produce the appearance of shattering, a mild form of which is shown in Figure 4. This type of propagation is termed "rapid crack propagation (RCP)". RCP has been observed many times in geomembrane, but only occasionally in pipe. RCP looks disastrous, but it is believed that it will not occur without a precursor SCG crack. Clearly, one objective in selecting and installing HDPE geomembranes is to minimize the possibility of SCG occurring.

Figure 3 Typical Stress Crack At Edge Of Seam

Figure 4 RCP Stress Cracking Failure

3 TESTING

There are two procedures for testing an HDPE geomembrane material to determine its fundamental resistance to stress cracking which is primarily a function of the resin used to manufacture the geomembrane. ASTM D5397 "Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test" uses a small dogbone specimen similar to a uniaxial tensile test specimen. The specimen contains a notch in one face (not the edge) 20% through the thickness of the geomembrane. It is subjected to a constant tensile load at 50°C in a surfactant, both of which accelerate the failure but without changing the fracture mechanism. The notch generates plane strain conditions at its root, similar to the conditions that occur in the field where the material cannot contract in a direction normal to the direction of the principle stress to produce the yielding and elongation that occur in a tensile test specimen (plane stress). Tests are performed at several loads to generate a stress rupture curve similar to one of those shown in Figure 5 (3). These curves were generated by testing five different commercially available geomembranes in 1992.

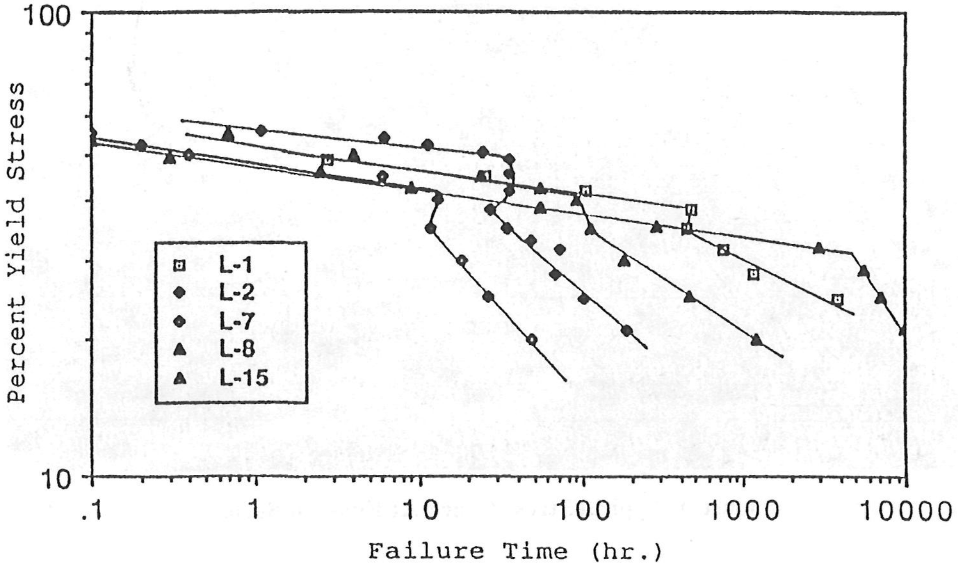

Figure 5 **HDPE Geomembrane Stress Rupture Curves (3)**

Above the "knee" in the curve the failure is ductile, below the knee it is quasi-brittle, with essentially no macroductility. Below the knee the material fails by stress cracking, hence the ductile segment cannot be extrapolated to determine a maximum service stress for a required service lifetime. There is a factor of about 1000 difference between the ductile /brittle transition times of these five geomembranes. In all other respects these five geomembranes would have essentially the same mechanical properties (yield, break, puncture, tear). Only a measure of stress cracking resistance differentiates the long term mechanical durabilities of the different HDPE geomembranes. Hsuan et al (3) also showed that the ASTM D1693 bent strip environmental stress cracking resistance test does not show these differences; this test should no longer be performed on HDPE geomembranes. Thus, specifying "HDPE" is a little like specifying "Steel" as a material for constructing a bridge. It is not adequate, and must be done in more detail if one wants to obtain the optimum performance characteristics from an HDPE geomembrane.

The second test (4) uses a wider unnotched strip specimen tested in a surfactant at 80°C at a constant load of 4 MPa. This test is particularly useful for evaluating the effects of seaming and surface texturing on the stress cracking resistance of the basic geomembrane. If a notch was to be placed in such a specimen it would penetrate the surface layer, and the influence of the surface texture and the stress concentration/heating at the seam surface would not be evaluated only the performance of the base material would be assessed.

4 FACTORS THAT INFLUENCE STRESS CRACKING

For a given HDPE resin, the factors that increase the susceptibility of an installed geomembrane to stress cracking have been found to be:

- overheating during seaming, which increases the crystallinity of the adjacent geomembrane material and consumes antioxidant, both of which reduce stress cracking resistance
- tack welding, which produces a stress concentration at a thermal concentration and incomplete bonding
- overgrinding and grinding gouges parallel to the seam direction, which produce stress concentrations normal to the major stresses (thermal contraction across side slopes)
- stress concentrations at protruding stones and penetrations through the geomembrane
- mechanical damage (scratches, creasing) during installation
- chlorinated solvents, oxidizing acids, detergents, and some other liquids (e.g.: pulp mill black liquor) in contained liquids (Environmental Stress Cracking)
- wrinkles and waves, particularly those that are folded over, that produce built-in stresses
- bridging at toes of slopes and in corners (concrete basin wall/floor) when the liner is loaded
- interface shear stress on the top surface of the geomembrane that is higher than that on the lower surface, which induces a tensile stress in the geomembrane
- differential settlement, that induces a stress in the geomembrane.
- welder wedge and nip roll widths, which influence residual stress magnitude and location in a seam

5 AVOIDING STRESS CRACKING

Clearly, without a stress there can be no stress cracking. Thus, all liners should be designed and installed to perform solely as a barrier and not to contain stress. However, as we all know, this is not practical in a construction site/landfill environment. Therefore, every attempt should be made to select a geomembrane made from a resin that has sufficient stress cracking resistance, to tolerate the damage induced during deployment, overheating during welding, and installation stresses that unavoidably occur.

The first step is to specify a geomembrane with an adequate stress cracking resistance. The new GRI GM13 (5) Specification requires a minimum ductile/brittle transition time (Tdb) in the ASTM D5397 test of 100 hr, or a single point (30% room temperature yield stress) test break time exceeding 200 hr. However, many failures have been observed in materials with a single point failure time of about 200 hr. Thus a Tdb of 100 hr should be considered an absolute minimum used only for decorative ponds where the impact of leakage is minimal. A Tdb consistent with the criticality of the containment function should be specified, up to a maximum, presently, of about 1000 hr. Times of about 300 or 400 hr are probably reasonable, recognizing that as the time increases there are fewer geomembranes that will provide that performance. At present there is no cost premium for high durability HDPE geomembranes but that will undoubtedly change as such materials are demanded. However, since stress cracking is the primary mode of premature failure (apart from basic poor workmanship) a price premium should still be economically tolerable.

The material should be specified on the basis of its Tdb, and the specifications should require that only geomembrane manufactured from that specific resin be supplied for the project. Single point conformance tests can be performed, at limited frequency, to ensure that the break time exceeds the Tdb by at least 100 hr - there is no need to test to actual break. Even though resins with higher Tdb may be supplied it would be better to remain with geomembrane made from one resin to facilitate, and for consistency of, welding.

If a high stress cracking geomembrane is specified, the following additional cautions are not as necessary, but it would still be good practice, for maximum geomembrane lifetime, to observe them. If the stress cracking resistance of the geomembrane is unknown, it is most advisable that the following cautions be implemented.

Chemical resistance tests under stress in the liquids to be contained must be performed, to ensure that environmental stress cracking will not occur. Most chemical resistance procedures, such as the now withdrawn EPA Method 9090 test "Compatibility Test for Waste and Membrane Liners", do not require a test under stress. This is a serious omission.

When deploying the geomembrane it should be done without dragging the liner on the subgrade and scratching/gouging it, and it should be done on a smooth subgrade without protruding stones and other debris.

When preparing for extrusion seaming, grinding should be done perpendicular to the seam rather than along the seam, even though the latter is easier, on the assumption that all the grinding marks will not be covered by extrudate. For example, EPA 1530/SW-91/051 (6) allows grinding marks to be exposed within 6 mm of the edge of the extruded bead. This is not good practice. However, if all the grinding marks are covered by the extrusion bead, their direction is immaterial.

Folds, wrinkles, and creases in the geomembrane should be avoided. In many cases intimate contact between geomembrane and a subgrade clay is required to mobilize the benefits of a composite liner, and for this objective alone folds, wrinkles, and creases should also be avoided.

To prevent overheating the adjacent geomembrane and making it more susceptible to stress cracking it should not be allowed to add an extruded bead to an already existing seam. Many failures have been initiated at such locations.

When testing seams the most important parameters to measure are shear elongation and peel separation. Strength values tell us nothing about the quality of the seam (7). Shear elongation should exceed 100% of the distance between the edge of the seam and the nearer grip (8) to confirm that the welding procedure has not reduced the ductility of the adjacent geomembrane. It is not sufficient to require only that "failure occur outside the seam" (9), such a failure must also be ductile. Peel separation should be zero, on both tracks of a double track seam. Peggs, (10) has shown that if peel separation can occur, the stress cracking resistance of the liner can be reduced by 70%. The act of separating a partially bonded seam can induce crazes that are the precursors of stress cracks in the separated surfaces. The argument that peel stresses do not occur in the field is just not valid. Due to the eccentric alignment of geomembranes in a shear test, peel stresses occur at the edges of the seam (11). Expansion and contraction of an exposed liner can induce peel stresses at waves and wrinkles (12). When soil is spread on a liner it can get under free flaps and induce a peel stress.

The liner should be installed in such a way that at the minimum service temperature (if it is exposed), or at the temperature of covering, it is fully supported by the subgrade and is not stressed e.g. bridging corners and toes of slopes. This may require the building in of compensation (wrinkles, waves) at elevated temperatures to allow for lower temperature thermal contraction. Corners of concrete basins and at columns or piers should be filled in to provide support. Thermal expansion may preclude the installation of liners at low temperatures when they are to be covered at much higher temperatures, when they will be wrinkled.

When repairs are made, reseaming a seam should not be allowed, as previously stated. However, if the flap of a hot wedge seam exceeds about 25 mm, reseaming may be acceptable such that the second application of heat does not occur at the same location as the first.

All penetrating holes, even pinholes. should be patched, otherwise a thermal concentration occurs at the same location as a stress concentration (the hole will not be filled).

When cover soil is placed on the liner it should be done in such a way so as not to build up wrinkles in front of the soil. Periodically soil can be spread from the sides to flatten a developing wrinkle. Alternatively, soil can be placed around an area of geomembrane that has been placed reasonably flat at the end of a working day to anchor it. The geomembrane will contract at the lower overnight temperatures to pull flat (without excessive stress), and the remainder of the soil can be placed on the flat liner early the next day, thereby precluding buried wrinkles and achieving intimate contact with the subgrade.

Until covered, a newly installed geomembrane should remain ballasted to prevent uniformly dispersed wrinkles (compensation) from being removed by contraction at night, then new wrinkles being formed at the toes of slopes the next day. Further contraction/expansion cycles will not redistribute the wrinkles up the slopes. If excessive wrinkles are present they should be cut along the top, laid flat, and seamed, with a patch seamed over the nonoverlapped end-of-cut.

When in operation, an exposed-liner liquid impoundment should be operated with the liner at as constant a temperature as possible, and at as high a temperature as possible at low ambient temperatures. This will minimize the low temperature contraction problems. Most stress cracking failures occur between 25% and 50% of the way down the slope so this segment should, if possible, be covered.

If these procedures are followed, the potential for stress cracking will be significantly reduced.

6 SUMMARY

Stress cracking is a fundamental phenomenon in HDPE geomembranes. It occurs in all HDPE geomembranes but the ductile/brittle transition temperature (the knee in the stress rupture curve) varies with the HDPE resin from which the geomembrane is made. However, with appropriate design, testing, specification, installation, seaming, and operational procedures, the potential for stress cracking failures can be significantly reduced.

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