Flexible Geomembrane Institute

Online Webinar - Executive Summary

AI SUMMARY

Investigating the Puncture Performance of Geomembranes in Cold Regions

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Executive Summary

Geomembranes installed in cold-climate applications — embankment dams, ponds, and industrial containment liners — are routinely exposed to direct contact with angular rock and aggregate, despite specifications and bedding designed to prevent it. Field evidence collected across four decades of installations confirms that this contact happens consistently regardless of engineering controls, and that vehicle traffic and equipment loading can drive that rock directly into the membrane surface. When this occurs under freezing conditions — at high-altitude and northern-climate dam sites in particular — the risk of puncture-related damage is compounded by temperature-dependent changes in polymer behavior.

This document summarizes a joint research study conducted at the South Dakota School of Mines and Technology examining how temperature and freeze-thaw cycling affect the initial puncture damage of reinforced and unreinforced geomembranes. The study evaluated four geomembrane materials — three reinforced, one unreinforced — across a temperature range from 20°C down to -80°C and up to 60 freeze-thaw cycles, using both standard ASTM puncture testing and a novel 3D-printed concrete "rock simulant" designed to better represent real-world aggregate contact than the standard steel piston probe.

Key Takeaway for Engineers & Students

Temperature, not freeze-thaw cycling, is the dominant driver of change in geomembrane puncture behavior. Ultimate puncture resistance changes relatively little across temperatures, but the *character* of the damage changes dramatically — shifting from scrim tearing at warm temperatures to polymer delamination at extreme cold — and materials become measurably more brittle in their post-peak response as temperatures drop. Standard ASTM puncture devices appear to produce conservative results relative to angular rock contact in the field.

1. Motivation: Why Study Cold-Weather Puncture Performance

1.1 Field Evidence of Rock-Geomembrane Contact

Embankment dams frequently place riprap — large rounded to subangular boulders — directly over a geomembrane, separated only by a relatively thin bedding layer. Photographic evidence spanning installations from the 1980s through a project observed within the past year confirms that despite specifications and drawings calling for rock-free bedding, angular rock ends up in direct contact with the geomembrane during installation with regularity. In one recent example, installation occurred at approximately 12°C with visible frost and rock present in both the fill and bedding despite pre-installation coordination with the engineer of record and contractor. Under these conditions, low-pressure equipment traversing the slope can push angular rock directly into the membrane.

This risk is not unique to dams — it extends to pond liners and exposed geomembrane applications in oil and gas and other industrial facilities, particularly in cold, high-altitude, and northern climates where equipment and vehicle traffic cross the membrane repeatedly over its service life.

1.2 Scope and Boundaries of the Study

The study focused specifically on **initial damage** caused by rock or vehicle-tread contact in cold weather. Several related but distinct cold-weather phenomena were explicitly excluded from scope:

- Folding damage during transport or field installation
- Weld and seam performance in cold weather
- Crack propagation following an initial flaw (a separate behavior studied elsewhere)

2. Theoretical Basis: The Glass Transition Zone

The study's theoretical foundation is the polymer **glass transition temperature (Tg)** — the temperature range across which an amorphous polymer shifts between a rigid, glassy state and a softer, rubbery state. Tg governs flexibility, strength, and working limits, and is treated in this study as a broad transition zone rather than a single sharp threshold, since glassy and rubbery plateaus can be flat or sloped depending on material. Polypropylene's glass transition sits around -20°C (material-dependent), while polyethylene's sits in the -80°C to -120°C range — informing the study's selected test temperatures.

Reinforced geomembranes — a woven scrim sandwiched between polymer sheet layers — are of particular practical interest because reinforcement is increasingly common in the marketplace, and how that reinforcement changes cold-weather puncture behavior was not well established prior to this study.

3. Research Questions and Knowledge Gaps

The study was designed around two primary questions:

- What is the cold-temperature puncture performance of geomembranes with and without reinforcement, within the glass transition zone?
- Can a more realistic penetrating device — rather than the standard ASTM steel piston — better capture the damage caused by real-world angular rock contact?

A third finding emerged during testing rather than being a starting hypothesis: at a given material and penetration device, the *qualitative damage pattern* differs meaningfully across temperatures even when the *ultimate resistance* is similar.

Prior to this study, cold-weather geomembrane aging was identified as poorly understood — existing ASTM standards do not represent actual field aggregates, nor do they explicitly account for temperature-dependent effects.

4. Testing Program Design

The study used a 4 × 4 × 5 testing matrix, with each condition tested in triplicate (and expanded to N=4–6 in select cases where variability warranted additional specimens).

Variable	Levels Tested
Geomembrane materials	HDPE (unreinforced), LLDPE (reinforced), Polypropylene (reinforced), plus one additional reinforced material
Freeze-thaw cycles	0, 5, 10, 30, 60
Temperatures	20°C (ambient), 0°C, -20°C, -80°C
Test methods	Tensile (dogbone), conventional ASTM puncture (steel piston), rock simulant (tear) test

All membranes were supplied by a South Dakota manufacturer. Freeze-thaw weathering was performed in 12-hour on/12-hour off cycles using a cryofreezer for -80°C exposure and conventional freezers/ice for warmer cold conditions; ice chests were used to maintain temperature during transport between labs.

5. Testing Methods

Tensile testing used standard dogbone-shaped specimens under indirect tension, with specimen temperature maintained using ice or dry ice and monitored via laser thermometer.

Conventional puncture testing used a steel piston pressed into a geomembrane specimen stretched over a mold, under the same temperature-control approach.

Rock simulant (tear) testing introduced a novel 3D-printed, cast-concrete penetrator (approximately 5 ksi compressive strength) designed to better represent an actual angular rock than a steel piston. The mold geometry — a trapezoidal ridge profile at roughly a 45-degree angle — was selected primarily for consistency in demolding without damage, balanced against the surface area needed for the range of specimens and replicates being tested. The rock simulant is not rigidly fixed to the test frame and can rotate slightly as damage accumulates, better approximating an in-situ contact condition. Testing with this method revealed two distinct failure mechanisms:

- **Primary failure** — tearing and separation of the scrim fibers themselves
- **Secondary failure** — delamination of the polymer sheet layers from the scrim, without scrim tearing

6. Results: Tensile Testing

Tensile results showed near-linear stress-strain trends across all materials at room temperature, with minimal difference in ultimate behavior between 20°C and 0°C. A modest, consistent bump in load capacity appeared at 5 freeze-thaw cycles across several materials before leveling off — a pattern the researchers could not fully explain, tentatively attributing it to shifting amorphous/crystalline balance within the polymer. At -20°C, LDPE and HDPE varied more than polypropylene across cycling; at -80°C, variability across materials was broadly suppressed as all materials sat well within the glassy region. The clearest consistent finding was that post-peak response becomes markedly more brittle — a sharper drop-off after peak load — as temperature decreases, even where ultimate strength itself changes little.

7. Results: Conventional Puncture Testing

Unreinforced HDPE showed a 25% reduction in maximum displacement with increasing freeze-thaw cycles at 0°C; all other materials remained relatively stable across cycling at that temperature. At -20°C, LDPE showed a modest drop in maximum load, with other materials largely unchanged. At -80°C, all materials converged to a near-uniform, more brittle response, though ultimate load again changed little.

8. Results: Rock Simulant (Tear) Testing

The rock simulant testing produced consistently higher maximum load and displacement than the steel-piston puncture tests, and — when normalized to contact area — indicated that the rock-shaped penetrator produces *less* damage per unit contact area than the steel piston. Unlike the tensile and conventional puncture results, freeze-thaw cycling produced pronounced, non-monotonic variation in the rock simulant results (dramatic single-cycle spikes, particularly in LDPE), even though variation *within* each triplicate packet remained low. Additional replicate specimens (up to N=6) confirmed this pattern was consistent rather than an artifact of small sample size.

The clearest trend from this method was that **material delamination becomes more prevalent as temperature decreases** — the scrim increasingly carries the load while the polymer coating separates from it — and that this effect is again suppressed at the coldest temperature tested (-80°C). Side-by-side specimens tested at room temperature versus -80°C at similar ultimate load showed clearly different damage patterns: predominantly scrim tearing at room temperature versus predominantly polymer delamination at extreme cold.

Based on these results, the researchers concluded that standard ASTM puncture devices likely produce a **conservative** estimate of puncture resistance relative to actual angular rock contact in the field, and are proposing to reframe this test as a “tear test” rather than a puncture test given the different failure mode it induces.

9. Statistical Observations

A notable and unexpected finding was the very low variability *within* each triplicate (or expanded replicate) test packet — coefficients of variation in the 3–16% range, well under the 5% threshold often considered indicative of a repeatable test method, for most conditions. This contrasts with variability reported in prior published cold-weather geomembrane studies (e.g., EPA testing in the 1990s, later freeze-thaw cycling studies), which generally reported much wider scatter. Variability *between* different test packets (across temperatures, cycles, and devices) was considerably higher than variability within any single packet.

10. Conclusions

- **Temperature is the dominant variable; freeze-thaw cycling is secondary.** Across nearly all testing methods, temperature drove more change in geomembrane behavior than the number of freeze-thaw cycles.
- **Increasing freeze-thaw cycles did not reduce puncture capacity** in the way repeated freeze-thaw cycling degrades brittle cementitious materials like concrete — geomembranes are a fundamentally different (polymeric) material class, and this distinction should not be conflated by engineers with concrete experience.
- **Reinforcement provides a statistically significant but modest improvement** in puncture resistance over unreinforced material — not the dramatic multiplier some practitioners might assume.
- **Damage mode, not just ultimate strength, changes with temperature.** Materials shift from scrim-tearing failure toward polymer delamination as temperatures drop, even when the ultimate load capacity is similar.
- **All materials become more brittle as temperature decreases**, evidenced by a sharper post-peak drop-off, even where peak load itself is largely unaffected.

- **Standard ASTM puncture testing (steel piston) appears conservative** relative to a more field-representative angular rock simulant.
- **A pin-style ASTM puncture probe was determined to be unrepresentative** of real-world rock contact for reinforced composite systems, as its narrow diameter can pass between scrim fibers rather than engaging the composite system as a whole.

11. Future Research Directions

- Dynamic mechanical analysis and polymer-level characterization before/after testing
- Systematic testing across equal material thicknesses, with and without reinforcement, in a controlled one-to-one comparison
- Investigation of combined freeze-thaw and shrink-swell weathering (e.g., in GCL applications)
- Continued development of tear testing with additional rock/aggregate simulant geometries
- Instrumentation of individual scrim and polymer-sheet layers to isolate their respective load contributions

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Disclaimer: This research was conducted at the South Dakota School of Mines and Technology with industry sponsor funding, prior to the presenter's employment with the U.S. Bureau of Reclamation. The findings and opinions presented do not represent the position of the U.S. Bureau of Reclamation or the United States government.