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FREEZE-THAW CYCLING AND COLD TEMPERATURE EFFECTS ON GEOMEMBRANE SHEETS AND SEAMS

Prepared in Cooperation with
U.S. Environmental Protection Agency
National Risk Management Research Laboratory

Under
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March 1996

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Bureau of Reclamation
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The Bureau of Reclamation and the U.S. Environmental Protection Agency sponsored this study of the effect of cold temperature and freeze-thaw cycles on geomembranes used as seepage barriers in water storage and transport and waste containment. Part I involved incubating unconfined specimens in freeze-thaw cycles and performing tests at +20 °C. Part II involved the same incubating condition as Part I, but tests were performed at -20 °C. In Part III, specimens were confined during freeze-thaw cycles and tested at +20 °C. Part IV monitored stress relaxation behavior and cold temperature induced stress between +30 °C and -20 °C.

Tensile behavior of geomembrane sheets and seams did not change significantly after 200 cycles in Parts I and II and 500 cycles in Part III. Effects of cold temperature testing (-20 °C) on tensile behavior were investigated by comparing Part I and II test results. In general, strengths increased and elongations decreased with decreasing temperature because of increased material stiffness. Part IV results showed that induced stress varied between polymers, ranging from 1380 to 9000 kPa (200 to 1300-lb/in^2) depending on the material's glass transition temperature, modulus, and thermal coefficient of expansion. On the other hand, induced stress was the same for each freezing cycle.

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ **BUREAU OF RECLAMATION**

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GLOSSARY

ASTM	=	American Society for Testing and Materials
CPE	=	Chlorinated polyethylene
CSPE	=	Chlorosulfonated polyethylene
EIA	=	Ethylene interpolymer alloy
EIA-R	=	Reinforced ethylene interpolymer alloy
EPA	=	Environmental Protection Agency
EPDM	=	Ethylene propylene diene monomer
EPS	=	Environmental Protection Service
FCEA	=	Fully crosslinked elastomer alloy
FCEA-R	=	Reinforced fully crosslinked elastomer alloy
FML	=	Flexible membrane lining
fPP	=	Flexible polypropylene
fPP-T	=	Textured flexible polypropylene
fPP-R	=	Reinforced flexible polypropylene
FTB	=	Film tear bond
HDPE	=	High density polyethylene
HDPE-T	=	Textured high density polyethylene
LLDPE	=	Linear low density polyethylene
LLDPE-T	=	Textured linear low density polyethylene
NSF	=	National Sanitation Foundation
PE	=	Polyethylene
PET	=	Polyethylene terephalate
PVC	=	Polyvinyl chloride
PVC-R	=	Reinforced polyvinyl chloride
QC/QA	=	Quality control/quality assurance
UV	=	Ultraviolet
VLDPE	=	Very low density polyethylene
VLDPE-T	=	Textured very low density polyethylene

INTRODUCTION

Geomembranes are widely used in the construction, protection, and rehabilitation of dams and other water conveyance structures. Geomembranes are also used in waste storage and disposal facilities. An area of common concern for Reclamation (Bureau of Reclamation) and the EPA (Environmental Protection Agency) is the behavior of geomembranes when subjected to freeze-thaw cycles in cold climate conditions.

Geomembranes are widely used as barrier materials for seepage control in dam and canal rehabilitation. Geomembranes have also been used for protection against erosion on the upstream face of embankment dams, erosion caused by overtopping of existing dams, and erosion occurring in emergency spillway applications.

To reduce detrimental impacts on water users, geomembrane installations are typically performed in the fall and winter when water demands are at a minimum level. Unfortunately, this timing results in the direct exposure of the material to cold temperature extremes and an increased susceptibility to damage during installation. Additionally, in applications like seepage control for dams and canals, geomembranes either have been buried with minimal earth cover or left exposed to the ambient environment. For the covered case, Reclamation requires a protective layer of 300 to 450 mm (12 to 18 in) of cover soil to protect the geomembrane from damage caused by animal traffic, vandalism, and ultraviolet radiation. The soil is not designed for frost penetration protection. Thus, geomembranes in both covered and exposed situations are subjected to a wide variety of freeze-thaw cycles.

Insofar as environmental applications, geomembranes are used in landfill caps and surface impoundments. In freezing climates, the geomembranes will experience freeze-thaw cycles unless the depth of cover soil is greater than the maximum frost penetration depth, which ranges from 0 to 3.0 m (10 ft) in the continental United States. As with canals, geomembranes in surface impoundments are often left uncovered or with only a thin veneer of cover soil.

As stated above, geomembranes will be subjected to freeze-thaw cycles in many situations. However, the impact of such cyclic temperature effects on the long-term behavior of geomembranes is largely unknown. In this research project, the effects of freeze-thaw cycling on the tensile behavior of 19 different types of geomembrane sheets and 31 combinations of seams were investigated. The study consisted of four parts using different experimental conditions:

Part I — Incubating unconstrained geomembrane sheet and seam specimens to freeze-thaw cycles between -20 °C and +20 °C and then performing tensile tests at +20 °C. The maximum number of cycles was 200.

Part II — Incubating unconstrained geomembrane sheet and seam specimens to freeze-thaw cycles between -20 °C and +20 °C and then performing tensile tests at -20 °C. The maximum number of cycles was 200.

Part III — Incubating constrained geomembrane sheet and seam specimens to freeze-thaw cycles between -20 °C and +30 °C and then performing tensile tests at +20 °C. The maximum number of the cycles was 500.

Part IV Evaluating the tensile induced cyclic stress acting on the constrained geomembrane sheet and seam specimens while the incubation temperature changed from -20 °C to +30 °C under the Part III experimental conditions.

The tensile test data were analyzed graphically by plotting percent change of tensile strength and elongation from the incubated material versus the number of freeze-thaw cycles.

CONCLUSIONS

For the effects of freeze-thaw cycles on geomembrane sheets and seams, test results showed no statistically significant change in any of the tested materials in Parts I, II, and III of the study.

The cold temperature induced tensile stress of constrained tested specimens was evaluated in Part IV of the study. The magnitude of the induced stress was the same for each polymer type regardless of the thickness, surface features, and seam types. The repeatability of the induced stress suggested that the constrained specimens in Part III of the study were subjected to the same magnitude of stress in each cold cycle of the freeze-thaw cycling.

Thus, tested specimens in Part III were exposed to both freeze-thaw cycling and thermally induced cyclic stresses. The tensile behavior of the geomembrane sheets and seams was not affected in a statistically significant manner after 500 cycles.

The effects of cold temperature testing were investigated by comparing Part II to Part I of the study. As anticipated, the strength of sheet and seam specimens increased and the elongation decreased.

The impact of cold temperature induced cyclic stress on the constrained geomembrane sheets and seams was examined by comparing Part III to Part I. No statistically significant difference existed between the two sets of data.

The general conclusion of the various parts of this study is that currently available geomembranes and their respective seaming methods are not sensitive to freeze-thaw cycling under constrained and unconstrained conditions within the limits of this study. However, as anticipated, a gradual stiffening of the geomembrane materials will occur with decreasing temperature. Thus, the cold temperature tensile behavior should be evaluated if the material is used in a sub-ambient environment.

LITERATURE REVIEW

The study of cold temperature effects on geomembranes (and their seams) can be considered in two different categories. The first is the sustained cold temperature effect on the stress/strain properties of the materials. Several studies are available on this topic. The second is the effect of freeze-thaw cycling on the subsequent stress/strain properties of the material. Only a few studies are available on this topic. Most of the studies in these two categories have been conducted on geomembranes that are no longer currently available. Thus, the data are of limited value but will nevertheless be reviewed so as to gain perspective for the work to follow.

Early Canadian Studies

In the 1970s, petroleum companies began investigating the possibility of using geomembranes in the construction of the spill containment areas and dike walls in northern Canada. At some sites where geomembranes were installed, the Canadian EPS (Environmental Protection Service) performed inspections. A report by Thornton and Blackall (1976) describes their concerns for geomembranes in cold regions.

Seven sites were investigated in the Mackenzie Delta (a section of the Canadian Western Arctic) where geomembranes had been installed by four different companies. Two main concerns were expressed for geomembranes used in such applications. The importance of cushioning material above and below geomembranes to prevent puncturing was discussed. The authors also noted that this cushion is less important for materials with high puncture resistance. They then discussed the ductile-brittle transition temperature of geomembranes. For fall, winter, and spring geomembrane installations (as are most Reclamation installations), they recommended using materials with "good" low temperature ductility. They pointed out that for oil resistant PVC geomembranes, the ductile to brittle transition temperature was -18 °C in the laboratory, but the same material showed brittle fractures at 5 °C in the field. They surmised that this apparent upward shift in the ductile-brittle transition temperature was caused by tensile strain imposed on the liner in its field application.

Of the seven sites inspected by EPS in the Thornton and Blackall (1976) report, only one used a type of geomembrane that is currently available. They evaluated a 0.25-mm (10-mil) thick polyethylene liner that was placed over a gravel base. A 900-mm (35-in) thick cushion of polyurethane foam was placed between the liner and the base. A fine gravel cover was placed directly over the geomembrane. Upon inspection, this site showed no punctures or other damage to the relatively thin geomembrane.

Effects of Sustained Cold Temperatures on Geomembranes

Rollin et al. (1984) conducted a study to evaluate different geomembranes for use in dams and dikes in northern climates. They determined that geomembranes in the field could be exposed to a temperature variation of 23 °C to -35 °C. The geomembranes would be exposed to subfreezing temperatures throughout the winter and to freeze-thaw cycles during fall and spring. Laboratory testing was conducted on 21 types of geomembranes at 23 °C, -5 °C, -15 °C, -25 °C, and -35 °C. The types of geomembranes that were tested included elastomers, bitumens, and thermoplastics. The incubated geomembranes were evaluated for tensile and burst strength, puncture resistance, and friction resistance. The results for thermoplastics showed tensile strength increasing with decreasing test temperatures. At 23 °C, the thermoplastics showed lower strengths than elastomers and bitumens, but at -35 °C, the thermoplastics showed higher strengths than the elastomers and bitumens. At -35 °C, the elastomers remained the most ductile material. Also, at -35 °C, -15 °C, and +23 °C, the strength of thermoplastic seams was slightly higher than the sheet strength.

Richards et al. (1985) also performed a study of cold temperature effects on geomembranes. They tested 0.5-mm (20-mil) and 0.8-mm (30-mil) PVC (polyvinyl chloride), 0.5-mm (20-mil) cold formulated PVC, 1.9-mm (75-mil) HDPE (high density polyethylene), and 0.8-mm (30-mil) CPE (chlorinated polyethylene) geomembranes. Strips in the form of 150 by 25 mm (6 by 1 in) were used for tensile strength at temperatures of 23 °C, -7 °C, and -26 °C. The

PVC geomembranes showed an increase in breaking stress and a decrease in breaking strain with decreasing temperatures. The CPE showed a slight increase in break stress and a decrease in break strain between 23 °C and -7 °C and generally behaved similarly to PVC. At -26 °C, the CPE behavior changed, showing an intermediate peak (or yield point) and then an increase in break stress and a decrease in break strain with the decreased temperature. The HDPE geomembranes showed a similar increase in yield and break stress and a decrease in yield strain. However, the break strain showed an increase at -7 °C and a decrease at -26 °C. Regarding the modulus, the PVC and CPE geomembranes showed an increase with decreasing temperature. The HDPE geomembranes showed no change.

A cold temperature laboratory study was performed by LaFleur et al. (1985). Their testing included a 1.7-mm (65-mil) CSPE (chlorosulfonated polyethylene) and a 1.8-mm (70-mil) PVC composite. Each membrane was adhesively bonded to a needle-punched, nonwoven geotextile. Seamed samples were also included. The results showed that the percentage of stress carried by the geomembrane portion increased with decreasing temperature until failure occurred at about -35 °C. They determined that the strength contribution of the geotextile portion was not significantly changed at low temperatures. Thus, the low temperatures resulted in higher strength in the geomembranes but not in the geotextiles.

A study by Peggs et al. (1990) included laboratory cold temperature testing on HDPE. Tensile testing was performed at 25 °C and -30 °C, and burst tests were performed at 25 °C, -26 °C, and -38 °C. The tensile tests showed increases in yield and break strength and decreases in the yield and break elongation at the low temperature. Burst testing also showed increasing strength at decreasing temperatures.

Giroud et al. (1993) tested HDPE at both low and high temperatures. Geomembrane thicknesses from 0.5 to 3.0 mm (20 to 120 mil) and from five different manufacturers were tensile tested in dumbbell shape according to ASTM D 638 at 50 mm/min (2 in/min). As in Richards et al. (1985) and Peggs et al. (1990), these results showed an increase in yield stress and a decrease in yield strain with decreases in temperature. Similar results were obtained for textured HDPE geomembranes.

Effects of Freeze-Thaw Cycling on Geomembranes

The cold temperature study by LaFleur et al. (1985) included freeze-thaw testing. The following seamed geomembranes were strained to 10-percent strain, subjected to 150 freeze-thaw cycles, and then tensile tested: solvent seamed EPDM (ethylene propylene diene monomer), solvent seamed isobutylene rubber, solvent seamed CSPE, and hot air seamed PVC. None of the specimens showed a decrease in strength because of the freeze-thaw cycling. It was concluded that the seams were not affected by the freeze-thaw cycling.

Hsuan et al. (1993) and Comer et al. (1995) presented the early portions of freeze-thaw test data from this study. Results of the first 50 freeze-thaw cycles in Parts I, II, and III of the study were included in both papers. They will be presented later in this report.

Budiman (1994) conducted a freeze-thaw study of 1.0-, 1.5-, and 2.0-mm (40-, 60- and 100-mil) HDPE geomembranes. Square samples of 300-mm (12-in) size were subjected to freeze-thaw cycles under both restrained and unrestrained conditions. The modes of restraint were the following: cross-machine direction restrained, machine direction restrained, and both the cross-machine direction and the machine direction strained. One freeze-thaw cycle consisted

of 12 hours at 65 °C and 12 hours at -20 °C. After incubation, the samples were cut into dumbbell shaped specimens for tensile testing. As-received specimens were tested as well as incubated specimens from 1, 5, 30, 60, and 150 freeze-thaw cycles. Testing was conducted at 20 °C, 0 °C, -10 °C, and -20 °C.

With respect to cold temperature testing effects, the Budiman (1994) results showed patterns of increasing strength at yield and break and decreasing strain at yield and break with decreasing testing temperature for all specimens. These results are similar to other studies mentioned in the previous section. The type of restraint used during incubation of the samples was found to "have no impact on the characteristics of the stress-strain diagrams" for any of the samples at any test temperature. The freeze-thaw cycling was determined to have had "no detrimental effect on the tensile load-elongation characteristics" of the specimens. Furthermore, Budiman (1994) concluded that "HDPE can be safely said to survive and perform acceptably for a long period of time under conditions involving repetitive temperature fluctuations within the range of -20 °C to 60 °C.

Although the above referenced studies showed no freeze-thaw effects, many of the geomembranes involved in these studies are not currently used by Reclamation, nor do they appear in designs evaluated by the EPA. Furthermore, the seaming was of different and largely unknown methods. Lastly, the studies referenced were not systematic in that cross-over analyses could not be made from one to another. Thus, this testing program was felt to be necessary.

TEST MATERIALS

This study involved 19 different sheet materials and 31 seam types. All are commercially available and are used on Reclamation and EPA projects.

Geomembrane Types

Seven different resin types were studied in this research. All are thermoplastic and currently available from a number of manufacturers. They are as follows: PVC (polyvinyl chloride), VLDPE (very low density polyethylene), HDPE (high density polyethylene), fPP (flexible polypropylene), CSPE (chlorosulfonated polyethylene), EIA (ethylene interpolymer alloy) and FCEA (fully crosslinked elastomeric alloy).

Additives which varied according to the type of polymer included: plasticizers, stabilizers, and fillers. Plasticizers are used to make PVC flexible by lowering the glass transition temperature. Stabilizers used in HDPE, VLDPE, and fPP commonly refer to antioxidants and UV (ultraviolet) protectors. Antioxidants protect polymers against oxidative degradation. UV protectors such as carbon black help to prevent UV damage. Fillers used in PVC and CSPE are incorporated to lower manufacturing costs and to increase flexibility.

Other ways in which geomembranes can be varied besides their composition include thickness, texture, and reinforcement. Because of such differences, 19 geomembrane sheet types were included in Parts I and III of the study. Only 6 of the 19 geomembranes were selected to be included in Part II. Part IV of the study used 12 different geomembranes. Table 1 lists the various types of geomembranes.

Table 1. - Type of geomembrane sheets and seams.

Part(s) of Study	Sample No.	Geomembrane Type (i.e., Polymer)	Thickness* (mm)	Style	Seam Type
I, II, III, IV	1(a)	PVC-R cold temperature formula	1.1	Scrim reinforced	Chemical
I, II, III	1(b)				Hot Wedge
I, III	2(a)	PVC	0.5	Smooth	Chemical
I, III, IV	2(b)				Hot Wedge
I, III	2(c)				Dielectric
I, II, III	3(a)	PVC	1.0	Smooth	Chemical
I, II, III, IV	3(b)				Hot Wedge
I, II, III	3(c)				Dielectric
I, II, III	4	VLDPE	1.0	Smooth	Hot Wedge
II, IV	4(a)				Fillet Extrusion
I, II, III	5	VLDPE	1.0	Textured	Hot Wedge
II	5(a)				Fillet Extrusion
I, III, IV	6	VLDPE	1.5	Smooth	Hot Wedge
I, III, IV	7	VLDPE	1.5	Textured	Hot Wedge
I, III	8	HDPE	1.0	Smooth	Hot Wedge
I, III	9	HDPE	1.0	Textured	Hot Wedge
I, II, III, IV	10	HDPE	1.5	Smooth	Hot Wedge
II	10(a)				Fillet Extrusion
I, II, III, IV	11	HDPE	1.5	Textured	Hot Wedge
II	11(a)				Fillet Extrusion

Table 1. - Type of geomembrane sheets and seams (continued).

Part(s) of Study	Sample No.	Geomembrane Type (i.e., Polymer)	Thickness* (mm)	Style	Seam Type
I, III, IV	12	fPP	1.0	Smooth	Thermal
I, III, IV	13	fPP-R	1.1	Scrim reinforced	Hot Wedge
I, III	14(a)	CSPE-R	0.9	Scrim reinforced	Chemical
I, III, IV	14(b)				Thermal
I, III, IV	15(a)	EIA	0.8	Smooth	Chemical
I, III	15(b)				Thermal
I, III	16(a)	EIA-R	0.9	Scrim reinforced	Chemical
I, III	16(b)				Thermal
I, III	17	FCEA	0.8	Smooth	Thermal
I, III	18	FCEA-R	0.8	Geotextile supported	Thermal
I, III	19	EIA-R	0.8	Scrim coated	Thermal

* Because this study consists of relative behavior within the same sheet or seamed material, only nominal values of thickness were used.

Key to Abbreviations:

PVC = polyvinyl chloride
VLDPE = very low density polyethylene
HDPE = high density polyethylene
fPP = flexible polypropylene
CSPE = chlorosulfonated polyethylene
EIA = ethylene interpolymer alloy
FCEA = fully crosslinked elastomeric alloy

t = textured
R = scrim reinforced

Seam Types

The above mentioned geomembranes were seamed using various seaming techniques. All seaming was performed by the geomembrane manufacturer that made the respective sheet or fabricators that made the respective panels. Five seaming techniques were used in this study: chemical seams, hot wedge seams, fillet extrusion seams, hot air seams (thermal seams), and dielectric seams. Figure 1 shows schematic diagrams of the seams. Parts I and III included 27 different combinations of seams. Part II included 13 seams, and Part IV included 12 seams. The various seam types are listed in table 1.

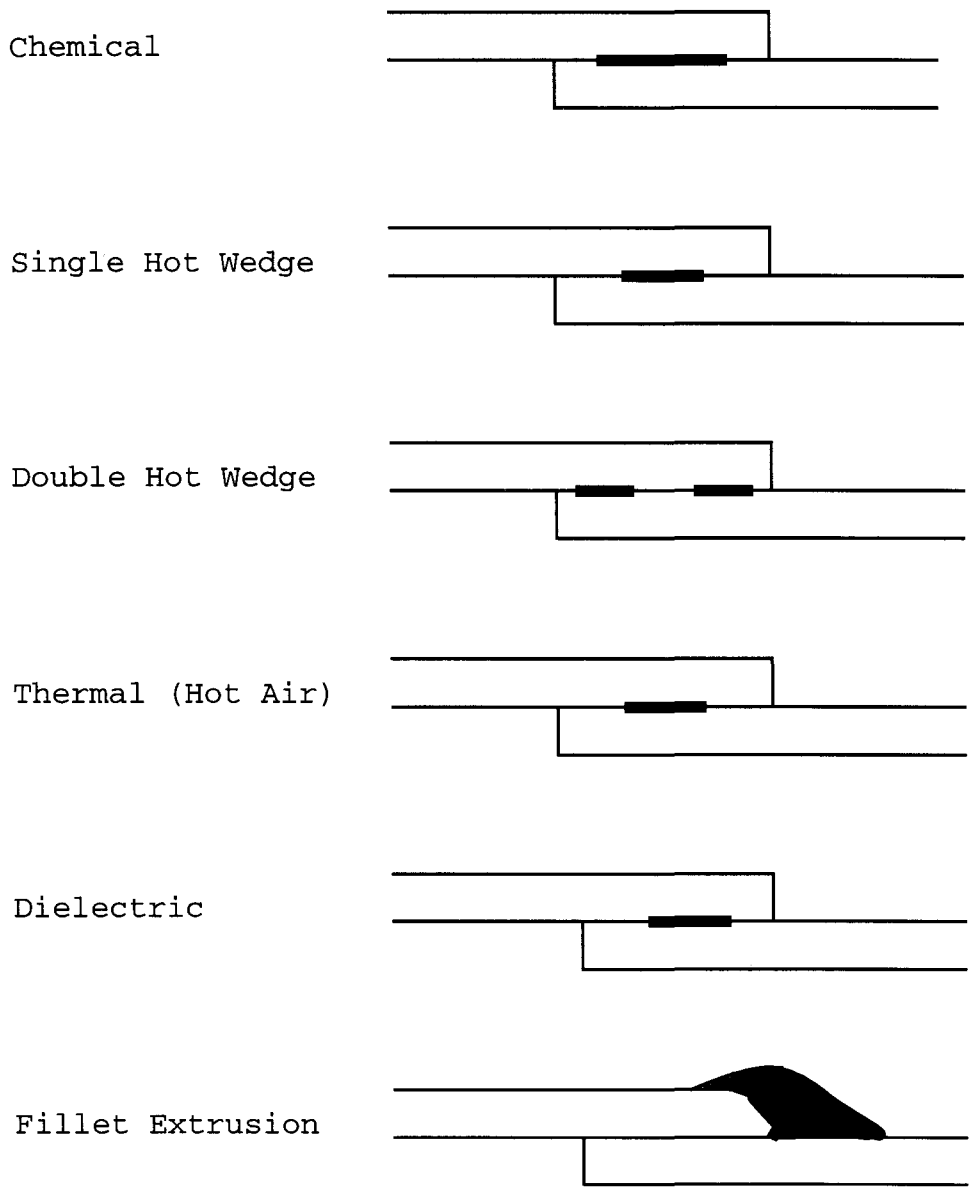

Figure 1. - Schematic diagrams of various geomembrane seams.

EXPERIMENTAL DESIGN

Sheet and seam samples from the respective manufacturers were cut into rectangular shaped specimens 25 mm (1.0 in) wide by 150 mm (6 in) long. Three specimens were included in each set for each designated test cycle.

The four parts of the study each had a different experimental design. Parts I, II, and III involved subjecting test specimens to a series of freeze-thaw cycles under different stress conditions and testing conditions as shown in table 2. Part IV was to investigate the cold temperature induced tensile stress. The specifics of each part are described in sections to follow.

Table 2. - Experimental design of different parts of study.

Part	Cyclic Temperature Range	Maximum Cycles	Incubation Condition	Tensile Test Temperature
I	+20 °C to -20 °C	200	relaxed	+20 °C
II	+20 °C to -20 °C	200	relaxed	-20 °C
III	+30 °C to -20 °C	500	constrained	+20 °C
IV	+30 °C to -20 °C	2	relaxed	varied

Part I—Incubation and Testing

Part I of the study consisted of 19 geomembrane sheets and 27 seamed materials (see table 1) that were tested at room temperature after freeze-thaw incubation. The freeze-thaw cycles were created by placing the specimens in a household freezer set at -20 °C for about 16 hours. They were then removed to room temperature (about +20 °C) conditions for about 8 hours. All specimens were incubated in a dry condition. However, condensation was observed on the specimens inside the plastic bag that contained them during the thaw cycle. Thus, the specimens experienced some amount of wet/dry exposure.

Following a pre-defined number of freeze-thaw cycles, i.e., 1, 5, 10, 20, 50, 100, and 200, the specimens were dried and equilibrated at room temperature for 24 hours before being tested at room temperature (about +20 °C).

Part II—Incubation and Testing

Part II of the study consisted of a group of 6 geomembrane sheets and 13 seamed materials (see table 1) that were tested at -20 °C after freeze-thaw cycling between +20 °C and -20 °C. Once a pre-defined number of freeze-thaw cycles, i.e. , 1, 5, 10, 20, 50, 100, and 200, was reached, the specimens remained in the freezer until they were tested.

The -20 °C tensile tests were conducted inside an environmental chamber. The equipment configuration allowed both the test specimens and the test grips to be contained within the chamber. The interior of the chamber can be seen on figure 2. A set of 100-mm (4-in) box grips was used for the sheet and seam shear tests; a set of jaw grips was used for the seam peel tests. These grips are shown on figures 3 and 4. The height of the chamber was limited to 460 mm (18 in).

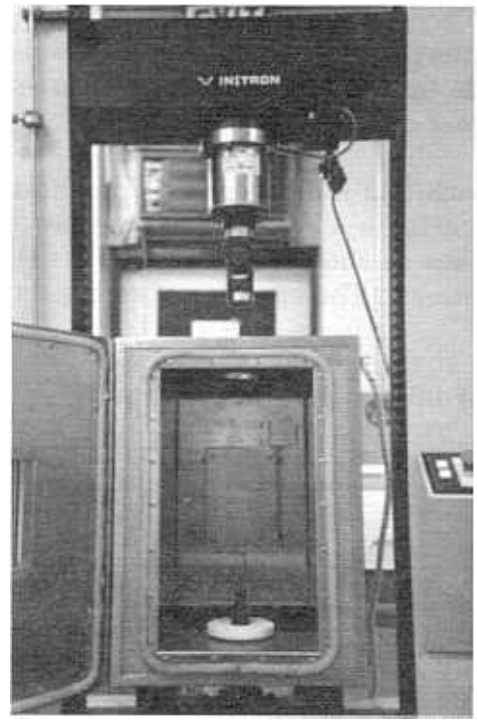

Figure 2. Environmental chamber used in Part II testing.

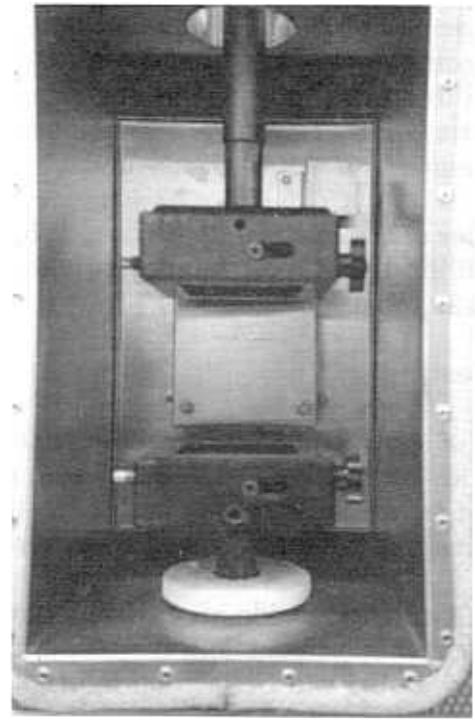

Figure 3. - Box grips used in Part II testing.

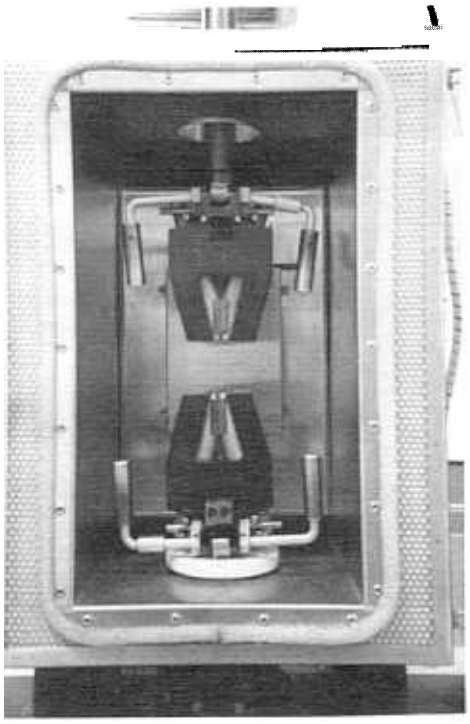

Figure 4. Jaw grips used in Part II testing.

The environmental test chamber was cooled by liquid nitrogen. Amounts of liquid nitrogen entering the chamber were controlled by a computerized temperature monitoring device. The chamber was set at -20 ±2 °C for testing. The specimens were taken directly from the -20 °C freezer into the cooled test chamber.

Part III—Incubation and Testing

In Part III of the study, test specimens consisted of the same group of 19 geomembrane sheet and 27 seam materials tested in Part I and listed in table 1. All specimens, however, were under a constant strain condition while they were subjected to freeze-thaw cycling in the environmental chamber.

Strips of 25-mm (1-in) wide geomembrane sheet or seam specimens were placed in metal racks designed to hold three sets of three specimens. Hence, each rack held 9 specimens as shown on figures 5 and 6. The amount of displacement that was induced into the specimens corresponded to 25 percent of the sheet peak load or seam shear peak load. Table 3 shows the displacement values for each type of sheet and seam specimen. The specimens were tensioned to their appropriate displacement length by tightening the upper grip of the rack as illustrated on figure 7. The racks with strained specimens were placed vertically in two holding boxes as seen on figure 8. These boxes were then placed in an environmental chamber as shown on figure 9. The incubation temperatures were set for 16 hours at -20 °C and 8 hours at +30 °C. It should be noted that the constrained specimens experienced an induced tensile stress while the chamber temperature decreased from +30 °C to -20 °C.

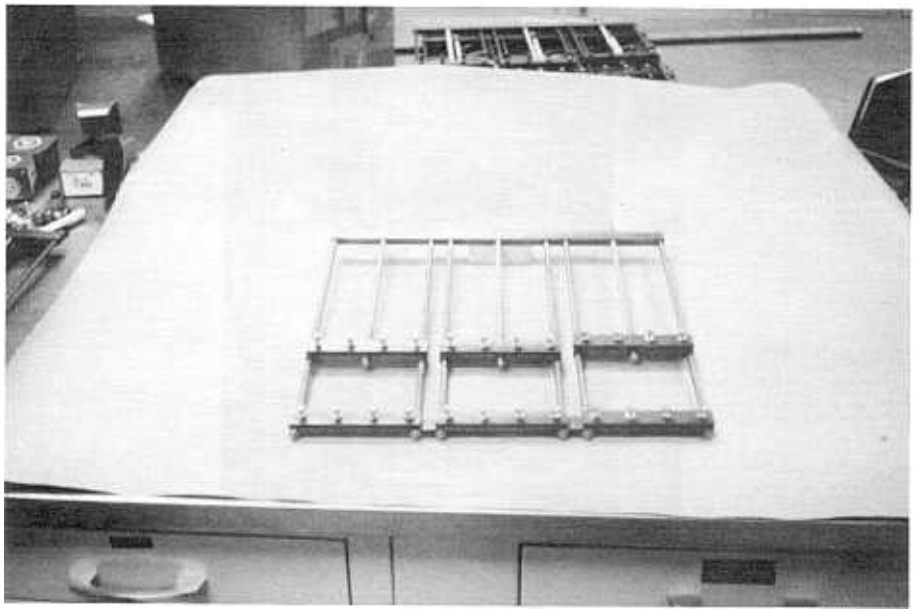

Figure 5. - Empty geomembrane holding racks used in Part III tests.

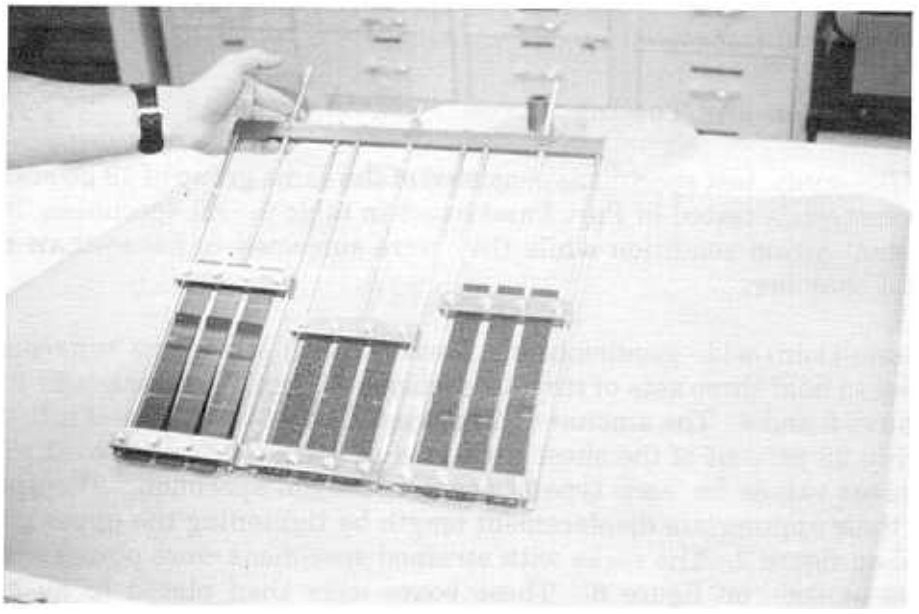

Figure 6. - Test specimen placed in geomembrane racks used in Part III tests.

Table 3. - Displacement values applied to the constrained specimens in Part III.

No.	Geomembrane (Polymer Type)	Thickness mm (mil)	Style	Seam Type	Displacement mm (inch)
1	PVC-R cold temp. formula	1.1 (45)	Scrim reinforced	Sheet	1.3 (0.05)
1(a)				Chemical	1.5 (0.06)
1(b)				Hot Wedge	1.3 (0.05)
2	PVC	0.5 (20)	Smooth	Sheet	14 (0.55)
2(a)				Chemical	13 (0.50)
2(b)				Hot Wedge	15 (0.60)
2(c)				Dielectric	17 (0.65)
3	PVC	1.0 (40)	Smooth	Sheet	12 (0.48)
3(a)				Chemical	20 (0.77)
3(b)				Hot Wedge	13 (0.50)
3(c)				Dielectric	10 (0.40)
4	VLDPE	1.0 (40)	Smooth	Sheet	1.7 (0.07)
				Hot Wedge	2.3 (0.09)
5	VLDPE	1.0 (40)	Textured	Sheet	2 (0.08)
				Hot Wedge	2.3 (0.09)
6	VLDPE	1.5 (60)	Smooth	Sheet	2 (0.08)
				Hot Wedge	2.3 (0.09)
7	VLDPE	1.5 (60)	Textured	Sheet	2 (0.08)
				Hot Wedge	2 (0.08)
8	HDPE	1.0 (40)	Smooth	Sheet	1.3 (0.05)
				Hot Wedge	1 (0.04)
9	HDPE	1.0 (40)	Textured	Sheet	1.5 (0.06)
				Hot Wedge	1 (0.04)
10	HDPE	1.5 (60)	Smooth	Sheet	1.5 (0.06)
				Hot Wedge	1.3 (0.05)
11	HDPE	1.5 (60)	Textured	Sheet	1.8 (0.07)
				Hot Wedge	1.5 (0.06)
12	fPP	1.0 (40)	Smooth	Sheet	2.8 (0.11)
				Thermal	2.5 (0.10)
13	fPP-R	1.1 (45)	Scrim reinforced	Sheet	2.5 (0.10)
				Hot Wedge	1.5 (0.06)

Table 3. - Displacement values applied to the constrained specimens in Part III (continued).

No.	Geomembrane Type (i.e. Polymer)	Thickness mm (mil)	Style	Seam Type	Displacement mm (inch)
14	CSPE-R	0.90 (36)	Scrim reinforced	Sheet	4.3 (0.17)
14(a)				Chemical	1.7 (0.07)
14(b)				Thermal	2.5 (0.1)
15	EIA	0.80 (30)	Smooth	Sheet	11 (0.45)
15(a)				Chemical	6.4 (0.25)
15(b)				Thermal	6.9 (0.27)
16	EIA	0.80 (30)	Scrim reinforced	Sheet	5.1 (0.20)
16(a)				Chemical	5.6 (0.22)
16(b)				Thermal	6.6 (0.27)
17	FCEA	0.80 (30)	Smooth	Sheet	2 (0.08)
				Thermal	1.7 (0.07)
18	FCEA	0.80 (30)	Fabric Supported	Sheet	2 (0.08)
				Thermal	1.5 (0.06)
19	EIA-R	0.80 (30)	Scrim Coated	Sheet	4.8 (0.19)
				Thermal	4.6 (0.18)

After the pre-defined number of freeze-thaw cycles, which were 1, 10, 50, 100, 200, and 500, the constrained specimens were removed from the racks, dried, and equilibrated at room temperature (about +20 °C) for at least 24 hours before being tested. Subsequently, they were tested at +20 °C.

Part IV—Testing

The purpose of Part IV of the study was to investigate the cold temperature induced tensile stress of the constrained specimens of the Part III tests during freeze-thaw cycles. Eight of the 19 geomembrane sheets and 8 of 27 geomembrane seams used in Part III were evaluated as listed in table 1. Test specimen strips 25 mm (1.0 in) wide were placed in the same type of grips and environmental chamber used in the Part II testing. Each specimen was elongated under a constant strain rate to the pre-determined displacements listed in table 3. Once the elongation was reached, the specimen was locked into position. Simultaneously, the load and time were recorded until the test was terminated. The specimen was equilibrated at room temperature (about +20 °C) for a half hour. It was then heated to 30 °C for 12 hours. The chamber temperature was then cooled to -20 °C for 2 hours and then was increased to +30 °C for 2 hours. The -20 °C and +30 °C temperature cycle was repeated a second time before the test was concluded. Figure 10 illustrates the temperature versus time profile of the test.

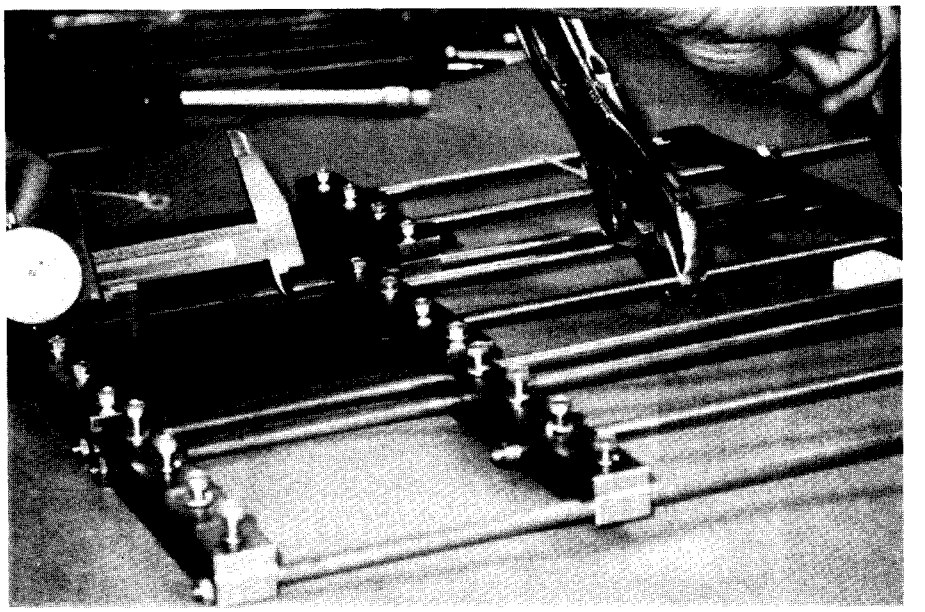

Figure 7. - Method of applying tensile load to test specimens in Part III tests.

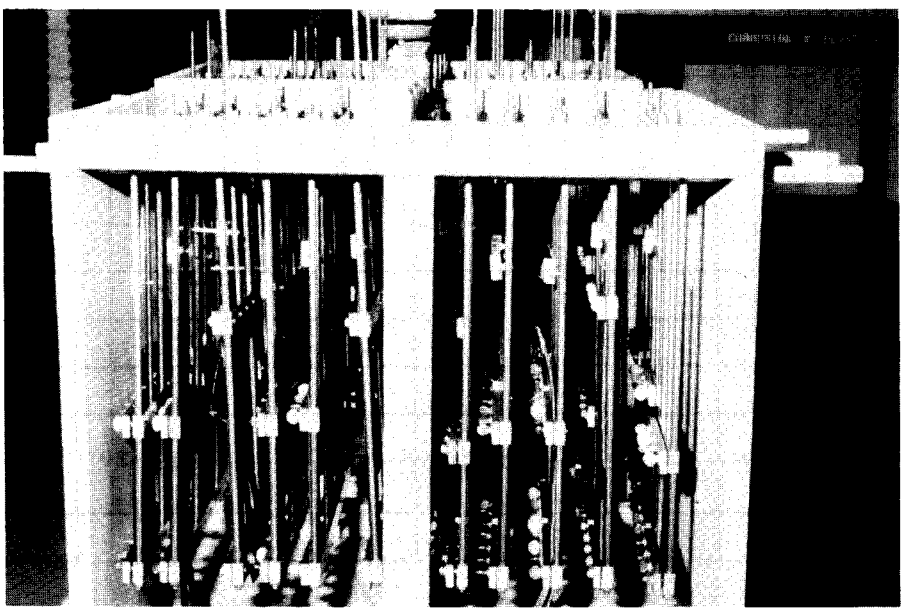

Figure 8. - Geomembrane racks in holding box used in Part III tests.

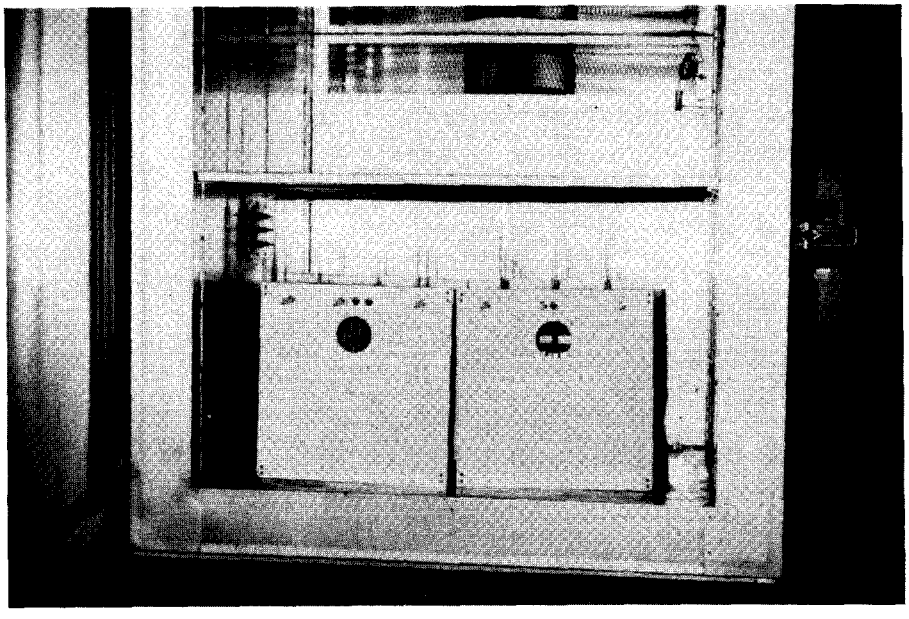

Figure 9. - Environmental chamber used in Part III tests.

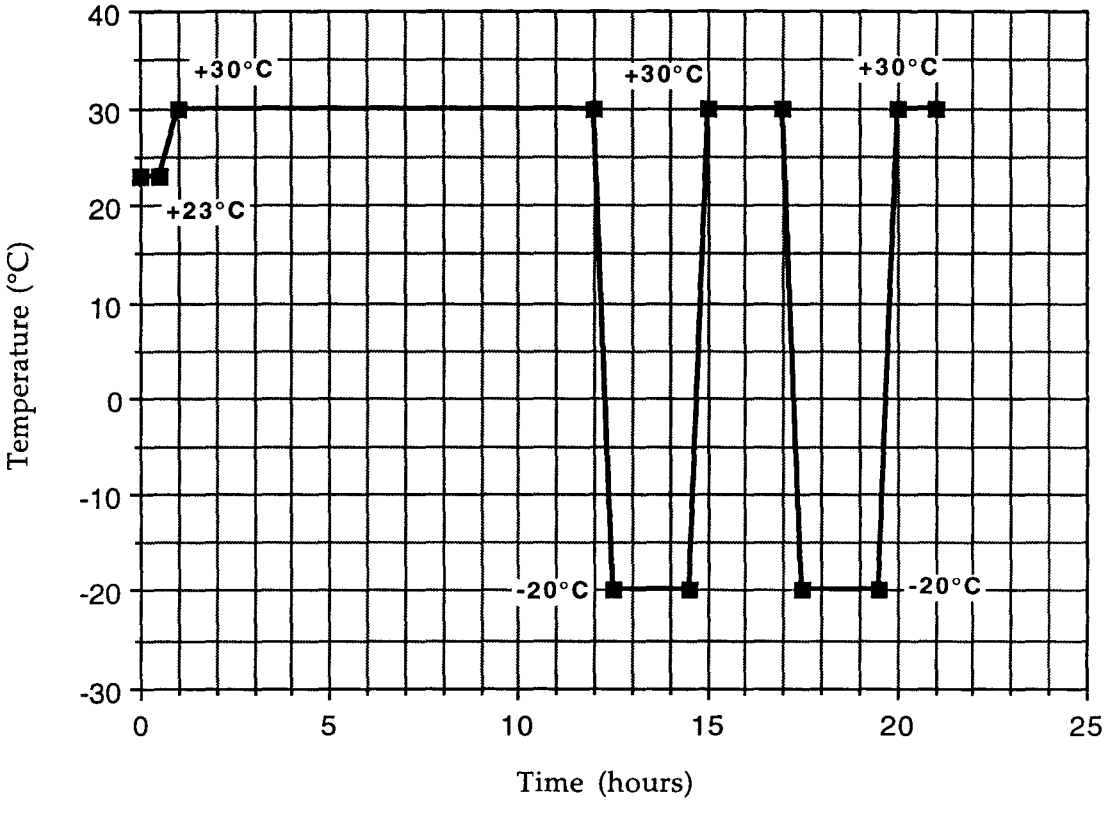

Figure 10. - Temperature profile of Part III tests.

The following items were investigated in this Part IV study:

- The stress relaxation behavior was determined within the first 12 hours after the predetermined strain was applied to the specimen at room temperature.
- The magnitude of the induced stress was calculated as the temperature decreased from +30 °C to -20 °C.
- The magnitude of the induced stress was determined for each freeze-thaw cycle.

TENSILE TEST METHODS

The geomembrane sheet tensile tests for Parts I, II, and III were evaluated using either 25-mm (1.0-in) strip or dumbbell shaped test specimens. Uniform 25-mm (1.0-in) strips were used for both seam shear and peel tensile tests. It should be noted that certain variations of current practice in sheet and seam testing were made. However, testing within a given material was consistent throughout, hence the resulting comparisons should be valid.

Tensile Tests for Geomembrane Sheets

Strip tensile tests were performed on PVC, CSPE, EIA, and FCEA test specimens. Dumbbell tensile tests were performed on VLDPE, HDPE, and fPP test specimens. Both the strip and dumbbell tensile test procedures followed NSF (National Sanitation Foundation) Standard No. 54 recommendations. ASTM D882 and ASTM D638 Type VI specimens are recommended for strip tensile tests of non-reinforced geomembranes and dumbbell specimens, respectively. Those materials not presently included in the standard were tested using methods for similar materials. Thus, fPP was tested under the same conditions as VLDPE; whereas, the EIA and FCEA were evaluated in the same way as PVC. All scrim reinforced geomembrane sheet specimens were tested using a 25-mm (1-in) wide strip test instead of the customary 100-mm (4.0-in) grab tensile test. All strip tests were performed using 100-mm (4.0-in) gage length and a 5-mm/sec (12-in/min) strain rate. Details of the tensile test procedures are given in table 4.

Shear Tests for Geomembrane Seams

The test procedure for seam shear strength followed NSF No. 54 recommendations. ASTM D3803 was used to test PVC, EIA, and FCEA geomembrane seams. HDPE, VLDPE, and fPP seams were tested according to ASTM D4437, but a strain rate of 8.5-mm/sec (20-in/min) was used for testing VLDPE and fPP. For reinforced materials, a 25-mm (1.0-in) wide strip tensile test was used instead of the 100-mm (4.0-in) grab tensile test, thus following the same procedure as the sheet test. Table 4 contains details of the seam shear tests.

Peel Tests for Geomembrane Seams

The test procedures for peel strength of seams generally followed NSF No. 54 recommendations. ASTM D4437 was used to test HDPE, VLDPE, and fPP; however, a strain rate of 8.5-mm/sec (20-in/min) was used for testing VLDPE evaluated in Part I. All other materials were tested according to ASTM D413. Because NSF No. 54 does not recommend the gage length for any of the tests, the 25-mm (1.0-in) gage length which is defined in ASTM D4437 was used throughout. Table 4 contains details of the seam peel tests.

Table 4. - Test conditions for geomembrane sheet tensile test and shear and peel seam tests.

Sample		Sheet Tensile Tests			Seam Type	Seam Tests			
						Shear Test		Peel Test	
No.	Material	Specimen Shape	Strain Rate mm/sec. (in./min)	Gage Length mm (in.)		Strain Rate mm /sec (in./min)	Gage Length mm (in.)	Strain Rate mm/sec (in./min)	Gage Length mm (in.)
1(a)	PVC-R (cool temperature)	strip	5.0 (12)	100 (4.0)	Chemical	5 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
1(b)					Hot Wedge	5 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
2(a)	Smooth PVC	strip	8.5 (20)	50 (2.0)	Chemical	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
2(b)					Hot Wedge	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
2(c)					Dielectric	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
3(a)	Smooth PVC	strip	8.5 (20)	50 (2.0)	Chemical	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
3(b)					Hot Wedge	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
3(c)					Dielectric	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
4	Smooth VLDPE	dumbbell	8.5 (20)	64 (2.5)	Hot Wedge	8.5 (20)	100 (4.0)	0.8 (2.0)*	25 (1.0)
5	Textured VLDPE	dumbbell	8.5 (20)	64 (2.5)	Hot Wedge	8.5 (20)	100 (4.0)	8.5 (20)*	25 (1.0)
6	Smooth VLDPE	dumbbell	8.5 (20)	64 (2.5)	Hot Wedge	8.5 (20)	100 (4.0)	8.5 (20)*	25 (1.0)
7	Textured VLDPE	dumbbell	8.5 (20)	64 (2.5)	Hot Wedge	8.5 (20)	100 (4.0)	8.5 (20)*	25 (1.0)

* In Part III study a strain rate of 0.8 mm/sec (2.0 in/min) was used for all peel tests.

Table 4. - Test conditions for geomembrane sheet tensile test and shear and peel seam tests (continued).

Sample		Sheet Tensile Test			Seam Type	Seam Tests			
						Shear Test		Peel Test	
No.	Material	Specimen Shape	Strain Rate mm/sec. (in./min)	Gage Length mm (in.)		Strain Rate mm/sec. (in./min)	Gage Length mm (in.)	Strain Rate mm/sec. (in./min)	Gage Length mm (in.)
8	Smooth HDPE	dumbbell	0.8 (2.0)	64 (2.5)*	Hot Wedge	0.8 (2.0)	100 (4.0)	0.8 (2.0)	25 (1.0)
9	Textured HDPE	dumbbell	0.8 (2.0)	64 (2.5)*	Hot Wedge	0.8 (2.0)	100 (4.0)	0.8 (2.0)	25 (1.0)
10	Smooth HDPE	dumbbell	0.8 (2.0)	64 (2.5)*	Hot Wedge	0.8 (2.0)	100 (4.0)	0.8 (2.0)	25 (1.0)
11	Textured HDPE	dumbbell	0.8 (2.0)	64 (2.5)*	Hot Wedge	0.8 (2.0)	100 (4.0)	0.8 (2.0)	25 (1.0)
12	fPP	dumbbell	8.5 (20)	64 (2.5)	Thermal	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
13	fPP-R	strip	5.0 (12)	100 (4.0)	Hot Wedge	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
14(a)	CSPE-R	strip	5.0 (12)	100 (4.0)	Chemical	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
14(b)					Thermal	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
15(a)	Smooth EIA	strip	8.5 (20)	100 (4.0)	Chemical	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
15(b)					Thermal	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
16(a)	EIA-R	strip	5.0 (12)	100 (4.0)	Chemical	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
16(b)					Thermal	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
17	Smooth FCEA	strip	8.5 (20)	100 (4.0)	Thermal	8.5 (20)	100 (4.0)	0.8 (2.0)	25 (1.0)
18	FCEA-R (fabric support)	strip	5.0 (12)	100 (4.0)	Thermal	5.0 (12)	100 (4.0)	0.8 (2.0)	25 (1.0)
19	EIA-R (scrim coated)	strip	5.0 (12)	100 (4.0)	Thermal	5.0 (12)	100 (4.0)	no test	no test

* The gage length used to calculate the percent elongation values was 33 mm (1.3 in.)

EFFECTS OF FREEZE-THAW CYCLING ON THE TENSILE BEHAVIOR OF GEOMEMBRANE SHEETS AND SEAMS

In this section, the tensile test results of Parts I, II, and III of the study are analyzed and presented. All parts focus on the effect of freeze-thaw cycling on the particular geomembrane sheets and seams stated earlier.

Data Analysis Approach

The potential effect of freeze-thaw cycling on the various geomembrane sheet and seam specimens was evaluated based on the magnitude of percent change of the specific measured property from its corresponding initial value. In Part I, the initial values were the test results of non-incubated original sheet and seam specimens. In Part II, the initial values were data of non-incubated sheet and seam specimens that were obtained by testing at -20 °C temperature. For Part III, the initial values were data of the first freeze-thaw cycle. These data were used because it was necessary to compare specimens that were also constrained.

The tensile properties of geomembrane sheets that were used in the analyses are listed in table 5. For seam specimens, shear and peel strength values were examined.

For each examined property, the percent change was plotted against the logarithm of number of freeze-thaw cycles (fig. 11). In addition to the average value, the maximum and minimum values of the three tests conducted at each freeze-thaw cycle were displayed as indicated by the solid squares on figure 11. As expected, the length of the error bar varies because of the following factors:

- variation in the geomembrane material
- variation in the seaming process (for seams)
- variation in the cutting of test samples or test specimens
- variation in the number of yarns per sample (for reinforced materials)

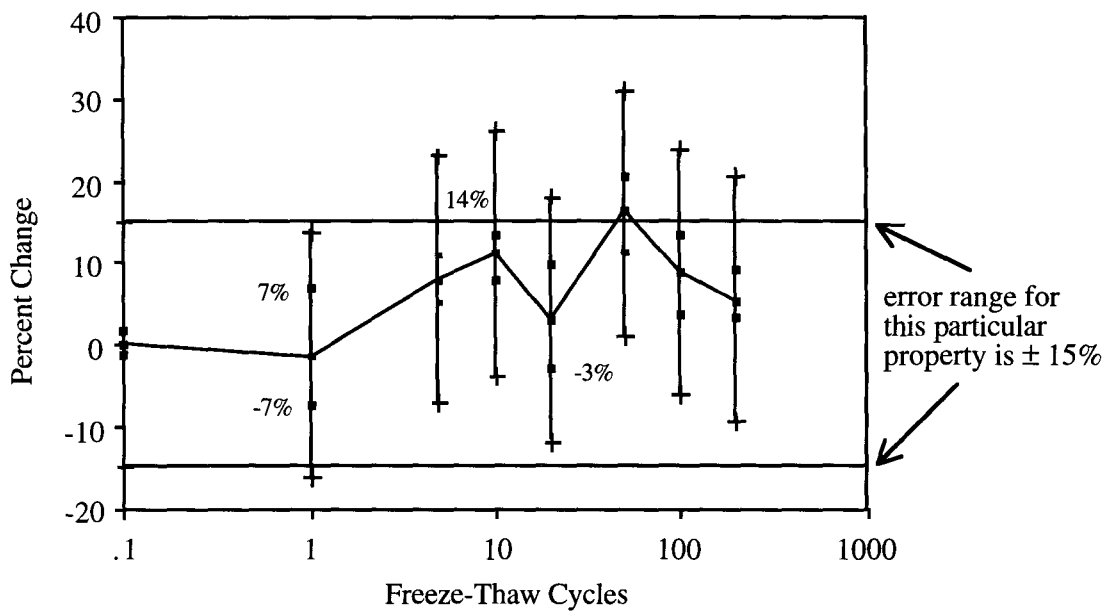

Figure 11. - Illustrating the data analysis to obtain the total error range.

Table 5. - Tensile properties of geomembrane sheets being evaluated.

No	Geomembrane Type	Thickness mm (mil)	Sheet Tensile Property
1	PVC-R cold temperature formula	1.1 (45)	Peak Strength Peak Elongation
2	PVC	0.5 (20)	Break Strength Break Elongation
3	PVC	1 (40)	Break Strength Break Elongation
4	VLDPE	1(40)	Break Strength Break Elongation
5	VLDPE-Textured	1 (40)	Break Strength Break Elongation
6	VLDPE	1.5 (60)	Break Strength Break Elongation
7	VLDPE-textured	1.5 (60)	Break Strength Break Elongation
8	HDPE	1 (40)	Yield Strength Yield Elongation
9	HDPE-textured	1 (40)	Yield Strength Yield Elongation
10	HDPE	1.5 (60)	Yield Strength Yield Elongation
11	HDPE-textured	1.5 (60)	Yield Strength Yield Elongation
12	fPP	1(40)	Break Strength Break Elongation
13	fPP-R	1.1 (45)	Peak Strength Peak Elongation
14	CSPE-R	0.9 (36)	Peak Strength Peak Elongation
15	EIA	0.8 (30)	Break Strength Break Elongation
16	EIA-R	0.9 (36)	Peak Strength Peak Elongation
17	FCEA	0.8 (30)	Break Strength Break Elongation
18	FCEA-R (textile supported)	0.8 (30)	Peak Strength Peak Elongation
19	EIA-R (scrim coated)	0.8 (30)	Break Strength Break Elongation

It should be noted that none of the ASTM test methods used has an associated established precision and bias statement. In addition, only three tests were performed at each cycle; therefore, a rigorous statistical analysis could not be performed. Hence, the error limits for each graph were arbitrarily developed. For each graph, two sources of variation were considered; they were caused by internal and external factors. The summation of the two factors was considered to be the upper and lower error limits. The cumulative limits were used as the reference to define a possible changing trend. The two variations are described as follows:

1. Internal variation - This type of variation was represented by the error bar of each freeze-thaw cycle. It included variations in material, seaming process (for seams), specimen preparation, and incubation error associated with these features. For each evaluated property, the largest error bar was selected because this variation was the greatest possible of the three tests.

2. External variation - This variation was reflected by the magnitude of fluctuation in the data. It was based on the assumption that changes in the polymer structure or seam structure were not reversible as the number of freeze-thaw cycles increased. This variation probably was attributable to the test environment, such as temperature, humidity, and machine and human error associated with these features.

As an illustration of the above variations, the largest error bar on figure 11 occurs at the first cycle, where maximum and minimum values of +7 and -7 percent are seen. The total is 14 percent, which is the greatest internal variation in the three replicate tests for this particular evaluated property, i.e., ±7 percent. For the external variation, the fluctuation in the data is from the maximum of the tenth cycle (14 percent) down to the minimum of the twentieth cycle (-3 percent). Hence, the maximum oscillation of the data caused by external variation is assumed to be 17 percent, i.e., ±8.5 percent. The summation of these two variations—internal (±7 percent) and external (±8.5 percent)—equals ±15.5 percent, which is considered to be the upper and lower error limit. Note that each data set could potentially have the same amount of total variation, in this case ±15.5 percent. Thus, this error range should be applied to every freeze-thaw set of data by adding 15 percent and subtracting 15 percent from the average value. Using this criterion on figure 11 results in the solid vertical line shown at each data set. Then, to consider a possible changing trend, the minimum or maximum value of any data set needs to fall outside the error range of the original data set. This error range is indicated by the two horizontal lines on figure 11 at either +15 percent or -15 percent. It can then be seen that all vertical lines have a portion falling within the error range of acceptability. Hence, the behavior shown on this curve would be judged as "no change."

In contrast, "change" is defined as when the percent change in the property being evaluated exceeds the error limits as described. These criteria were used to judge all of the response graphs.

RESULTS

Based on the analysis described above, the effects of freeze-thaw cycling in different incubation and test conditions are now presented.

Part I Results

This section presents the results of Part I of the study. After test specimens were exposed to a maximum of 200 freeze-thaw cycles in a relaxed condition, they were tested at +20 °C.

Tensile Tests of Geomembrane Sheets. - Nineteen different geomembrane sheets were evaluated. The analyzed percent change graphs are included as appendix A. The results show no change in either the peak strength or peak elongation of any of the tested materials.

Shear Tests of the Seams. - Twenty-seven geomembrane seams were evaluated in the shear mode. The analyzed percent change graphs are included as appendix B. The results show no change in shear strength of any of the tested seam materials. In addition, all seams passed typical QC/QA (quality control/quality assurance) criteria, i.e., they failed in the FTB (film tear bond) mode.

Peel Tests of the Seams. - Twenty-six different seams was evaluated for their peel strength. The analyzed percent change graphs are included as appendix C. The results show no change in peel strength of any of the tested seam materials. The majority of these peel tests passed typical QC/QA criteria. Although some of seams failed as non-FTB, they did fail in a manner consistent with the as-received to the 200th cycle. This result suggests that the non-FTB failure of these seams probably was not caused by freeze-thaw effects, rather, they were poorly fabricated seams from the start.

Part II Results

This section presents the results of Part II of the study. After test specimens were exposed to a maximum of 200 freeze-thaw cycles in a relaxed condition, they were then tested at -20 °C temperature.

Tensile Tests of Geomembrane Sheets. - Six different geomembranes were tested. However, it should be pointed out that ultimate breakage was not reached for VLDPE and HDPE materials because of the limited environmental chamber height. Thus, the initial peak strength and elongation were considered in the analyses. The analyzed percent change graphs are included as appendix D. The results show no change in either the peak strength or peak elongation of any of the tested materials.

Shear Tests of the Seams. - Twelve seams were tested in shear tensile mode. Similar to the sheet tensile tests, ultimate breakage was not reached for the VLDPE seams and HDPE seams because of the limited environmental chamber height. Thus, the initial peak strength and elongation were considered in the analyses. The analyzed percent change graphs are included as appendix E. The results show no change in shear strength of any of the tested seam materials. In addition, seams that failed all passed the typical QC/QA criteria, i.e., they failed in an FTB mode.

Peel Tests of the Seams. - Thirteen seams were tested in the peel mode. It should be pointed out that ultimate breakage was not reached for the VLDPE seams because of the limited environmental chamber height. On the other hand, HDPE seams were able to reach ultimate breakage. The analyzed percent change graphs are included as appendix F. The results show no change in peel strength of any of the tested seam materials. The majority of these peel tests passed typical QC/QA criteria, i.e., FTB mode. Although some of seams failed as non-FTB, they did fail in a consistent manner from the as-received to the 200th cycle. This result suggests that the non-FTB failure of these seams probably was not caused by freeze-thaw effects, rather, they were poorly fabricated seams from the start.

Part III Results

This section presents the results of Part III of the study. After the test specimens were exposed to a maximum of 500 freeze-thaw cycles in a constrained condition, they were then tested at +20 °C.

Tensile Tests of Geomembrane Sheets. - Nineteen different geomembranes were evaluated for tensile strength and elongation. The analyzed percent change graphs are included as appendix G. Sample 1, PVC-R, exhibited grip slipping during testing of the 500-cycle specimens; hence, their peak strength and elongation values were not detected. The results show no change in either the peak strength or peak elongation of any of the tested materials.

Shear Tests of the Seams. - Twenty-six different seams were tested for shear strength. The analyzed percent change graphs are included as appendix H. The results show no change in any of the seam shear strengths.

Peel Tests of the Seams. - Twenty-five seams were tested in the peel mode. The analyzed percent change graphs are included as appendix I. The results show no change in peel strengths of any of the tested seam materials. The majority of these peel tests passed typical QC/QA criteria. Although some of the seams did not fail as FTB, they did fail in a manner consistent with the as-received to the 500th cycle. This result indicates that the non-FTB failure of these seams was not caused by freeze-thaw effects, rather, they were poorly fabricated seams from the start.

COLD TEMPERATURE INDUCED TENSILE STRESS IN CONSTRAINED GEOMEMBRANE SHEET AND SEAM SPECIMENS

This section presents the results of the Part IV study. Eight of the 19 geomembrane sheets and 8 of the 27 geomembrane seams used in Part III were evaluated. Tests were performed by gripping the test specimen inside an environmental chamber in a tensile machine. A pre-defined displacement was introduced to the specimen using a constant strain rate. Once the displacement value was reached, the specimen was locked in that position. Simultaneously, the load values were recorded with time. The temperature of the specimen was changed following the temperature profile shown on figure 10. The data were presented by plotting load values versus time for both the geomembrane sheets and seams as shown on figure 12. Three items were investigated and they are presented as follows:

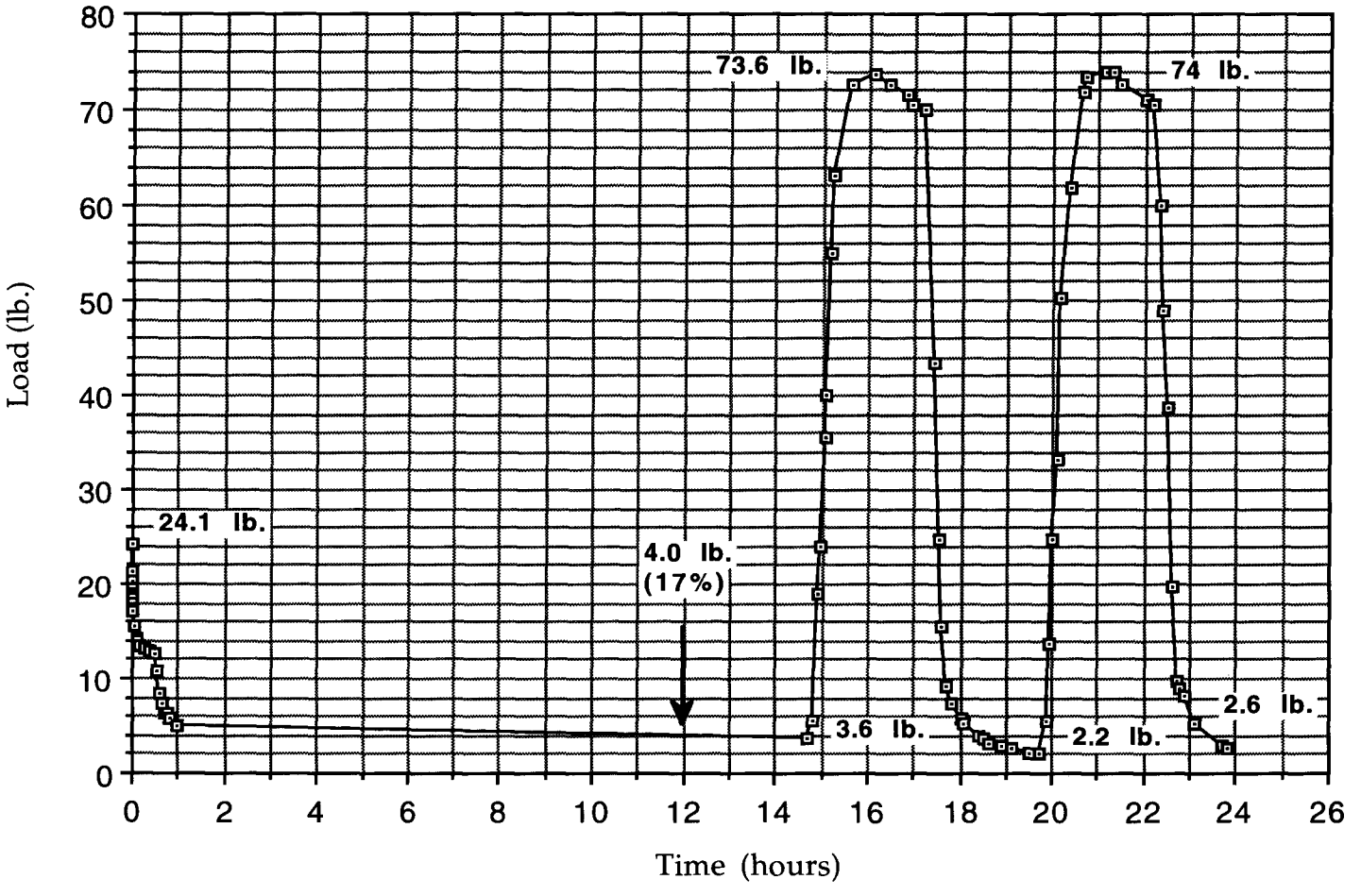

Figure 12. - An example of load versus time plot (1.5-mm [60-mil] HDPE-smooth sheet).

Stress Relaxation Within the First 12 Hours

The reduction of load with time within the first 12 hours of the experiment was evaluated to obtain insight into the stress relaxation behavior of different geomembrane sheets and seams. The load values were then converted to stress. For comparison purposes, the effects of variation in strain rate, gauge length, and displacement that were used in the tests were minimized by normalizing all stress data to the corresponding initial stress value (i.e., the stress at time zero). The normalized stress data were then plotted against the logarithmic of time as illustrated on figure 13. All stress relaxation plots are included in appendix J.

Following are the observations made from the results:

1. In the first 12 hours of the test, the specimens were exposed to room temperature for 30 minutes and then heated to +30 °C for 12 hours. Both the geomembrane sheets and seams showed a significant amount of stress relaxation. For the non-reinforced geomembrane sheets and seams, 70 to 80 percent of the initial stress was relaxed. For the reinforced geomembrane sheets and seams, the values were around 40 to 75 percent, as can be seen in table 6.

2. For non-reinforced geomembranes, the stress relaxation behavior of sheets and seams is very similar, as shown on figure 14. In contrast, the seams of reinforced geomembranes exhibited a greater stress relaxation than the corresponding sheet materials, as indicated on figure 15.

3. Overall, non-reinforced geomembranes exhibited a greater relaxation than reinforced geomembranes, as can be seen on figure 16. This difference is attributable to the scrim in the reinforced geomembranes, which has less relaxation tendency than the membrane component and thus restricts the total relaxation of the geomembrane.

Magnitude of Cold Temperature Induced Tensile Stress

As the chamber temperature cooled from +30 °C to -20 °C, a tensile load was induced in the specimens. The magnitude of this induced load was calculated by subtracting the minimum load value at +30 °C before onset of the cooling from the maximum load value at -20 °C. The induced stress was obtained by dividing the load by the thickness and width of the respective test specimens. Table 6 lists the induced load and induced stress values of all tested materials. All cold temperature induced tensile stress curves are included as appendix K.

Following are comments that can be made from observing the values listed in table 6:

1. For non-reinforced geomembranes, similar induced stresses were obtained in the same type of polymer, regardless of the variation in the thickness, surface finishing, and seam types. For example:

    - The PVC group consists of an induced stress around 250 lb/in^2.
    - The VLDPE group consists of an induced stress around 550 lb/in^2.
    - The HDPE group consists of an induced stress around 1200 lb/in^2.

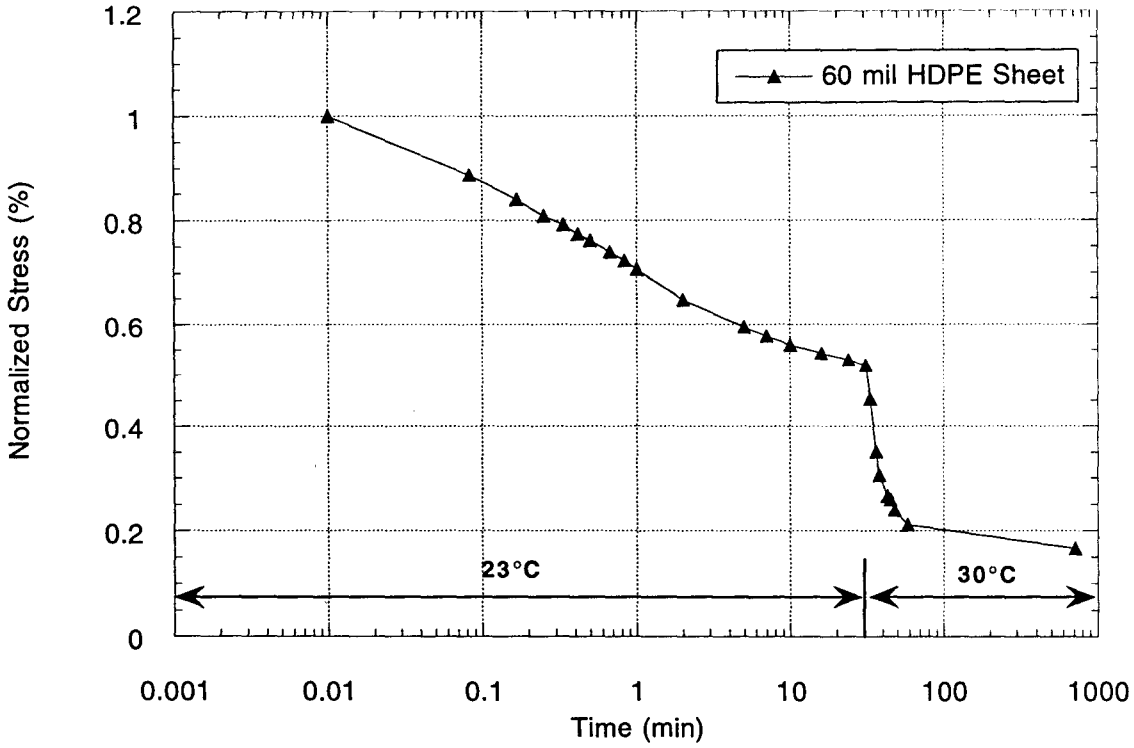

Figure 13. - Stress relaxation behavior in first 12 hours of the test.

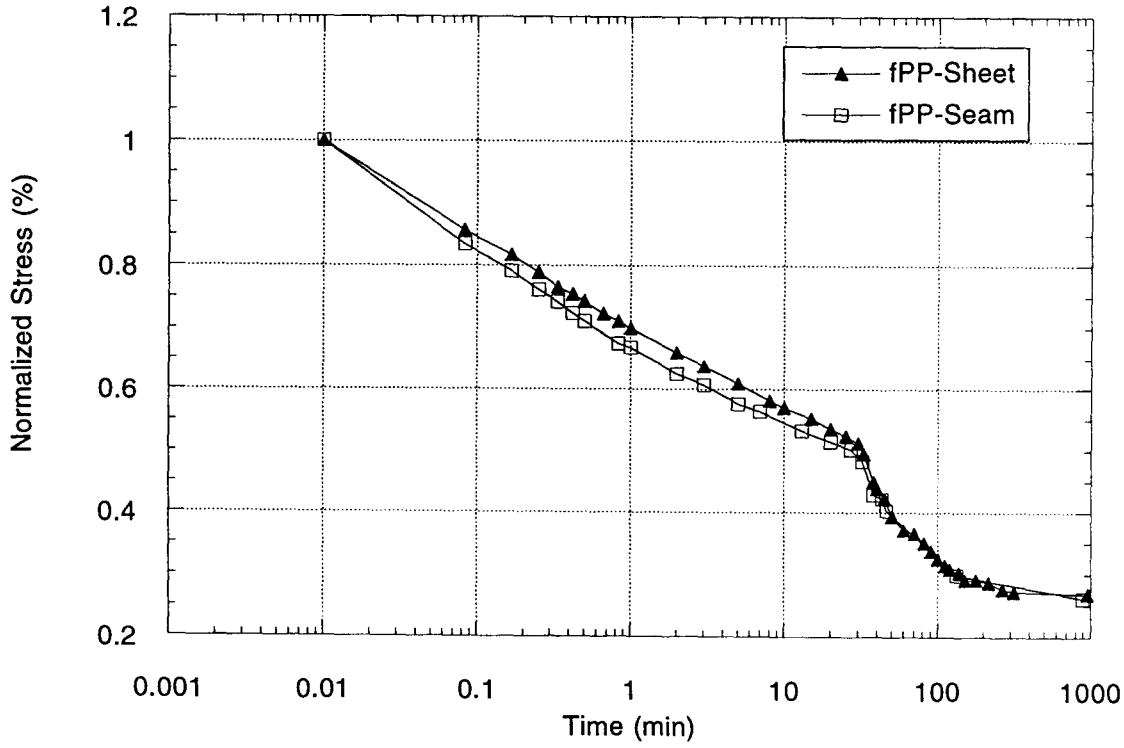

Figure 14. - An example of stress relaxation behavior of non-reinforced geomembrane sheets and seams.

Table 6. - Stress relaxation values and cold temperature induced stress values for sheets and seams.

No.	Geomembrane	Thickness mm (mil)	Seam Type	% relaxation after 12 hrs.	Induced Load (lb)	Induced Stress (lb/in-sq.)
1	PVC-R	1.1 (45)	Sheet	56	46.0	1020
1(a)			Chemical	70	52.0	1160
2	PVC	0.5 (20)	Sheet	75	6.0	300
2(b)			Hot Wedge	71	5.0	250
3	PVC	1.0 (40)	Sheet	76	9.0	220
3(b)			Hot Wedge	81	8.4	210
4	VLDPE	1.0 (40)	Sheet	77	20.0	500
			Extrusion	83	23.0	570
6	VLDPE	1.5 (60)	Sheet	82	33.0	550
			Hot Wedge	80	33.0	550
7	VLDPE-textured	1.5 (60)	Sheet	76	34.0	560
			Hot Wedge	79	33.0	550
10	HDPE	1.5 (60)	Sheet	83	71.0	1200
			Hot Wedge	83	73.0	1200
11	HDPE-textured	1.5 (60)	Sheet	84	72.0	1200
			Hot Wedge	89	76.0	1300
12	fPP	1.0 (40)	Sheet	73	14.6	370
			Thermal	74	11.8	290
13	fPP-R	1.1 (45)	Sheet	52	18.0	400
			Hot Wedge	67	17.0	380
14	CSPE-R	0.90 (36)	Sheet	43	18.0	500
14(b)			Hot Air	62	18.0	500
15	EIA	0.80 (30)	Sheet	87	12.0	400
15(a)			Chemical	80	15.0	500

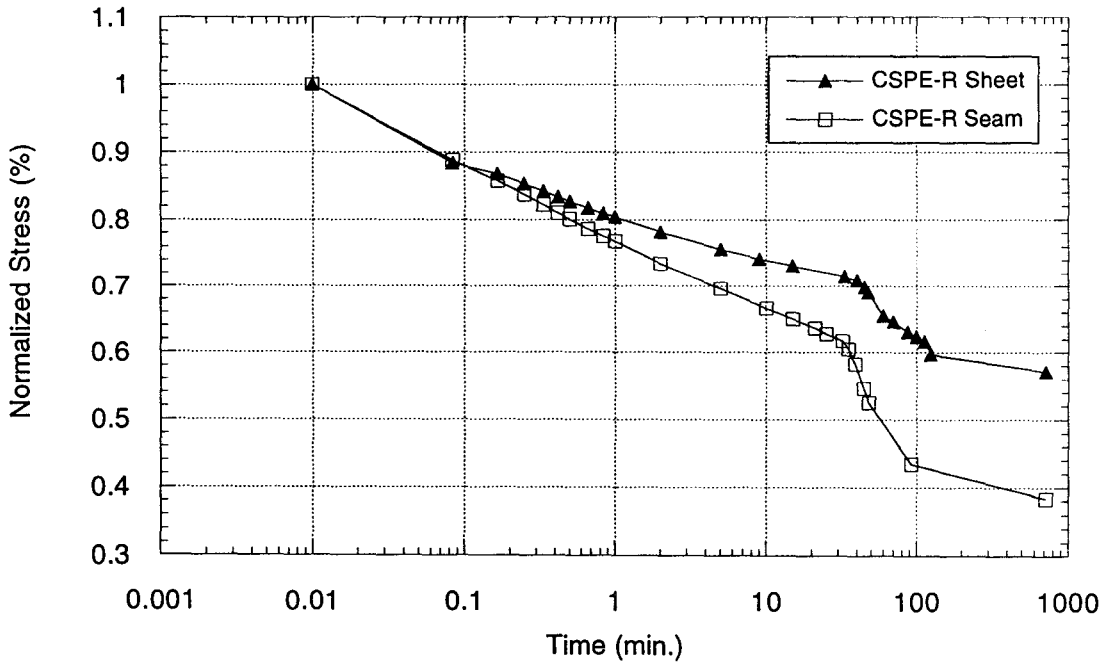

Figure 15. - An example of stress relaxation behavior of reinforced geomembrane sheets and seams.

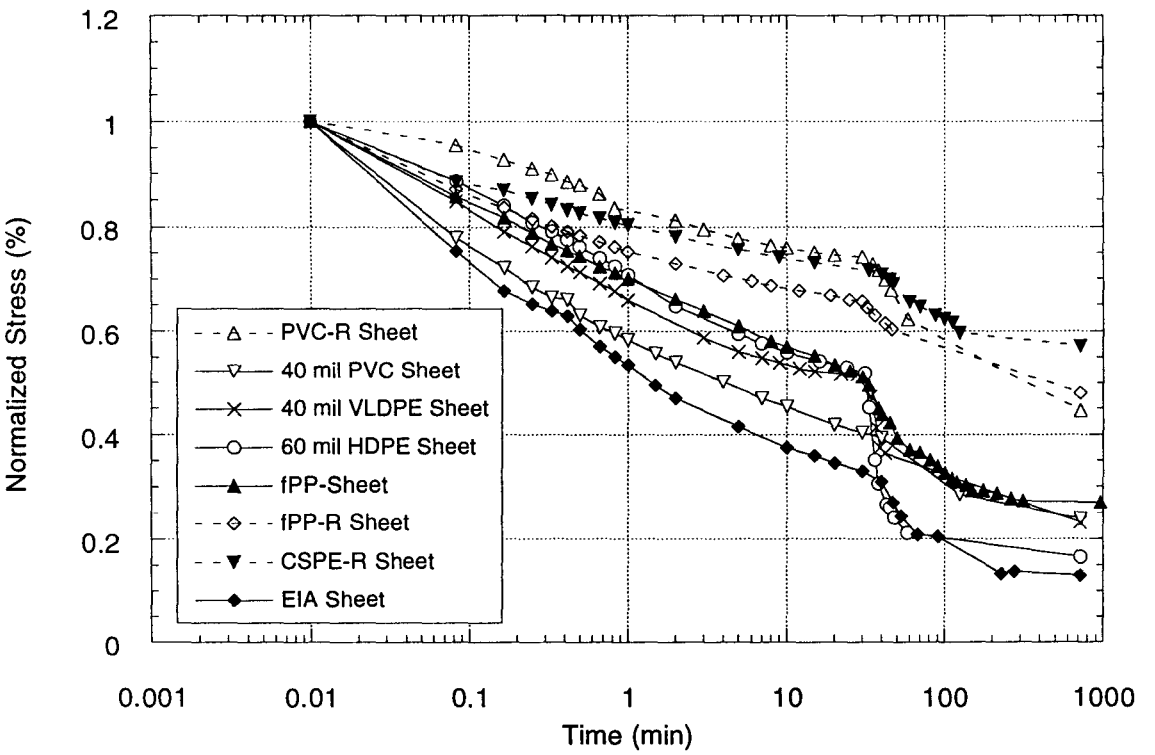

Figure 16. - Stress relaxation behavior of geomembrane sheets for each polymer type.

2. For the seven polymer types involved in this test, HDPE exhibited the highest induced stress. HDPE has a high linear thermal expansion coefficient in addition to a high tensile modulus. Based on the equation below, a comparably high induced stress was expected.

$$\sigma = \alpha * \Delta T * E$$

where: σ = induced stress
α = linear thermal expansion coefficient
ΔT = temperature difference
E = tensile modulus

This equation also explains the low induced stress exhibited by the VLDPE materials. Although VLDPE has a higher linear thermal expansion coefficient than HDPE, it has a much lower tensile modulus.

3. A large difference exists in the induced stress between non-reinforced PVC and reinforced PVC. For non-reinforced PVC geomembranes, about 250 lb/in^2 was induced from +20 to -20 °C. In contrast, the induced stress of PVC-R material was 4 times higher. This stress is probably caused by the relatively high T_g (glass transition temperature) of PVC-R geomembrane, which is -30 °C, whereas the T_g of PVC is -45 °C. See figures 17 and 18 for PVC-R and PVC thermal curves, respectively. At -20 °C testing temperature, the PVC-R geomembrane was approaching a glassy state. Thus, the modulus of the material increased as demonstrated by the E' curve on figure 15, resulting in a high induced stress.

Repeatability in the Magnitude of the Cold Temperature Induced Tensile Stress

The repeatability of the induced stress was investigated by repeating the cooling and heating cycle from +30 °C to -20 °C twice, as illustrated in the temperature profile graph on figure 10. From the load versus time graphs included as appendix K, the magnitude of the induced stresses in both cooling cycles was very similar for all tested materials. This similarity suggests that the constrained specimens in Part III of the study were subjected to the same magnitude of cyclic loading during each of the 500 freeze-thaw cycles.

DISCUSSION OF FREEZE-THAW EFFECTS

In this section, the results of Parts I, II, and III are separately discussed so that the effects of freeze-thaw cycling can be clearly described.

Part I

After the 19 geomembrane sheet and 27 geomembrane seam specimens were exposed to 200 freeze-thaw cycles in a relaxed stage and then were tested at room temperature, no changes were detected in any of the sheet tensile behavior and seam shear and peel strengths.

Part II

Six geomembrane sheet and 13 geomembrane seam specimens were exposed to 200 freeze-thaw cycles in a relaxed state and then were tested at -20 °C. If defects were created in the tested materials during freeze-thaw cycling, they probably would be more sensitive to cold temperature testing than the +20 °C testing of Part I. However, no changes were observed in either the sheet tensile behavior or the seam shear and peel strengths.

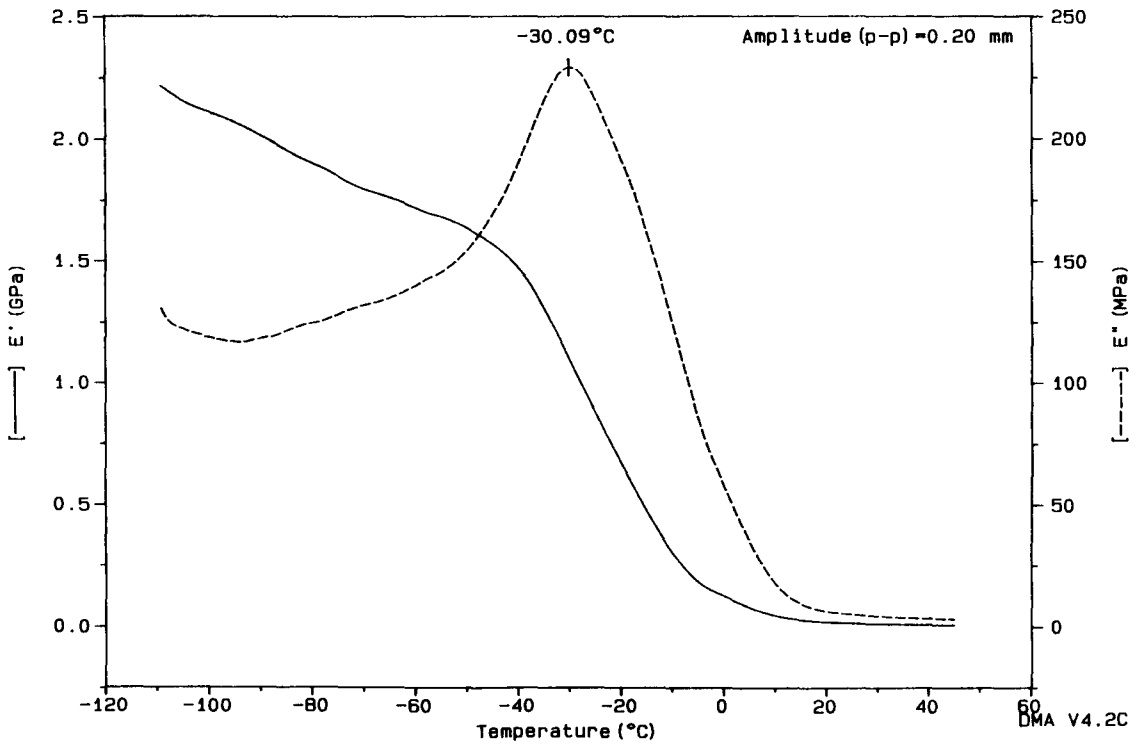

Figure 17. - Thermal curve of PVC-R indicating its T_g is at -30 °C.

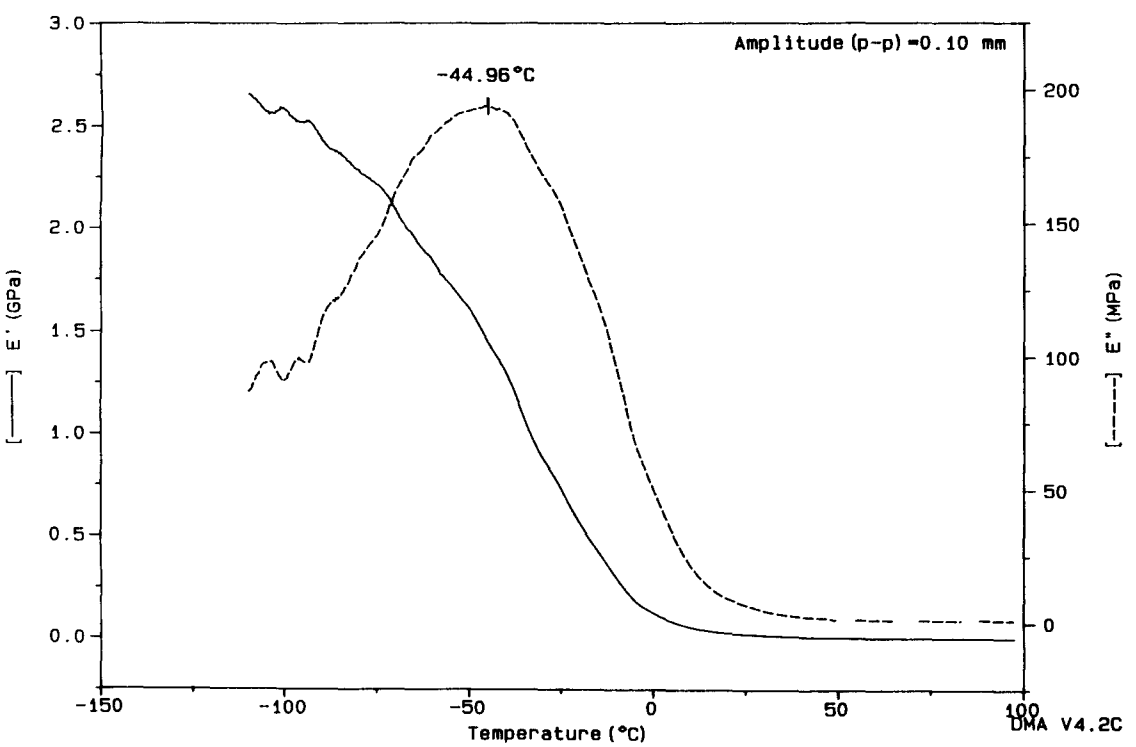

Figure 18. - Thermal curve of PVC indicating its T_g is at -45 °C.

Part III

The same 19 geomembrane sheet and 27 seam specimens as used in Part I were exposed to 500 freeze-thaw cycles in a constrained condition. As indicated in the results of Part IV, a repeatable thermal induced stress was also imposed onto the constrained specimens during each freeze part of the cycles. The magnitude of the induced stresses depended on the type of the polymer. In addition, the cold temperature induced stress remained in the specimen until the temperature of the specimen was changed, as proved by Lord et al. (1995). Thus, tested specimens of this part of the study were subjected to a more severe incubation condition than those in Part I. In spite of this difference, no changes were observed in any of the sheet tensile properties or seam shear and peel strengths.

DISCUSSION OF THE EFFECTS OF COLD TEMPERATURE TESTING

The effects of cold temperature testing can be evaluated by comparing data of Part II tests to data of Part I tests. The evaluation included strength and elongation of 6 geomembrane sheets and 9 geomembrane seam shear and peel strengths.

Sheet Testing

For the PVC, HDPE, and HDPE-T geomembranes, strength values at -20 °C were all higher than those at +20 °C. In contrast, corresponding elongation values were lower.

However, a different type of tensile behavior was observed in the PVC-R geomembrane sheet. Only a single breaking peak was detected at -20 °C instead of the customary two peaks at +20 °C, which corresponded to the breaking of the reinforcing scrim and membrane, respectively. The change in the tensile behavior is probably attributable to the high T_g of PVC-R. At -20 °C, the PVC membrane component, which was approaching its T_g, became stronger than the reinforcing scrim. The glass transition temperature of PET (polyethylene terephalate) reinforcing scrim is +70 °C; thus, the strength of the PET scrim would have less change between +20 and -20 °C).

For the VLDPE and VLDPE-T materials, direct comparison was unable to be performed because of the different tensile behavior. A pronounced yielding was detected at -20 °C which was not observed at +20 °C. However, at -20 °C testing, breaking strength was not measured because of limited chamber height. Nevertheless, the overall tensile load at -20 °C seems to be higher than that at +20 °C, at least over the evaluated elongation range.

Seam Testing

In the seam shear tests, all other seams showed a higher strength at -20 °C than at +20 °C, except VLDPE materials. For the VLDPE seams, the shear strength from Parts I and II could not be directly compared for the same reasons as explained in the sheet testing. However, a higher shear tensile load was observed at -20 °C than at +20 °C over the tested elongation range.

In the seam peel tests, the seam strengths of PVC-R, PVC, and VLDPE materials were greater at -20 °C than at +20 °C. On the other hand, no significant changes were detected in the peel strength of HDPE materials.

DISCUSSION OF THE EFFECTS OF TEMPERATURE INDUCED CYCLIC STRESS

The influence of the cold temperature induced cyclic stress during the freeze-thaw cycling on the tensile behavior of the test specimens was investigated by comparing data of Part III tests to those of Part I tests. The evaluation included strength and elongation of geomembrane sheets and seam shear and peel strengths.

Sheet Testing

The tensile strength and elongation of 19 geomembrane sheet materials in Parts I and III of the study were compared. No significant difference exists between the two sets of data. In addition, the initial straining was also evaluated by comparing the first cycle data of Part III to the as-received data. The tensile behavior was not affected, probably because of the rapid stress relaxation in the material as explained in the previous section. Therefore, neither the initial straining nor cold temperature induced cyclic stress altered the tensile properties of the geomembrane sheet after 500 freeze-thaw cycles.

Seam Testing

The shear strengths of 27 geomembrane seams in Parts I and III of the study were compared. No substantial difference existed between the two sets of data. In addition, the initial straining did not show an influence in the shear strength.

For the peel strength, 25 geomembrane seams were compared between Parts I and III. Overall, no significant difference was observed. Although the peel tests of VLDPE in Part I were performed using a strain rate of 8.5 mm/sec (20-in/min) instead of the 0.8-mm/sec (2-in/min) rate used in Part III tests, the seam peel strength values were very similar. The initial straining also did not affect the peel strength of the seams.

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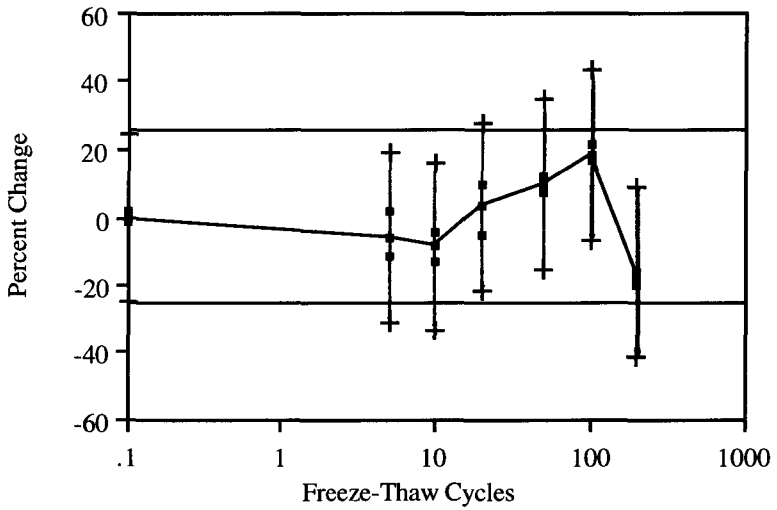
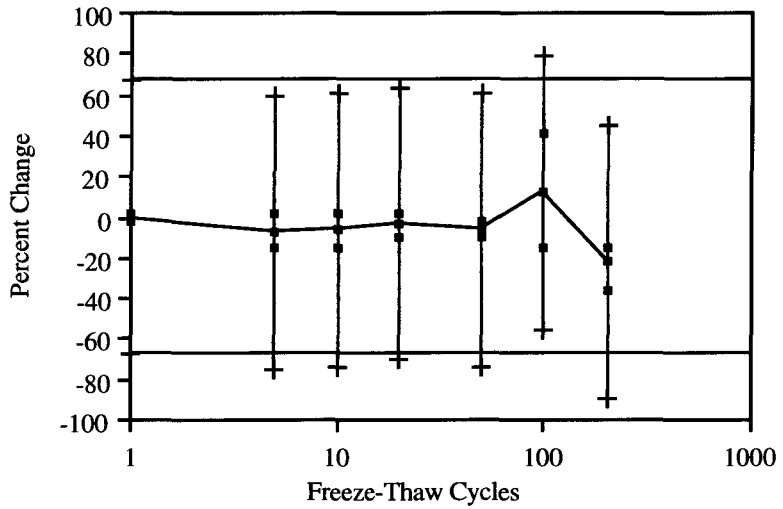
APPENDIX A

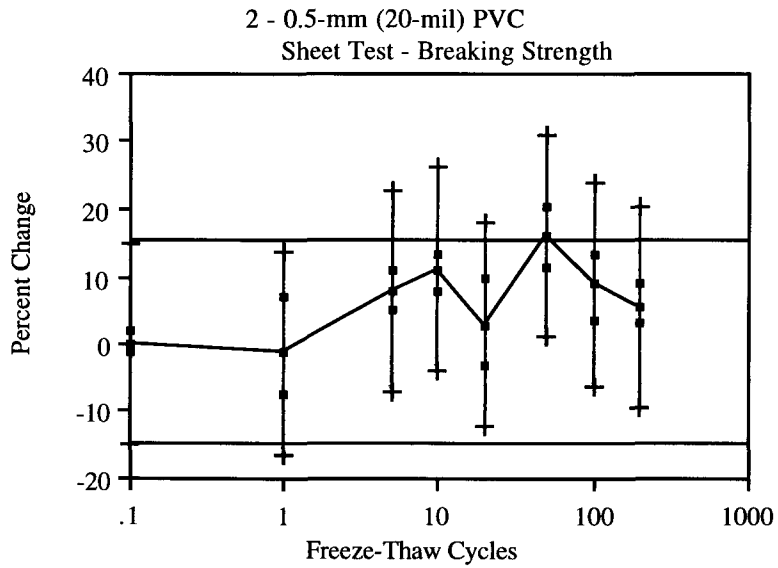
Part I — Sheet Tensile Test Results

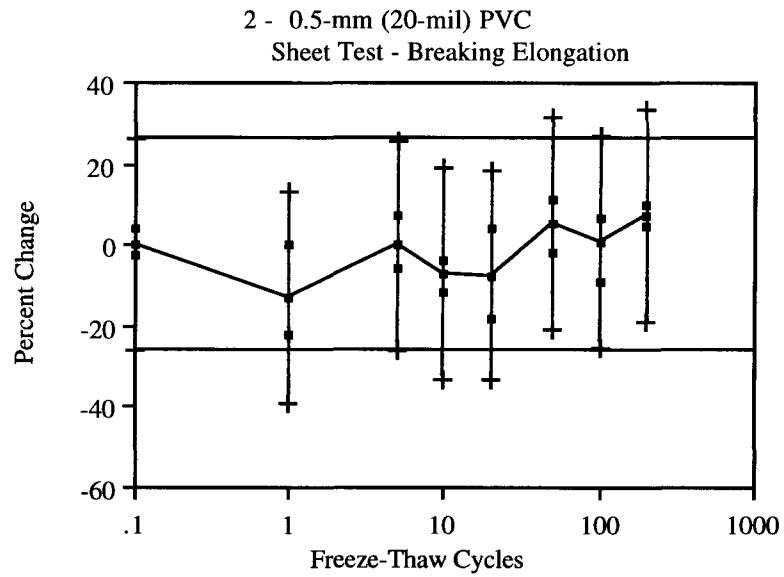
1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Strength

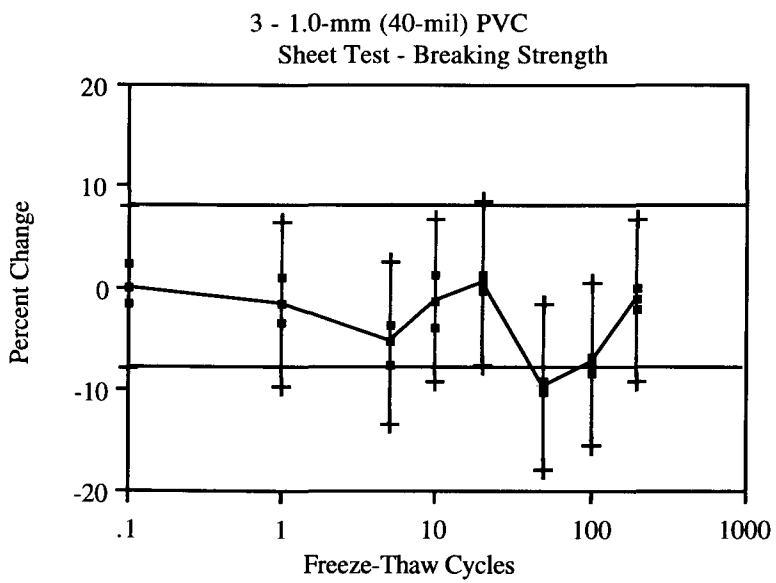


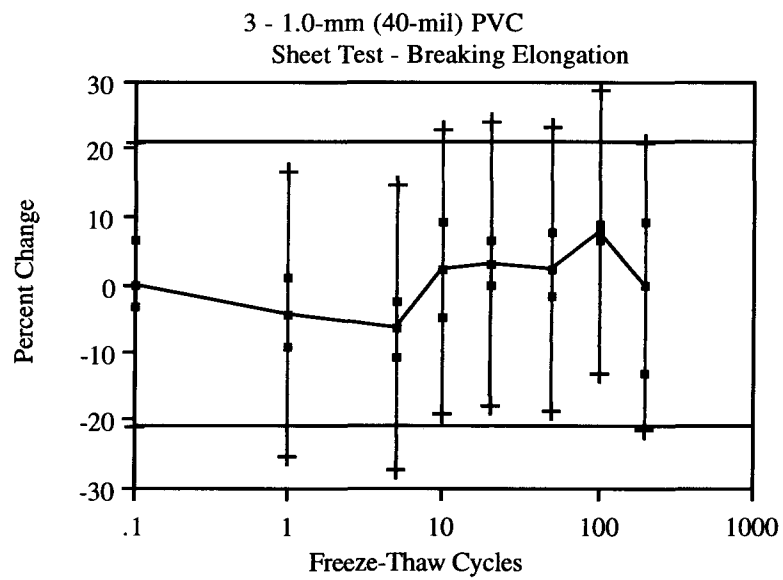
1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Elongation

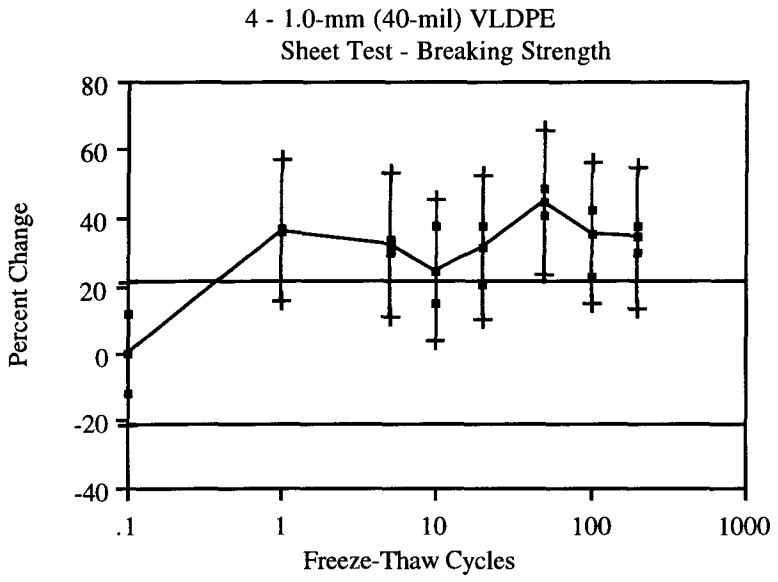


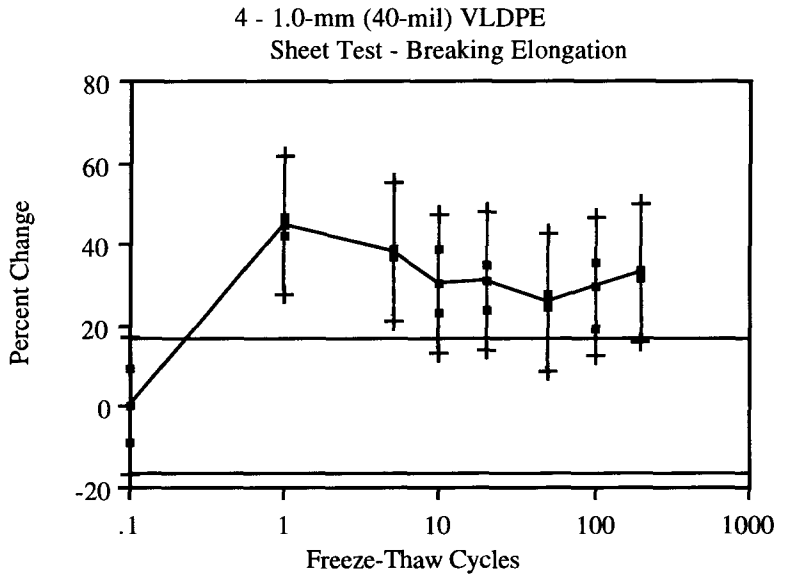

2 - 0.5-mm (20-mil) PVC
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
.1
1
10
100
1000
Freeze-Thaw Cycles

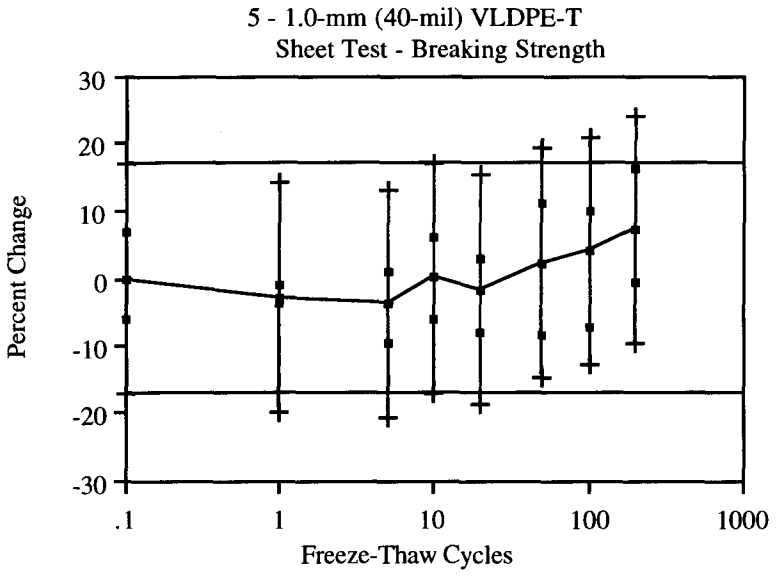

2 - 0.5-mm (20-mil) PVC
Sheet Test - Breaking Elongation
Percent Change
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles

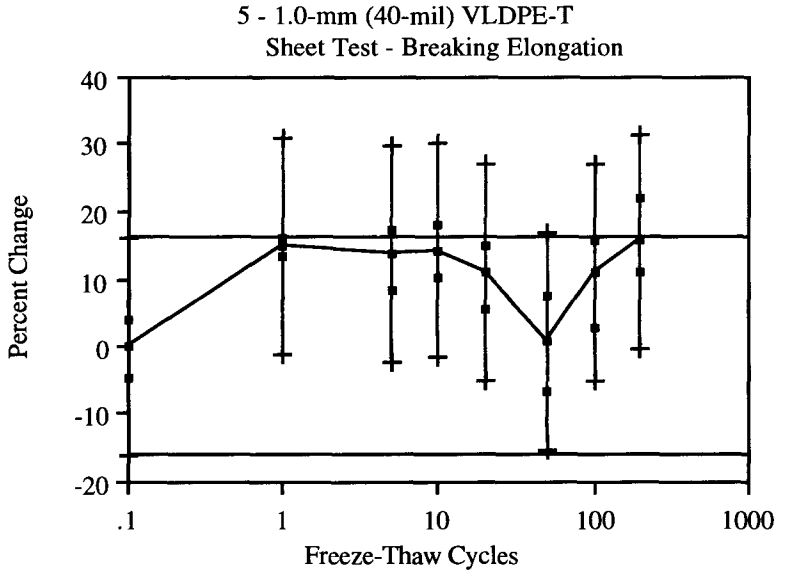

3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Strength
Percent Change
20
10
0
-10
-20
.1
1
10
100
1000
Freeze-Thaw Cycles

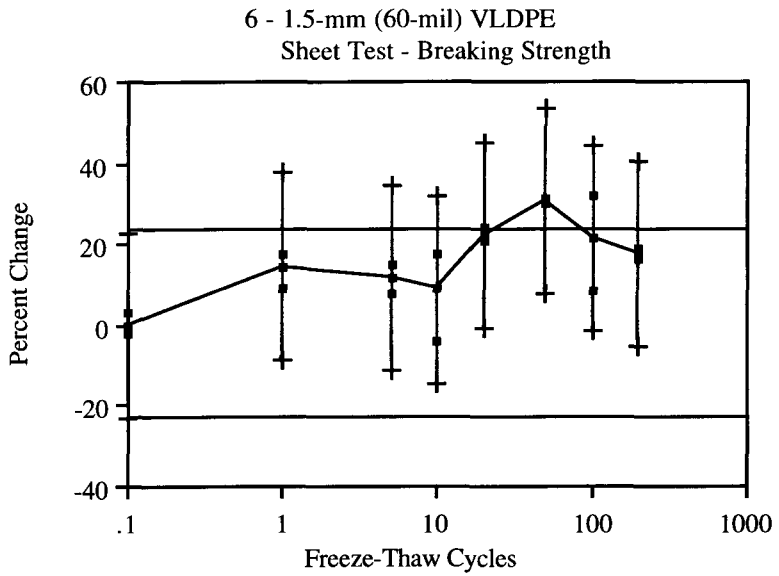

3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

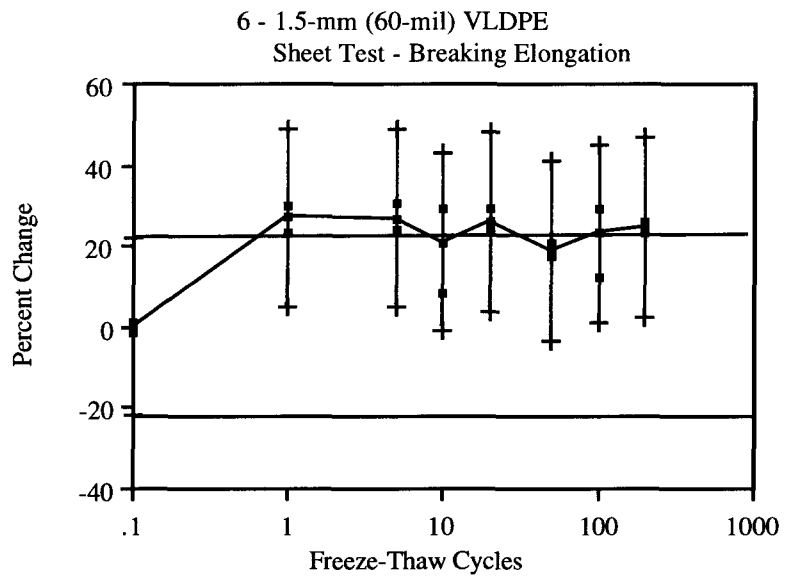

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Breaking Strength
Percent Change
80
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

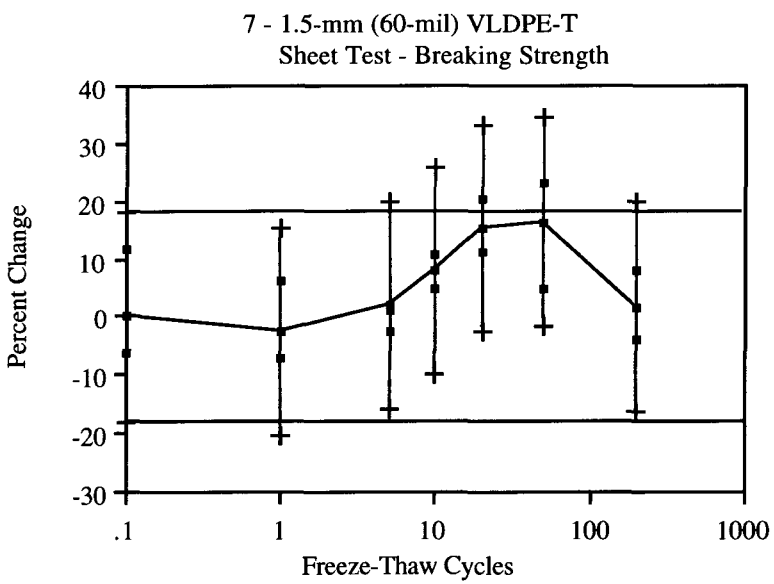

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Breaking Elongation
Percent Change
80
60
40
20
0
-20
.1
1
10
100
1000
Freeze-Thaw Cycles

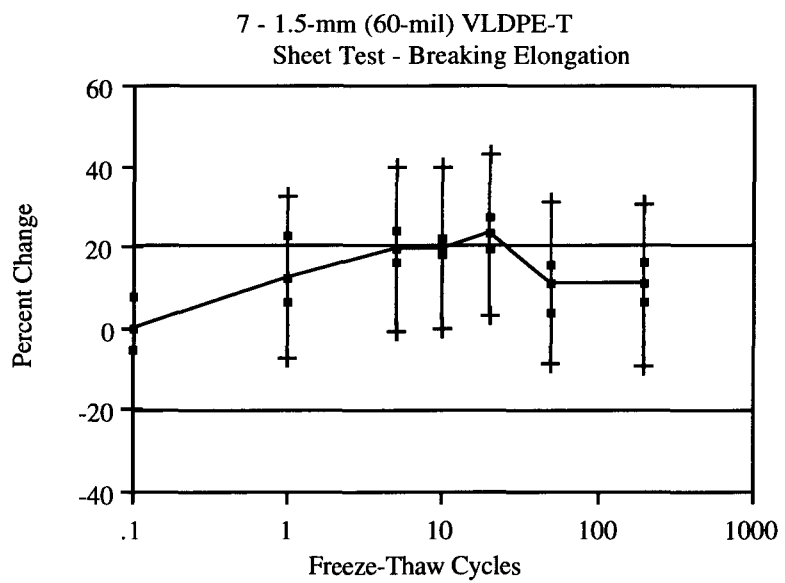

5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Breaking Strength
Percent Change
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

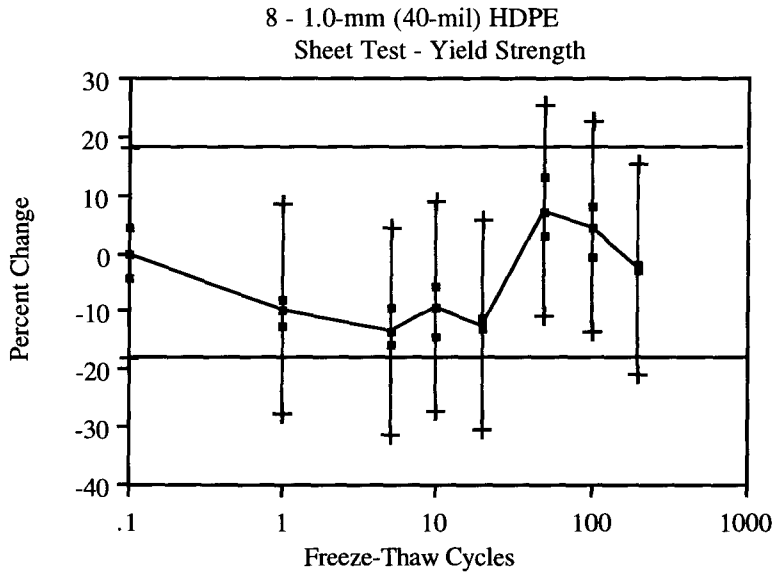

5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Breaking Elongation
Percent Change
40
30
20
10
0
-10
-20
.1
1
10
100
1000
Freeze-Thaw Cycles

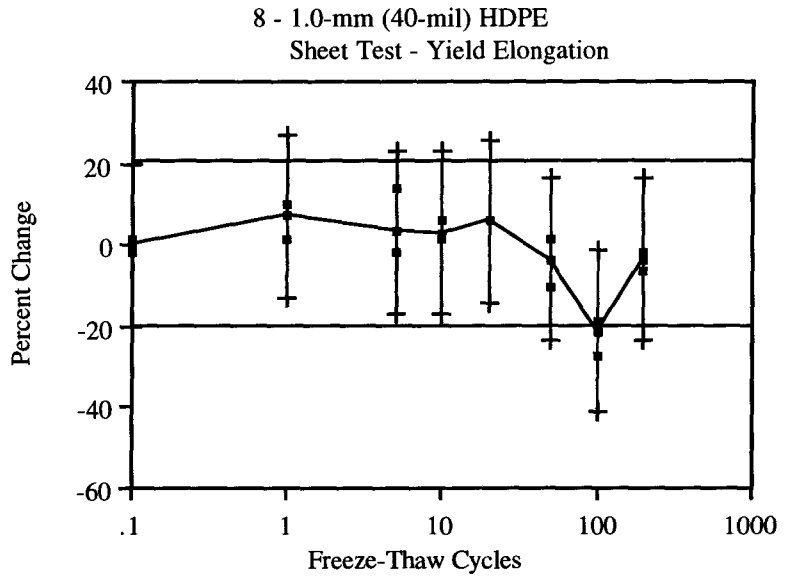

6 - 1.5-mm (60-mil) VLDPE
Sheet Test - Breaking Strength
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

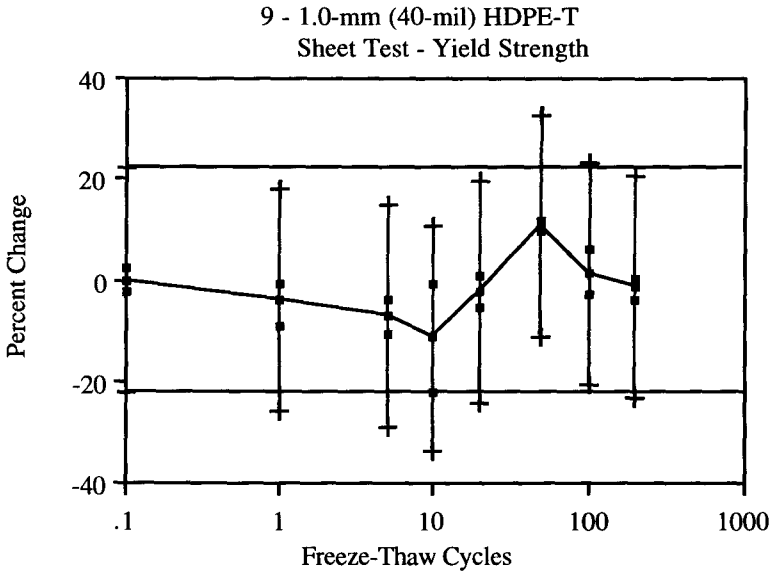

6 - 1.5-mm (60-mil) VLDPE
Sheet Test - Breaking Elongation
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

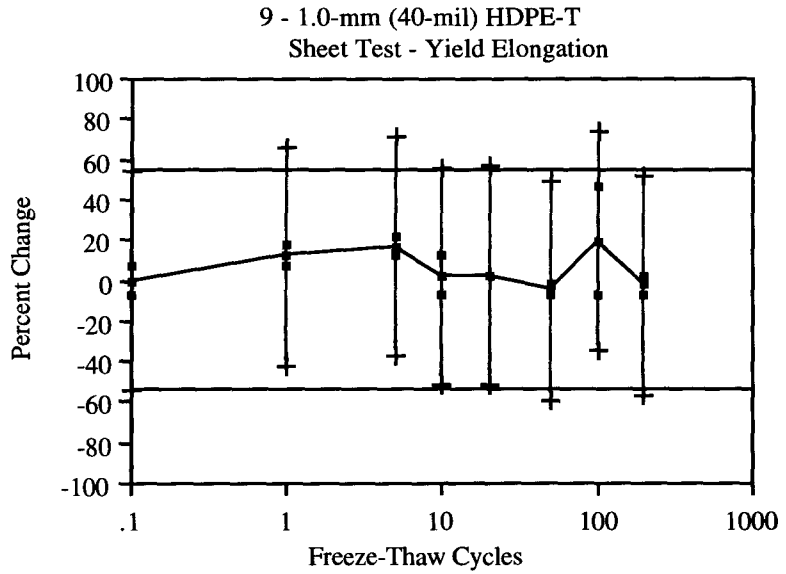

7 - 1.5-mm (60-mil) VLDPE-T
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

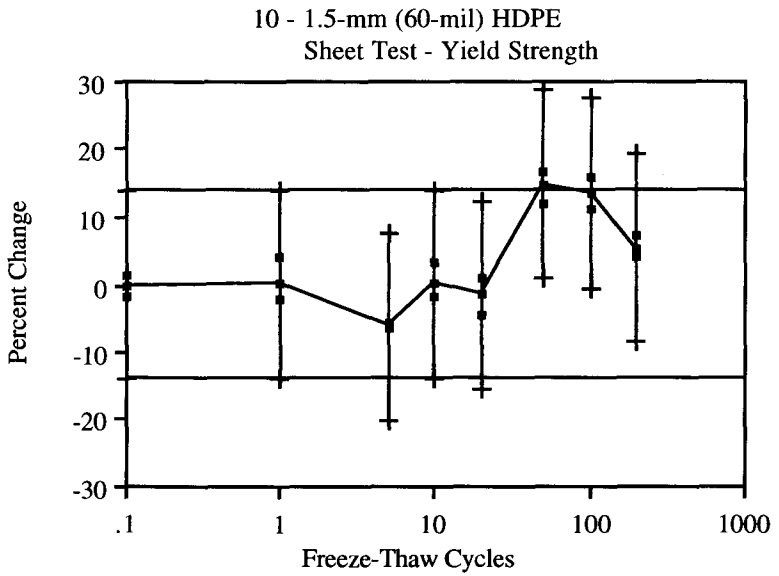

7 - 1.5-mm (60-mil) VLDPE-T
Sheet Test - Breaking Elongation
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

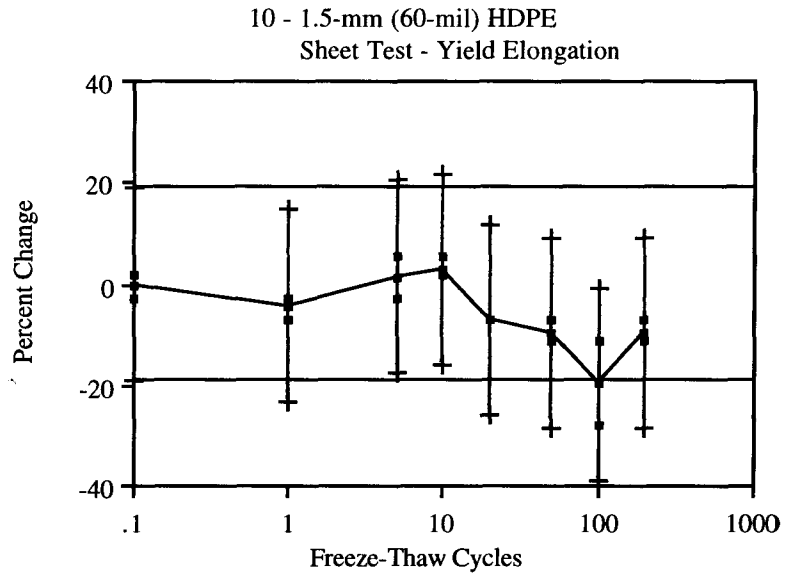

8 - 1.0-mm (40-mil) HDPE
Sheet Test - Yield Strength
Percent Change
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

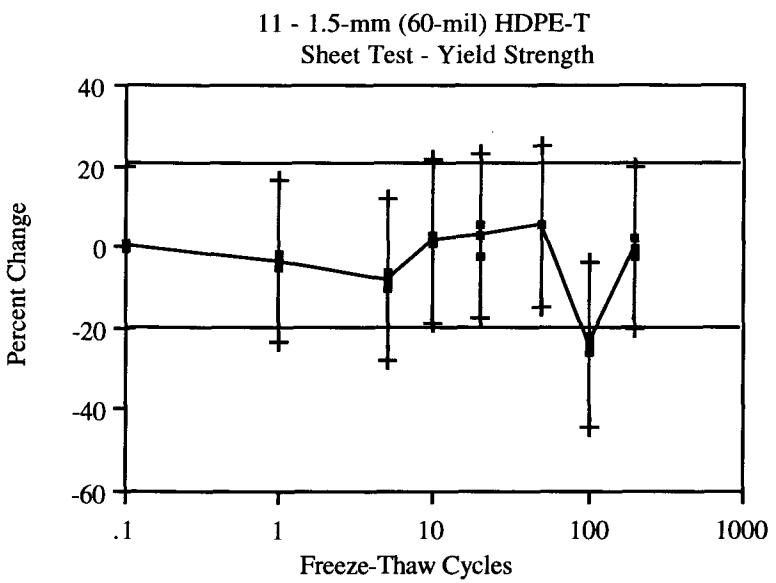

8 - 1.0-mm (40-mil) HDPE
Sheet Test - Yield Elongation
Percent Change
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles

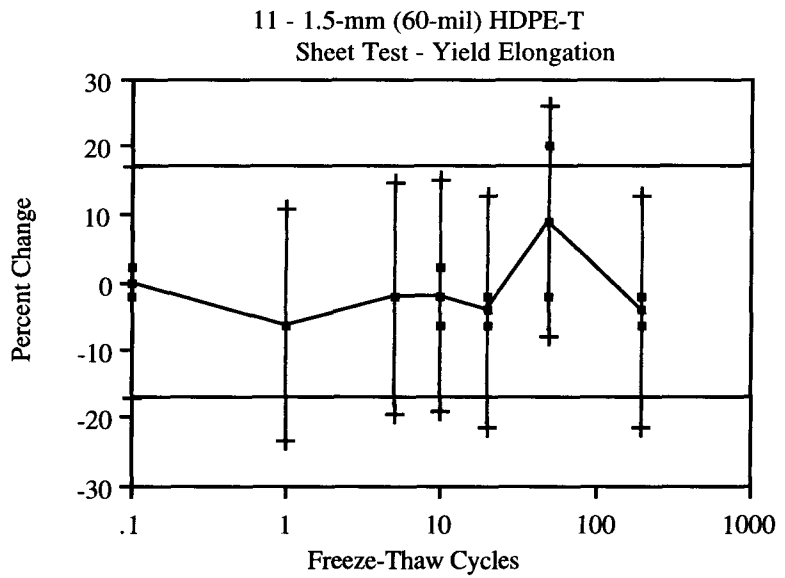

9 - 1.0-mm (40-mil) HDPE-T
Sheet Test - Yield Strength
Percent Change
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

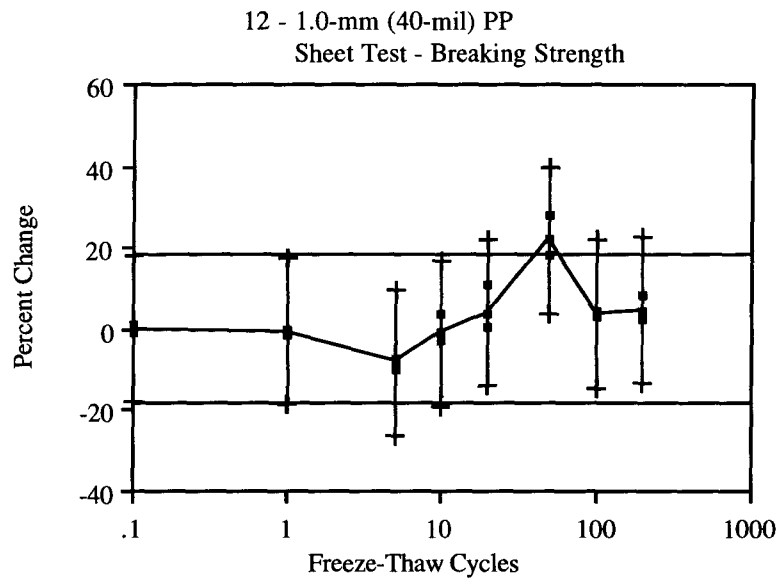

9 - 1.0-mm (40-mil) HDPE-T
Sheet Test - Yield Elongation
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
.1
1
10
100
1000
Freeze-Thaw Cycles

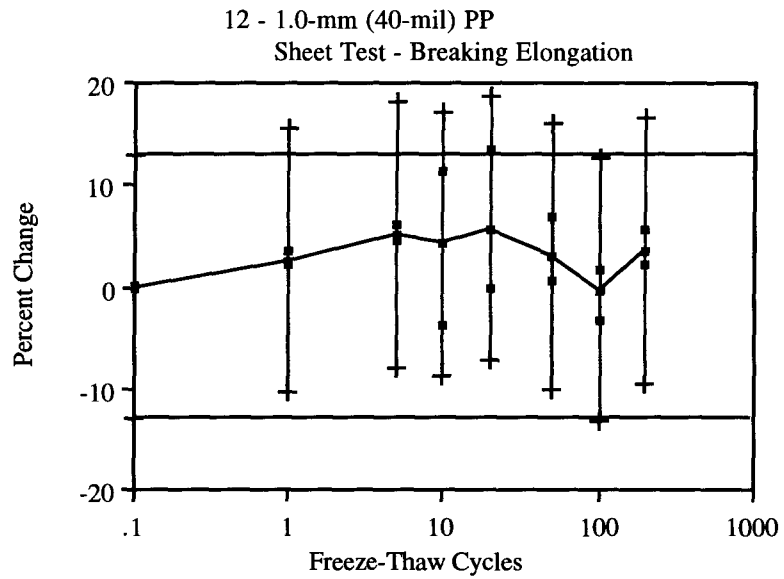

10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Strength
Percent Change
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

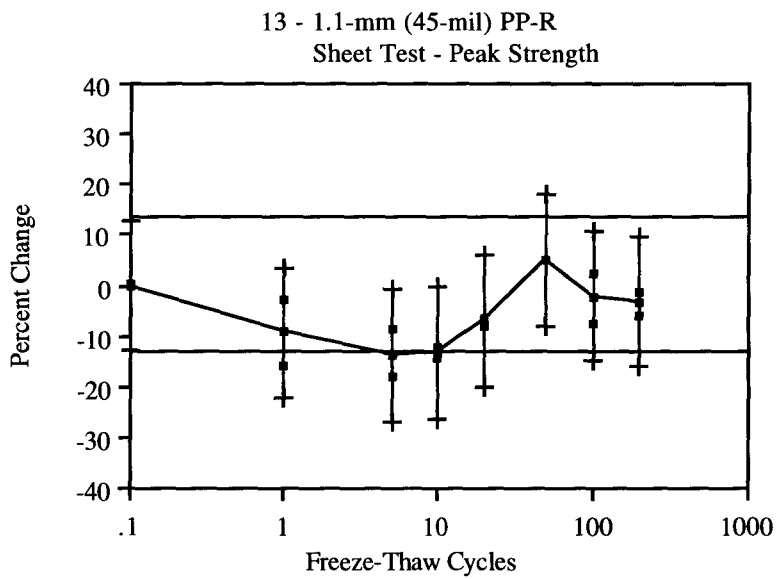

10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Elongation
Percent Change
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

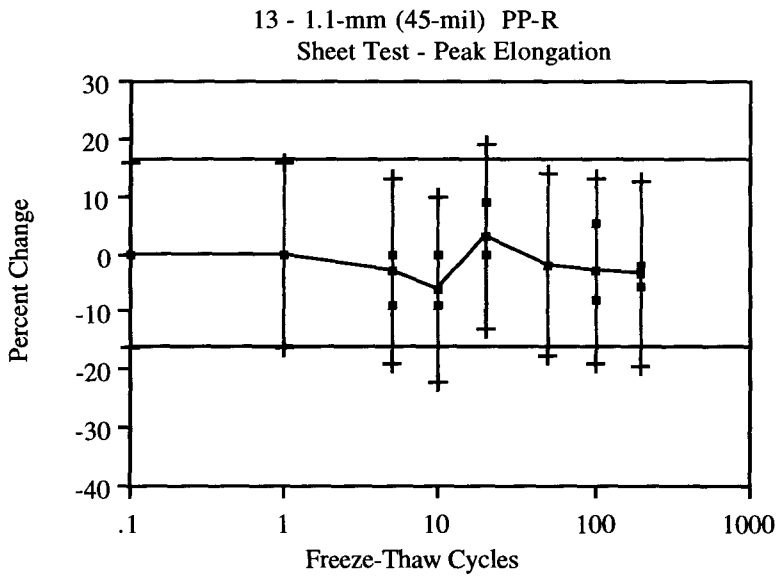

11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Strength
Percent Change
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles

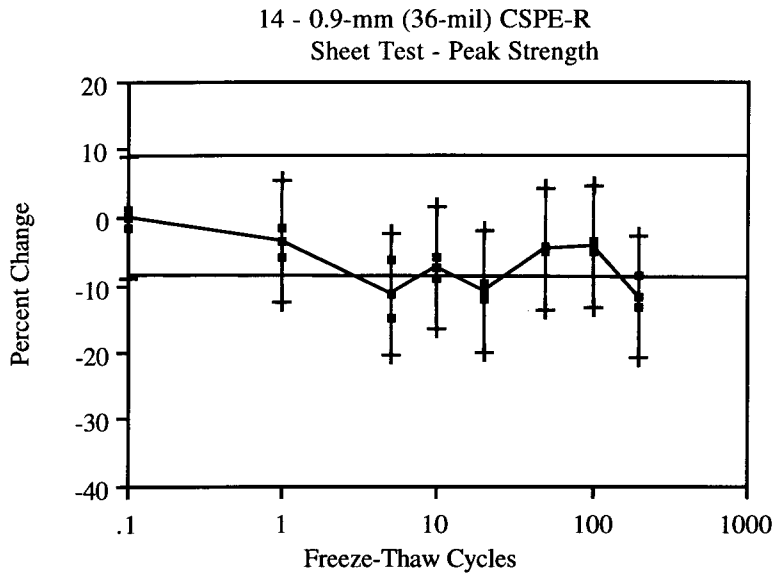

11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Elongation
Percent Change
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

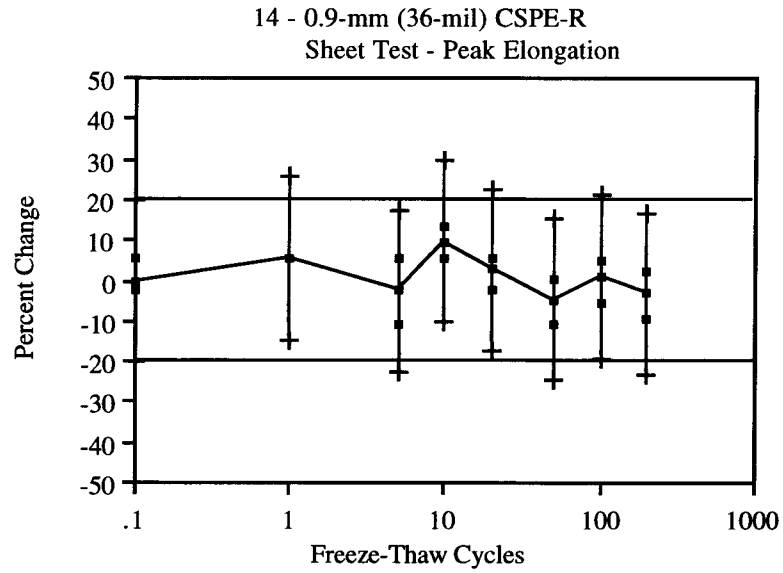

12 - 1.0-mm (40-mil) PP
Sheet Test - Breaking Strength
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

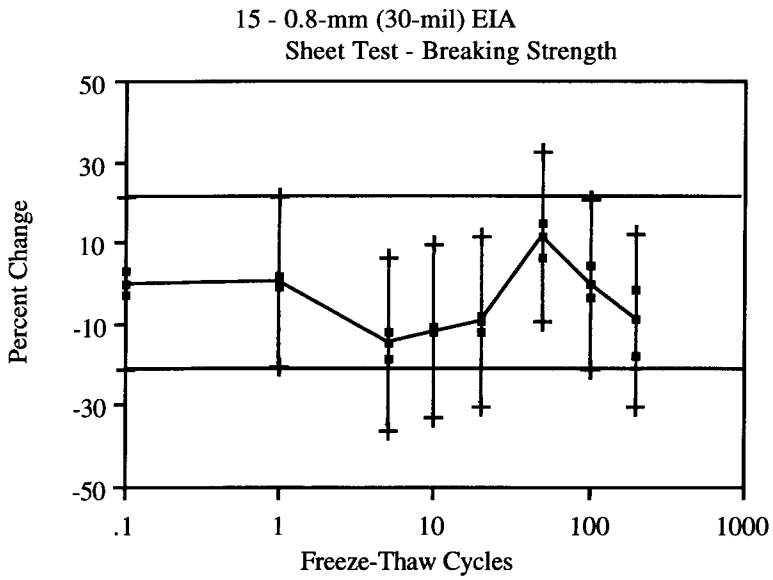

12 - 1.0-mm (40-mil) PP
Sheet Test - Breaking Elongation
Percent Change
20
10
0
-10
-20
.1
1
10
100
1000
Freeze-Thaw Cycles

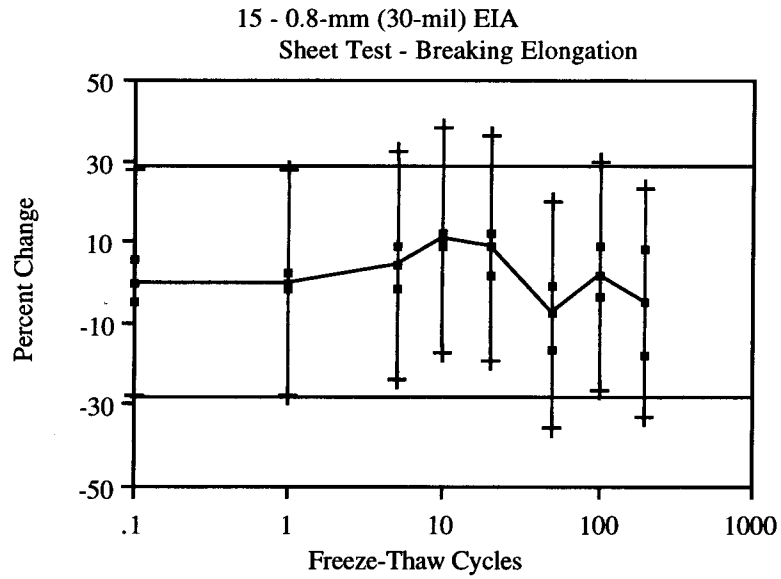

13 - 1.1-mm (45-mil) PP-R
Sheet Test - Peak Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

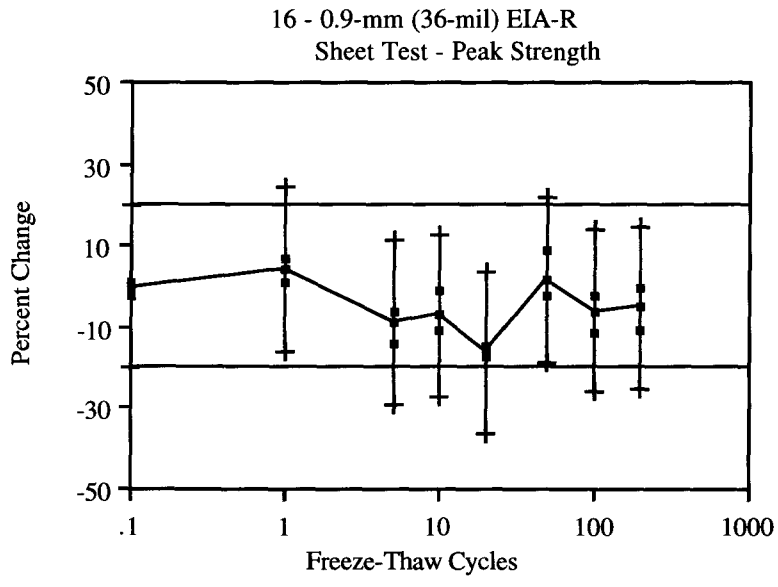

13 - 1.1-mm (45-mil) PP-R
Sheet Test - Peak Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

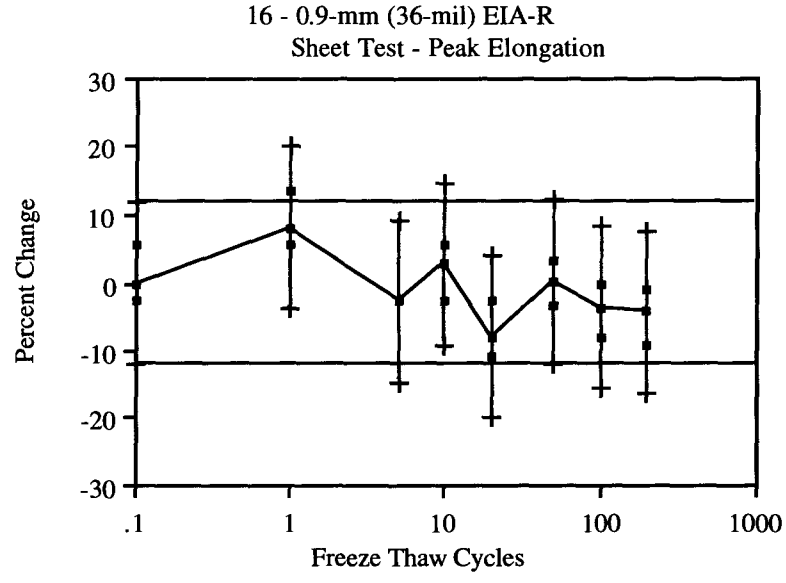

14 - 0.9-mm (36-mil) CSPE-R
Sheet Test - Peak Strength
Percent Change
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

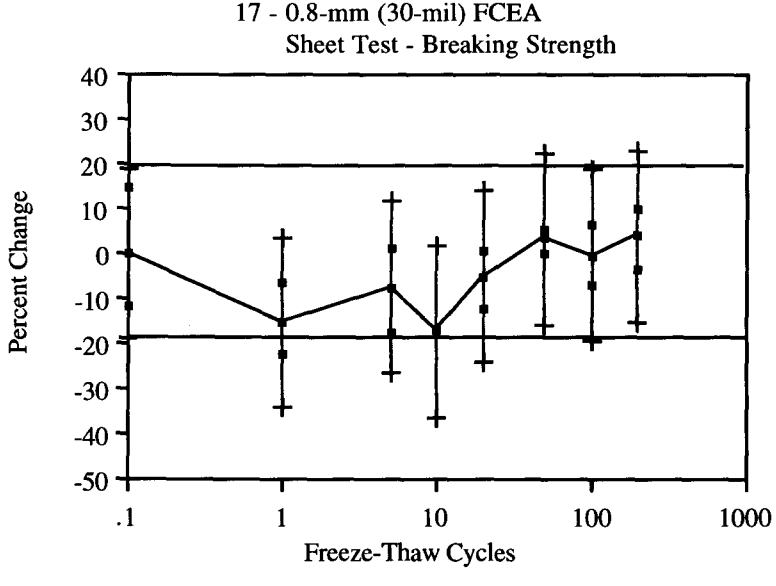

14 - 0.9-mm (36-mil) CSPE-R
Sheet Test - Peak Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

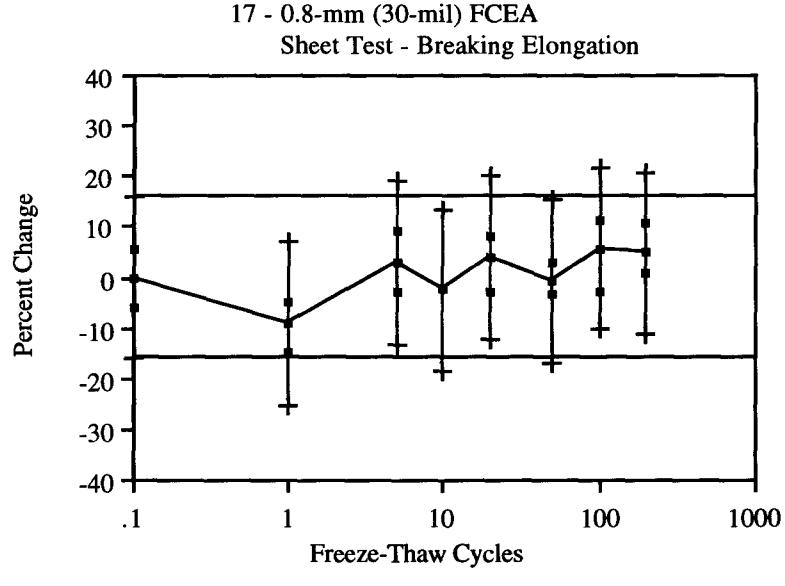

15 - 0.8-mm (30-mil) EIA
Sheet Test - Breaking Strength
Percent Change
50
30
10
-10
-30
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

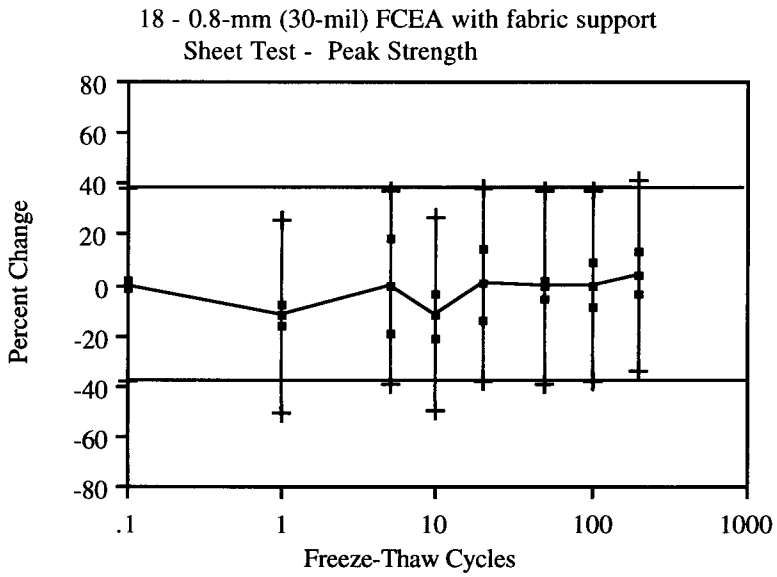

15 - 0.8-mm (30-mil) EIA
Sheet Test - Breaking Elongation
Percent Change
50
30
10
-10
-30
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

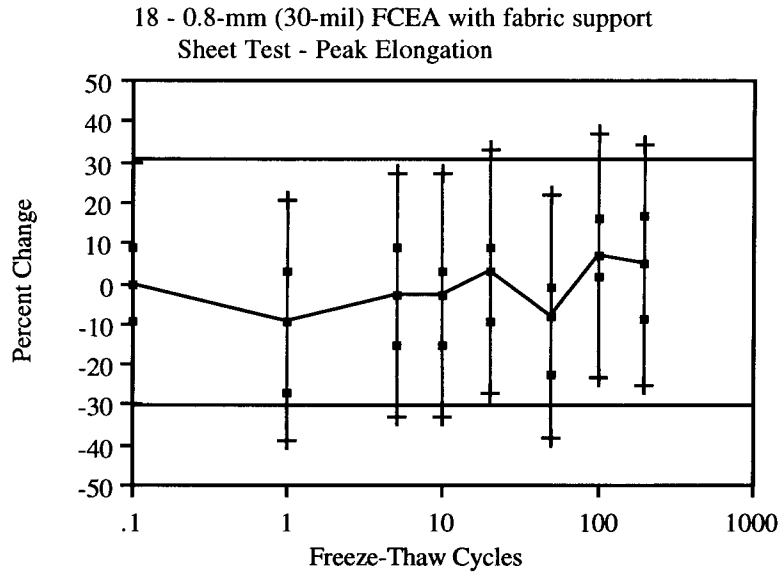

16 - 0.9-mm (36-mil) EIA-R
Sheet Test - Peak Strength
Percent Change
50
30
10
-10
-30
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

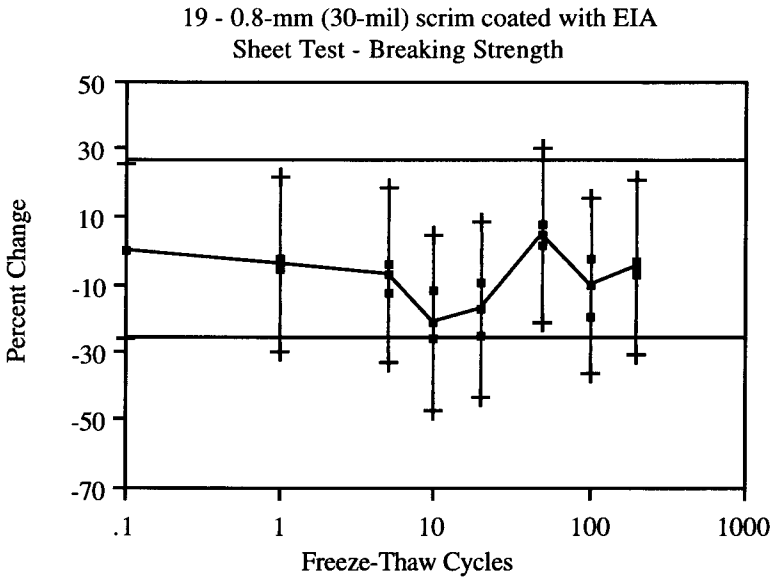

16 - 0.9-mm (36-mil) EIA-R
Sheet Test - Peak Elongation
Percent Change
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze Thaw Cycles

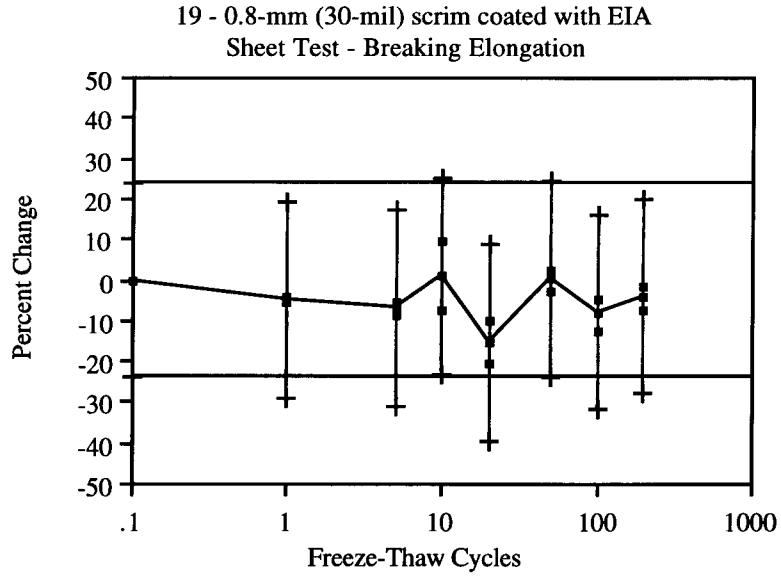

17 - 0.8-mm (30-mil) FCEA
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
-50
.1
1
10
100
1000
Freeze-Thaw Cycles


17 - 0.8-mm (30-mil) FCEA
Sheet Test - Breaking Elongation
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


18 - 0.8-mm (30-mil) FCEA with fabric support
Sheet Test - Peak Strength
Percent Change
80
60
40
20
0
-20
-40
-60
-80
.1
1
10
100
1000
Freeze-Thaw Cycles


18 - 0.8-mm (30-mil) FCEA with fabric support
Sheet Test - Peak Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

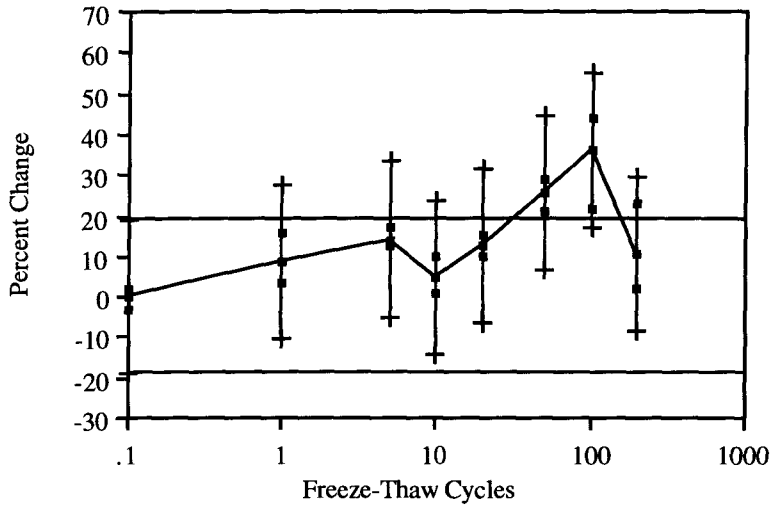

19 - 0.8-mm (30-mil) scrim coated with EIA
Sheet Test - Breaking Strength
Percent Change
50
30
10
-10
-30
-50
-70
.1
1
10
100
1000
Freeze-Thaw Cycles


19 - 0.8-mm (30-mil) scrim coated with EIA
Sheet Test - Breaking Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
.1
1
10
100
1000
Freeze-Thaw Cycles

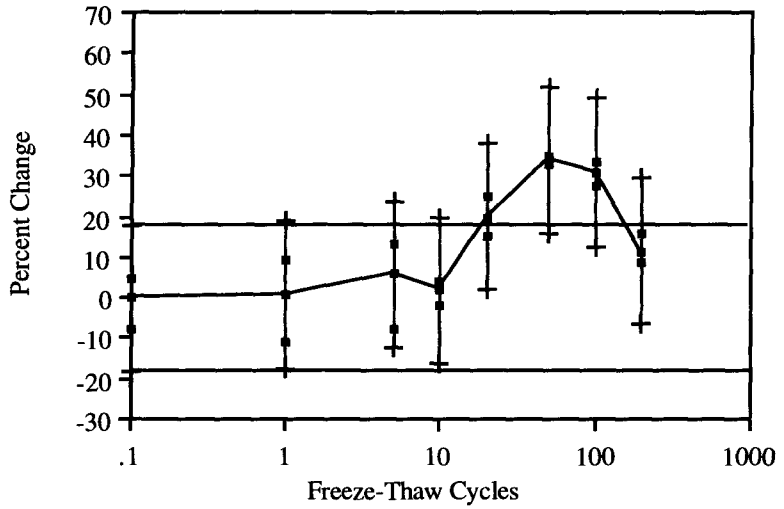
APPENDIX B

Part I — Seam Shear Tensile Test Results

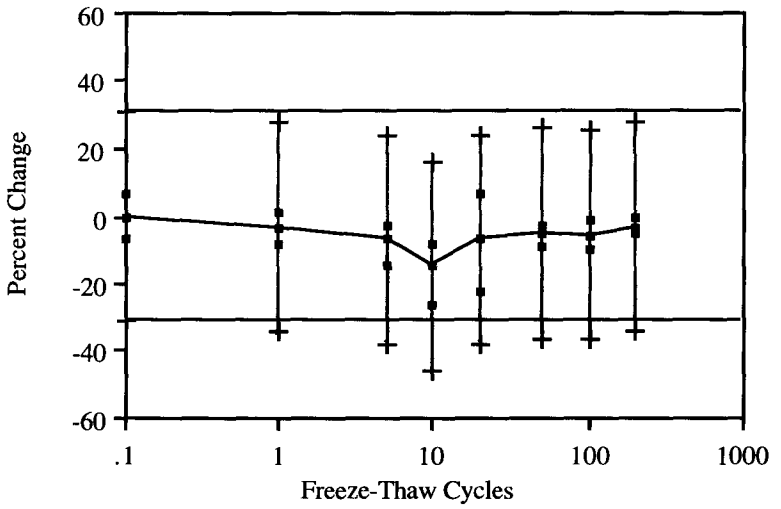
1(a) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Shear Test - Chemical Seam - Peak Strength



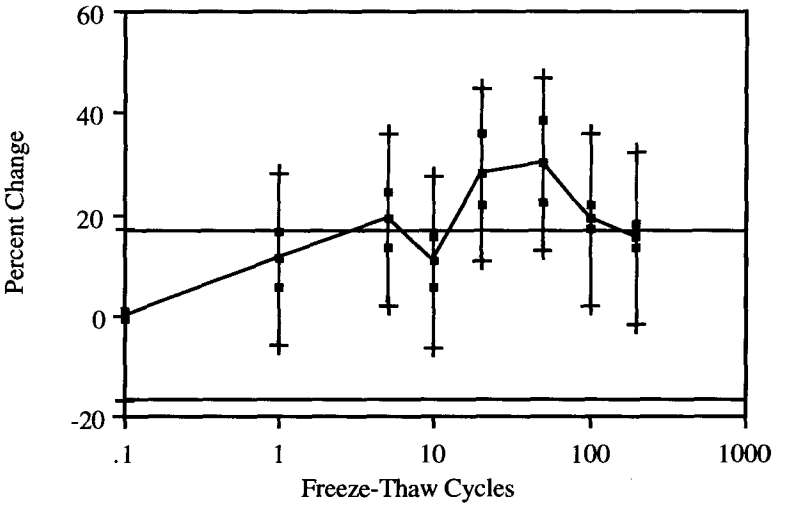
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Shear Test - Wedge Seam - Peak Strength



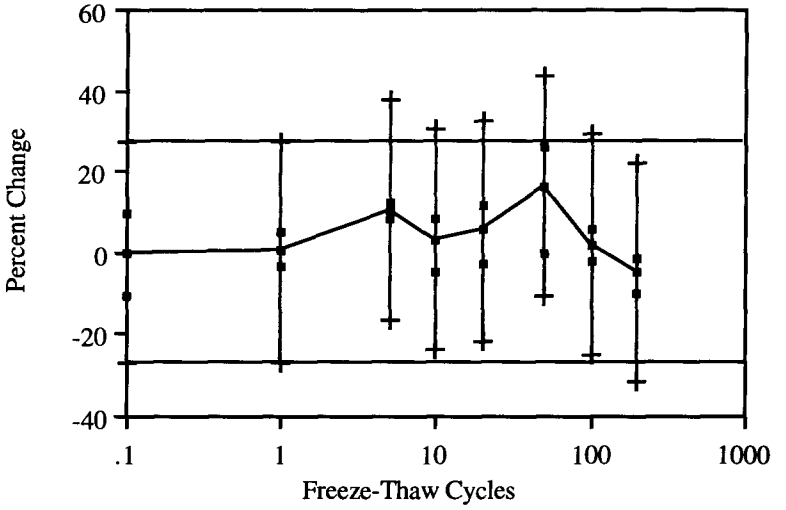
2(a) - 0.5-mm (20-mil) PVC
Shear Test-Chemical Seam - Break Strength



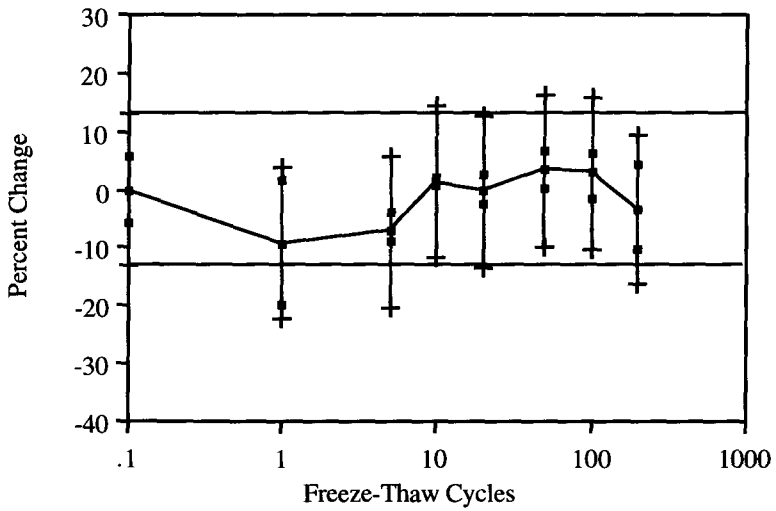
2(b) - 0.5-mm (20-mil) PVC
Shear Test - Wedge Seam - Break Strength



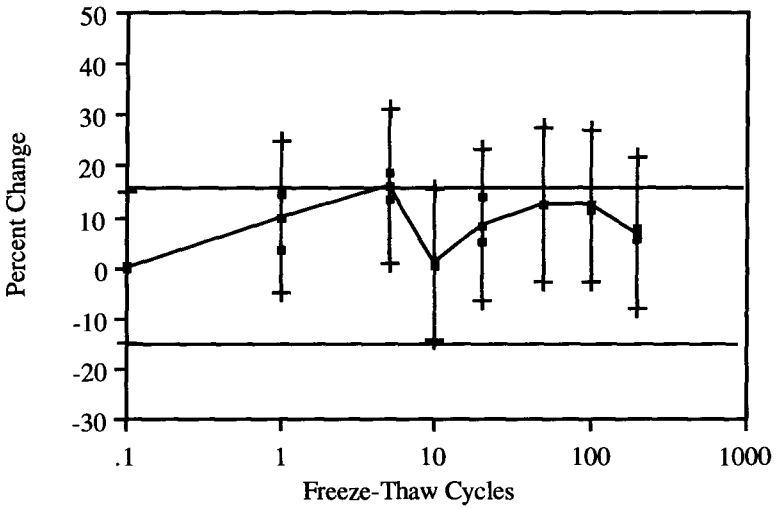
2(c) - 0.5-mm (20-mil) PVC
Shear Test-Dielectric Seam-Break Strength



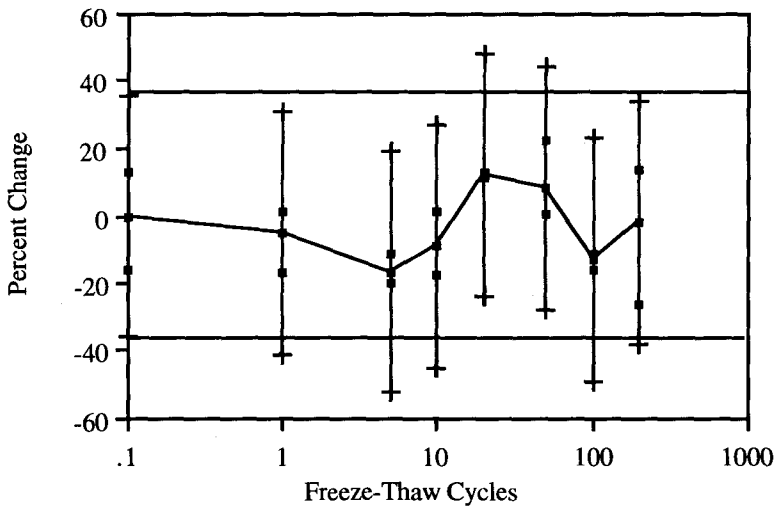
3(a) - 1.0-mm (40-mil) PVC
Shear Test-Chemical Seam - Break Strength

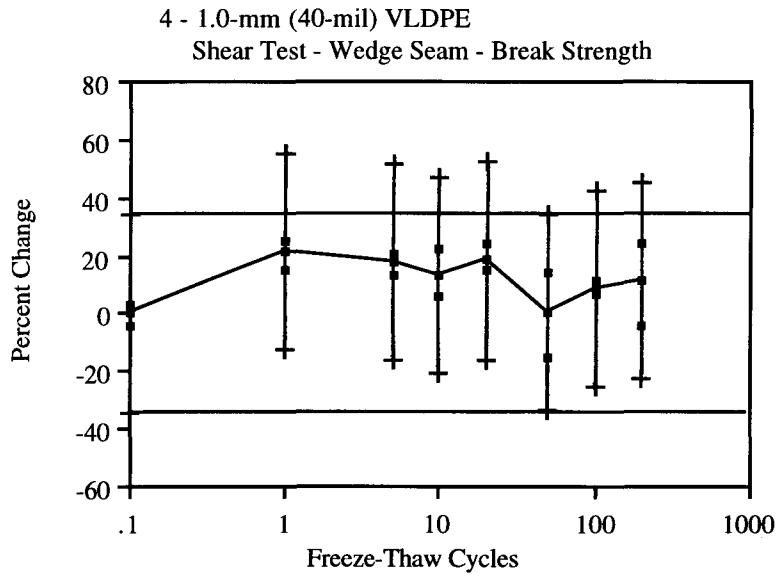


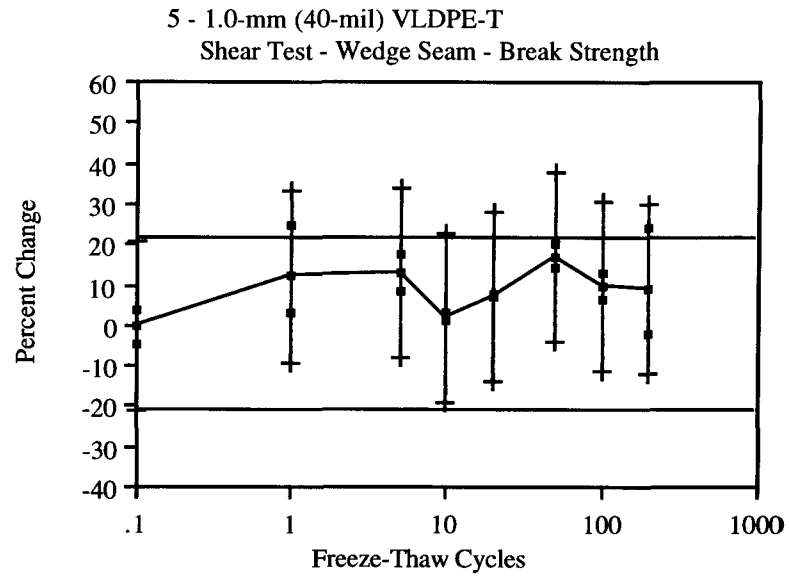
3(b) - 1.0-mm (40-mil) PVC
Shear Test - Wedge Seam - Break Strength

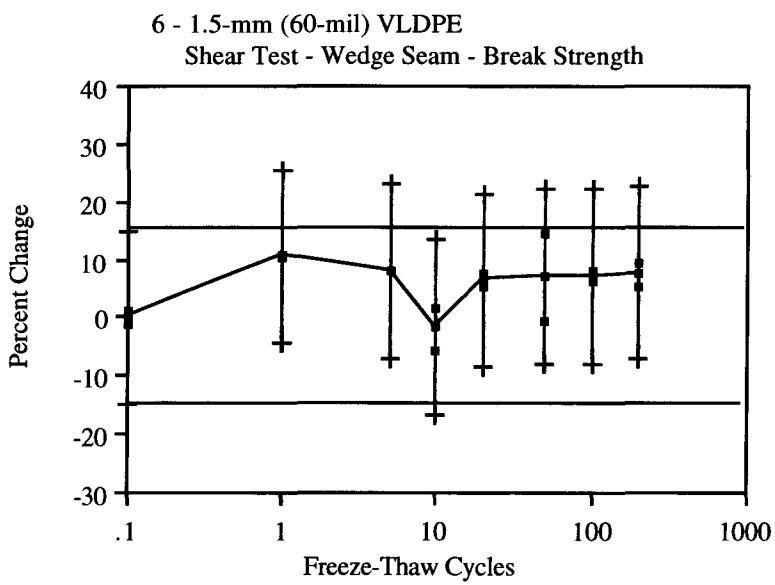


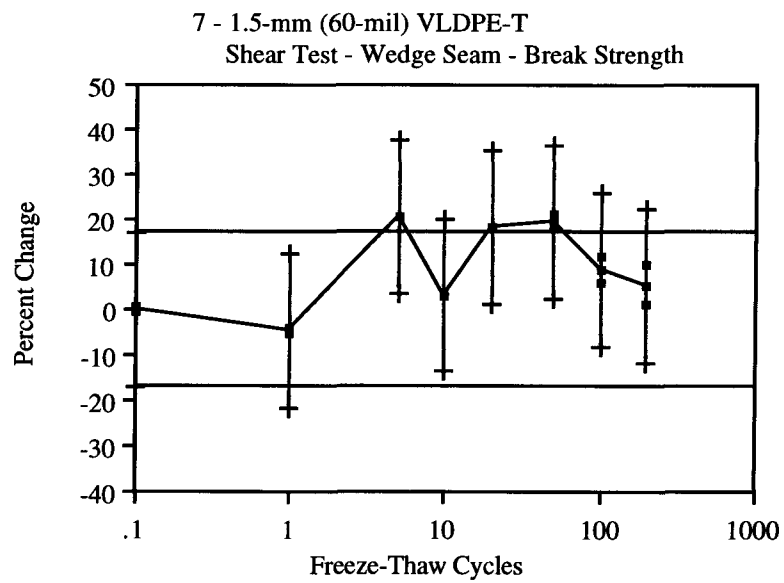
3(c) - 1.0-mm (40-mil) PVC
Shear Test-Dielectric Seam-Break Strength



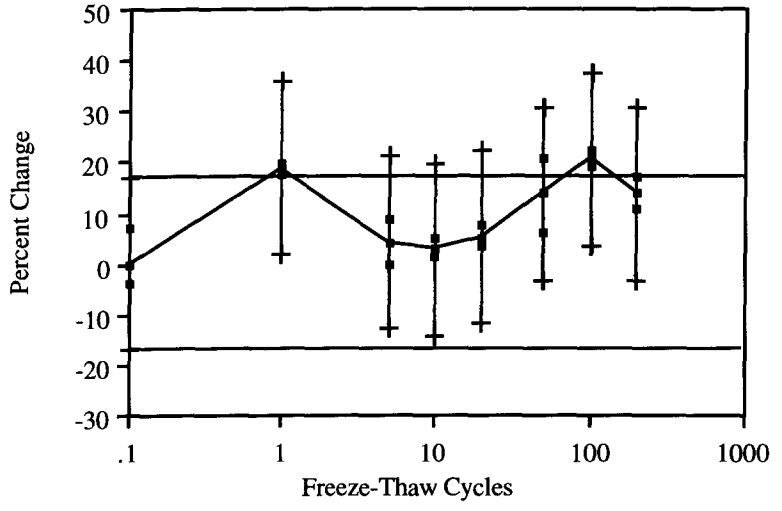

4 - 1.0-mm (40-mil) VLDPE
Shear Test - Wedge Seam - Break Strength
Percent Change
80
60
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles


5 - 1.0-mm (40-mil) VLDPE-T
Shear Test - Wedge Seam - Break Strength
Percent Change
60
50
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

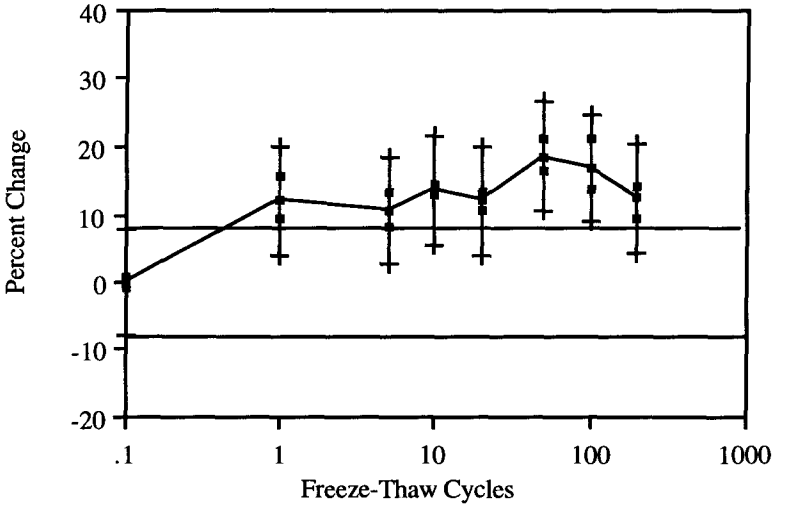

6 - 1.5-mm (60-mil) VLDPE
Shear Test - Wedge Seam - Break Strength
Percent Change
40
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles


7 - 1.5-mm (60-mil) VLDPE-T
Shear Test - Wedge Seam - Break Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

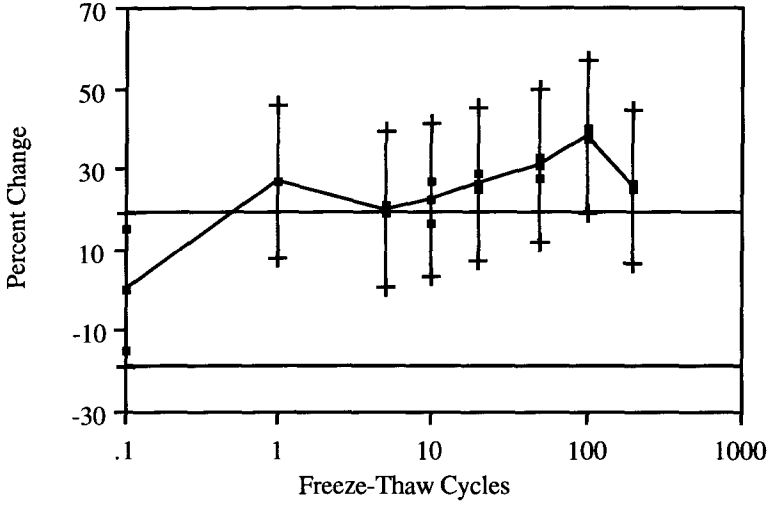
8 - 1.0-mm (40-mil) HDPE
Shear Test - Wedge Seam - Peak Strength



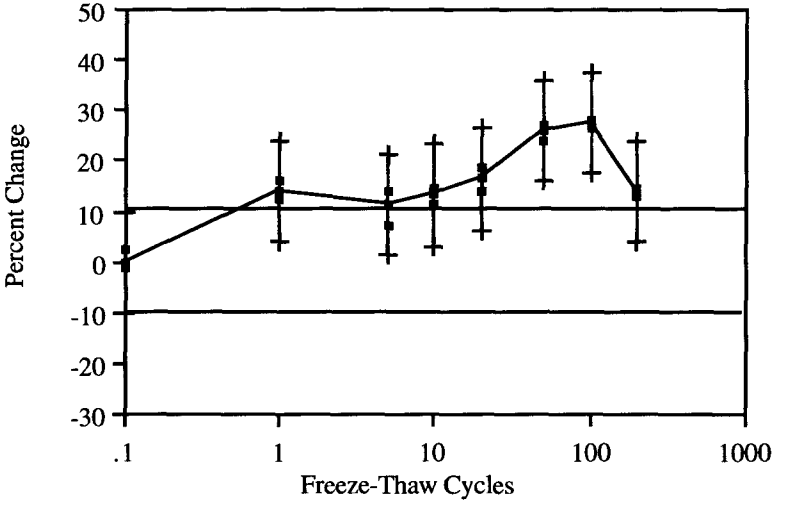
9 - 1.0-mm (40-mil) HDPE-T
Shear Test - Wedge Seam - Peak Strength



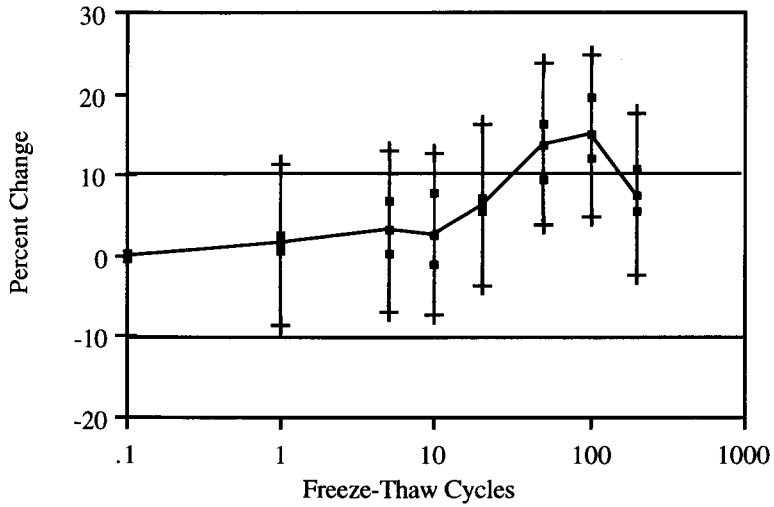
10 - 1.5-mm (60-mil) HDPE
Shear Test - Wedge Seam - Peak Strength



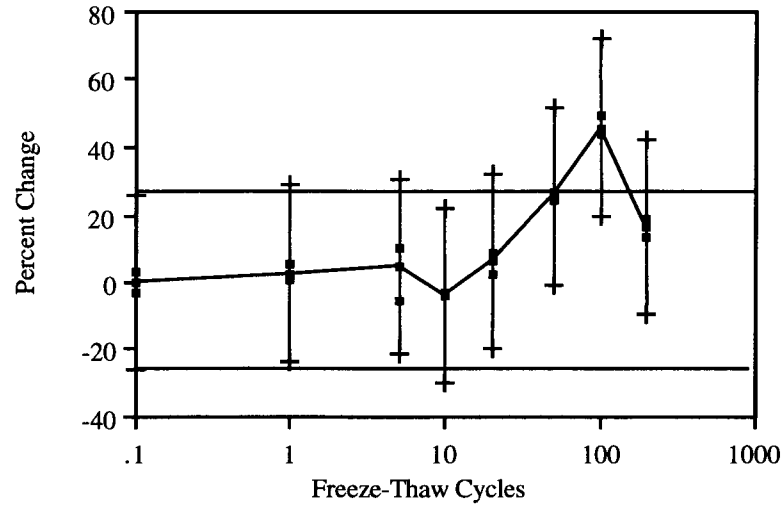
11 - 1.5-mm (60-mil) HDPE-T
Shear Test - Wedge Seam - Peak Strength



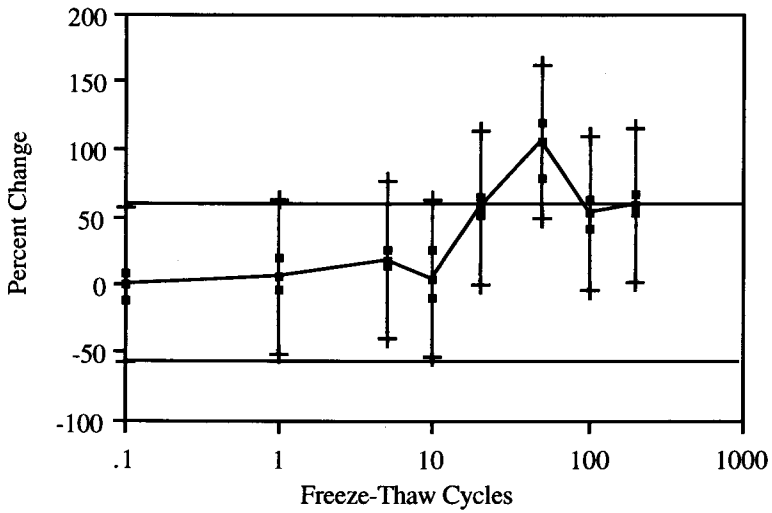
12 - 1.0-mm (40-mil) PP
Shear Test - Thermal Seam - Break Strength



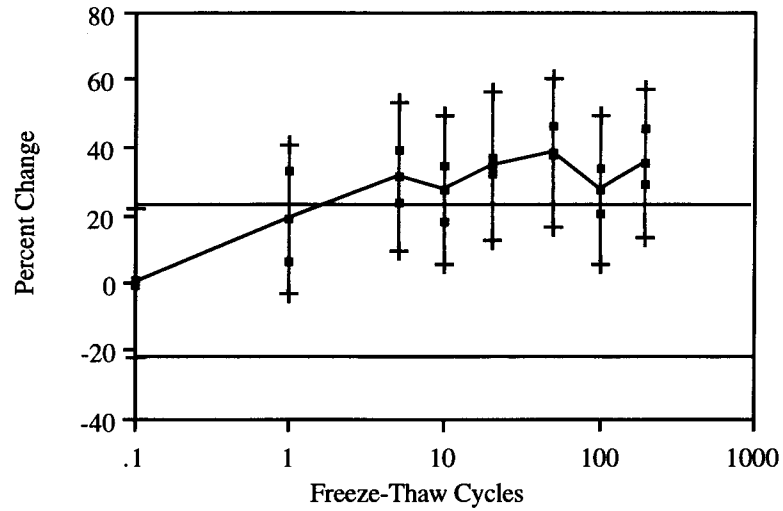
13 - 1.1-mm (45-mil) PP-R
Shear Test - Wedge Seam - Peak Strength



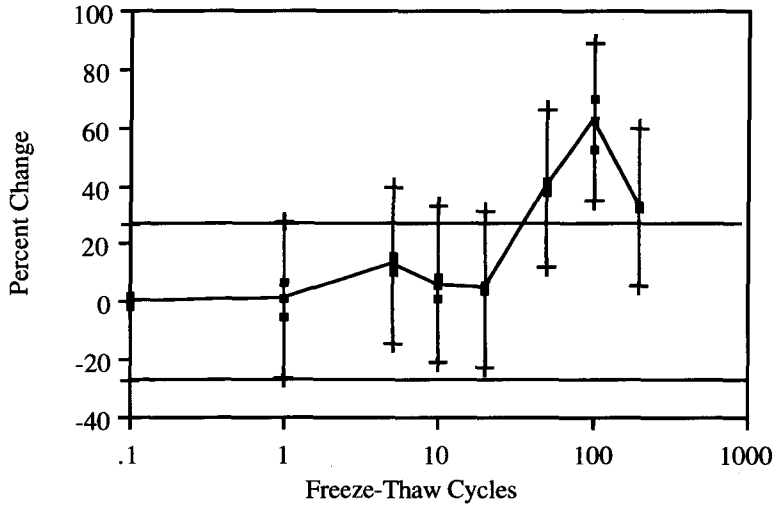
14(a) - 0.9-mm (36-mil) CSPE-R
Shear Test - Chemical Seam - Peak Strength



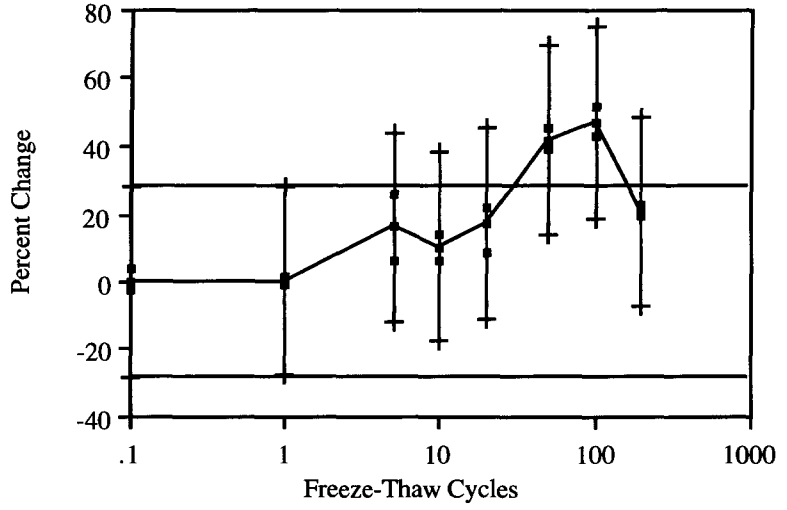
14(b) - 0.9-mm (36-mil) CSPE-R
Shear Test - Thermal Seam - Peak Strength



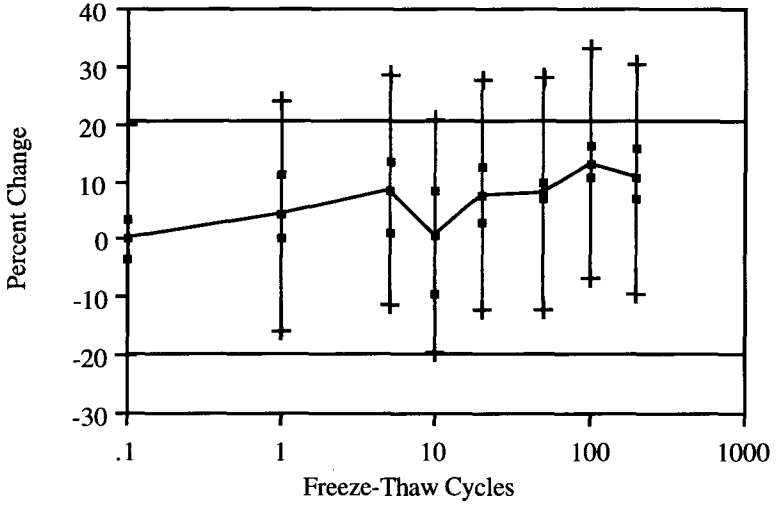
15(a) - 0.8-mm (30-mil) EIA
Shear Test-Chemical Seam - Break Strength



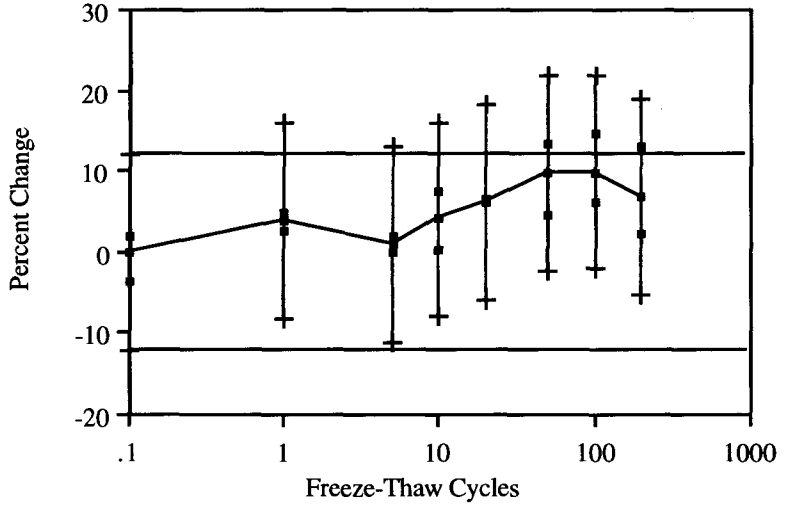
15(b) - 0.8-mm (30-mil) EIA
Shear Test - Thermal Seam - Break Strength



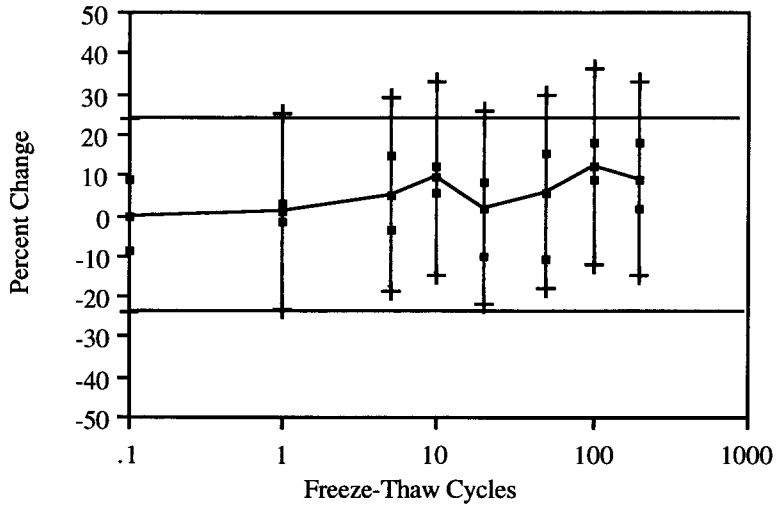
16(a) - 0.9-mm (36-mil) EIA-R
Shear Test-Chemical Seam - Break Strength



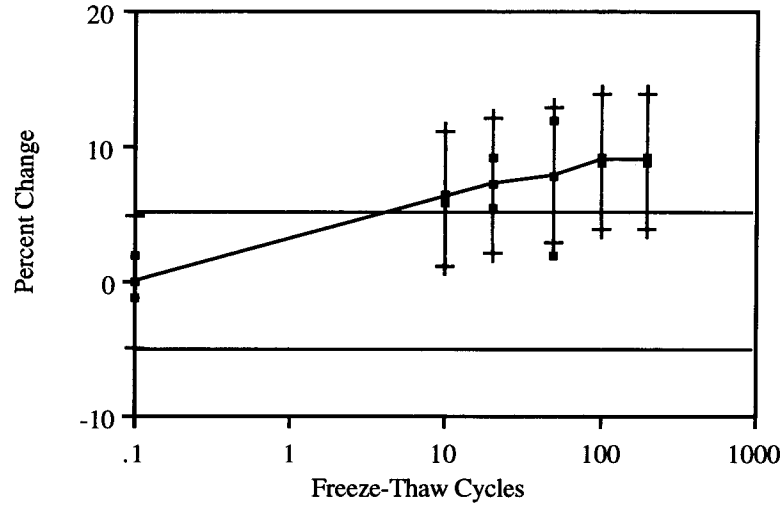
16(b) - 0.9-mm (36-mil) EIA-R
Shear Test - Thermal Seam - Break Strength



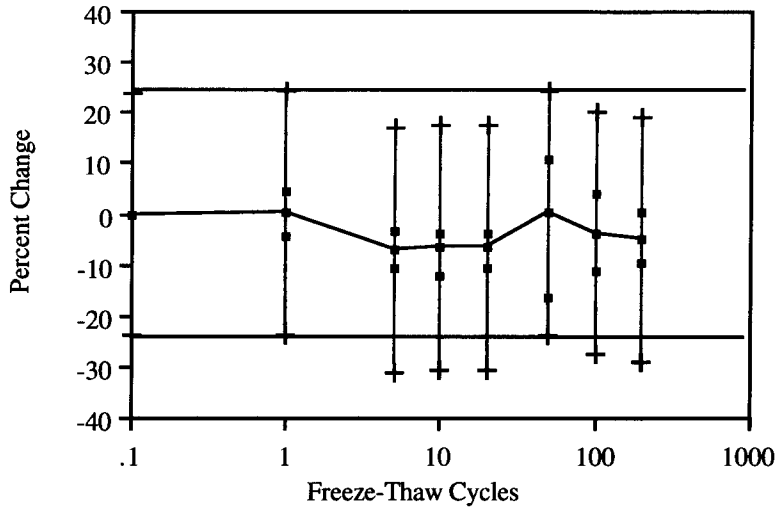
17 - 0.8-mm (30-mil) FCEA
Shear Test - Thermal Seam - Break Strength



18 - 0.8-mm (30-mil) FCEA with fabric support
Shear Test - Thermal Seam - Break Strength



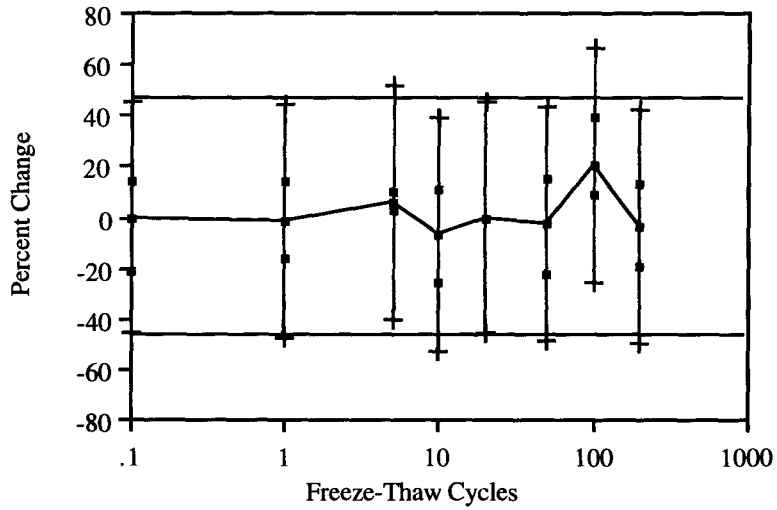
19 - 0.8-mm (30-mil) scrim coated EIA
Shear Test - Thermal Seam - Break Strength



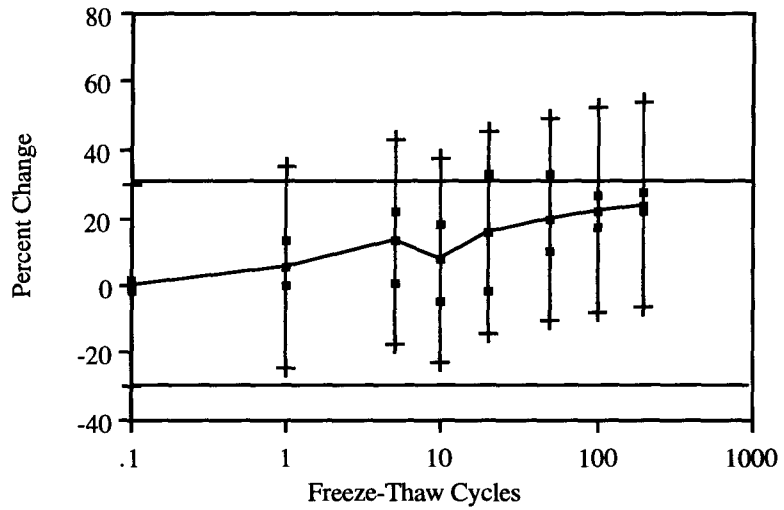
APPENDIX C

Part I — Seam Peel Tensile Test Results

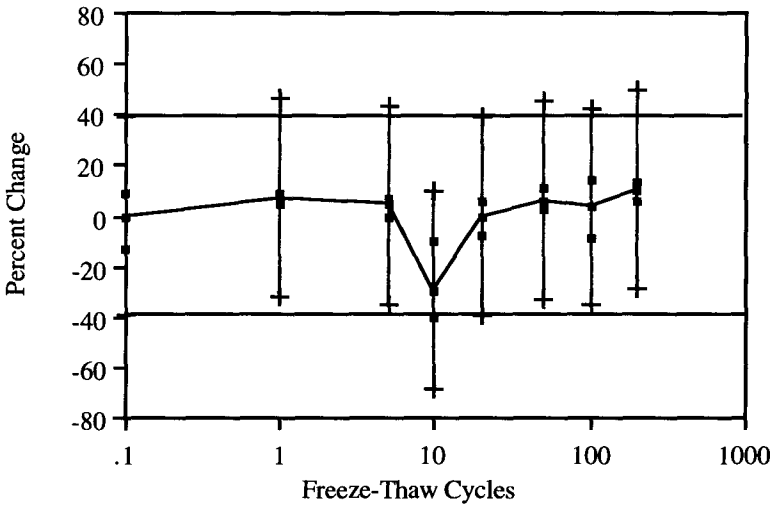
1(a) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Chemical Seam - Peak Strength



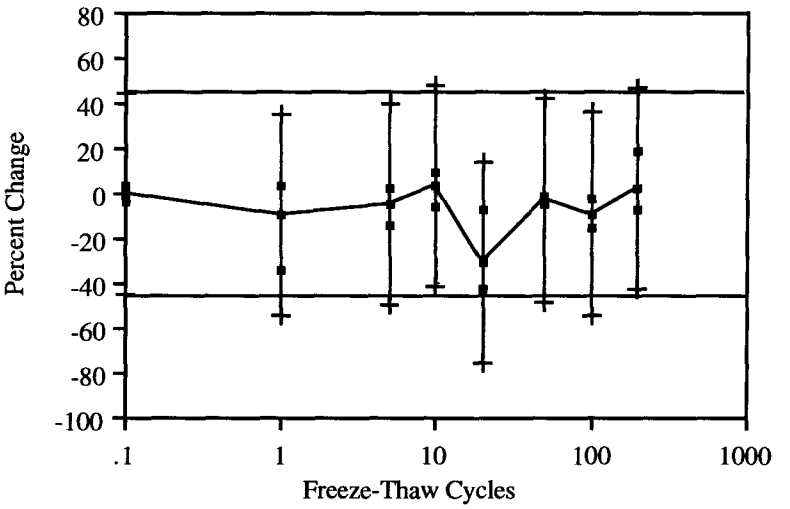
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Wedge Seam - Peak Strength



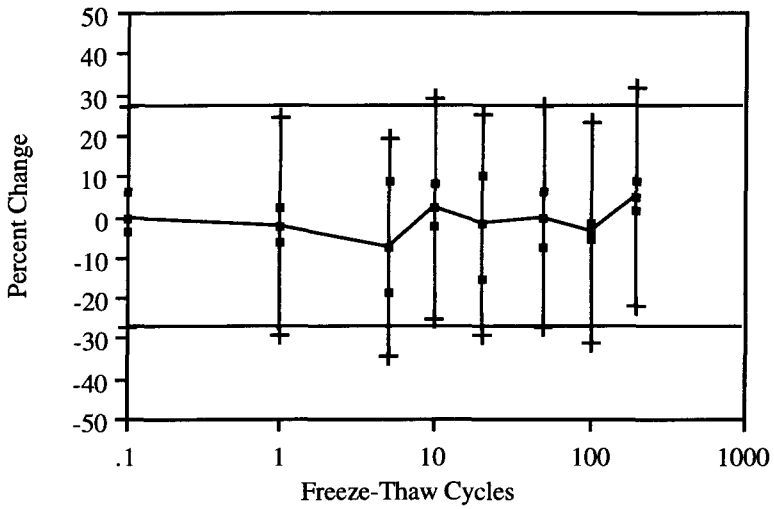
2(b) - 0.5-mm (20-mil) PVC
Peel Test - Wedge Seam - Peak Strength



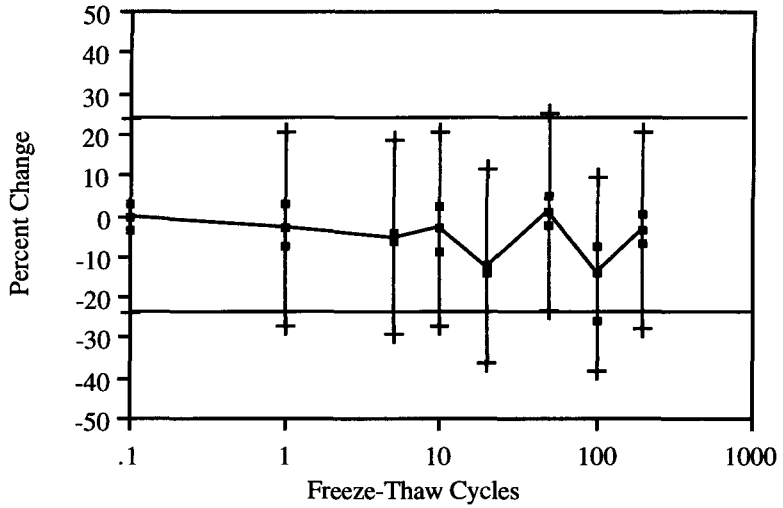
2(c) - 0.5-mm (20-mil) PVC
Peel Test - Dielectric Seam - Peak Strength



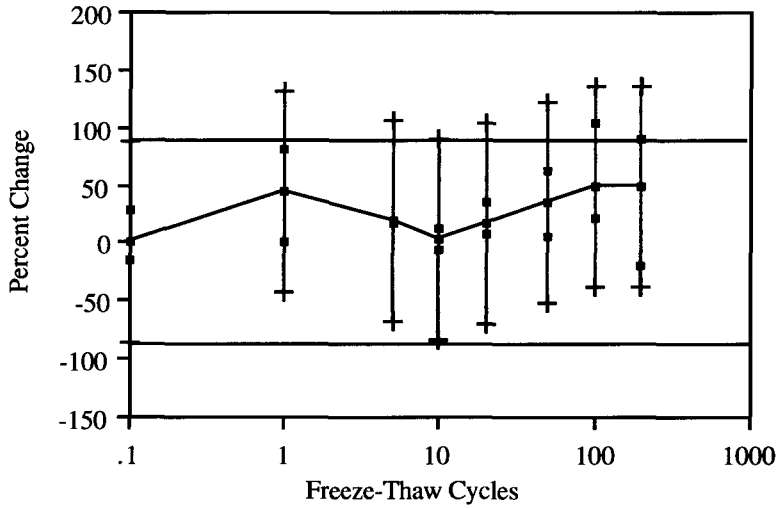
3(a) - 1.0-mm (40-mil) PVC
Peel Test - Chemical Seam - Peak Strength



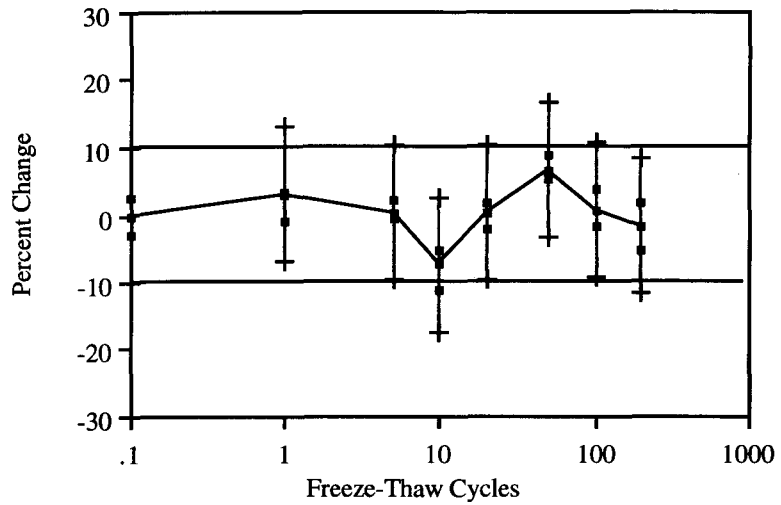
3(b) - 1.0-mm (40-mil) PVC
Peel Test - Wedge Seam - Peak Strength



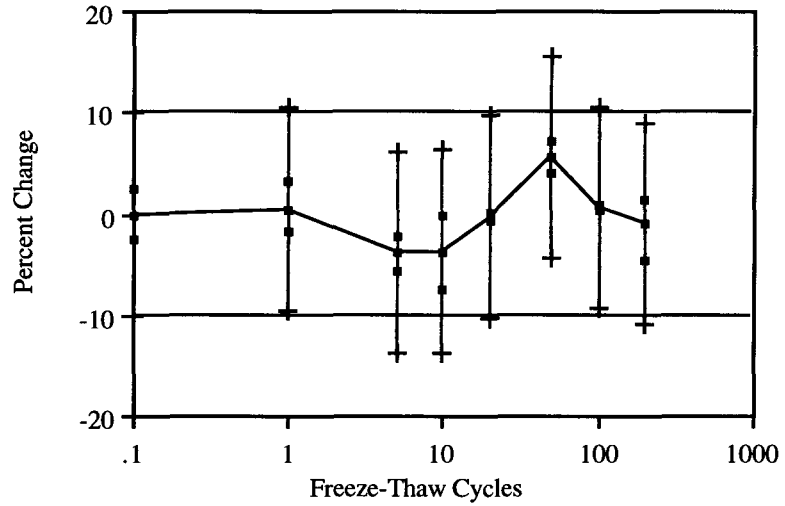
3(c) - 1.0-mm (40-mil) PVC
Peel Test - Dielectric Seam - Peak Strength



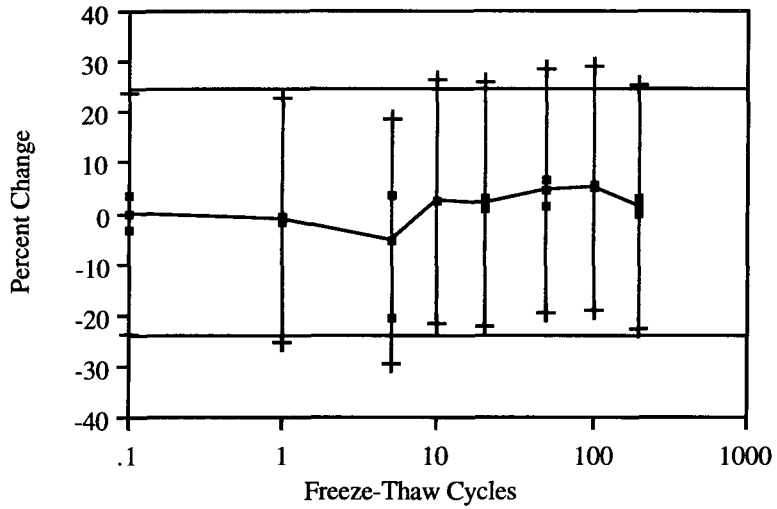
4 - 1.0-mm (40-mil) VLDPE
Peel Test - Wedge Seam - Peak Strength



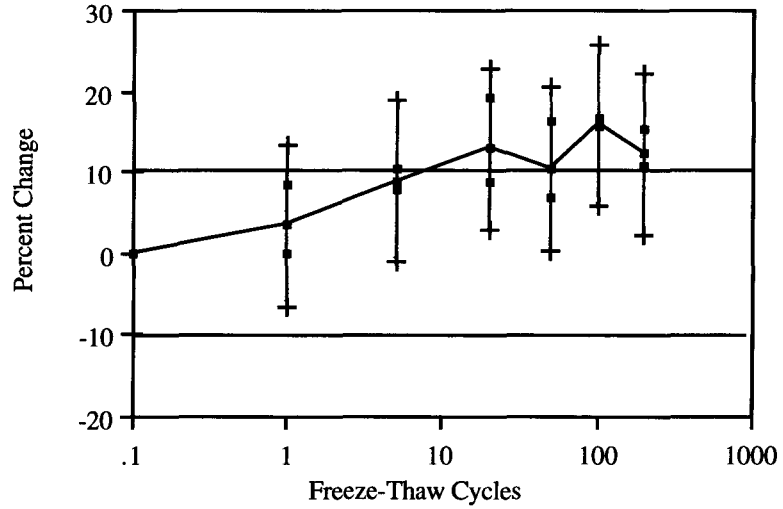
5 - 1.0-mm (40-mil) VLDPE-T
Peel Test - Wedge Seam - Peak Strength

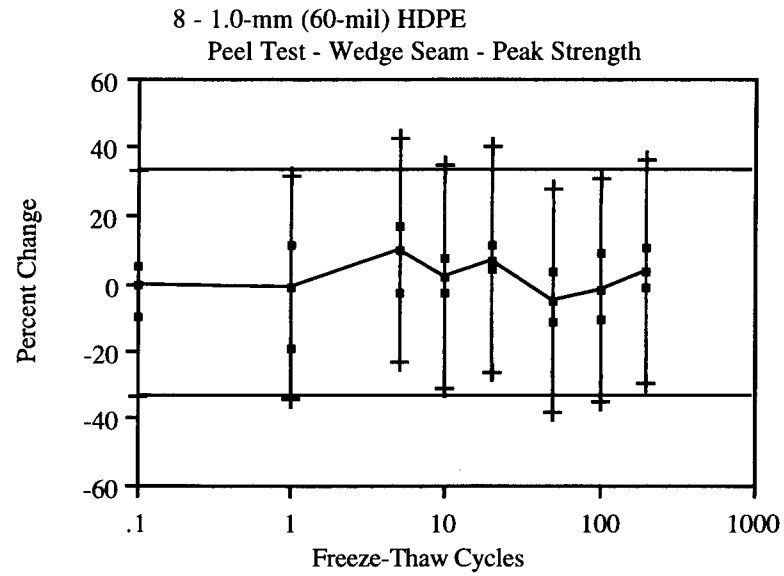


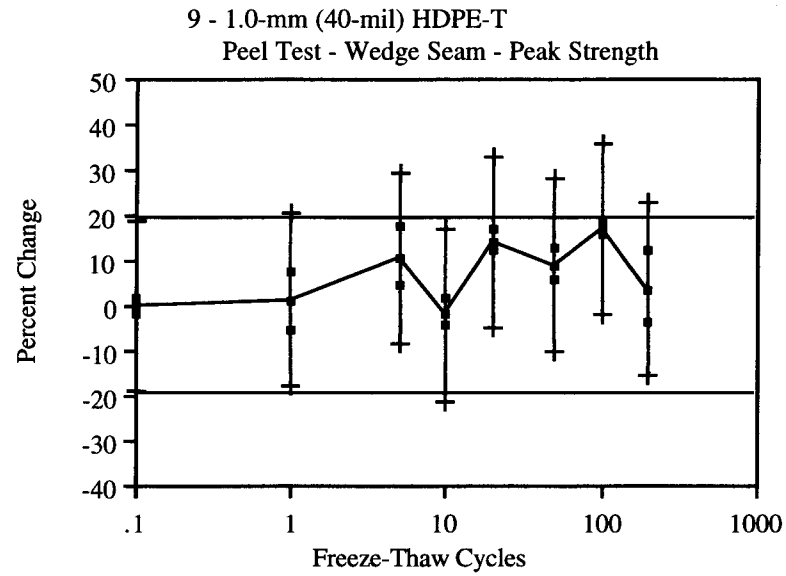
6 - 1.5-mm (60-mil) VLDPE
Peel Test - Wedge Seam - Peak Strength

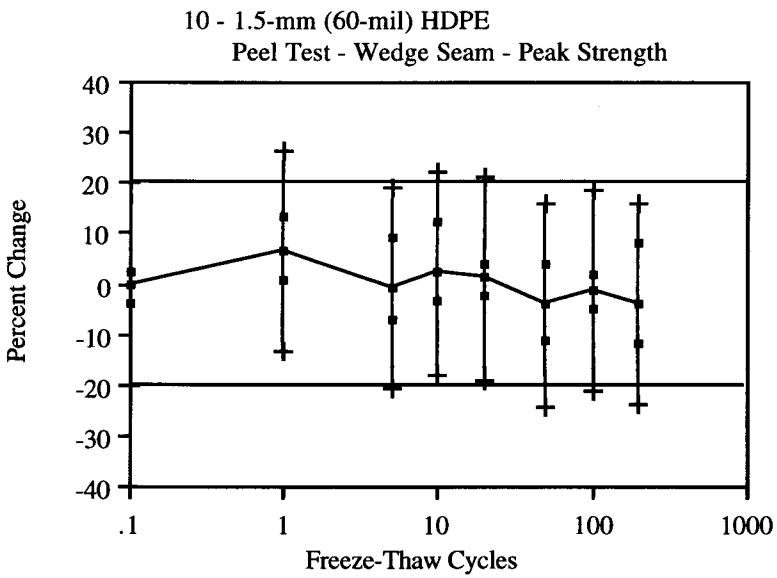


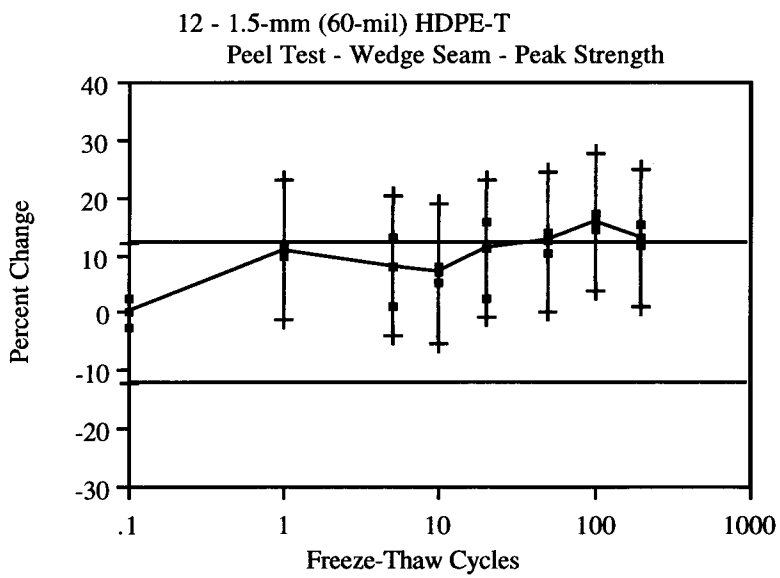
7 - 1.5-mm (60-mil) VLDPE-T
Peel Test - Wedge Seam - Peak Strength



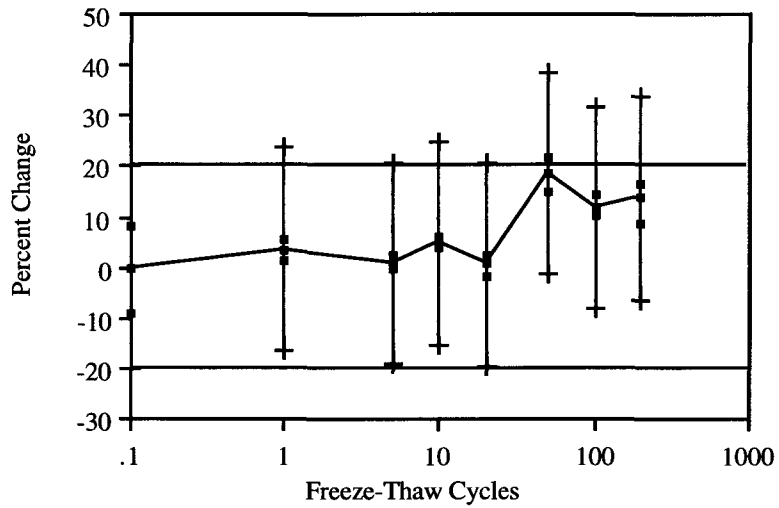

8 - 1.0-mm (60-mil) HDPE
Peel Test - Wedge Seam - Peak Strength
Percent Change
60
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles


9 - 1.0-mm (40-mil) HDPE-T
Peel Test - Wedge Seam - Peak Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

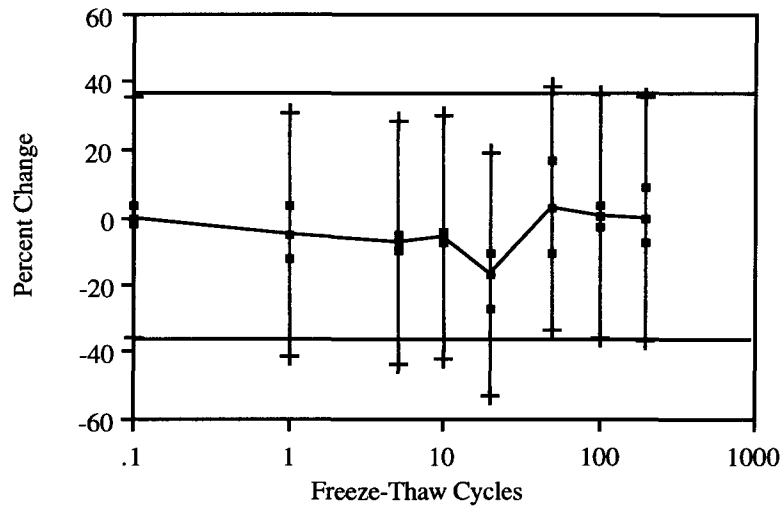

10 - 1.5-mm (60-mil) HDPE
Peel Test - Wedge Seam - Peak Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


12 - 1.5-mm (60-mil) HDPE-T
Peel Test - Wedge Seam - Peak Strength
Percent Change
40
30
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles

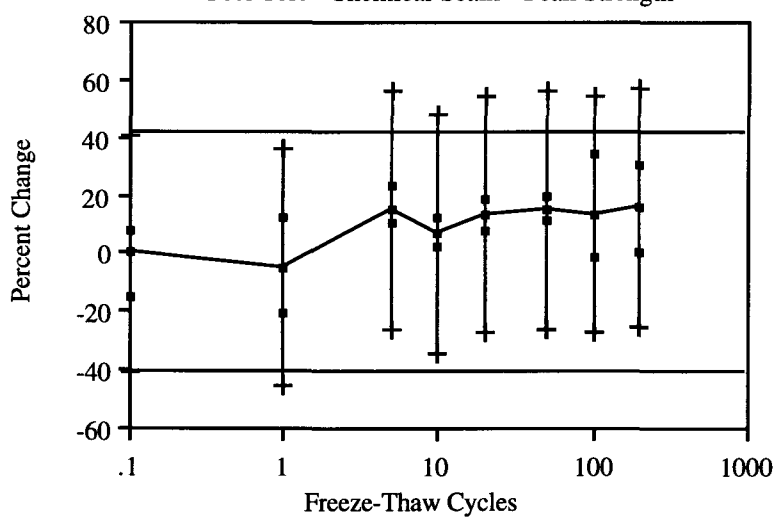
12 - 1.0-mm (40-mil) PP
Peel Test - Thermal Seam - Peak Strength



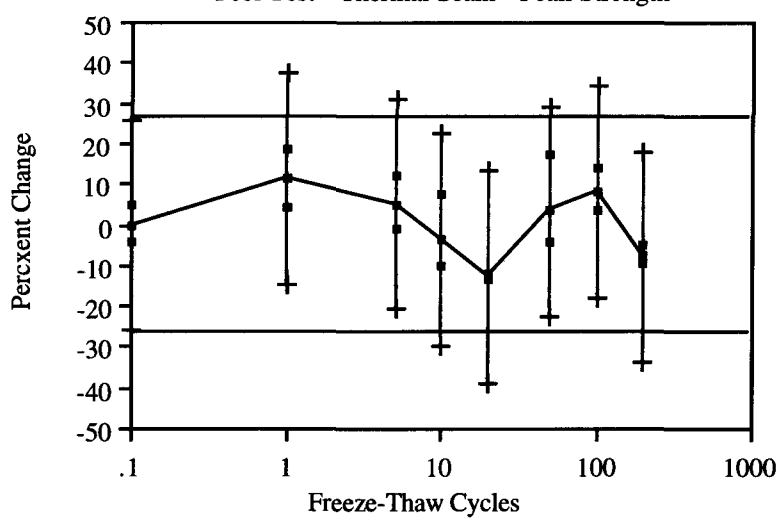
13 - 1.1-mm (45-mil) PP-R
Peel Test - Wedge Seam - Peak Strength



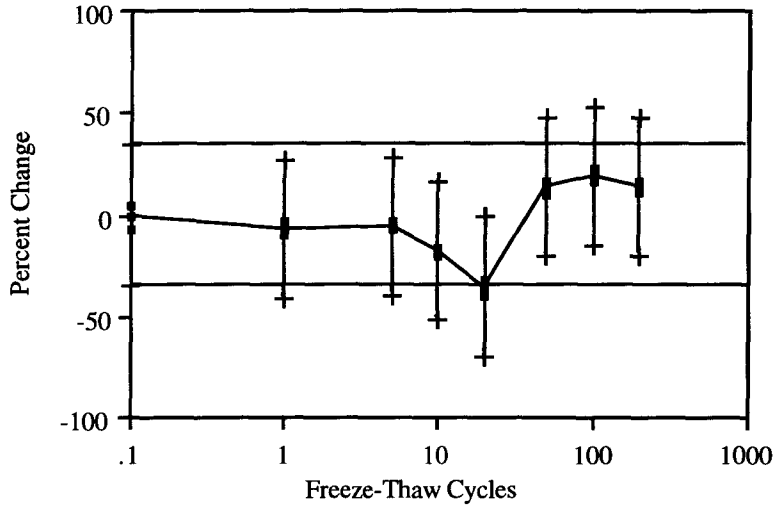
14(a) - 0.9-mm (36-mil) CSPE-R
Peel Test - Chemical Seam - Peak Strength



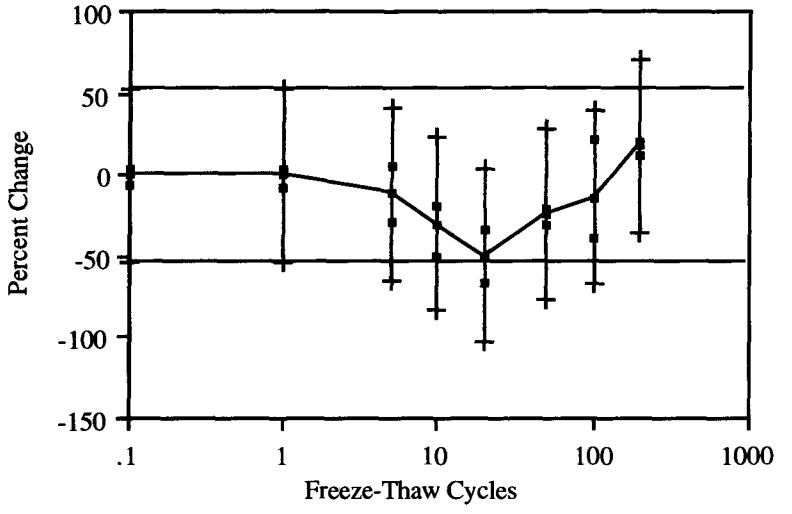
14(b) - 0.9-mm (36-mil) CSPE-R
Peel Test - Thermal Seam - Peak Strength



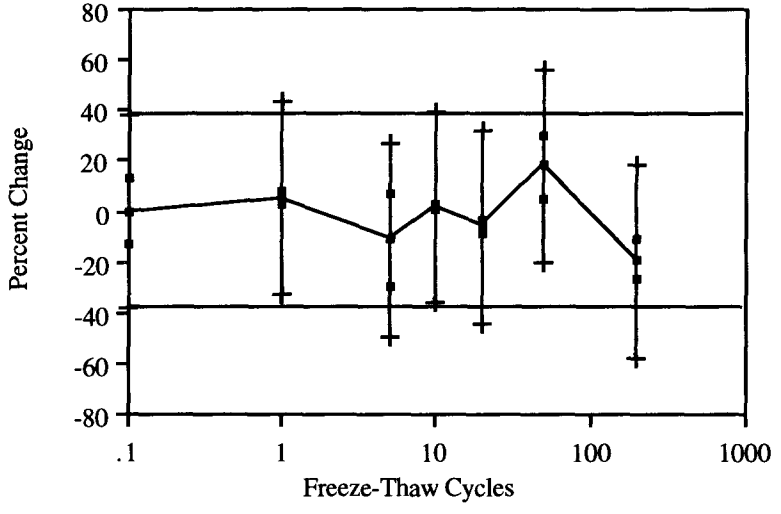
15(a) - 0.8-mm (30-mil) EIA
Peel Test - Chemical Seam - Peak Strength



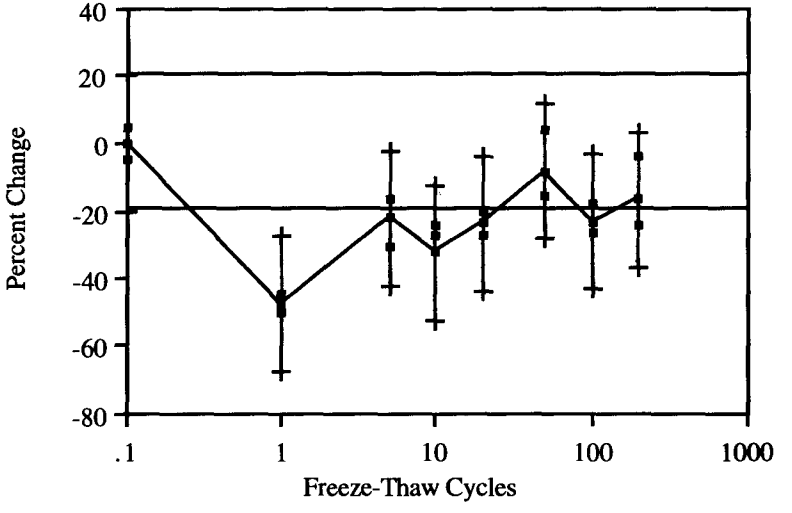
15(b) - 0.8-mm (30-mil) EIA
Peel Test - Thermal Seam - Peak Strength

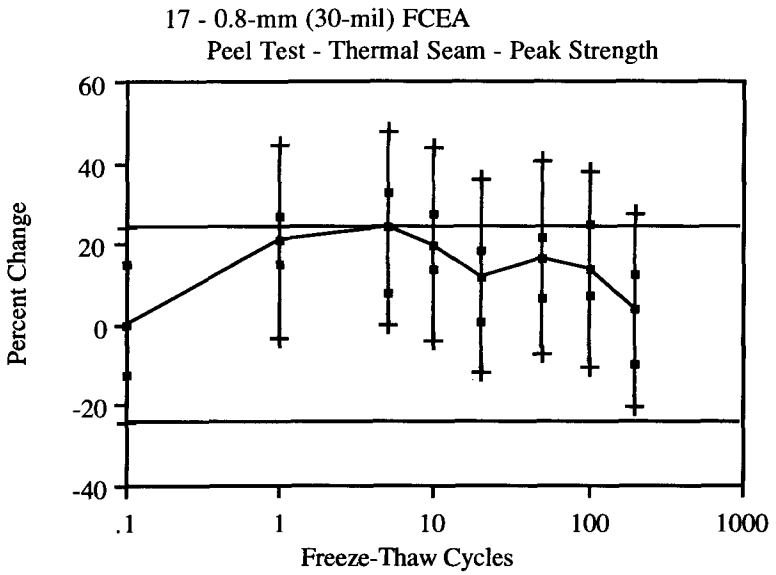


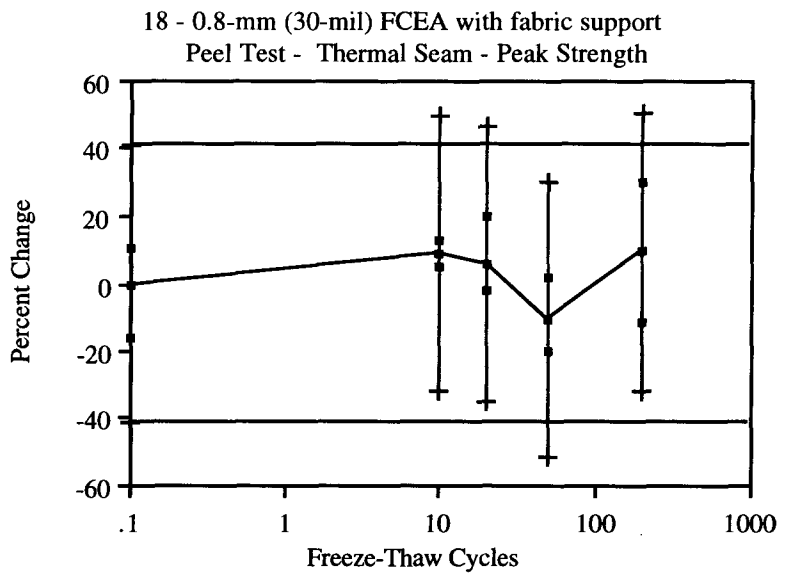
16(a) - 0.9-mm (36-mil) EIA-R
Peel Test - Chemical Seam - Peak Strength



16(b) - 0.9-mm (36-mil) EIA-R
Peel Test - Thermal Seam - Peak Strength



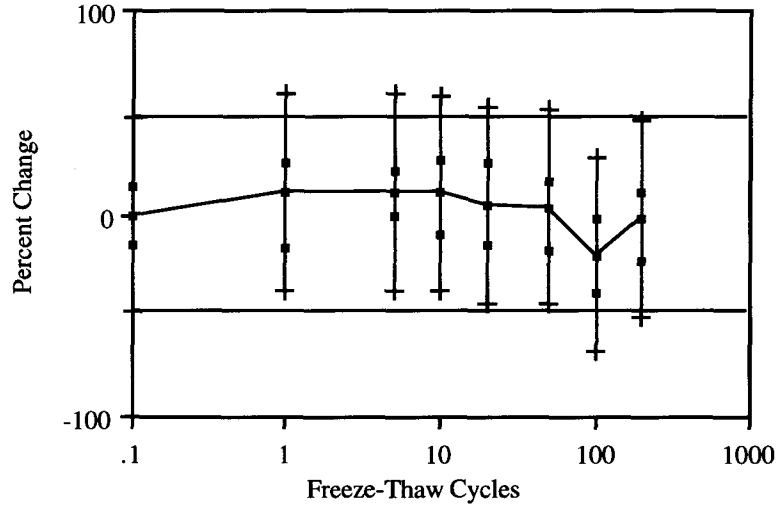

17 - 0.8-mm (30-mil) FCEA
Peel Test - Thermal Seam - Peak Strength
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


18 - 0.8-mm (30-mil) FCEA with fabric support
Peel Test - Thermal Seam - Peak Strength
Percent Change
60
40
20
0
-20
-40
-60
.1
1
10
100
1000
Freeze-Thaw Cycles

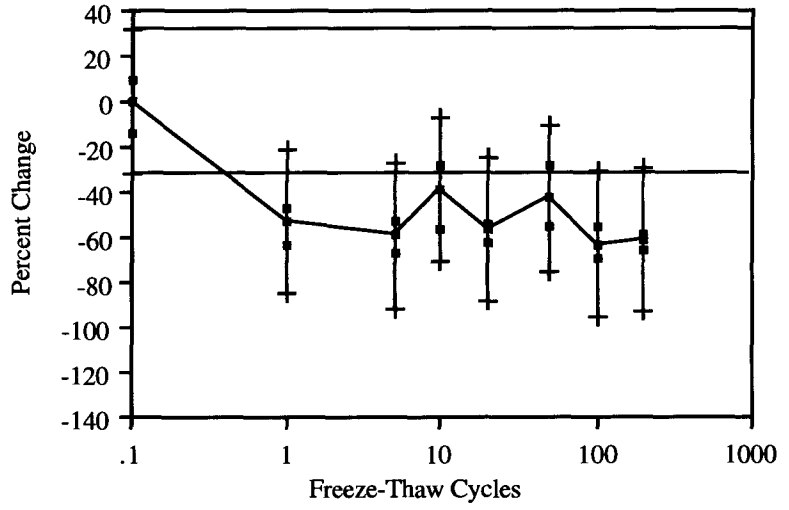
APPENDIX D

Part II — Sheet Tensile Test Results

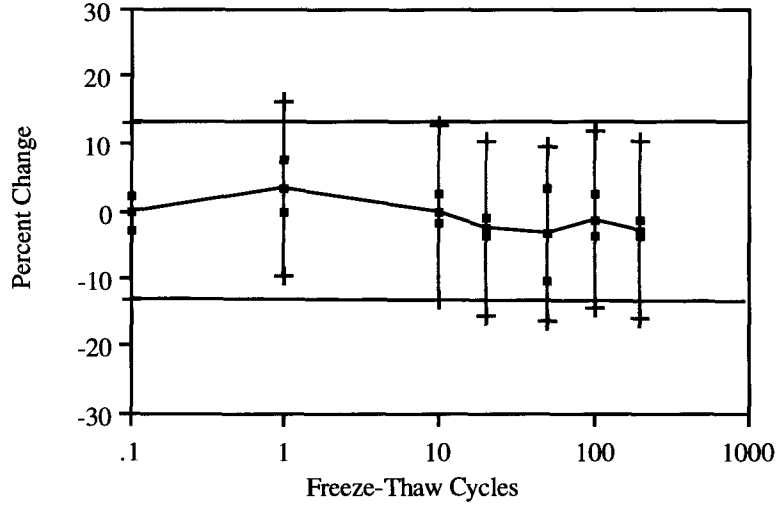
1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Strength



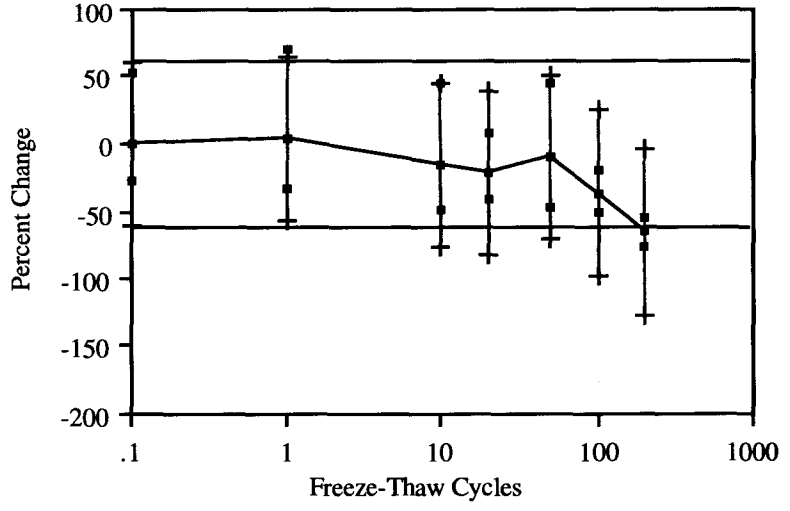
1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Elongation

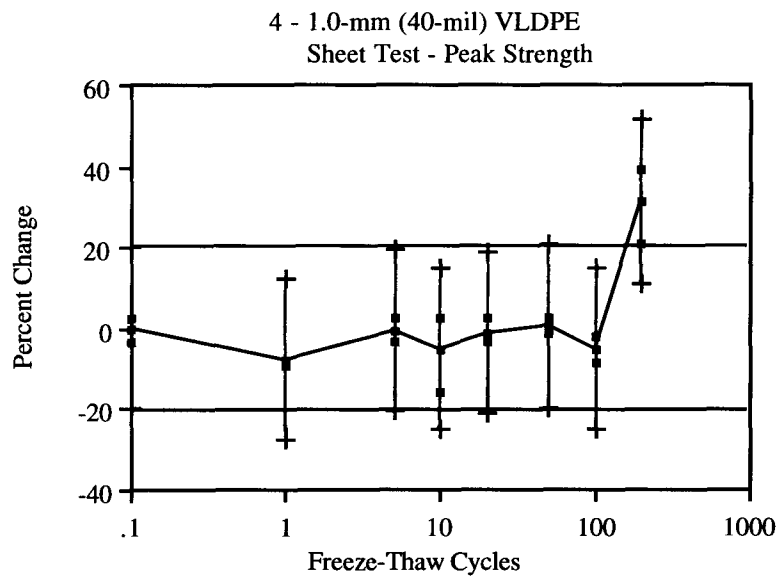


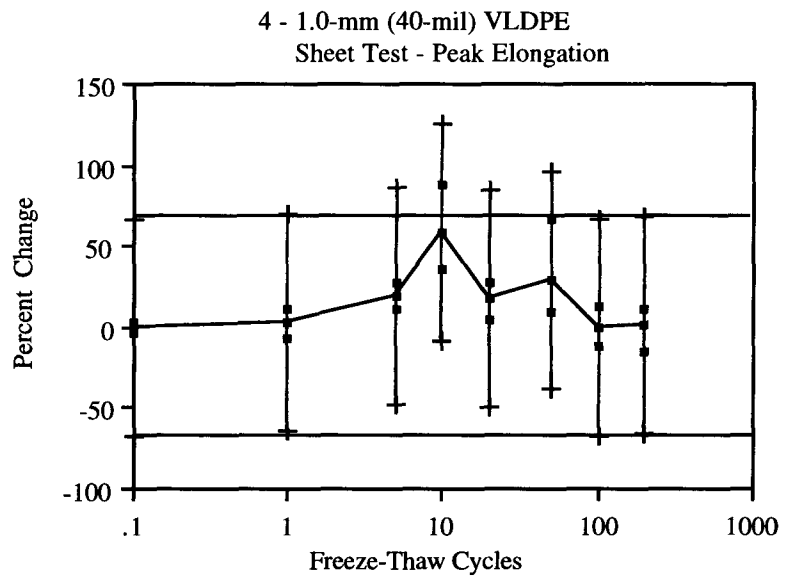
3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Strength

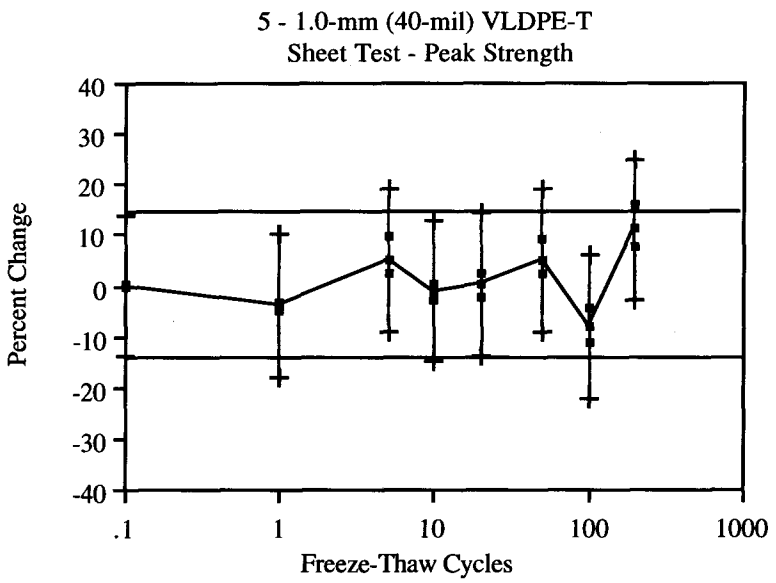


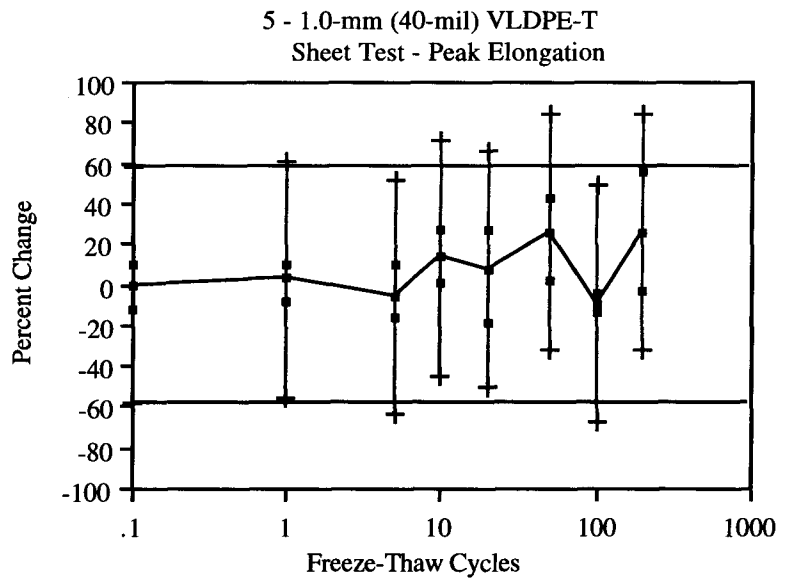
3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Elongation

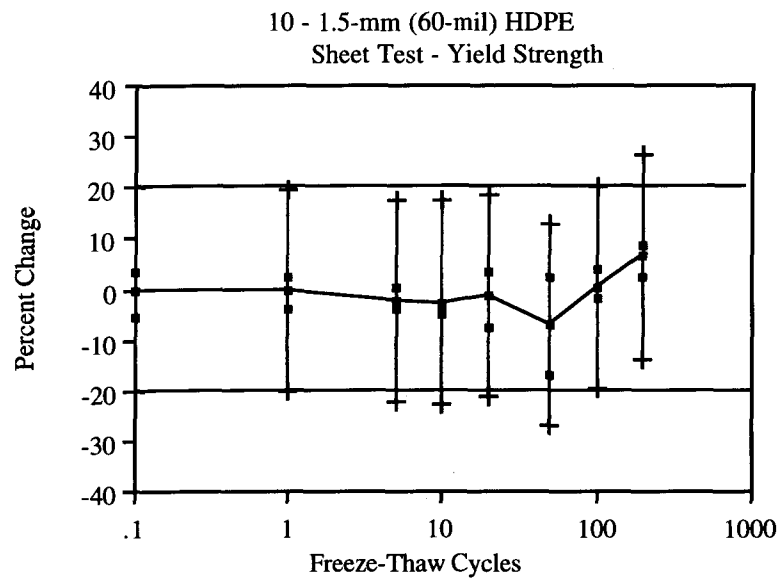


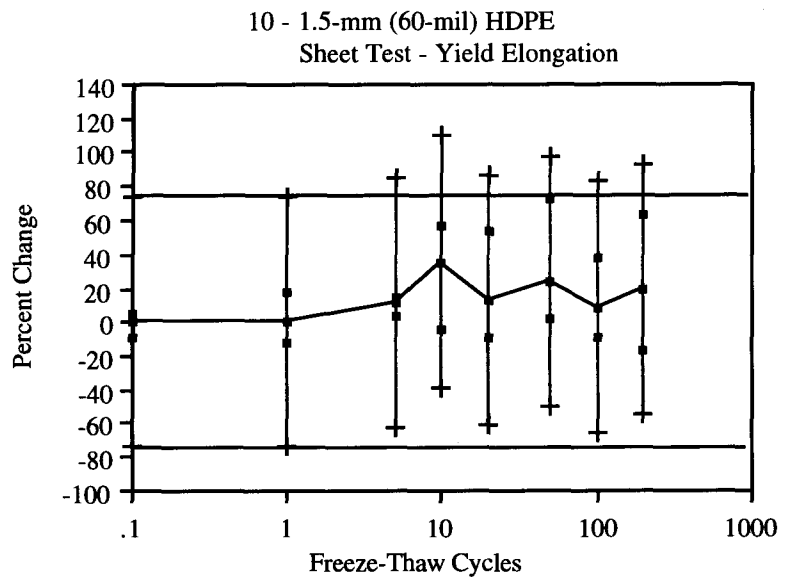

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Peak Strength
Percent Change
60
40
20
0
-20
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

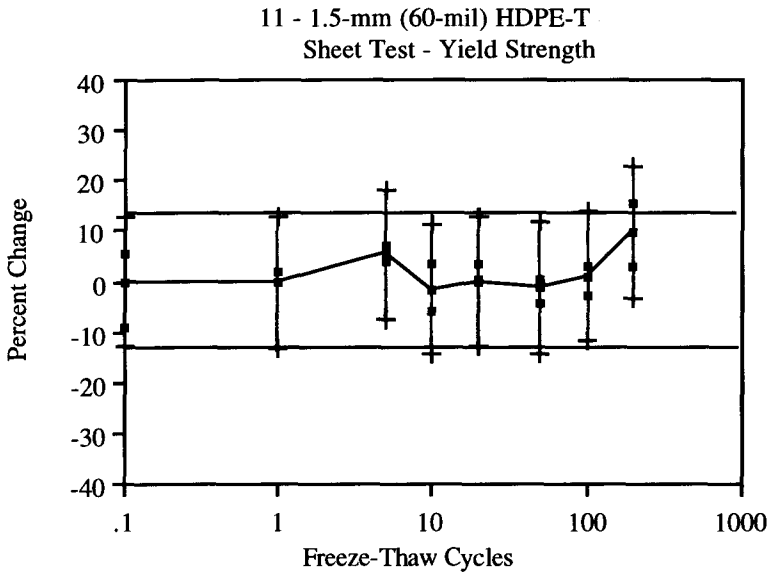

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Peak Elongation
Percent Change
150
100
50
0
-50
-100
.1
1
10
100
1000
Freeze-Thaw Cycles

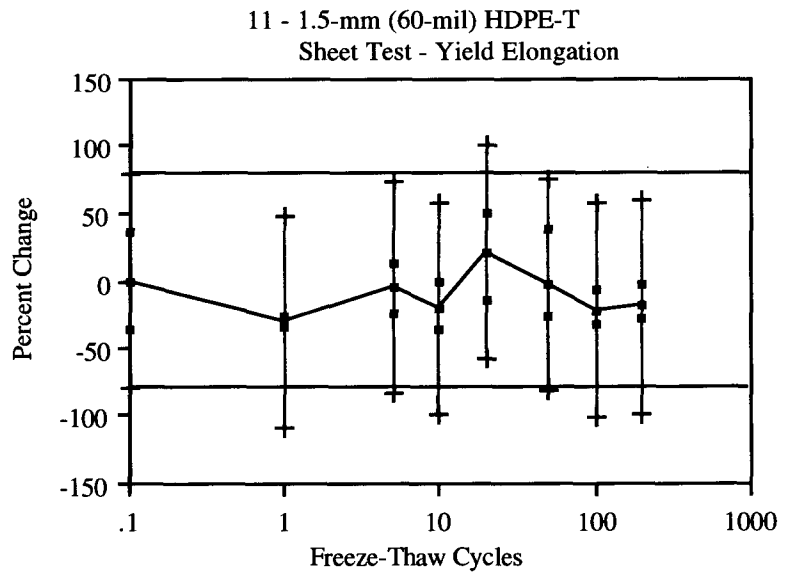

5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Peak Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Peak Elongation
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
.1
1
10
100
1000
Freeze-Thaw Cycles


10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Elongation
Percent Change
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
.1
1
10
100
1000
Freeze-Thaw Cycles

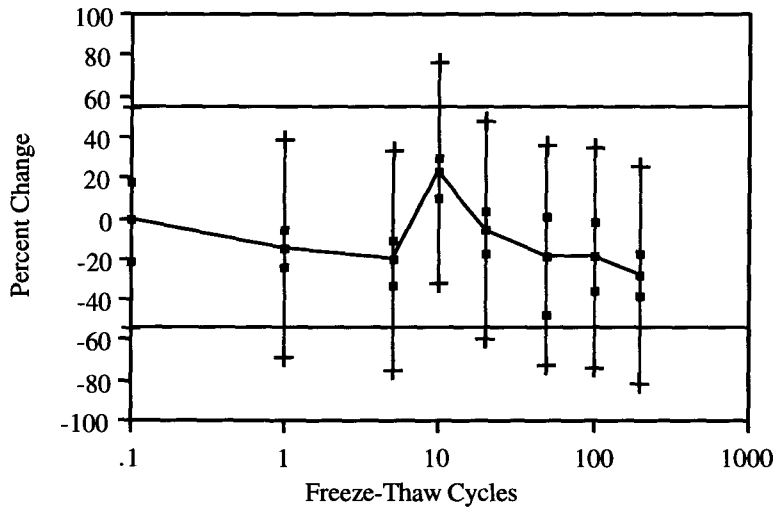

11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Elongation
Percent Change
150
100
50
0
-50
-100
-150
.1
1
10
100
1000
Freeze-Thaw Cycles

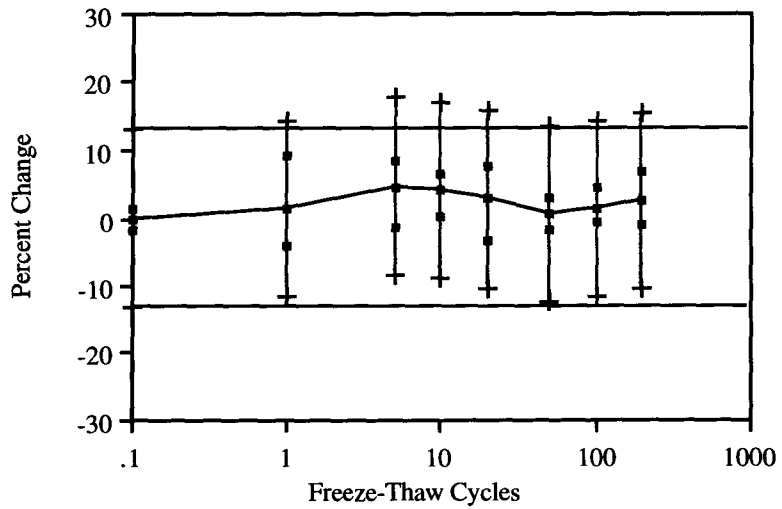
APPENDIX E

Part II — Seam Shear Tensile Test Results

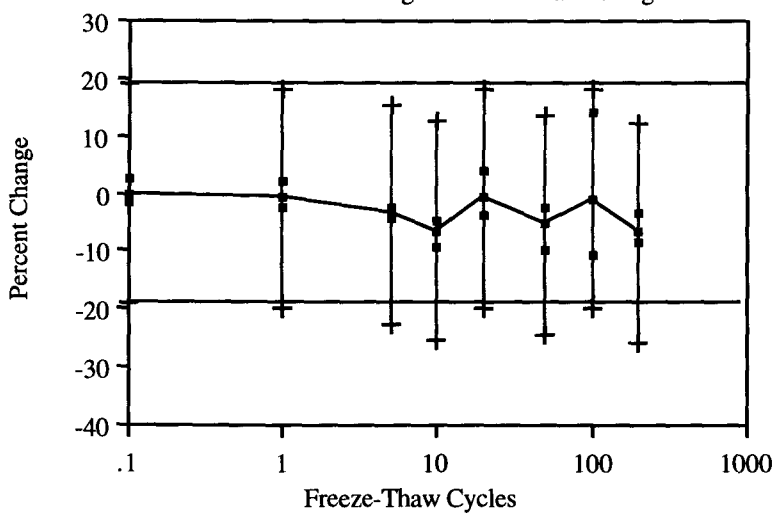
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Shear Test - Wedge Seam - Peak Strength



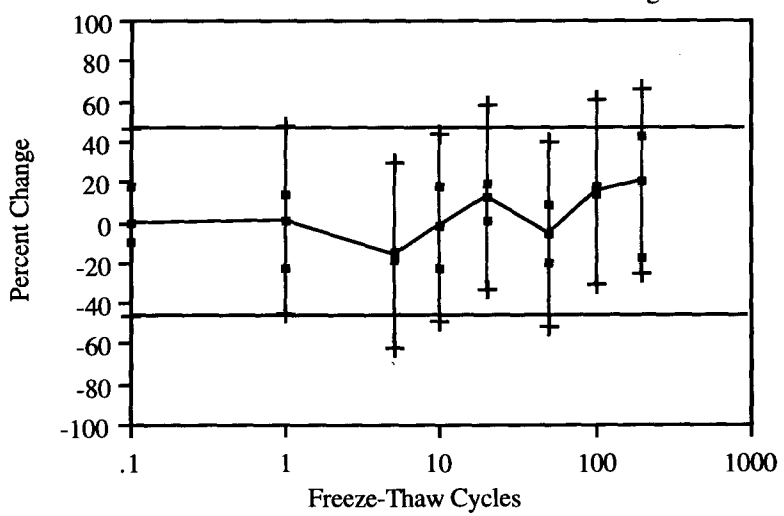
3(a) - 1.0-mm (40-mil) PVC
Shear Test - Chemical Seam - Break Strength



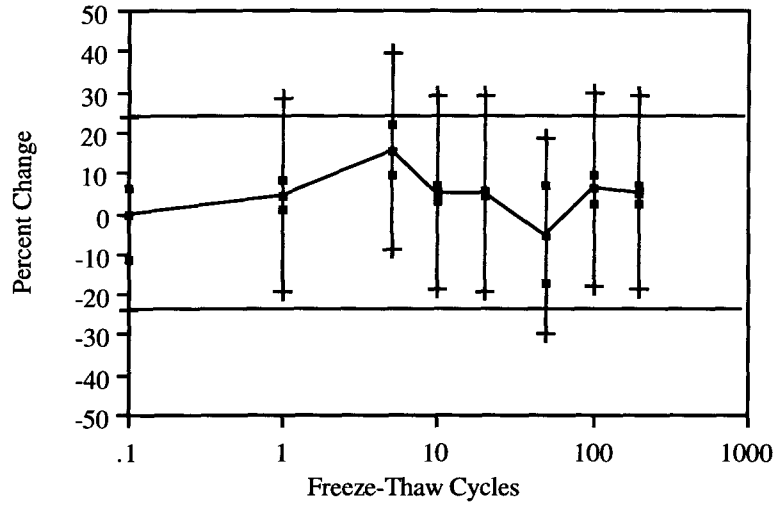
3(b) - 1.0-mm (40-mil) PVC
Shear Test - Wedge Seam - Break Strength



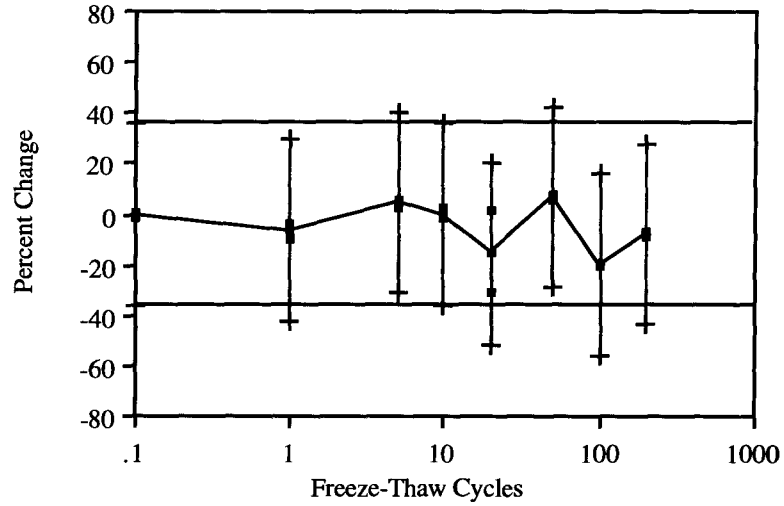
3(c) - 1.0-mm (40-mil) PVC
Shear Test - Dielectric Seam - Break Strength



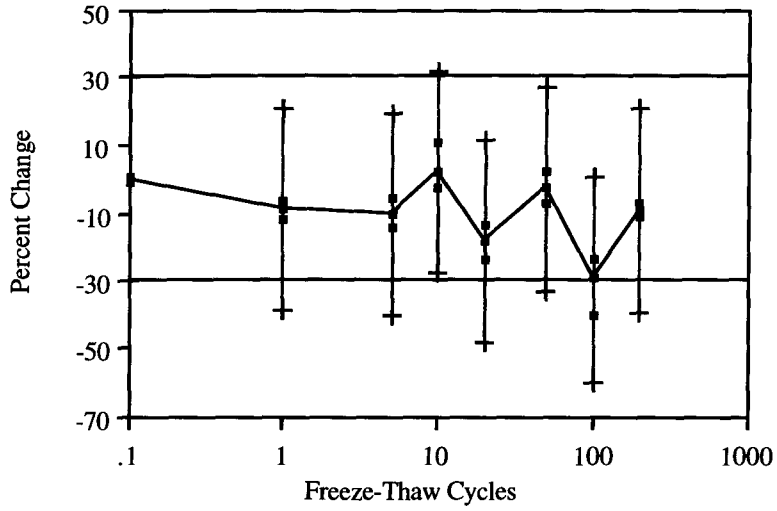
4 - 1.0-mm (40-mil) VLDPE
Shear Test - Wedge Seam - Yield Strength



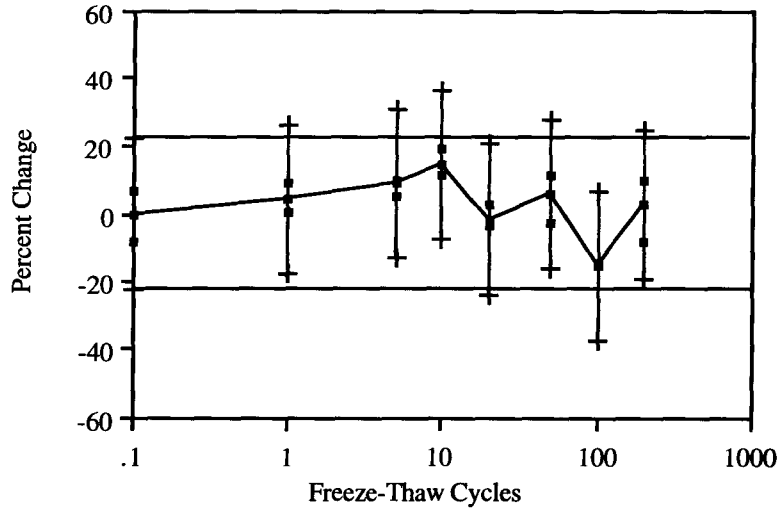
4(a) - 1.0-mm (40-mil) VLDPE
Shear Test - Fillet Extrusion Seam - Yield Strength



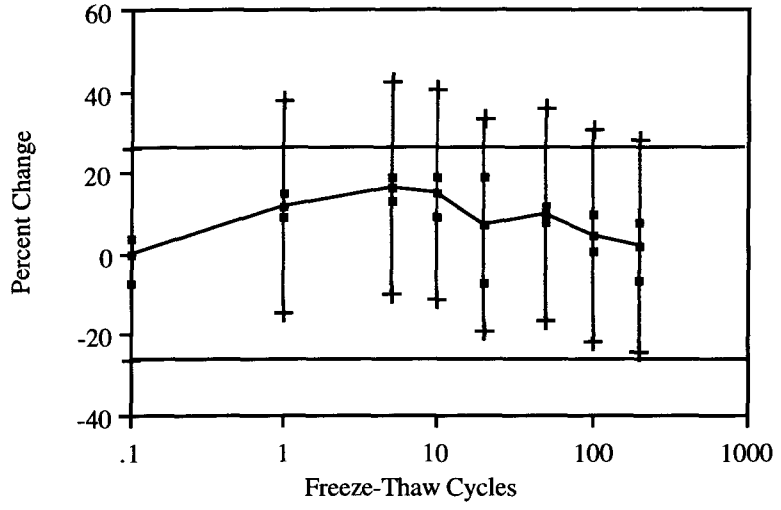
5 - 1.0-mm (40-mil) VLDPE-T
Shear Test - Wedge Seam - Yield Strength



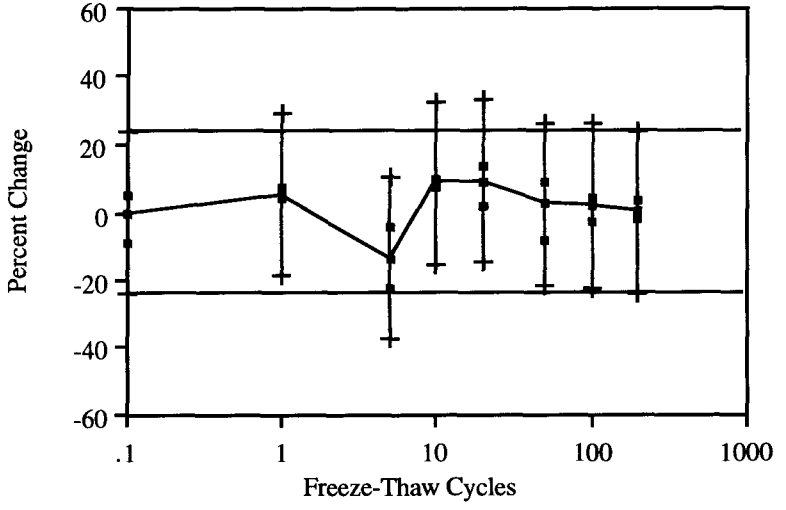
5(a) - 1.0-mm (40-mil) VLDPE-T
Shear Test - Fillet Extrusion Seam - Yield Strength



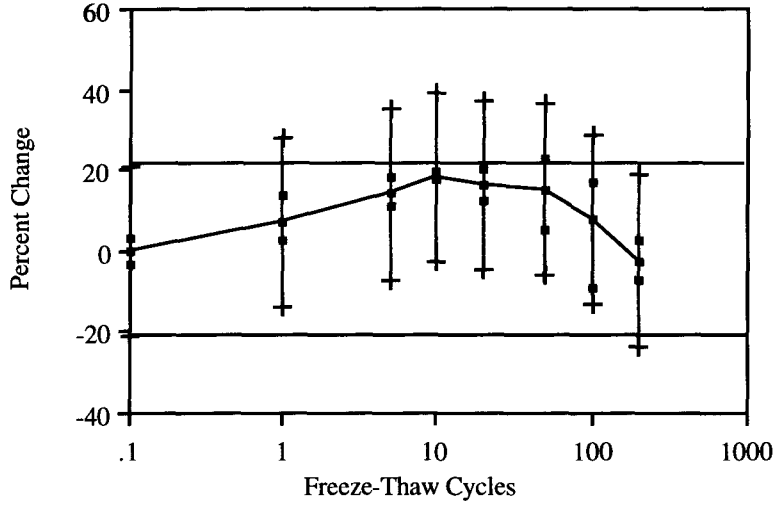
10 - 1.5-mm (60-mil) HDPE
Shear Test - Wedge Seam - Yield Strength



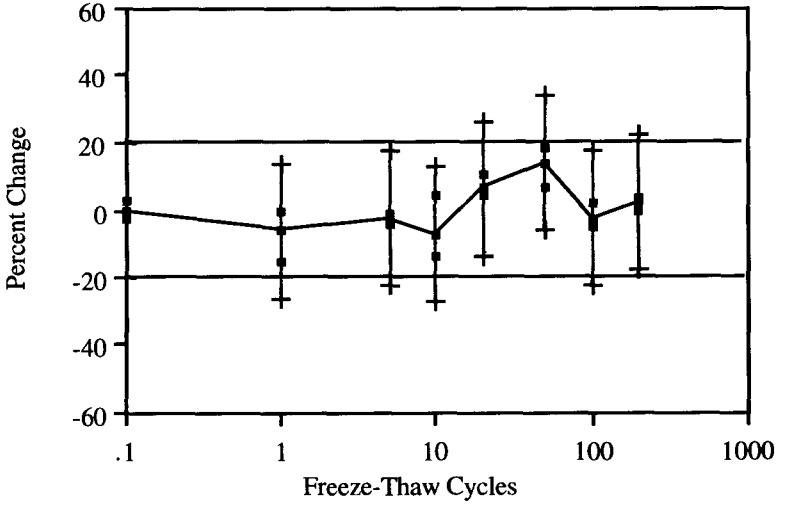
10(a) - 1.5-mm (60-mil) HDPE
Shear Test - Fillet Extrusion Seam - Yield Strength



11 - 1.5-mm (60-mil) HDPE-T
Shear Test - Wedge Seam - Yield Strength



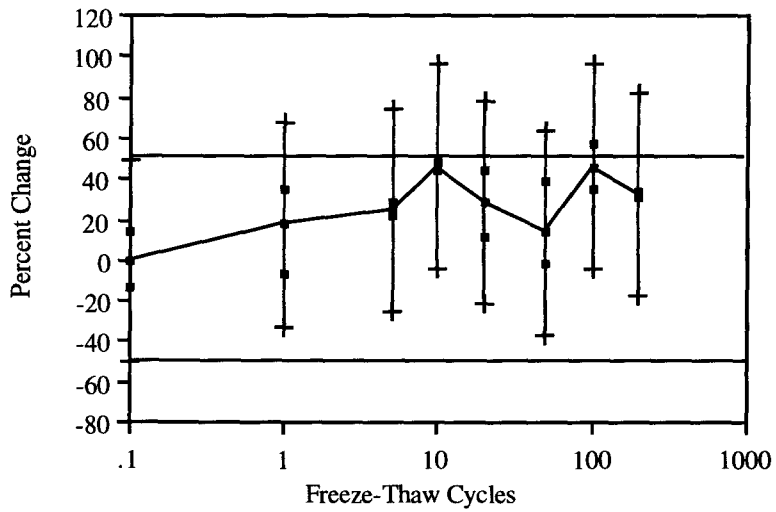
11(a) - 1.5-mm (60-mil) HDPE-T
Shear Test - Fillet Extrusion Seam - Yield Strength



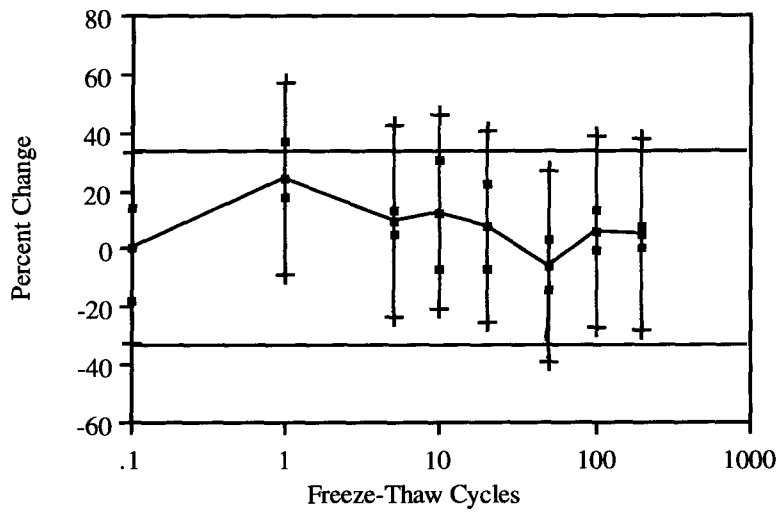
APPENDIX F

Part II — Seam Peal Tensile Test Results

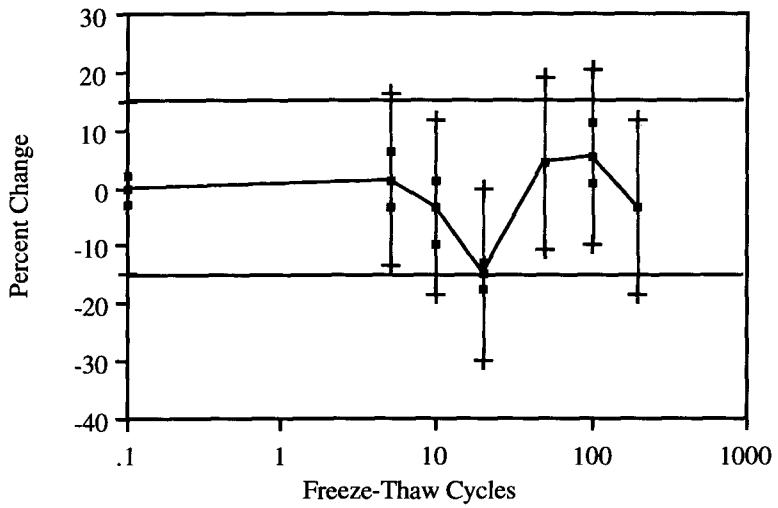
1(a) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Chemical Seam - Peak Strength



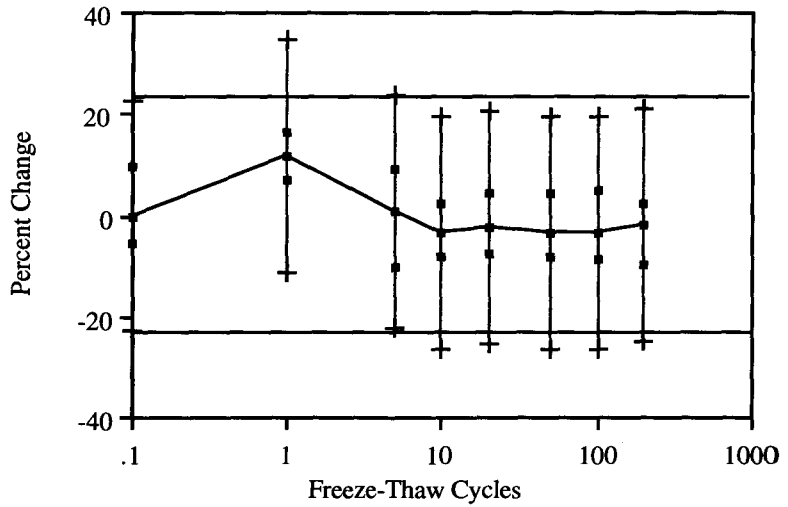
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Wedge Seam - Peak Strength



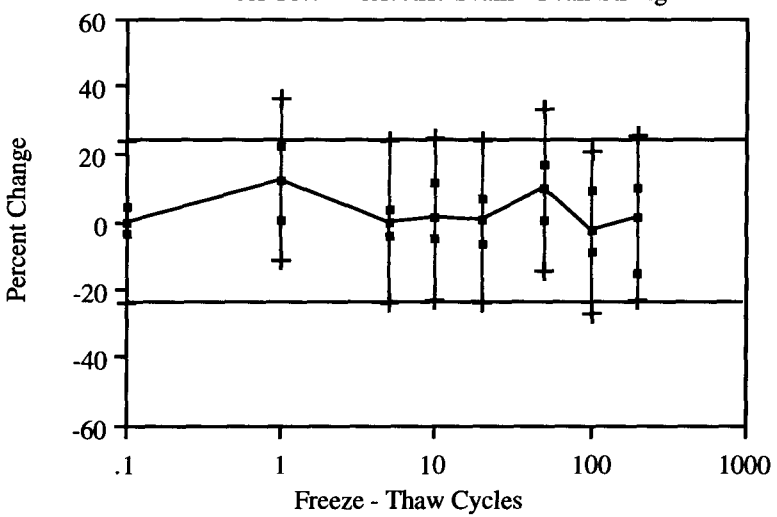
3(a) - 1.0-mm (40-mil) PVC
Peel Test - Chemical Seam - Peak Strength

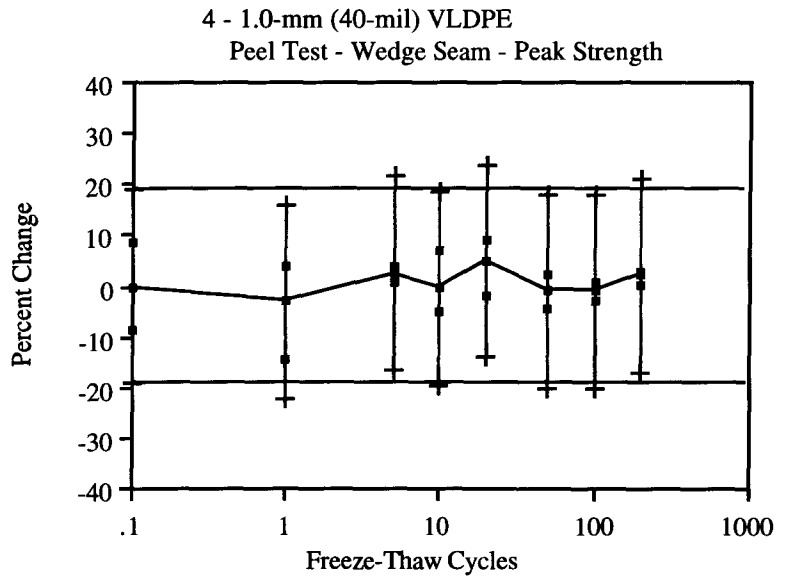


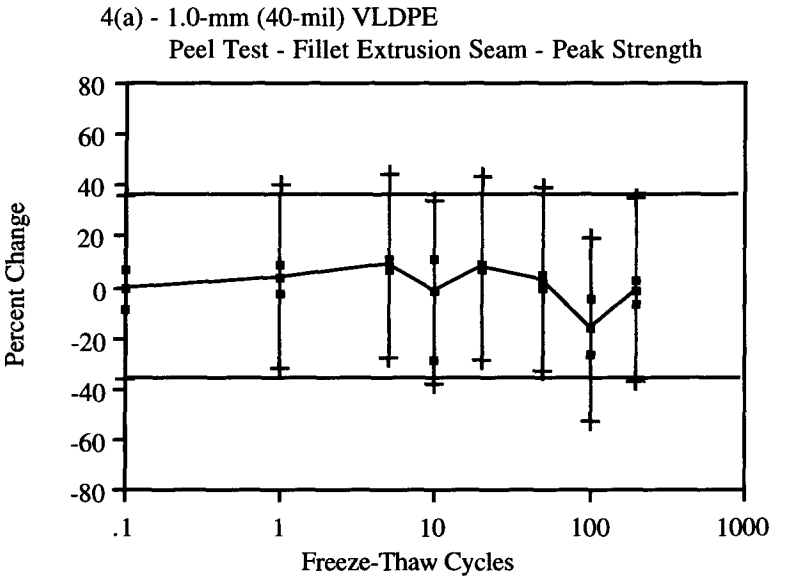
3(b) - 1.0-mm (40-mil) PVC
Peel Test - Wedge Seam - Peak Strength

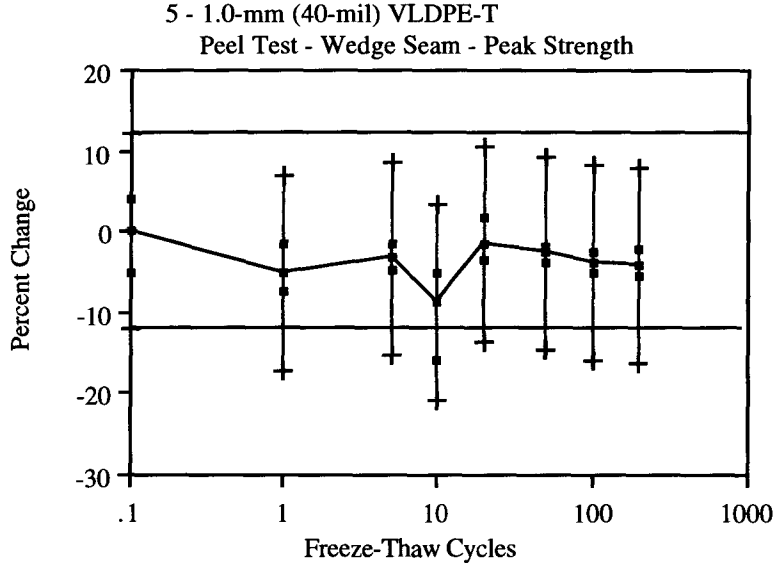


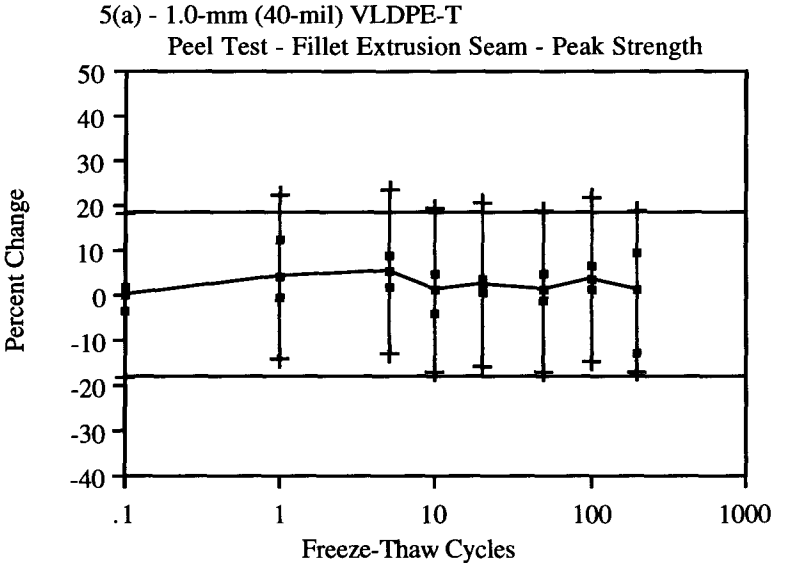
3(c) - 1.0-mm (40-mil) PVC
Peel Test - Dielectric Seam - Peak Strength



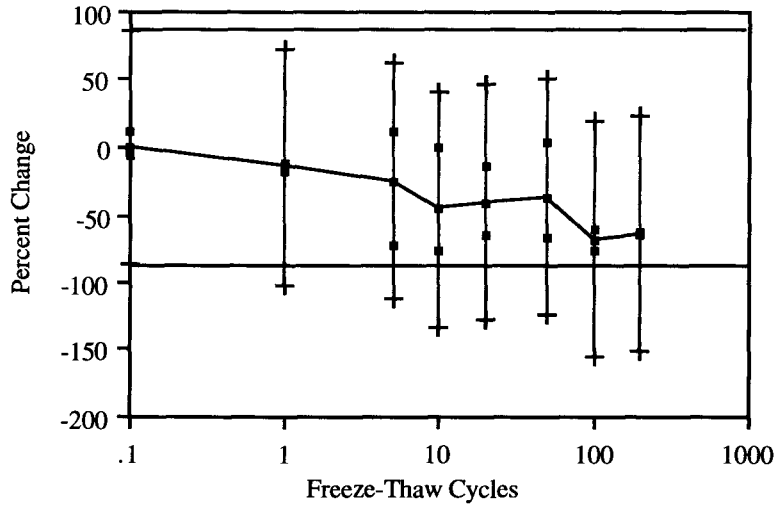

4 - 1.0-mm (40-mil) VLDPE
Peel Test - Wedge Seam - Peak Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles


4(a) - 1.0-mm (40-mil) VLDPE
Peel Test - Fillet Extrusion Seam - Peak Strength
Percent Change
80
60
40
20
0
-20
-40
-60
-80
.1
1
10
100
1000
Freeze-Thaw Cycles

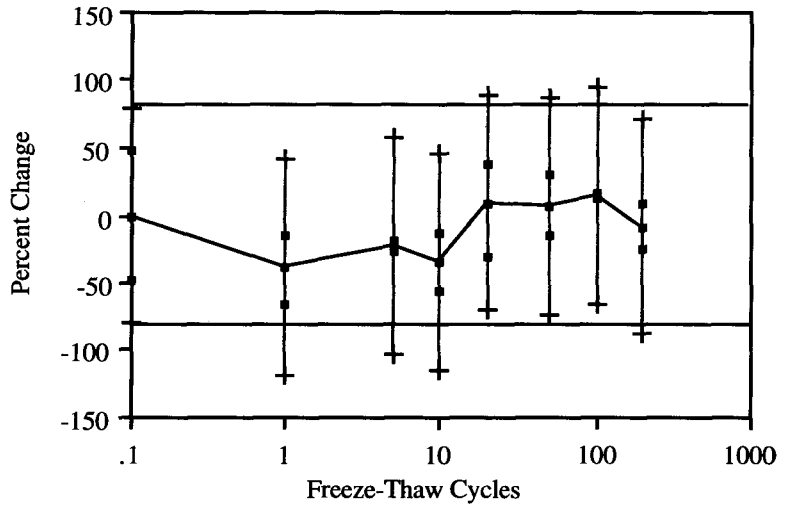

5 - 1.0-mm (40-mil) VLDPE-T
Peel Test - Wedge Seam - Peak Strength
Percent Change
20
10
0
-10
-20
-30
.1
1
10
100
1000
Freeze-Thaw Cycles


5(a) - 1.0-mm (40-mil) VLDPE-T
Peel Test - Fillet Extrusion Seam - Peak Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
.1
1
10
100
1000
Freeze-Thaw Cycles

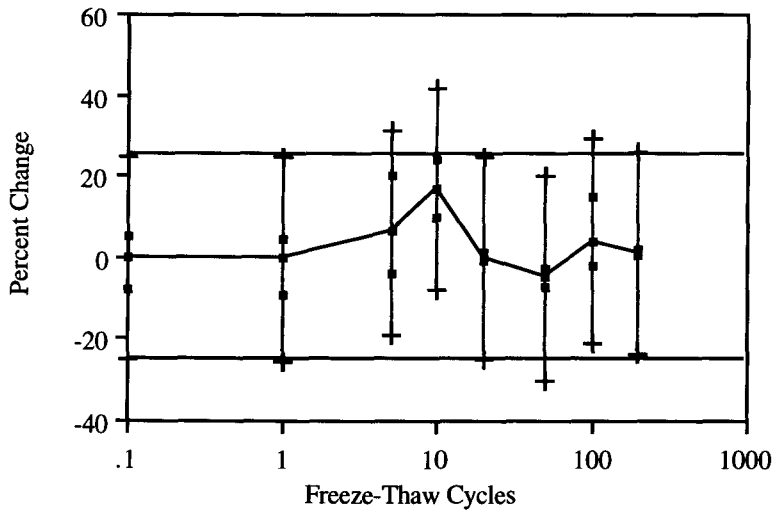
10 - 1.5-mm (60-mil) HDPE
Peel Test - Wedge Seam - Peak Strength



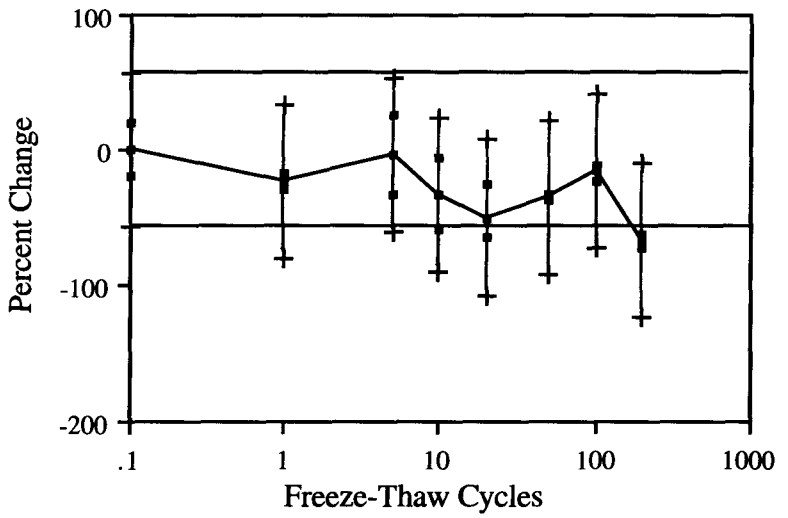
10(a) - 1.5-mm (60-mil) HDPE
Peel Test - Fillet Extrusion Seam - Peak Strength



11 - 1.5-mm (60-mil) HDPE-T
Peel Test - Wedge Seam - Peak Strength

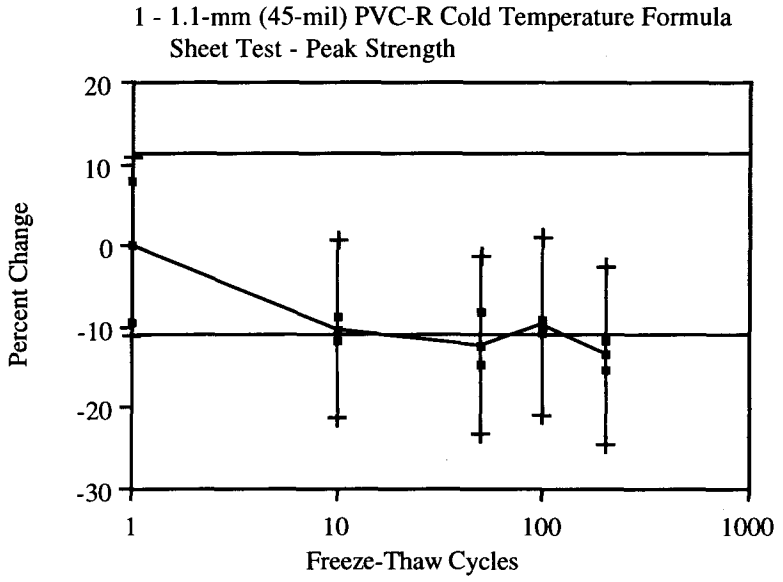


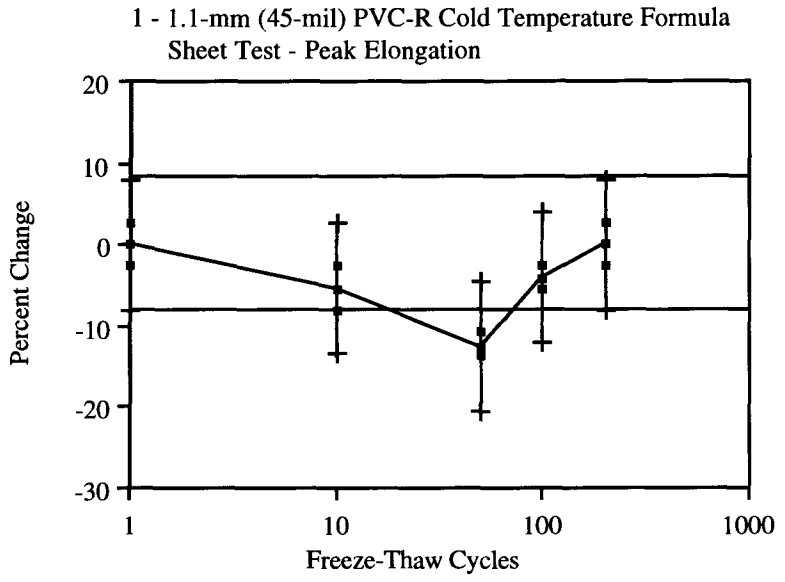
11(a) - 1.5-mm (60-mil) HDPE-T
Peel Test - Fillet Extrusion Seam - Peak Strength

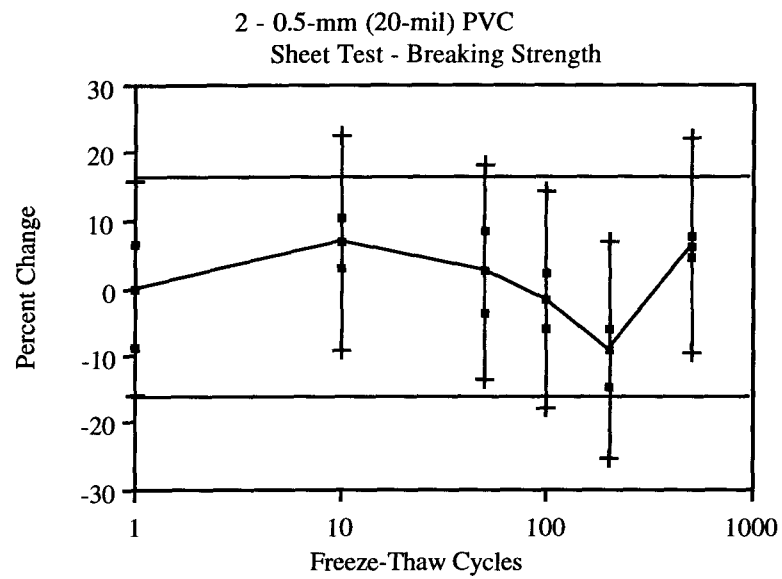


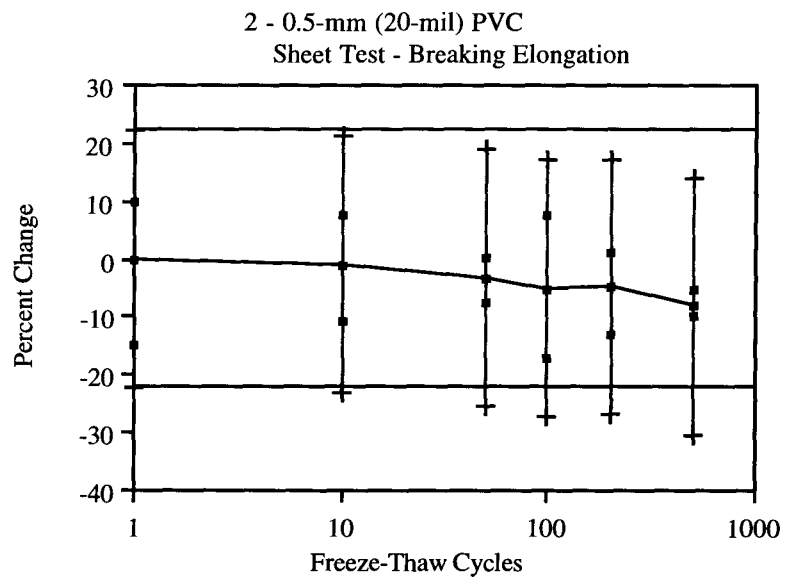
APPENDIX G

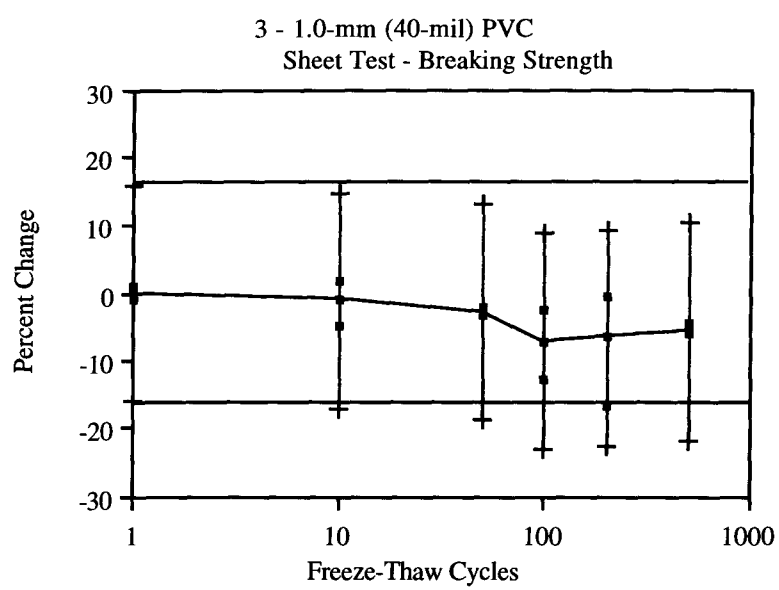
Part III — Sheet Tensile Test Results

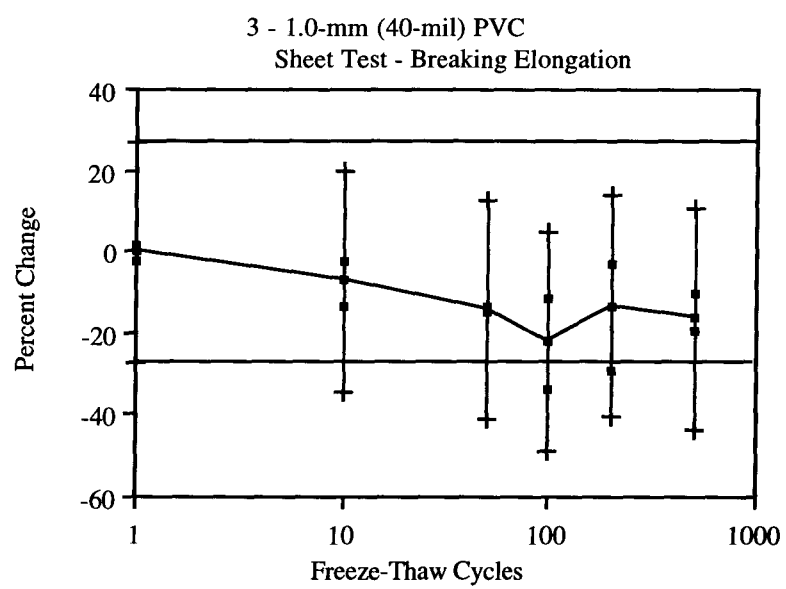

1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Strength
Percent Change
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

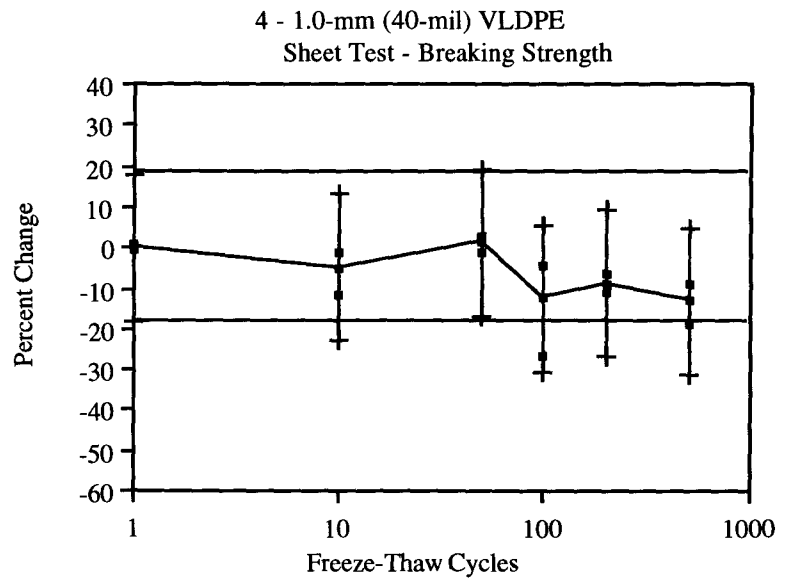

1 - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Sheet Test - Peak Elongation
Percent Change
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

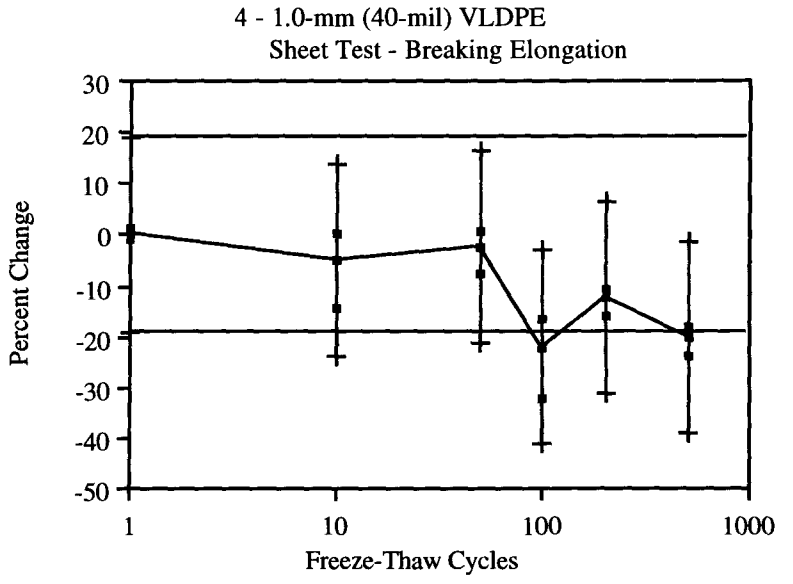

2 - 0.5-mm (20-mil) PVC
Sheet Test - Breaking Strength
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

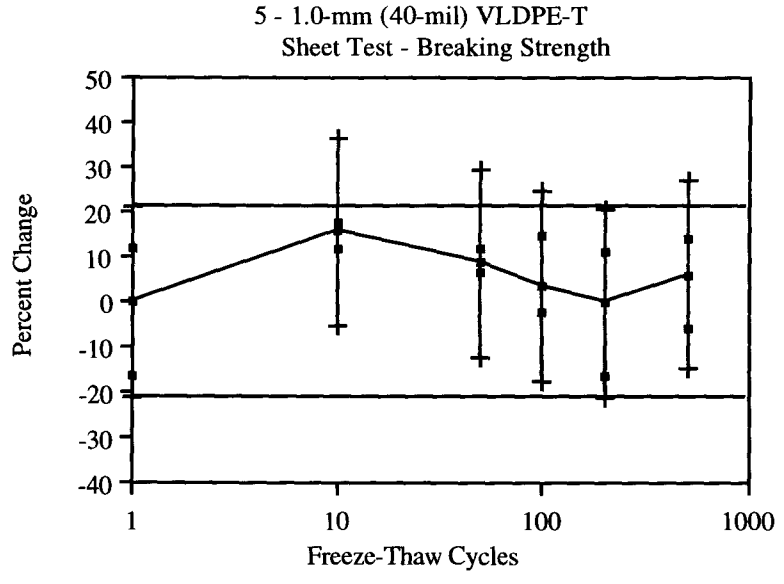

2 - 0.5-mm (20-mil) PVC
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

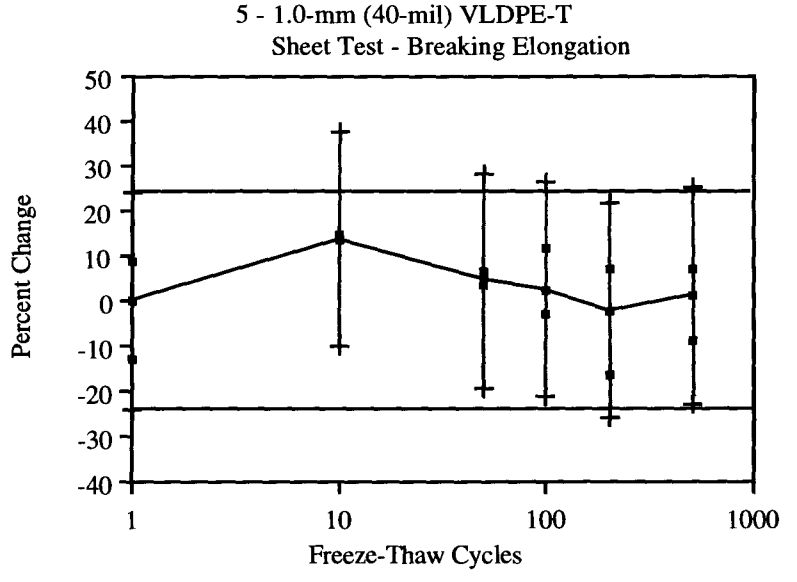

3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Strength
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

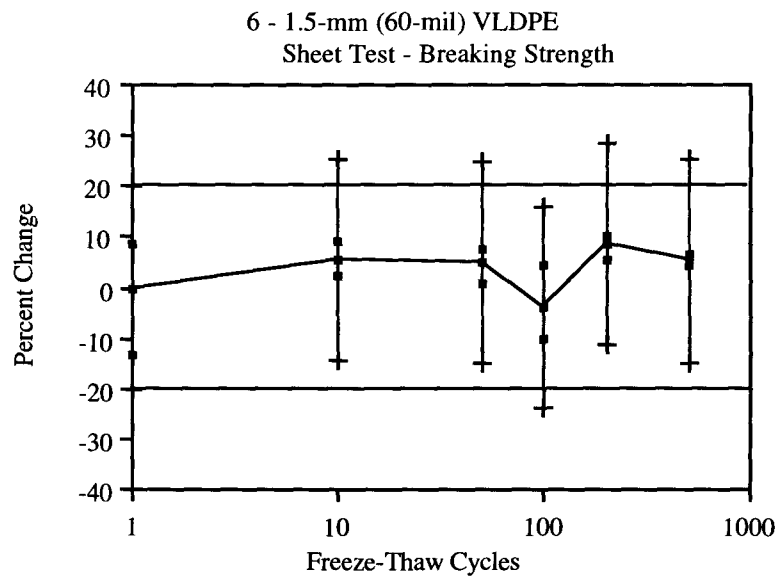

3 - 1.0-mm (40-mil) PVC
Sheet Test - Breaking Elongation
Percent Change
40
20
0
-20
-40
-60
1
10
100
1000
Freeze-Thaw Cycles

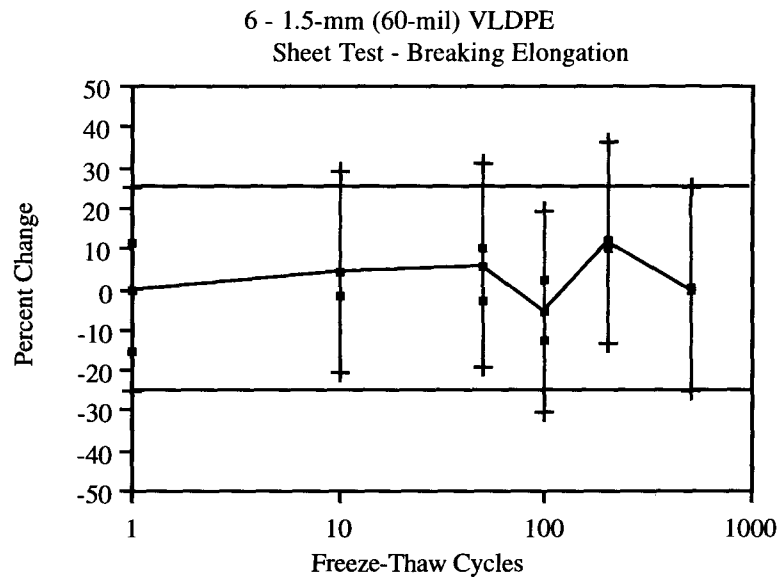

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
-50
-60
1
10
100
1000
Freeze-Thaw Cycles

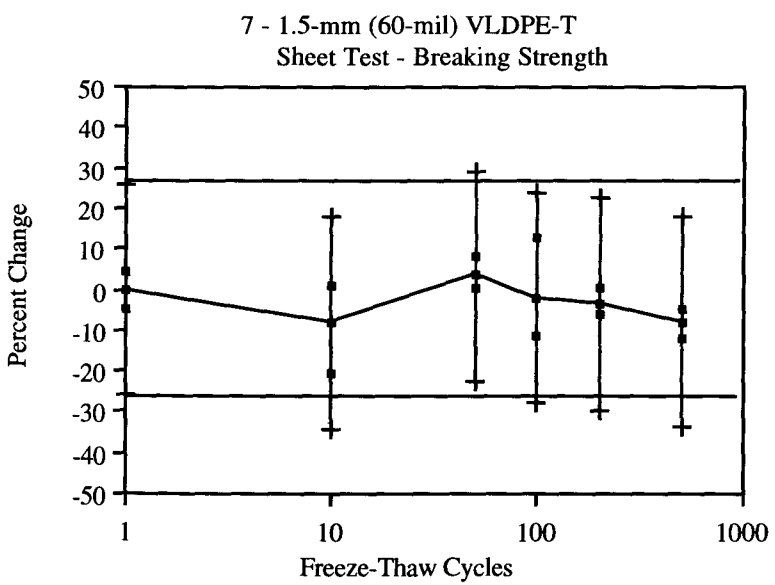

4 - 1.0-mm (40-mil) VLDPE
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles

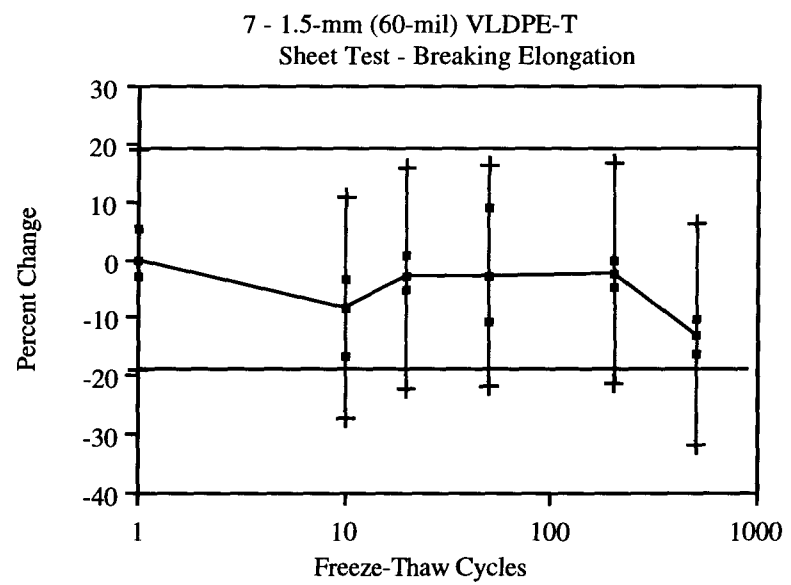

5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Breaking Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

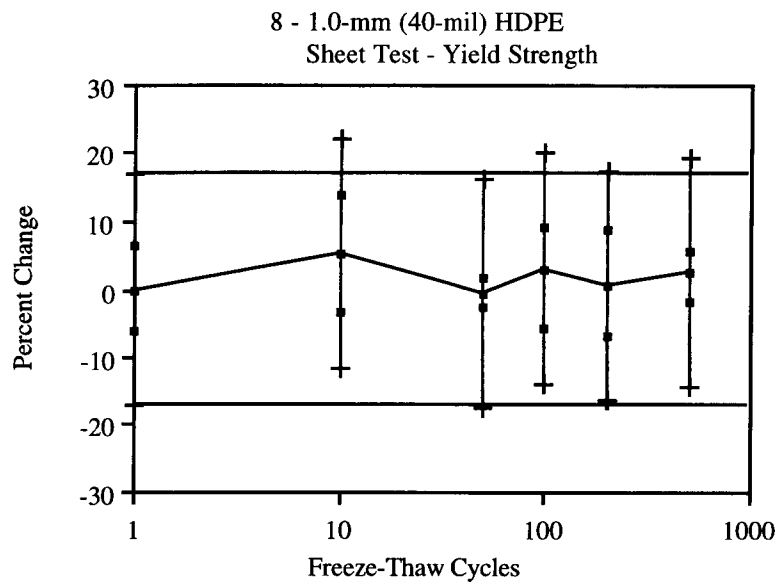

5 - 1.0-mm (40-mil) VLDPE-T
Sheet Test - Breaking Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

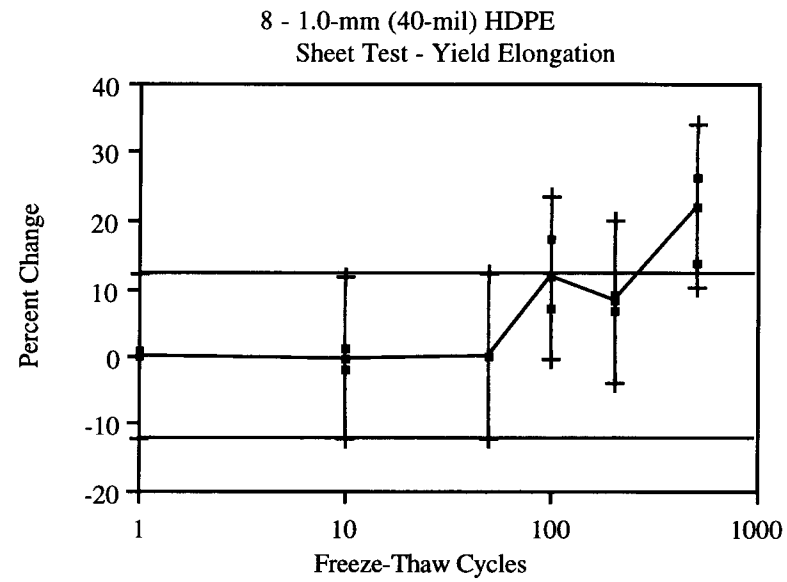

6 - 1.5-mm (60-mil) VLDPE
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

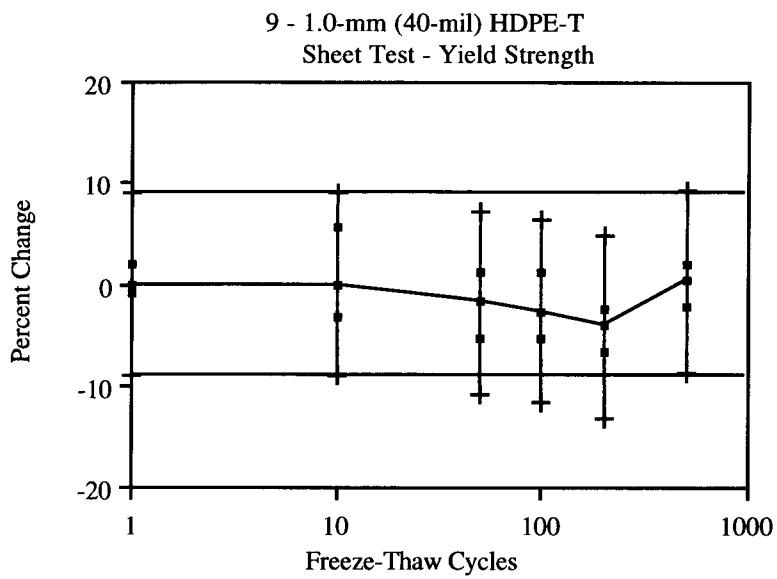

6 - 1.5-mm (60-mil) VLDPE
Sheet Test - Breaking Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles

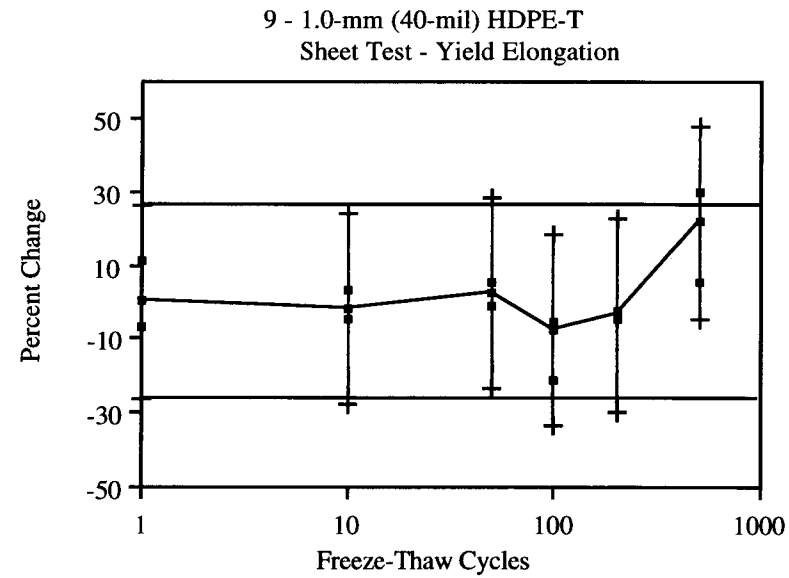

7 - 1.5-mm (60-mil) VLDPE-T
Sheet Test - Breaking Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles

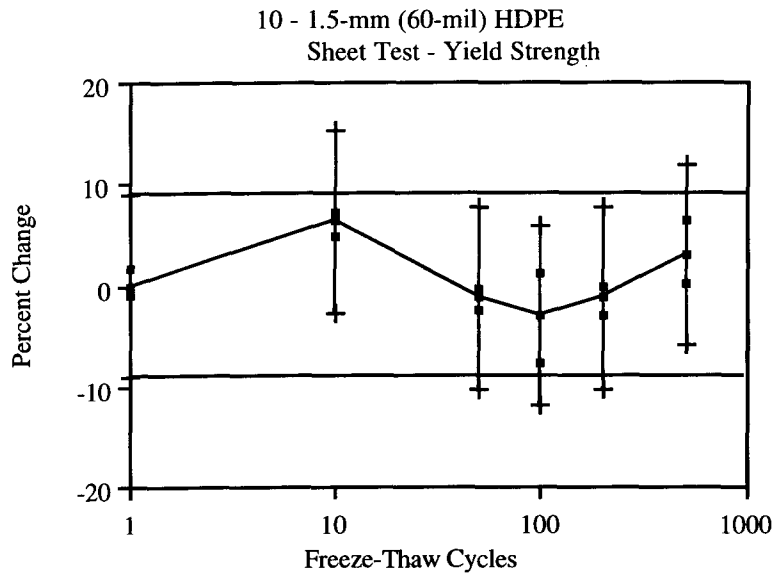

7 - 1.5-mm (60-mil) VLDPE-T
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

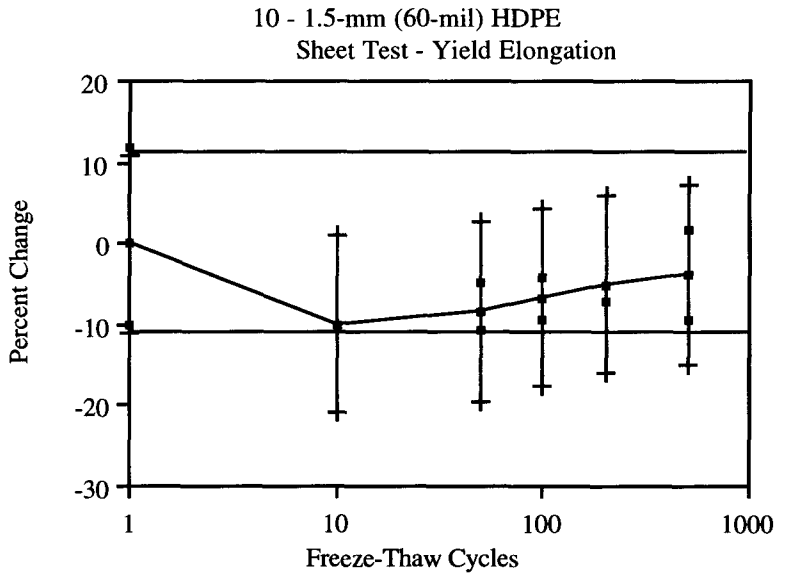

8 - 1.0-mm (40-mil) HDPE
Sheet Test - Yield Strength
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

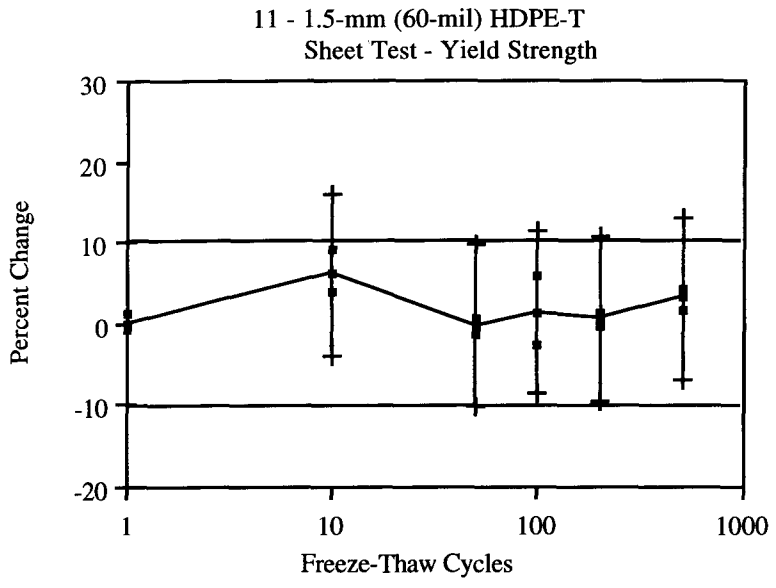

8 - 1.0-mm (40-mil) HDPE
Sheet Test - Yield Elongation
Percent Change
40
30
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

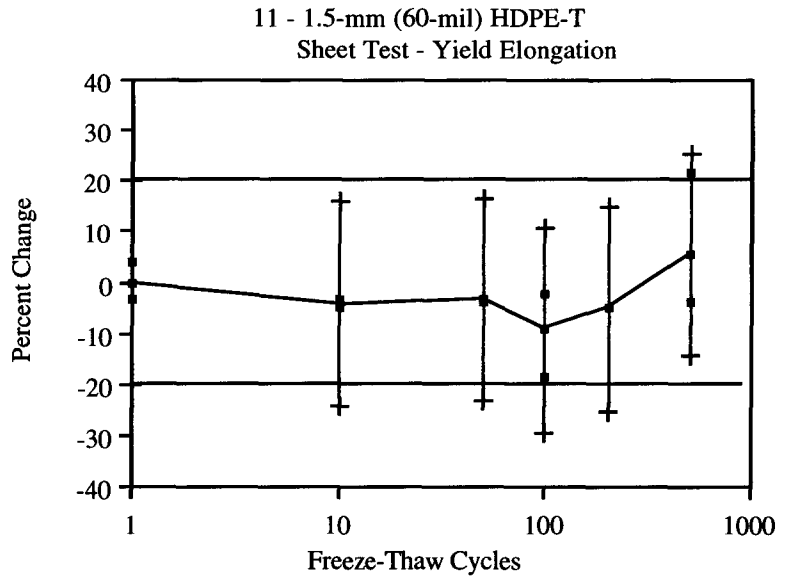

9 - 1.0-mm (40-mil) HDPE-T
Sheet Test - Yield Strength
Percent Change
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

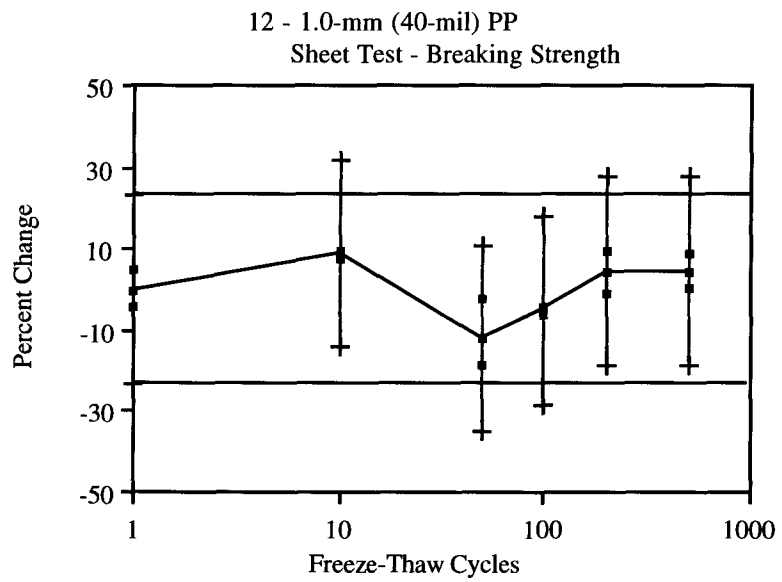

9 - 1.0-mm (40-mil) HDPE-T
Sheet Test - Yield Elongation
Percent Change
50
30
10
-10
-30
-50
1
10
100
1000
Freeze-Thaw Cycles

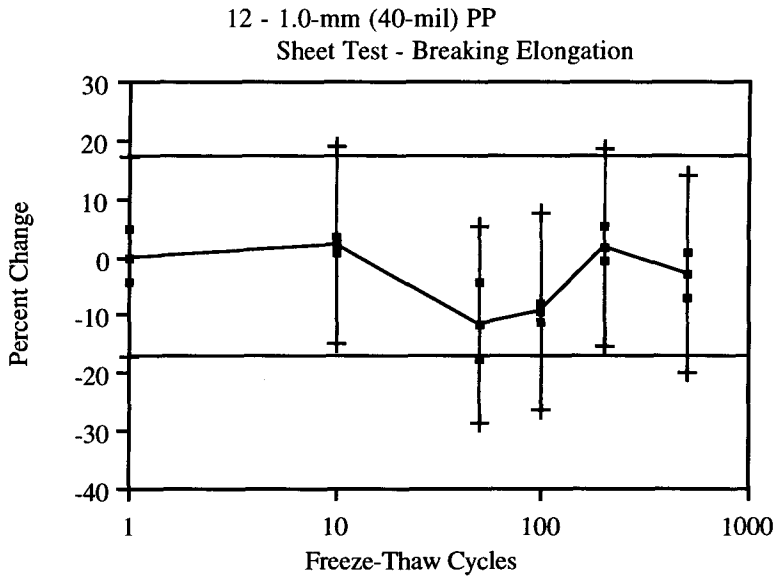

10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Strength
Percent Change
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

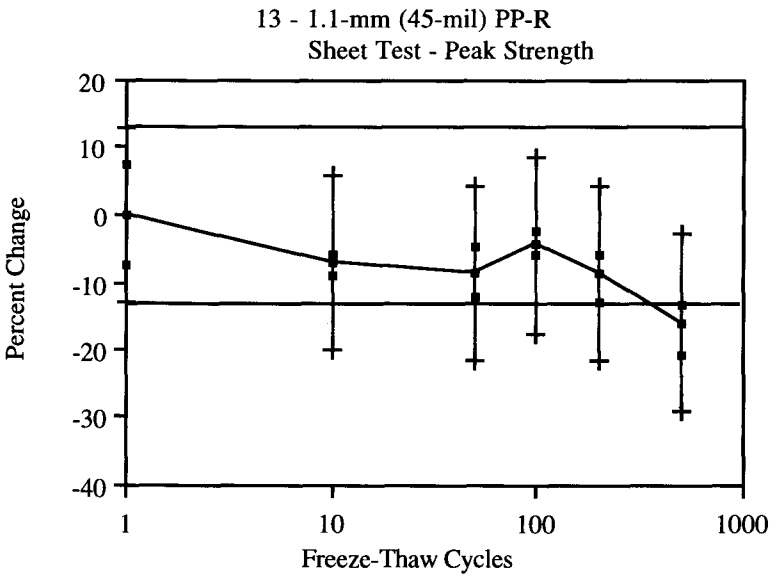

10 - 1.5-mm (60-mil) HDPE
Sheet Test - Yield Elongation
Percent Change
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

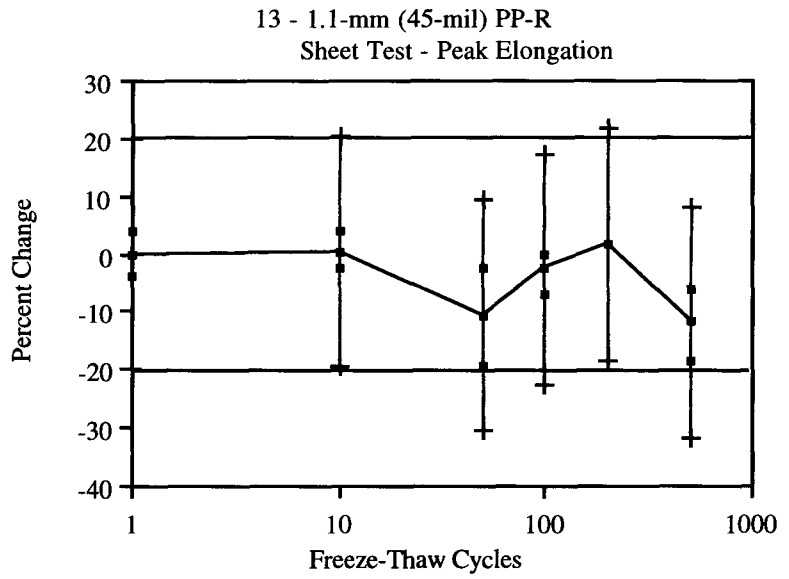

11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Strength
Percent Change
30
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles


11 - 1.5-mm (60-mil) HDPE-T
Sheet Test - Yield Elongation
Percent Change
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

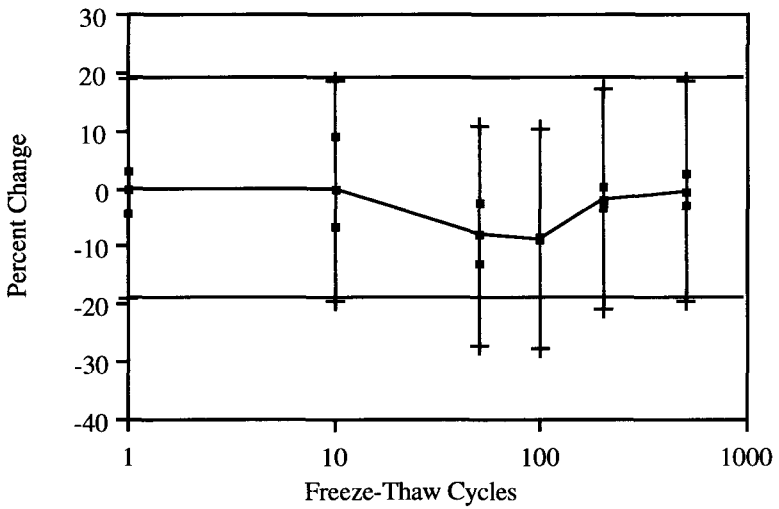

12 - 1.0-mm (40-mil) PP
Sheet Test - Breaking Strength
Percent Change
50
30
10
-10
-30
-50
1
10
100
1000
Freeze-Thaw Cycles


12 - 1.0-mm (40-mil) PP
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

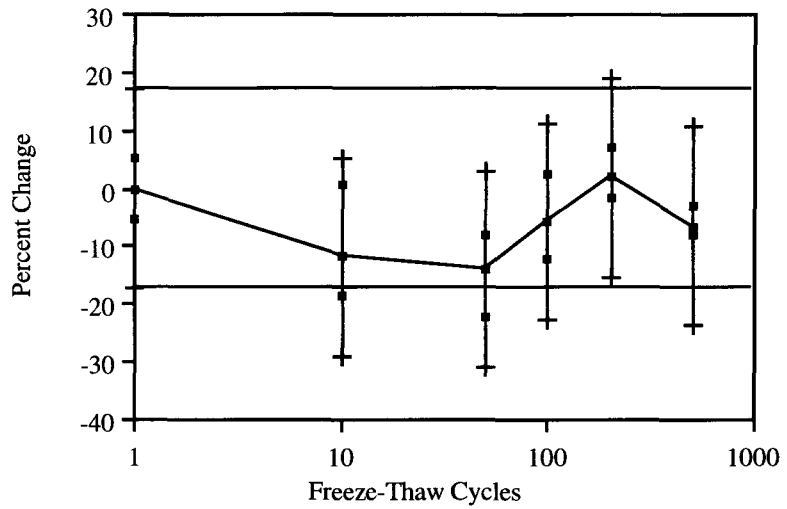

13 - 1.1-mm (45-mil) PP-R
Sheet Test - Peak Strength
Percent Change
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles


13 - 1.1-mm (45-mil) PP-R
Sheet Test - Peak Elongation
Percent Change
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

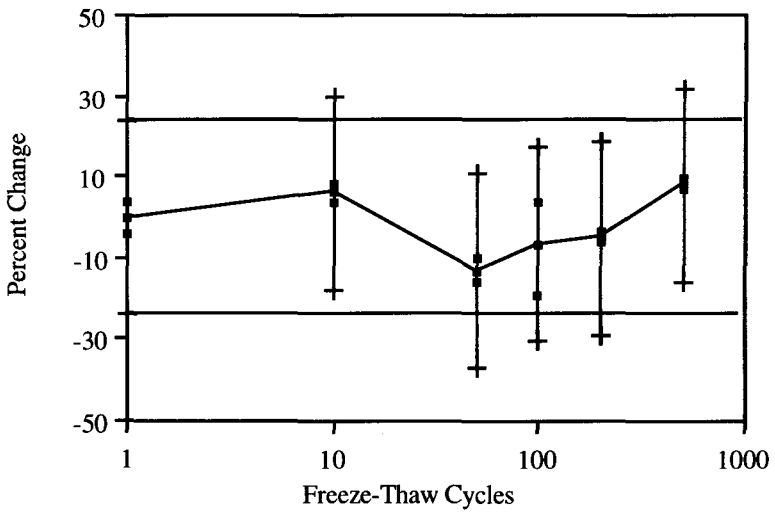
14 - 0.9-mm (36-mil) CSPE-R
Sheet Test - Peak Strength



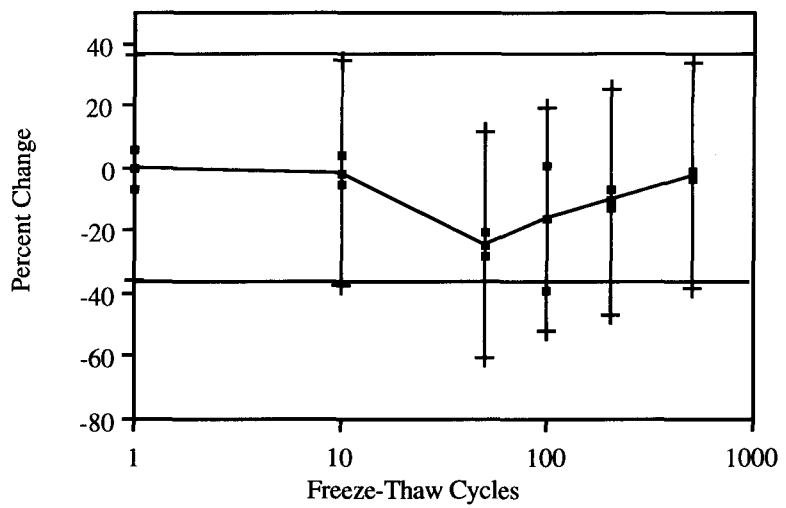
14 - 0.9-mm (36-mil) CSPE-R
Sheet Test - Peak Elongation

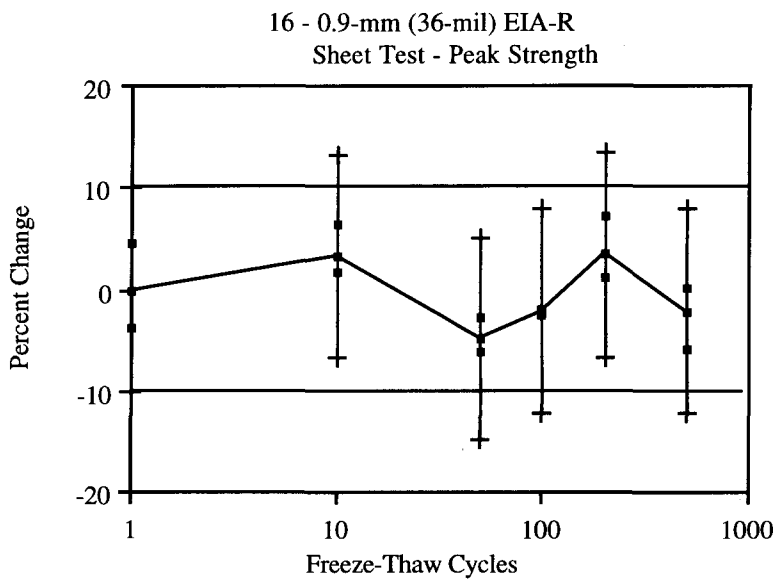


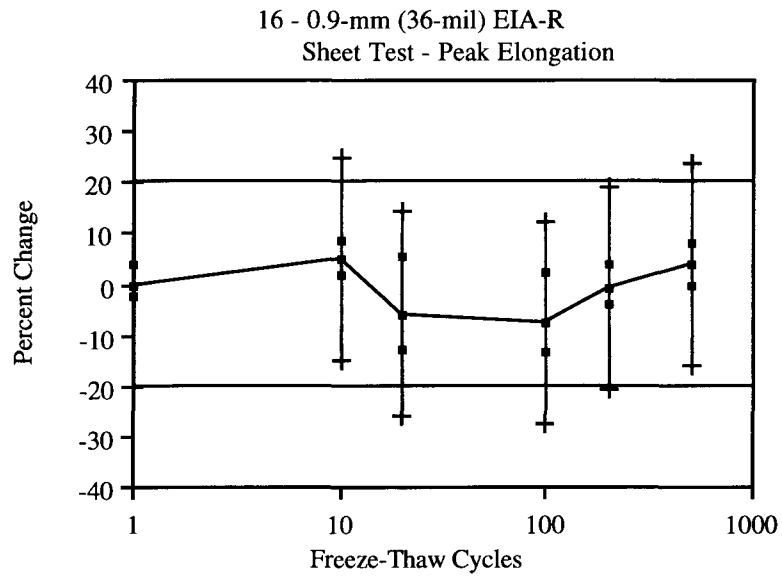
15 - 0.8-mm (30-mil) EIA
Sheet Test - Breaking Strength

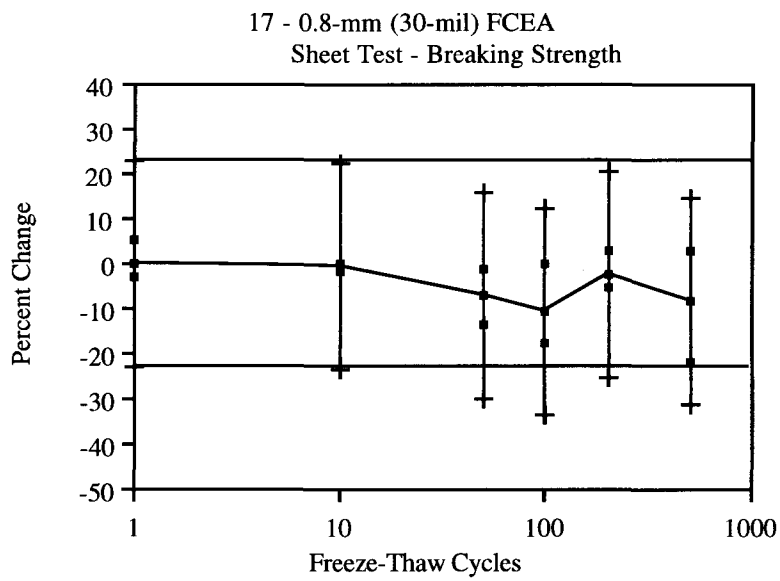


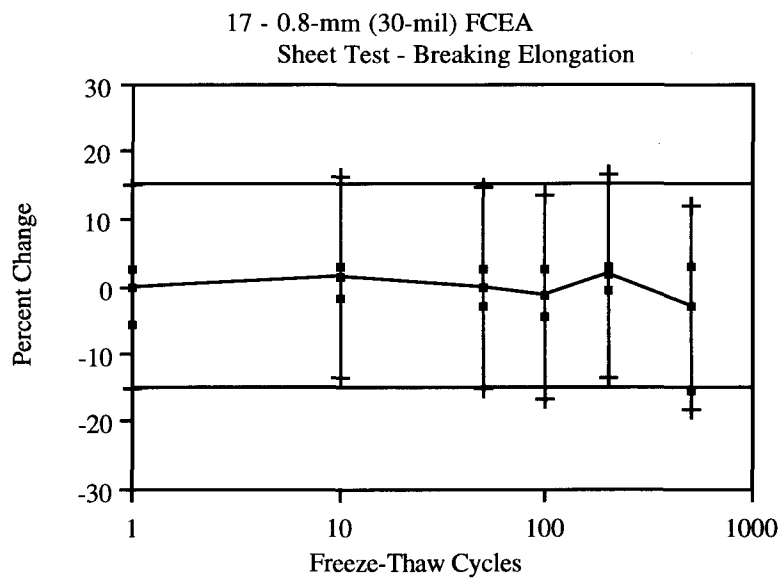
15 - 0.8-mm (30-mil) EIA
Sheet Test - Breaking Elongation

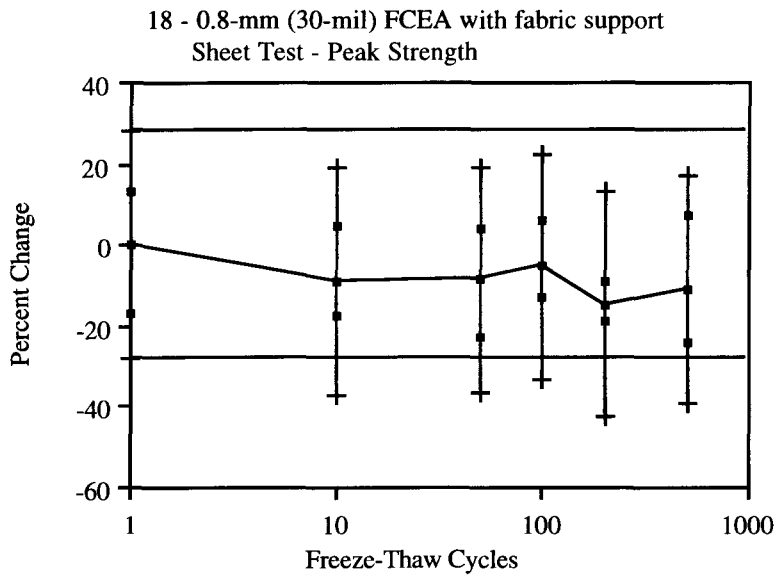


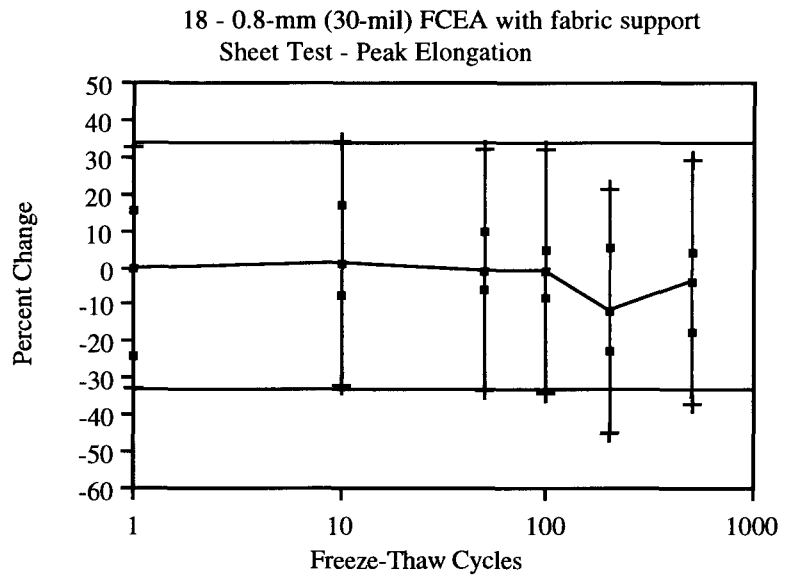

16 - 0.9-mm (36-mil) EIA-R
Sheet Test - Peak Strength
Percent Change
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

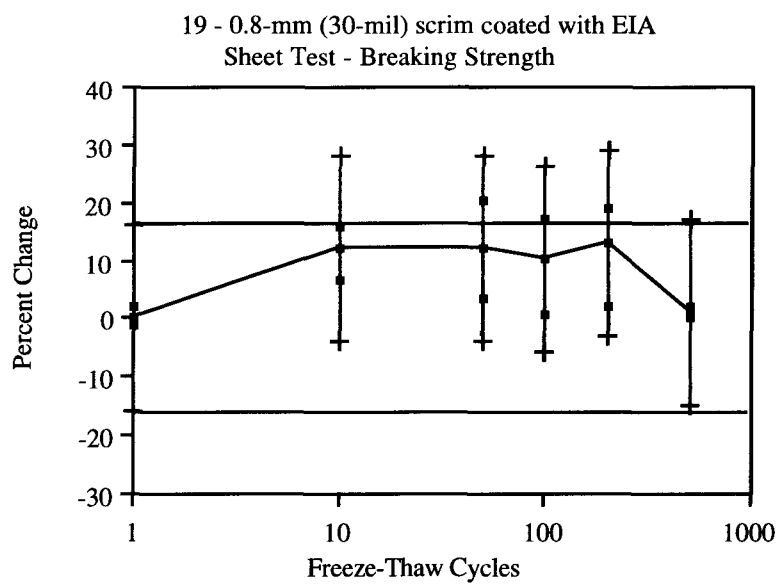

16 - 0.9-mm (36-mil) EIA-R
Sheet Test - Peak Elongation
Percent Change
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles

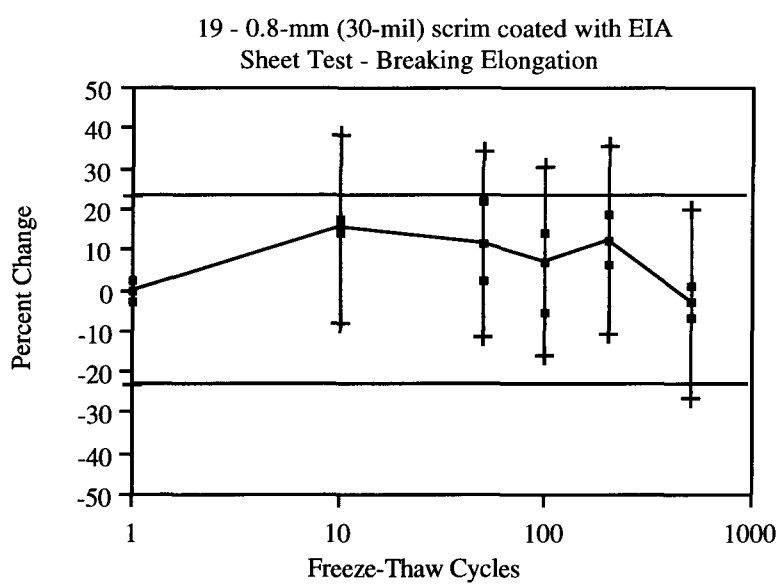

17 - 0.8-mm (30-mil) FCEA
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles


17 - 0.8-mm (30-mil) FCEA
Sheet Test - Breaking Elongation
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles


18 - 0.8-mm (30-mil) FCEA with fabric support
Sheet Test - Peak Strength
Percent Change
40
20
0
-20
-40
-60
1
10
100
1000
Freeze-Thaw Cycles


18 - 0.8-mm (30-mil) FCEA with fabric support
Sheet Test - Peak Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
1
10
100
1000
Freeze-Thaw Cycles

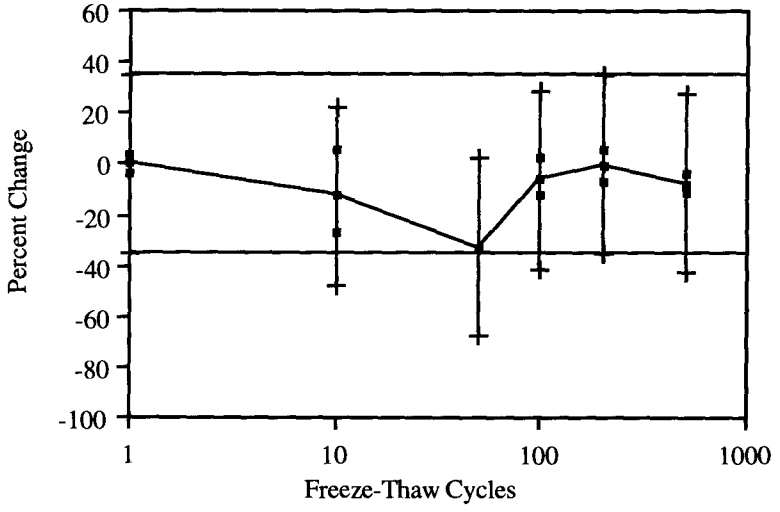

19 - 0.8-mm (30-mil) scrim coated with EIA
Sheet Test - Breaking Strength
Percent Change
40
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles


19 - 0.8-mm (30-mil) scrim coated with EIA
Sheet Test - Breaking Elongation
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles

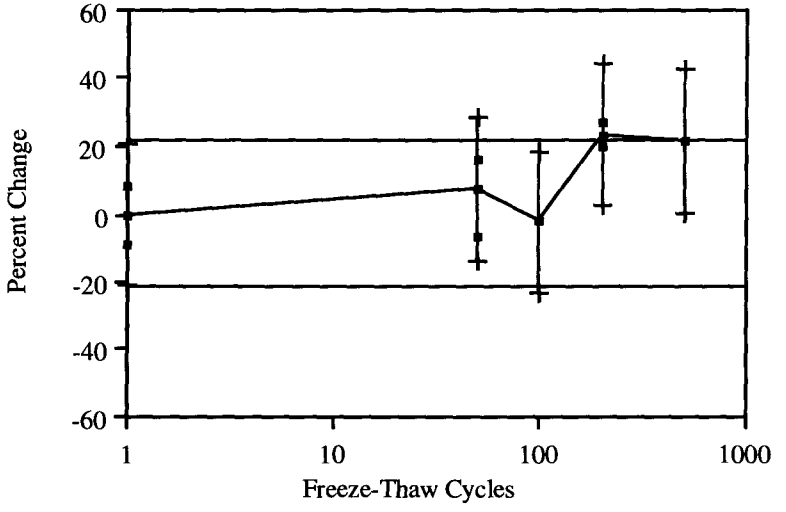
APPENDIX H

Part III — Seam Shear Tensile Test Results

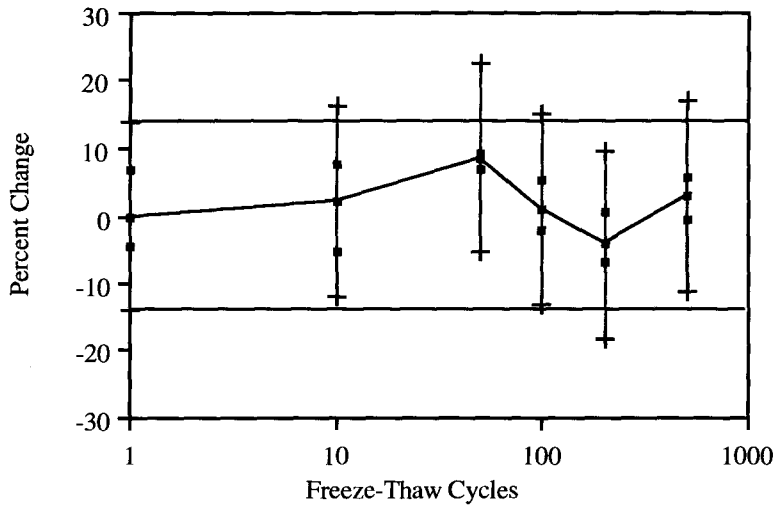
1(a) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Shear Test - Chemical Seam - Peak Strength



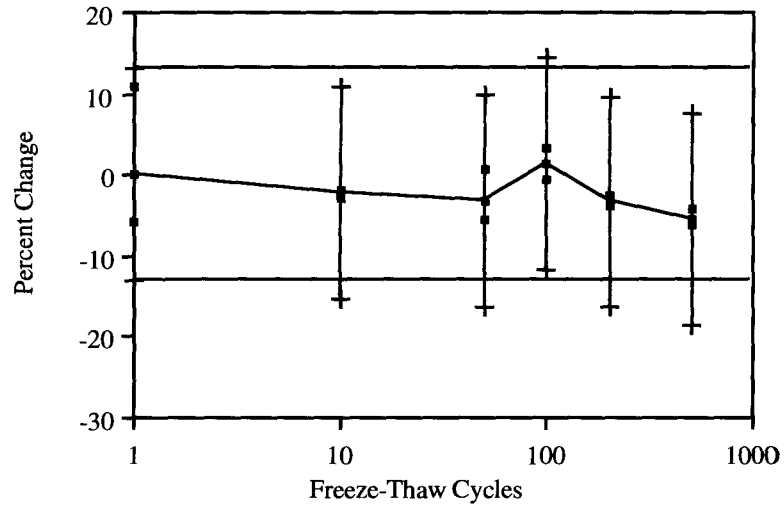
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Shear Test - Wedge Seam - Peak Strength



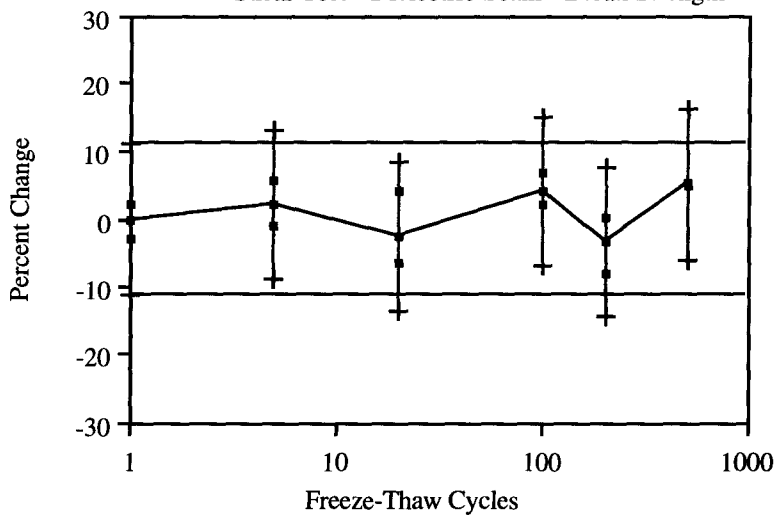
2(a) - 0.5-mm (20-mil) PVC
Shear Test - Chemical Seam - Break Strength



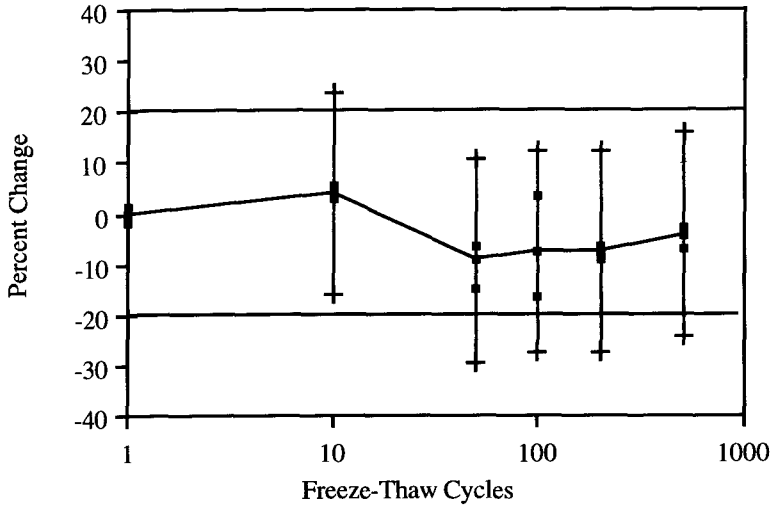
2(b) - 0.5-mm (20-mil) PVC
Shear Test - Wedge Seam - Break Strength



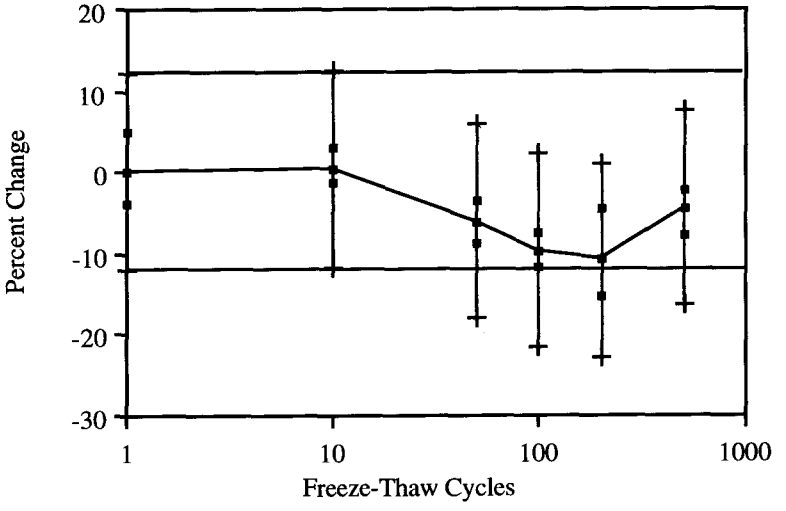
2(c) - 0.5-mm (20-mil) PVC
Shear Test - Dielectric Seam - Break Strength



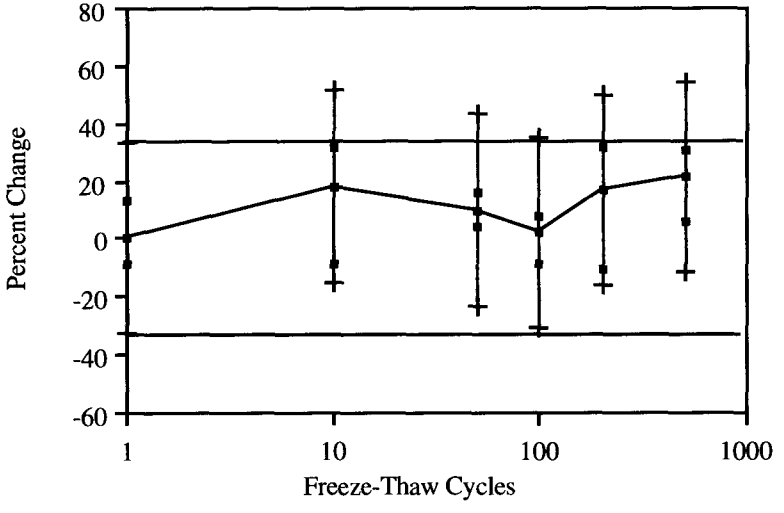
3(a) - 1.0-mm (40-mil) PVC
Shear Test - Chemical Seam - Break Strength



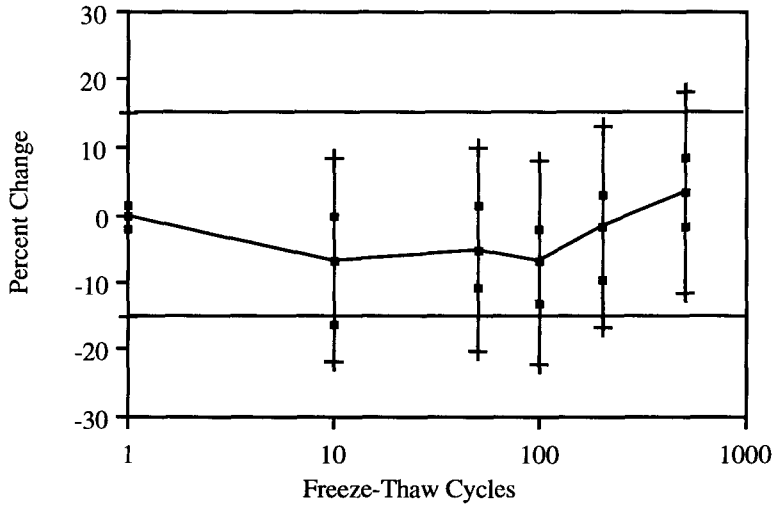
3(b) - 1.0-mm (40-mil) PVC
Shear Test - Wedge Seam - Break Strength



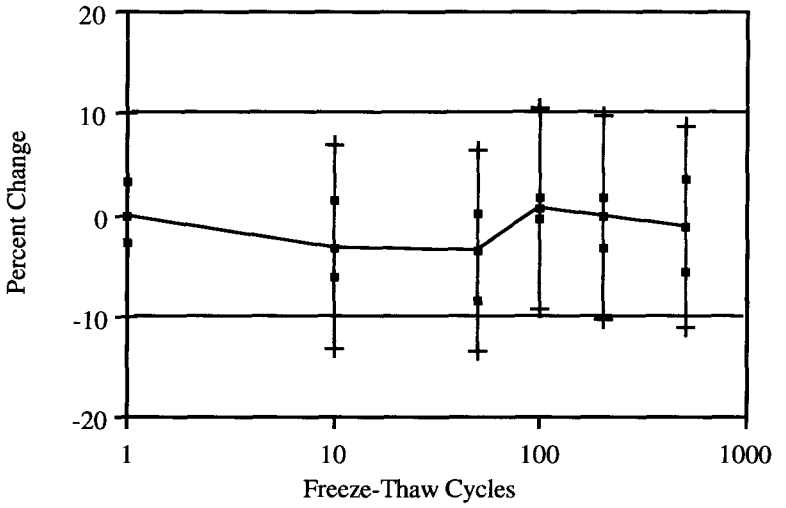
3(c) - 1.0-mm (40-mil) PVC
Shear Test - Dielectric Seam - Break Strength



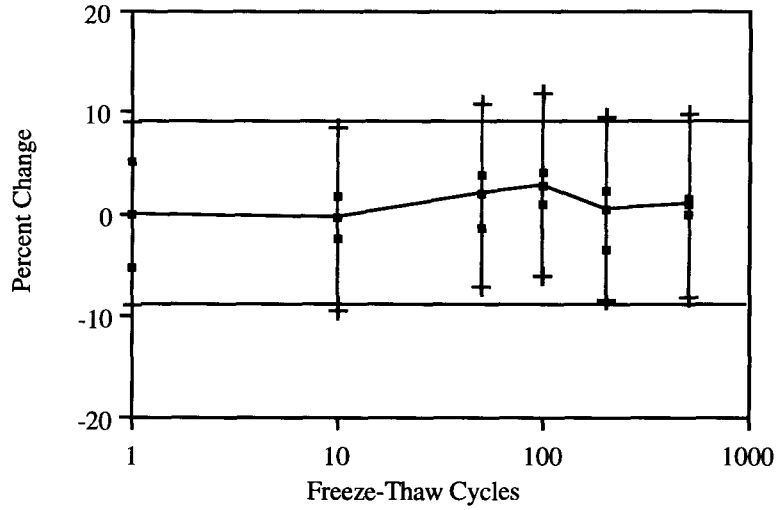
4 - 1.0-mm (40-mil) VLDPE
Shear Test - Wedge Seam - Break Strength



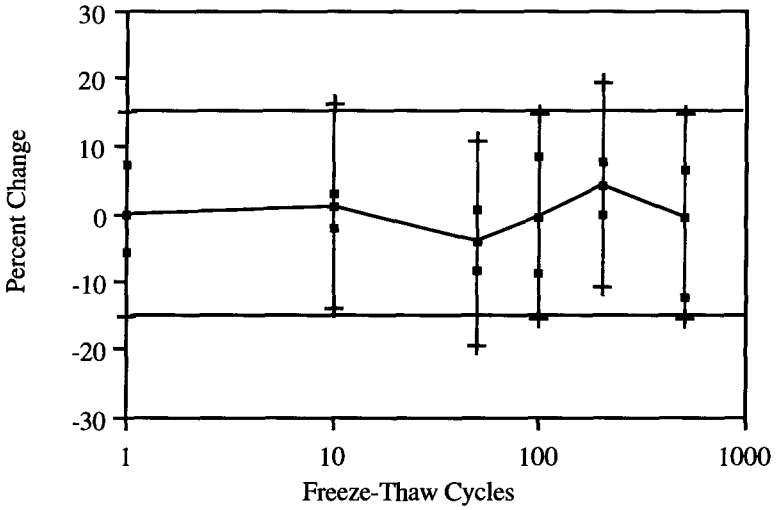
5 - 1.0-mm (40-mil) VLDPE-T
Shear Test - Wedge Seam - Break Strength



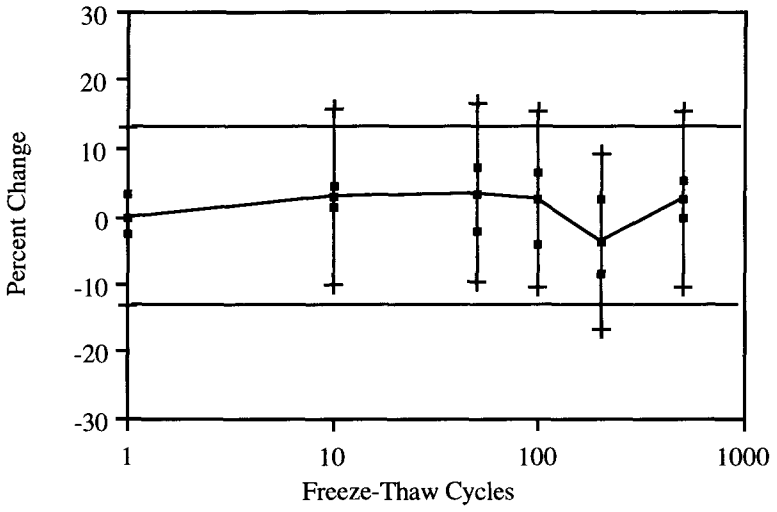
6 - 1.5-mm (60-mil) VLDPE
Shear Test - Wedge Seam - Break Strength



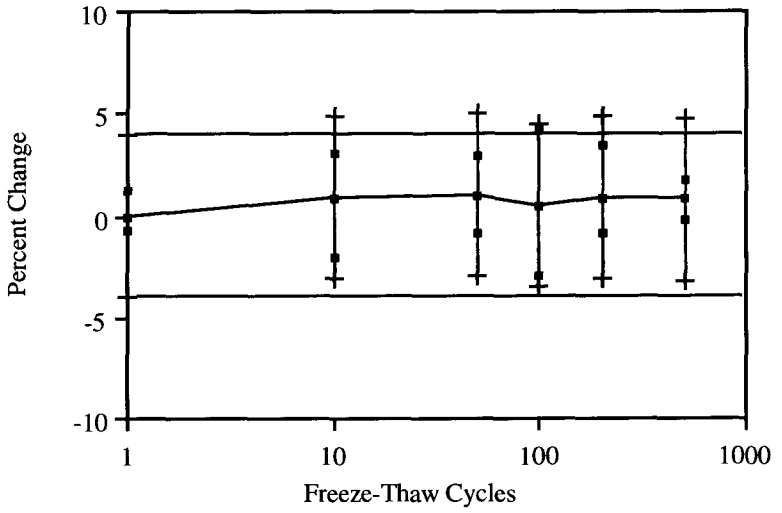
7 - 1.5-mm (60-mil) VLDPE-T
Shear Test - Wedge Seam - Break Strength



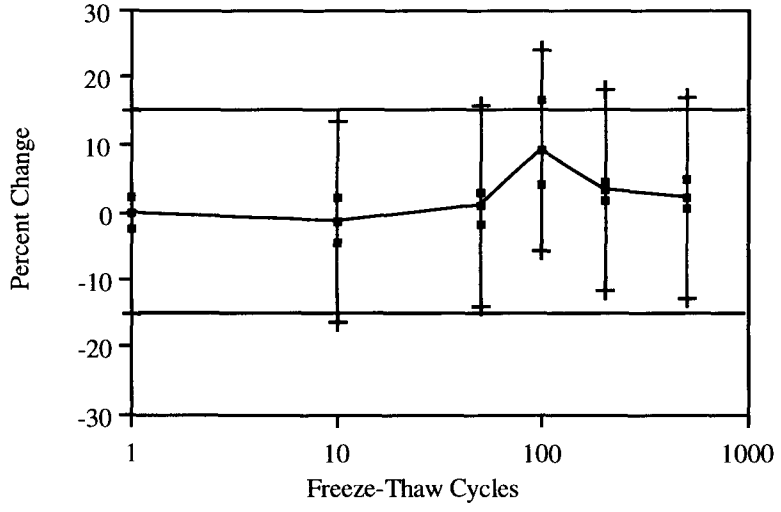
8 - 1.0-mm (40-mil) HDPE
Shear Test - Wedge Seam - Peak Strength



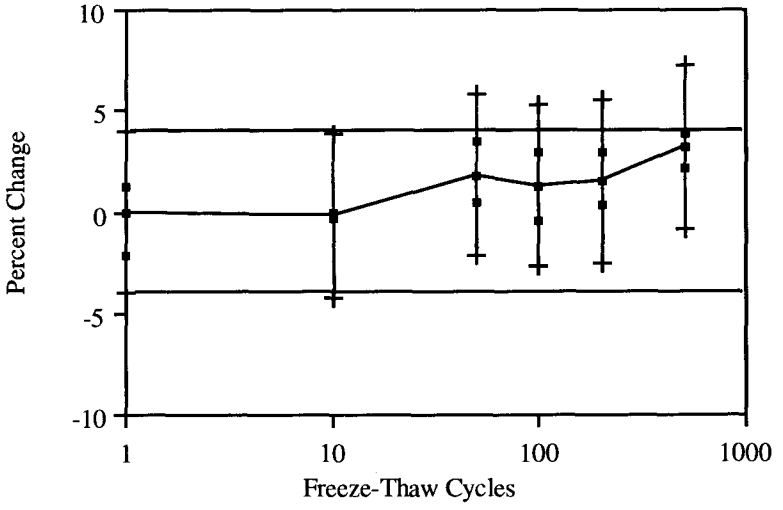
9 - 1.0-mm (40-mil) HDPE-T
Shear Test - Wedge Seam - Peak Strength



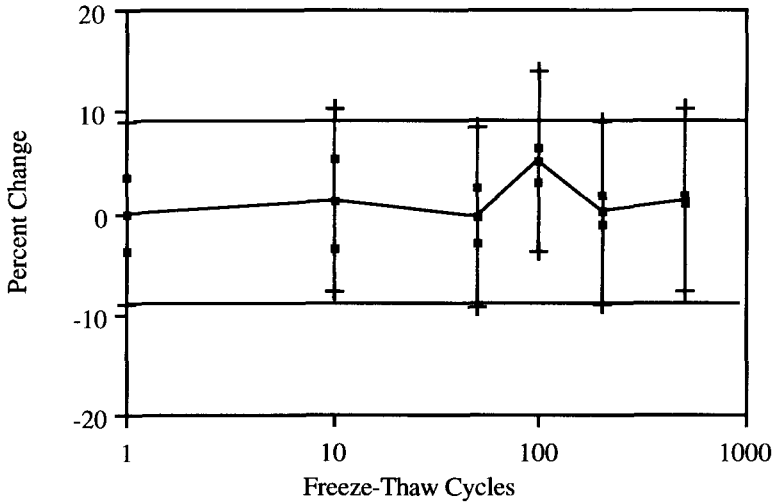
10 - 1.5-mm (60-mil) HDPE
Shear Test - Wedge Seam - Peak Strength



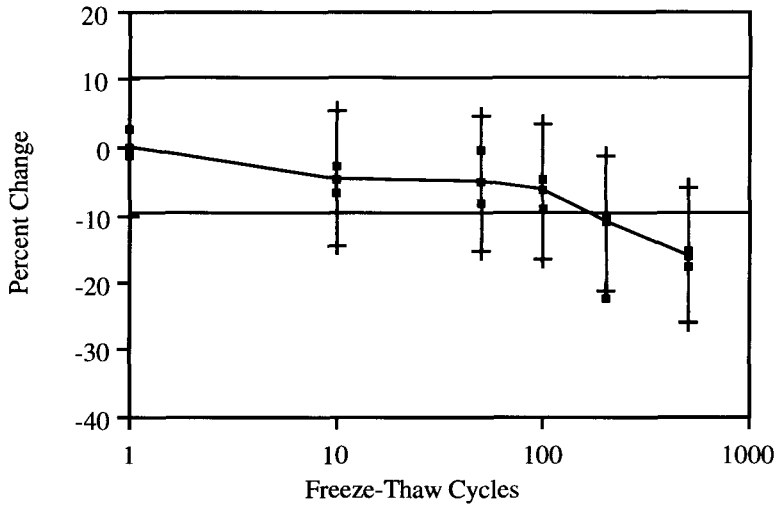
11 - 1.5-mm (60-mil) HDPE-T
Shear Test - Wedge Seam - Peak Strength



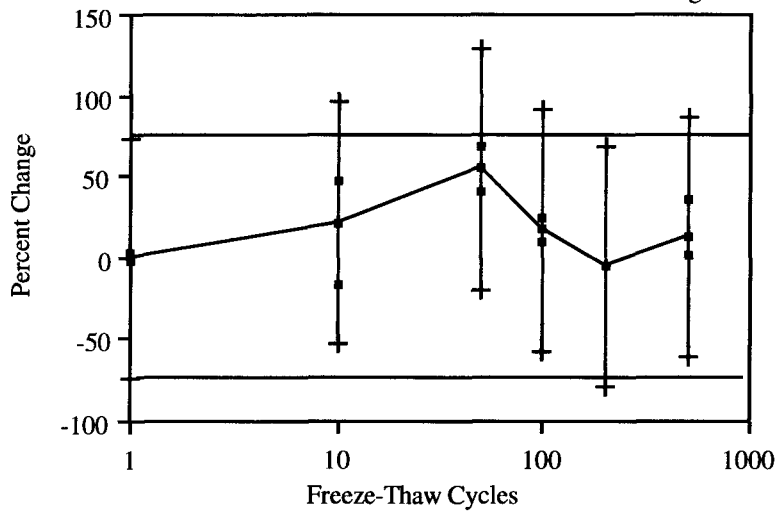
12 - 1.0-mm (40-mil) PP
Shear Test - Thermal Seam - Break Strength



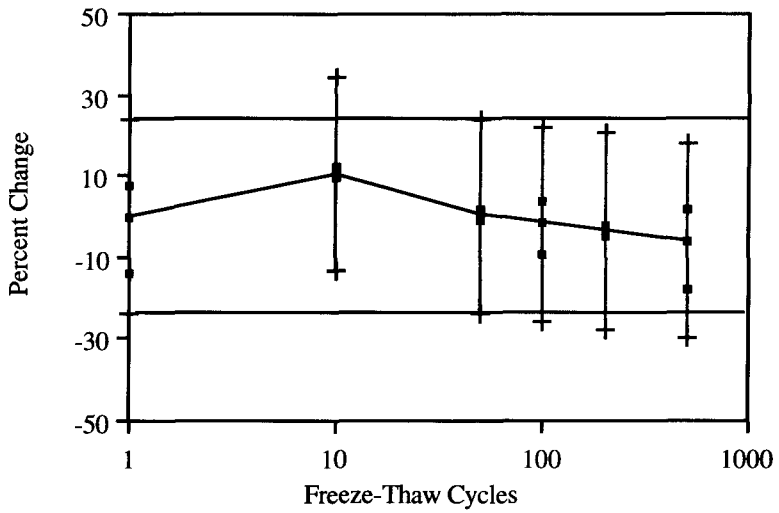
13 - 1.1-mm (45-mil) PP-R
Shear Test - Wedge Seam - Peak Strength



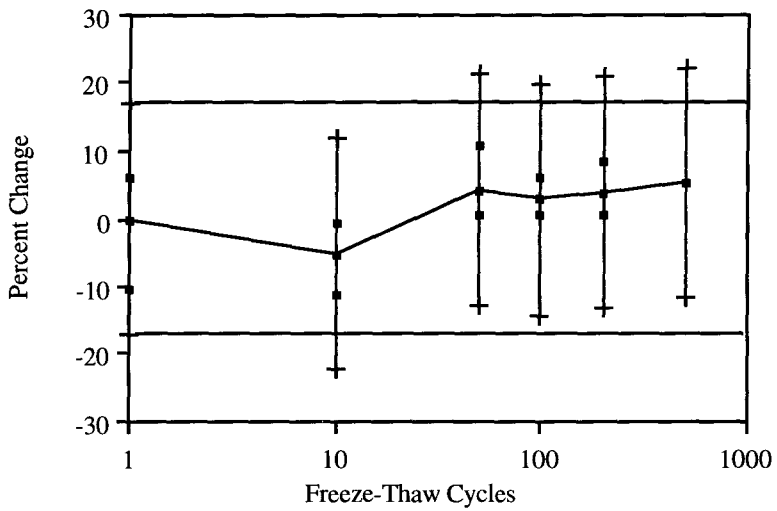
14(a) - 0.9-mm (36-mil) CSPE-R
Shear Test - Chemical Seam - Peak Strength



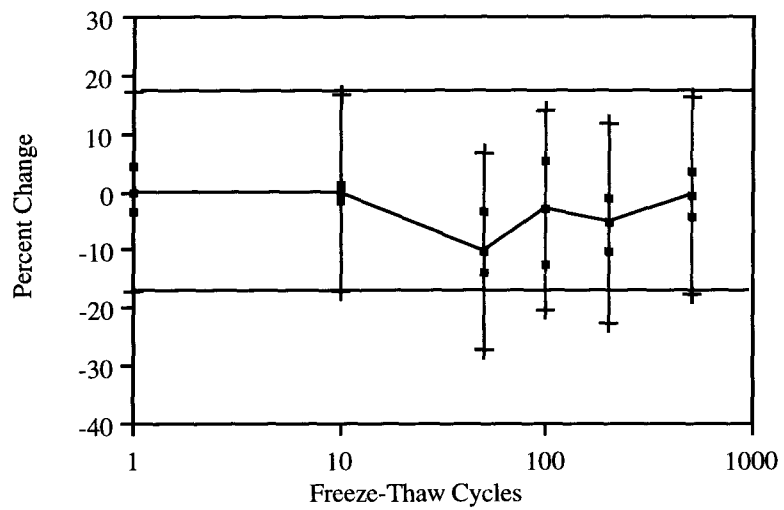
14(b) - 0.9-mm (36-mil) CSPE-R
Shear Test - Thermal Seam - Peak Strength



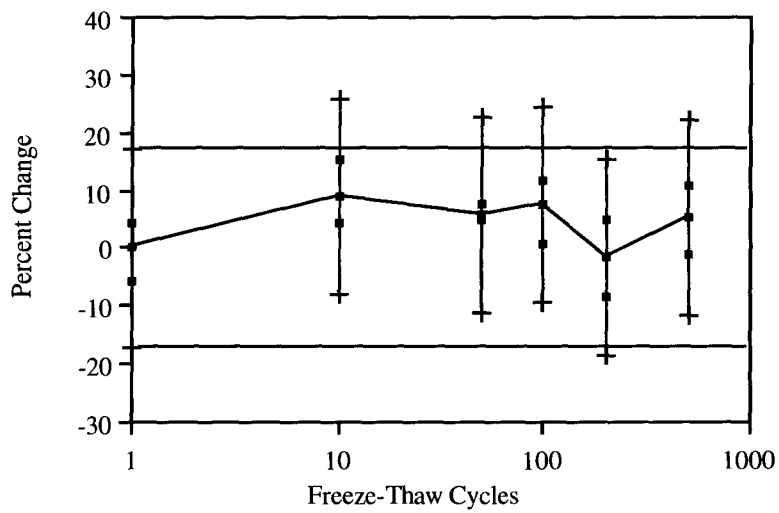
15(a) - 0.8-mm (30-mil) EIA
Shear Test - Chemical Seam - Break Strength



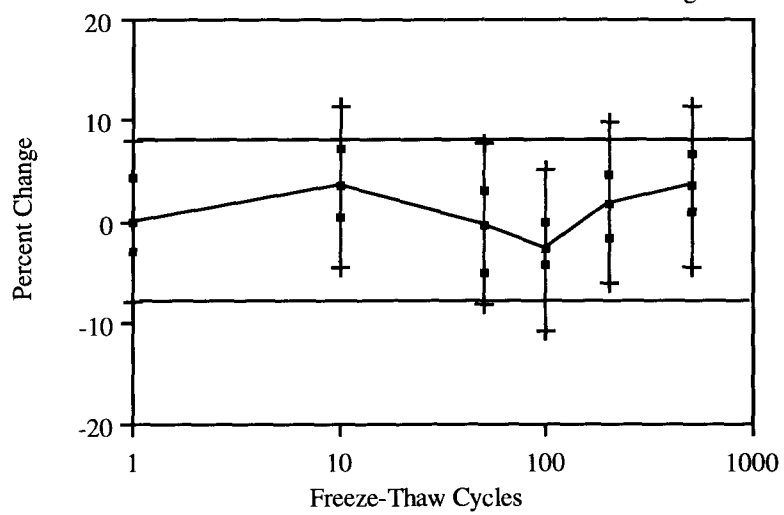
15(b) - 0.8-mm (30-mil) EIA
Shear Test - Thermal Seam - Break Strength



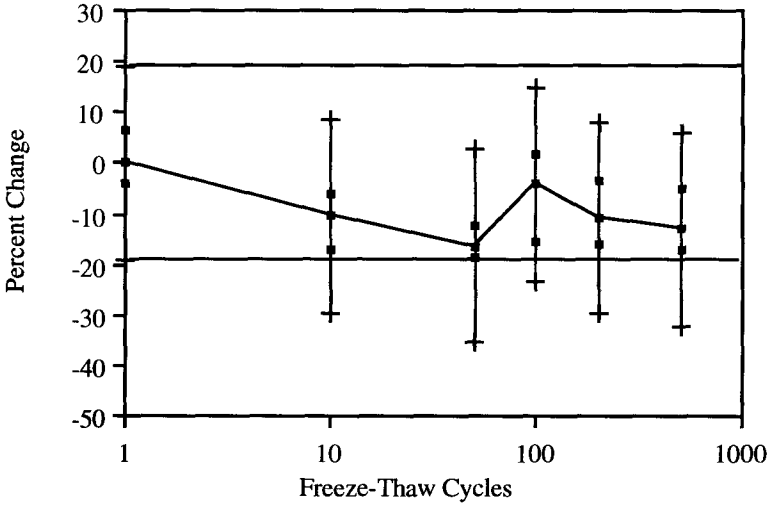
16(a) - 0.9-mm (36-mil) EIA-R
Shear Test - Chemical Seam - Break Strength



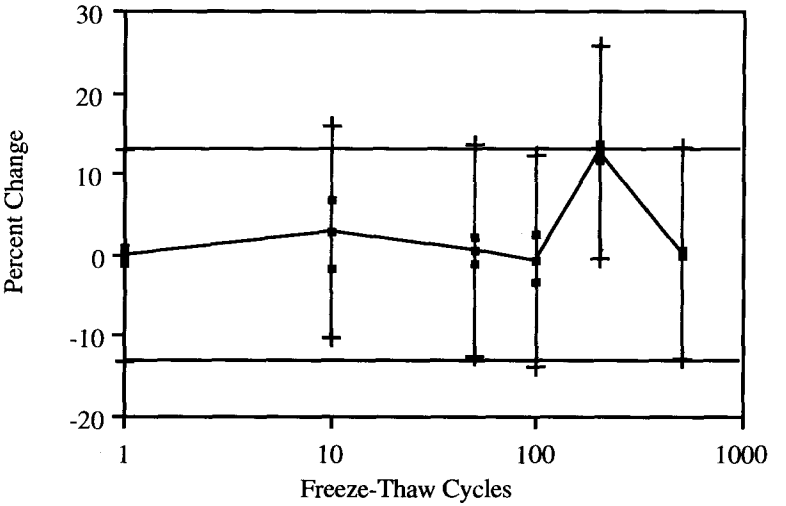
16(b) - 0.9-mm (36-mil) EIA-R
Shear Test - Thermal Seam - Break Strength



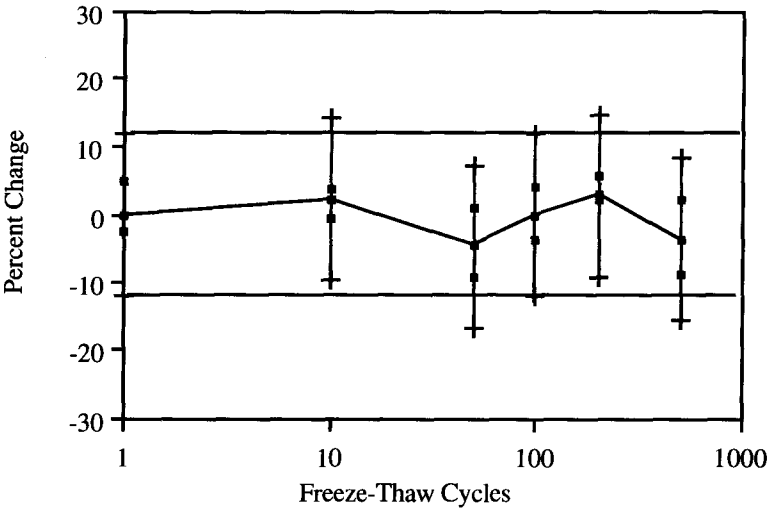
17 - 0.8-mm (30-mil) FCEA
Shear Test - Thermal Seam - Break Strength



18 - 0.8-mm (30-mil) FCEA with fabric support
Shear Test - Thermal Seam - Break Strength



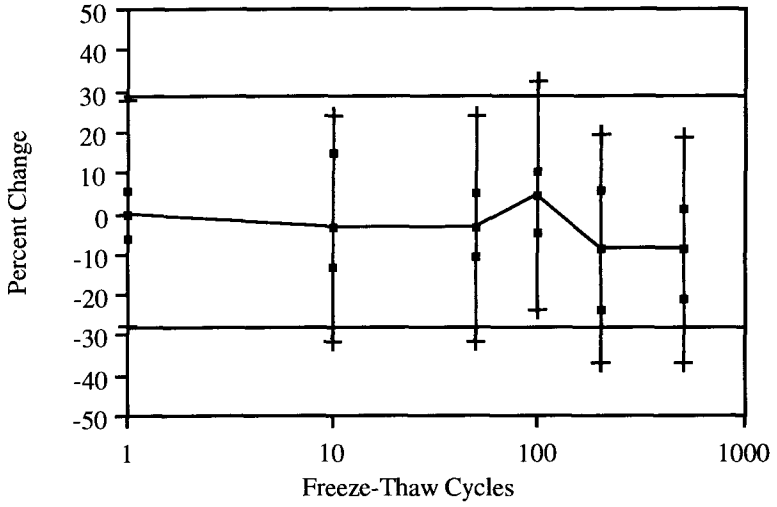
19 - 0.8-mm (30-mil) scrim coated EIA
Shear Test - Thermal Seam - Break Strength



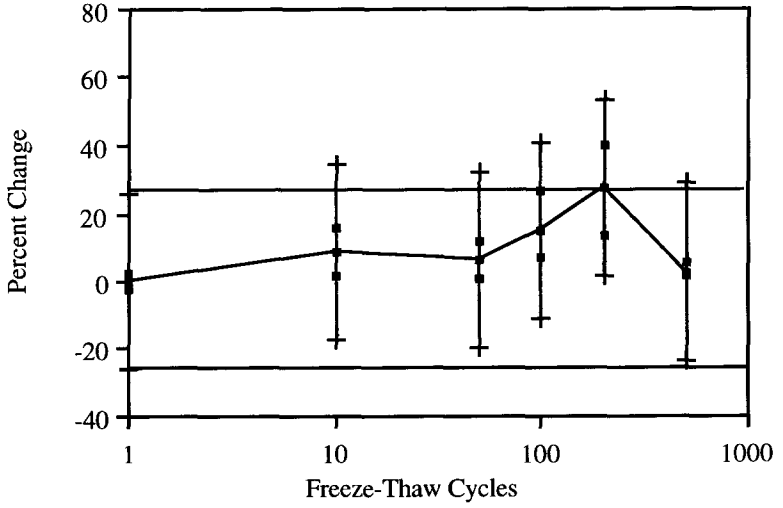
APPENDIX I

Part III — Seam Peel Tensile Test Results

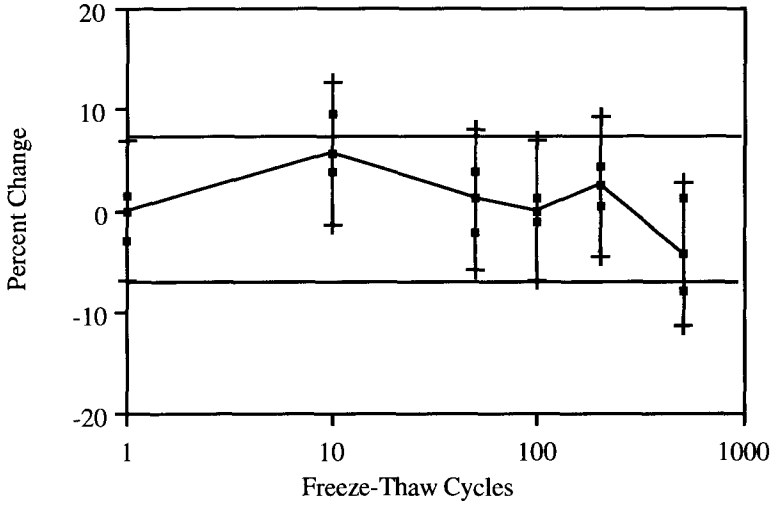
1(a) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Chemical Seam - Peak Strength



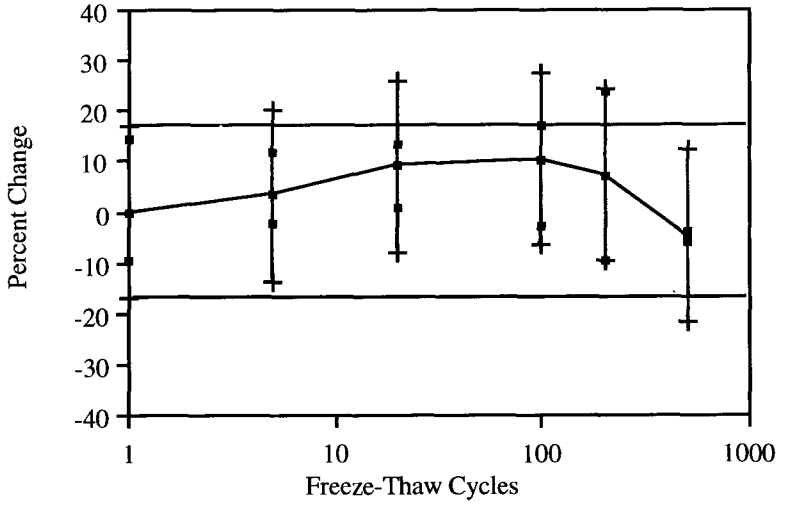
1(b) - 1.1-mm (45-mil) PVC-R Cold Temperature Formula
Peel Test - Wedge Seam - Peak Strength



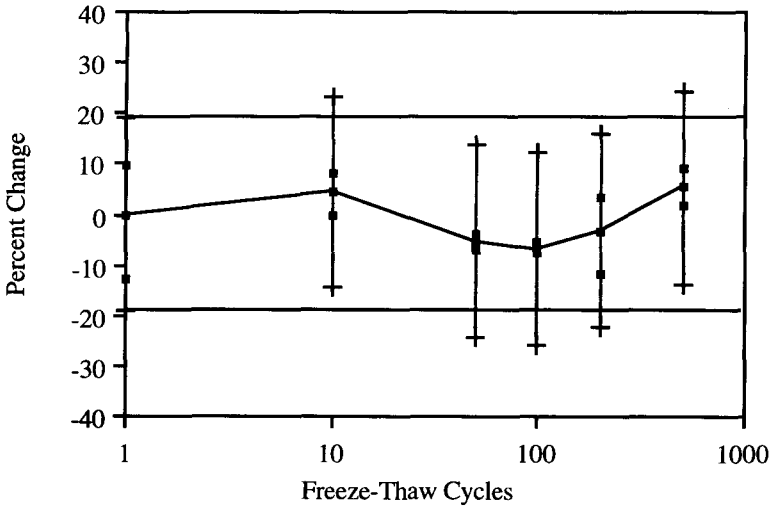
2(b) - 0.5-mm (20-mil) PVC
Peel Test - Wedge Seam - Break Strength



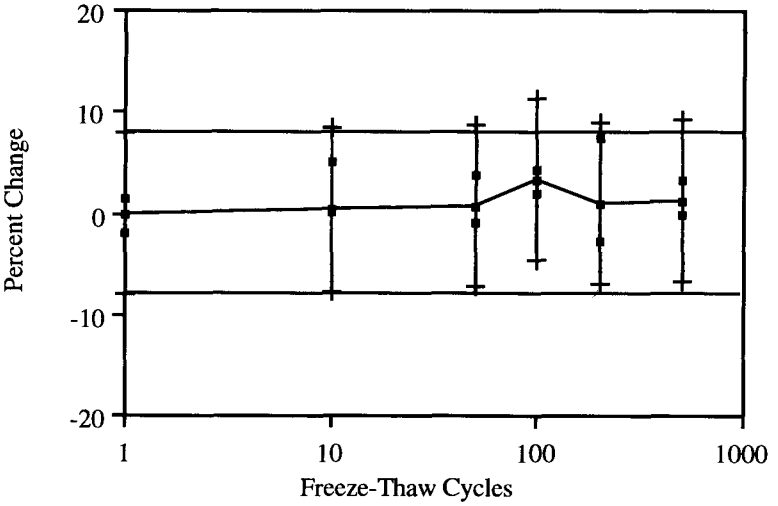
2(c) - 0.5-mm (20-mil) PVC
Peel Test - Dielectric Seam - Break Strength



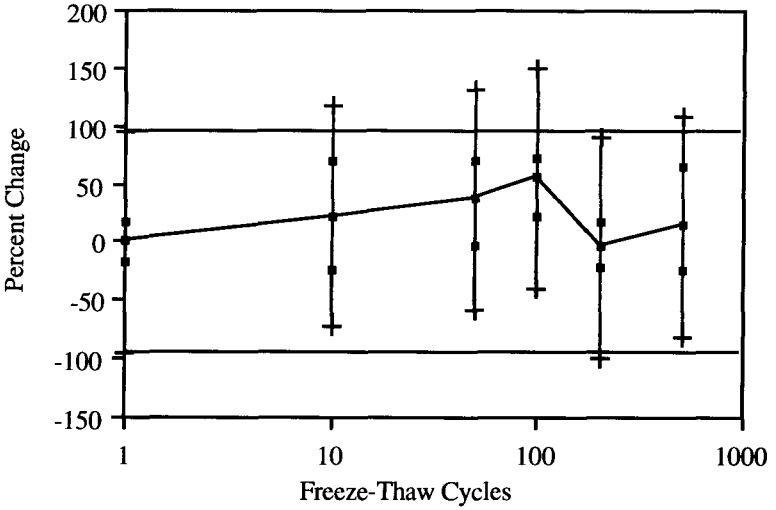
3(a) - 1.0-mm (40-mil) PVC
Peel Test - Chemical Seam - Break Strength

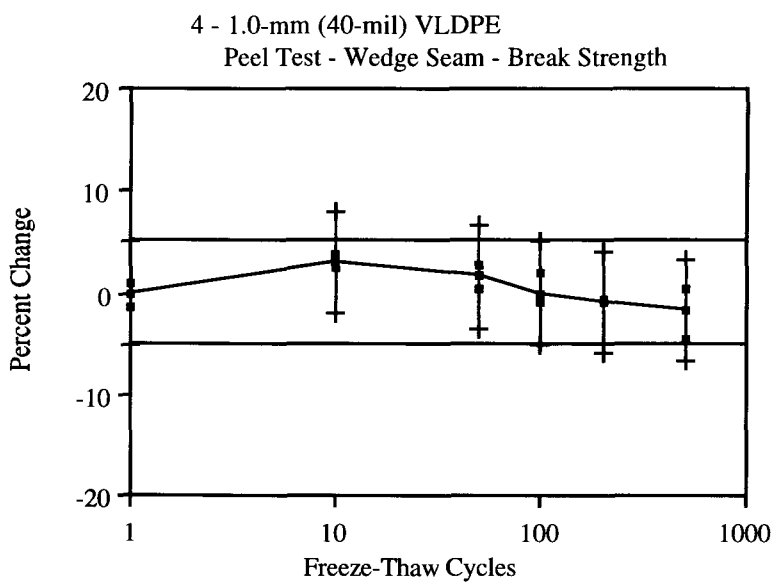


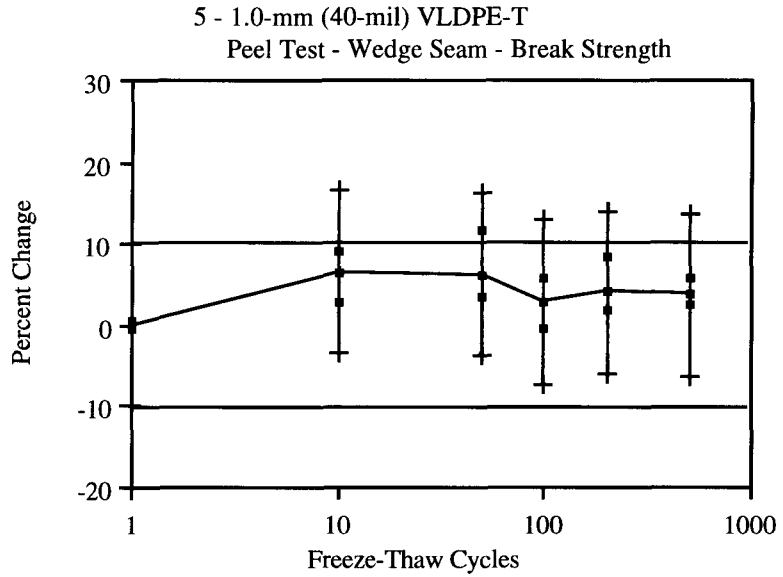
3(b) - 1.0-mm (40-mil) PVC
Peel Test - Wedge Seam - Break Strength

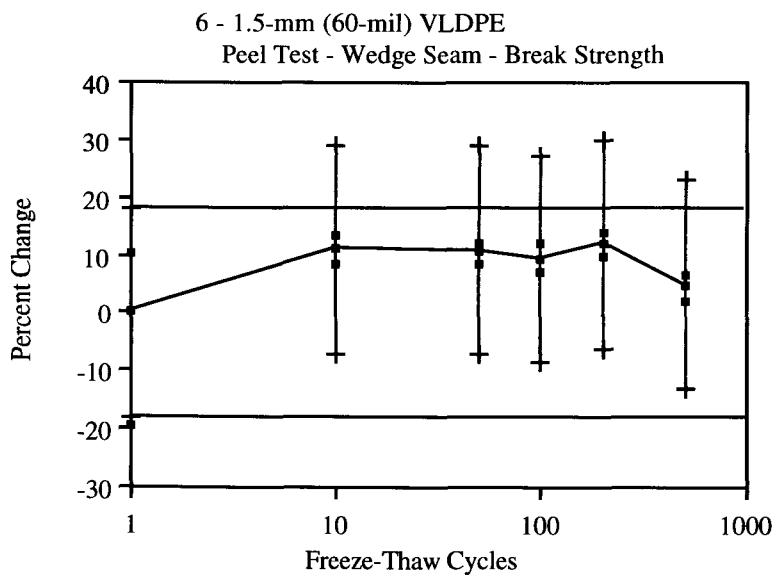


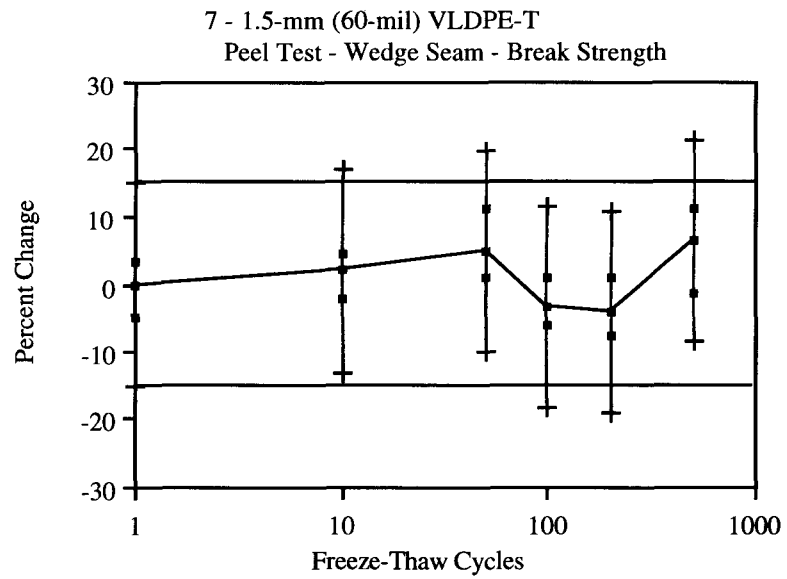
3(c) - 1.0-mm (40-mil) PVC
Peel Test - Dielectric Seam - Break Strength

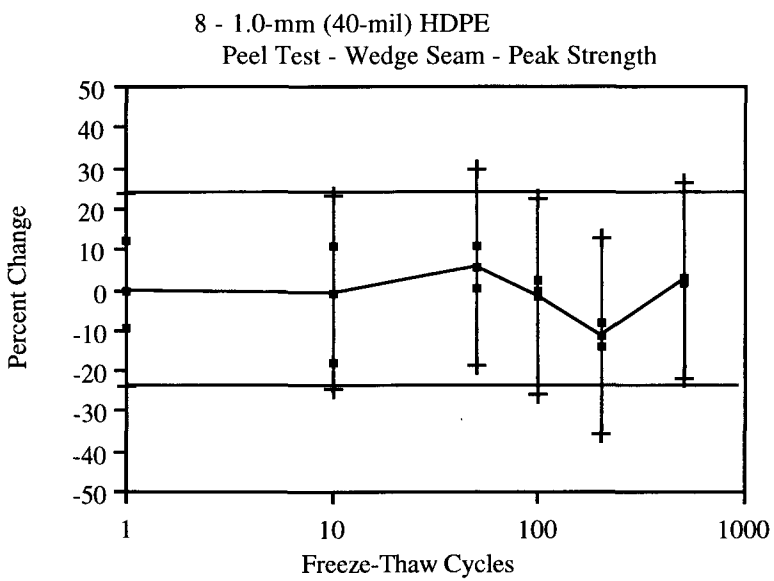


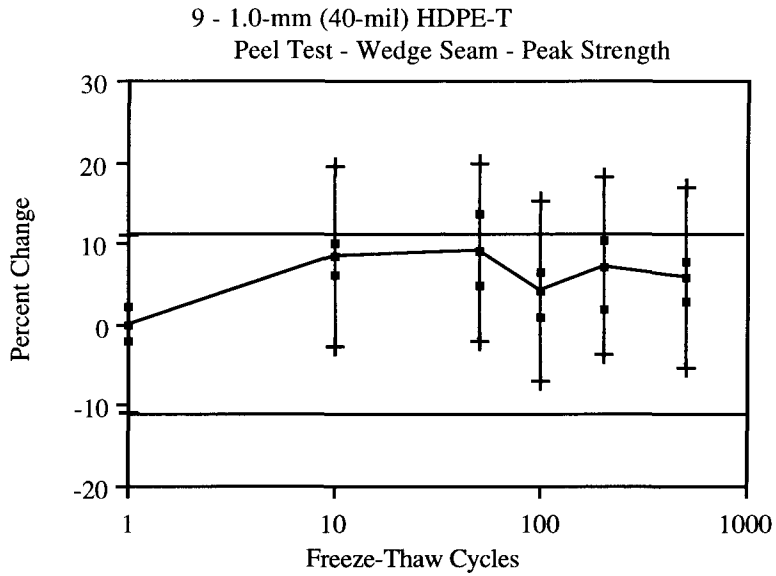

4 - 1.0-mm (40-mil) VLDPE
Peel Test - Wedge Seam - Break Strength
Percent Change
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

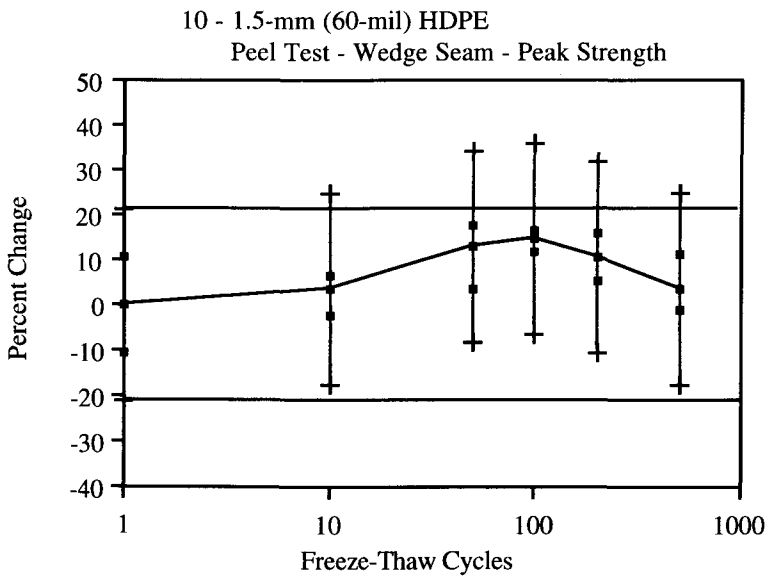

5 - 1.0-mm (40-mil) VLDPE-T
Peel Test - Wedge Seam - Break Strength
Percent Change
30
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

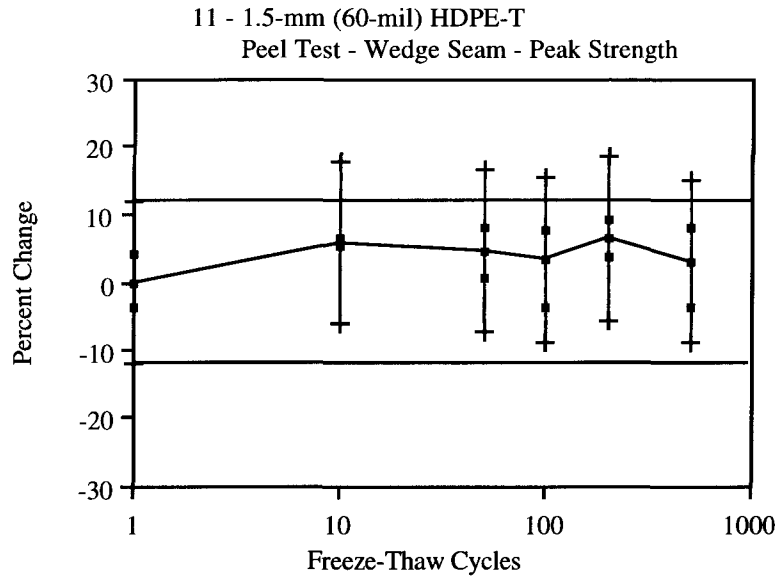

6 - 1.5-mm (60-mil) VLDPE
Peel Test - Wedge Seam - Break Strength
Percent Change
40
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles


7 - 1.5-mm (60-mil) VLDPE-T
Peel Test - Wedge Seam - Break Strength
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

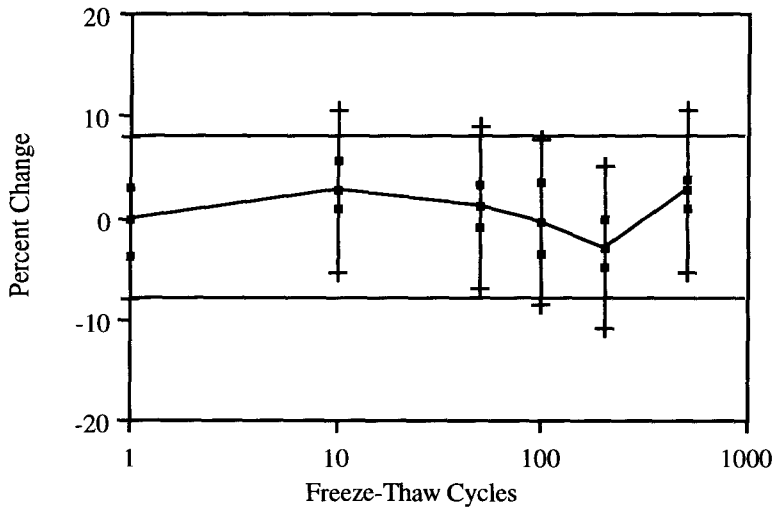

8 - 1.0-mm (40-mil) HDPE
Peel Test - Wedge Seam - Peak Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles


9 - 1.0-mm (40-mil) HDPE-T
Peel Test - Wedge Seam - Peak Strength
Percent Change
30
20
10
0
-10
-20
1
10
100
1000
Freeze-Thaw Cycles

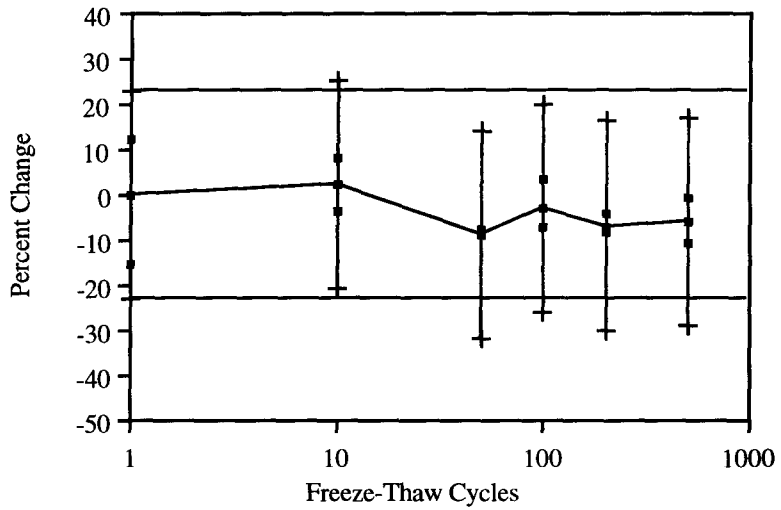

10 - 1.5-mm (60-mil) HDPE
Peel Test - Wedge Seam - Peak Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
1
10
100
1000
Freeze-Thaw Cycles


11 - 1.5-mm (60-mil) HDPE-T
Peel Test - Wedge Seam - Peak Strength
Percent Change
30
20
10
0
-10
-20
-30
1
10
100
1000
Freeze-Thaw Cycles

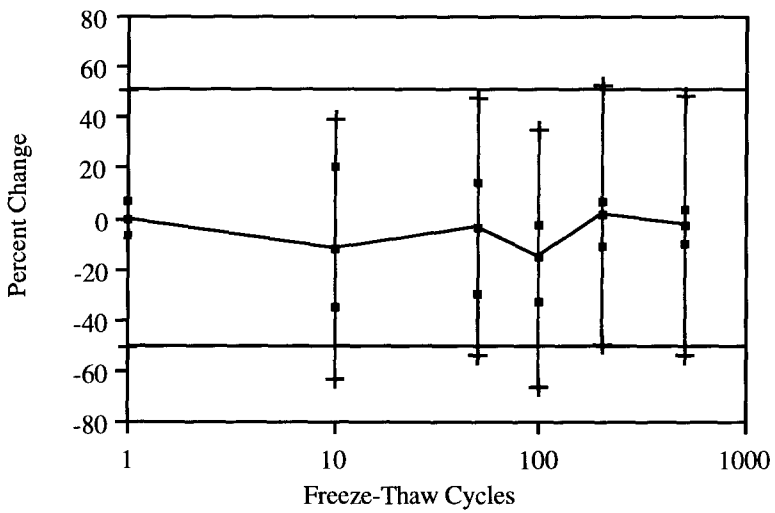
12 - 1.0-mm (40-mil) PP
Peel Test - Thermal Seam - Break Strength



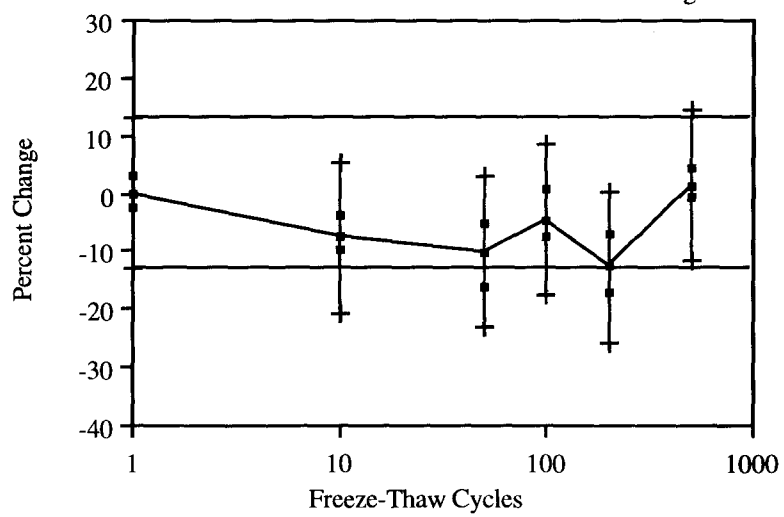
13 - 1.1-mm (45-mil) PP-R
Peel Test - Wedge Seam - Peak Strength



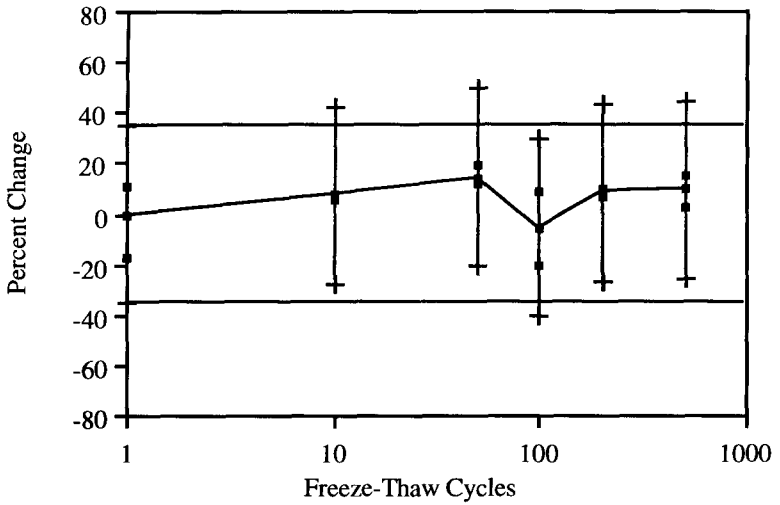
14(a) - 0.9-mm (36-mil) CSPE-R
Peel Test - Chemical Seam - Peak Strength



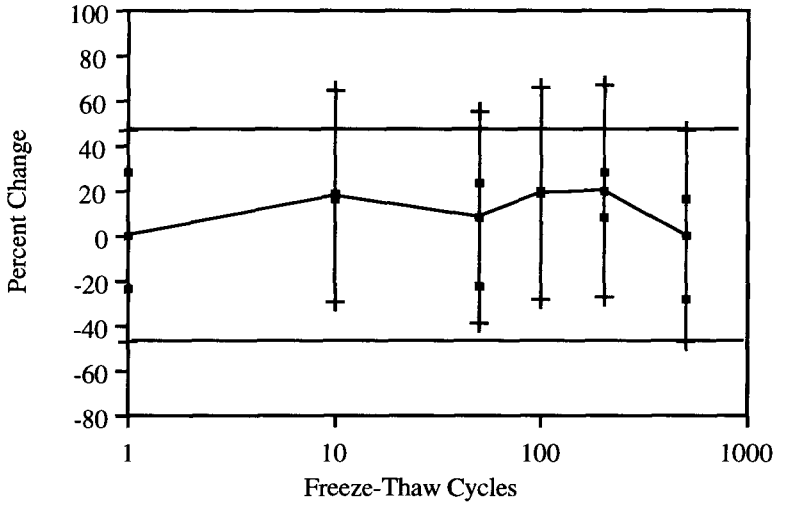
14(b) - 0.9-mm (36-mil) CSPE-R
Peel Test - Thermal Seam - Peak Strength



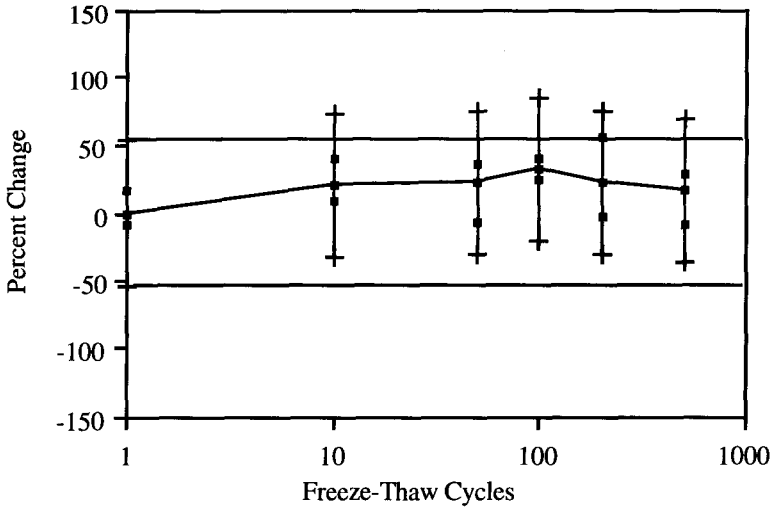
15(a) - 0.8-mm (30-mil) EIA
Peel Test - Chemical Seam - Break Strength



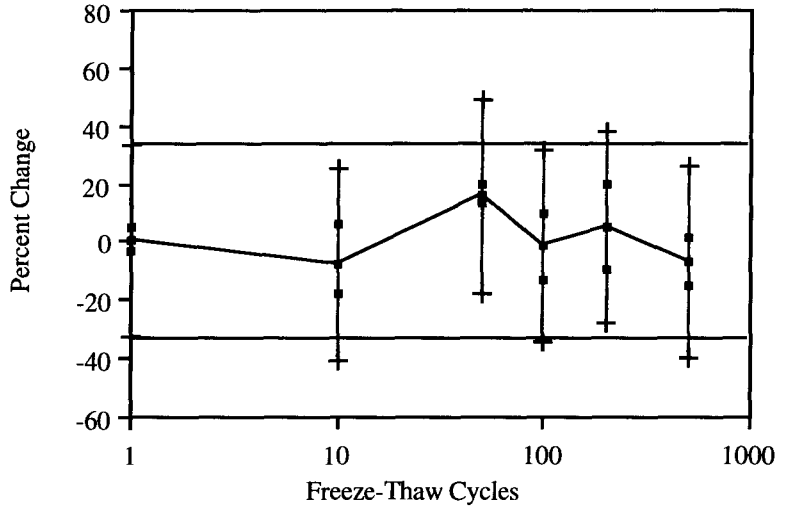
15(b) - 0.8-mm (30-mil) EIA
Peel Test - Thermal Seam - Break Strength

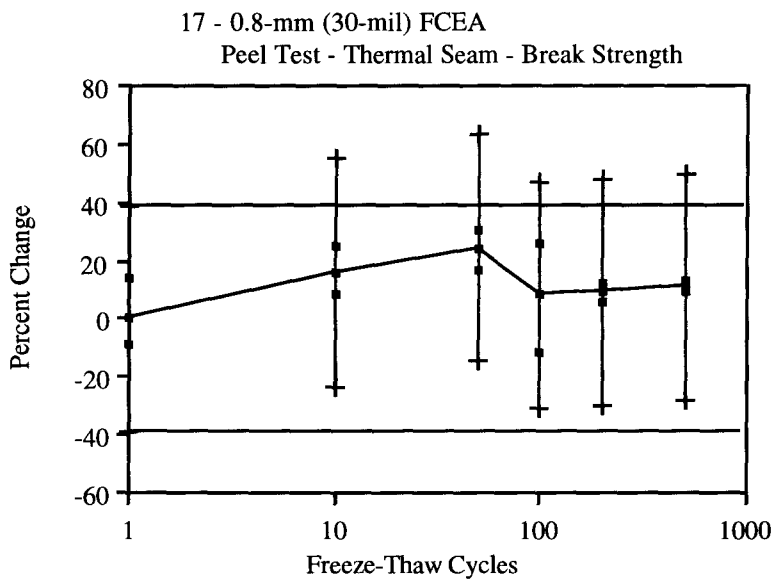


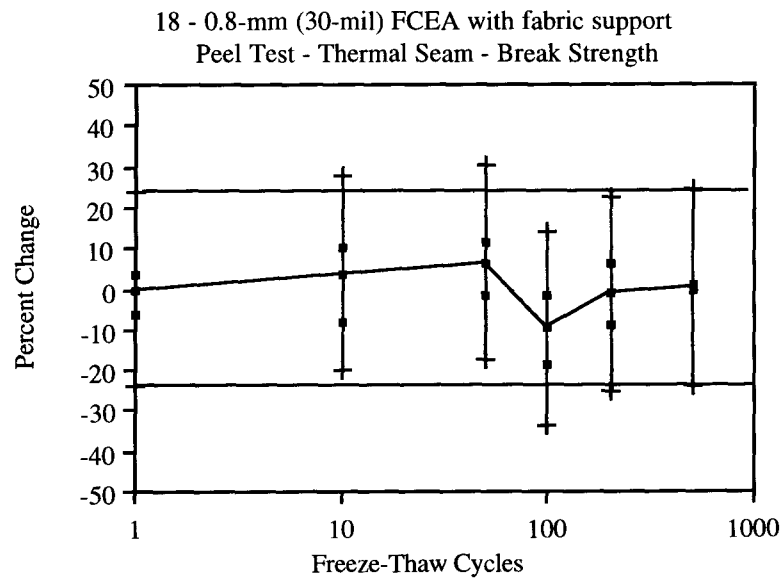
16(a) - 0.9-mm (36-mil) EIA-R
Peel Test - Chemical Seam - Break Strength



16(b) - 0.9-mm (36-mil) EIA-R
Peel Test - Thermal Seam - Break Strength

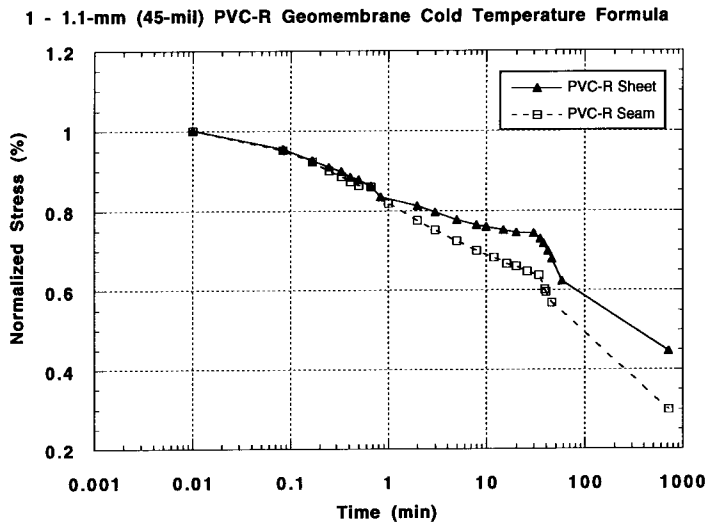


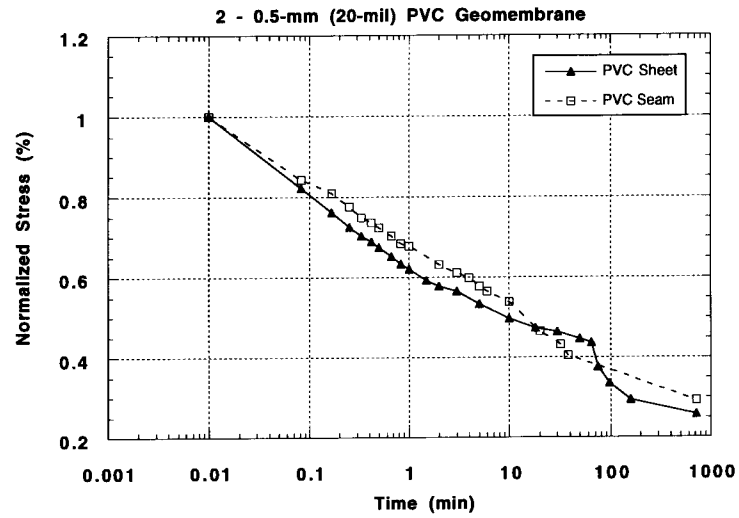

17 - 0.8-mm (30-mil) FCEA
Peel Test - Thermal Seam - Break Strength
Percent Change
80
60
40
20
0
-20
-40
-60
1
10
100
1000
Freeze-Thaw Cycles

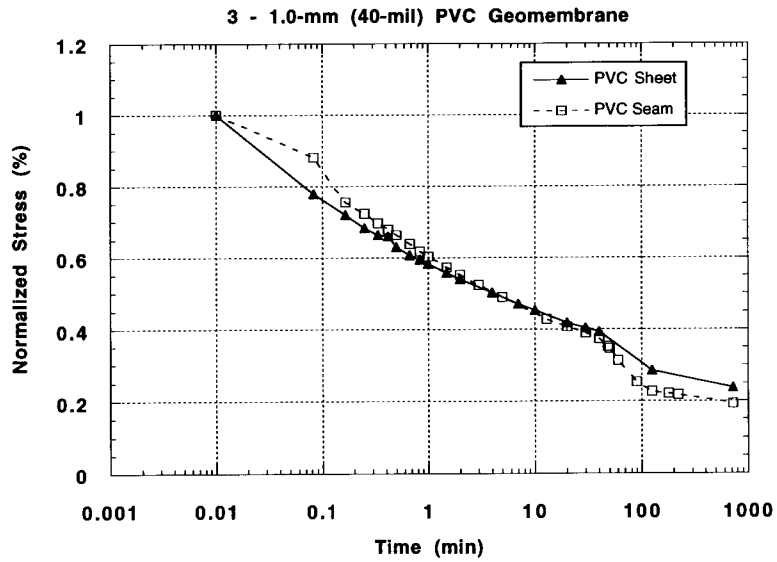

18 - 0.8-mm (30-mil) FCEA with fabric support
Peel Test - Thermal Seam - Break Strength
Percent Change
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
100
1000
Freeze-Thaw Cycles

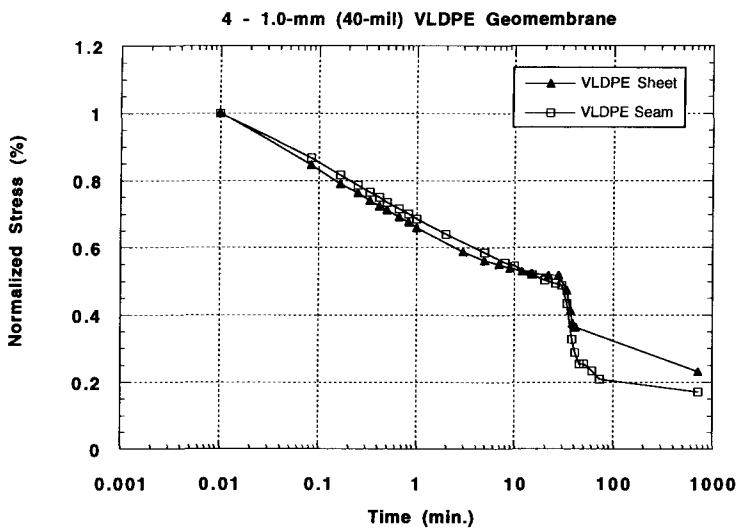
APPENDIX J

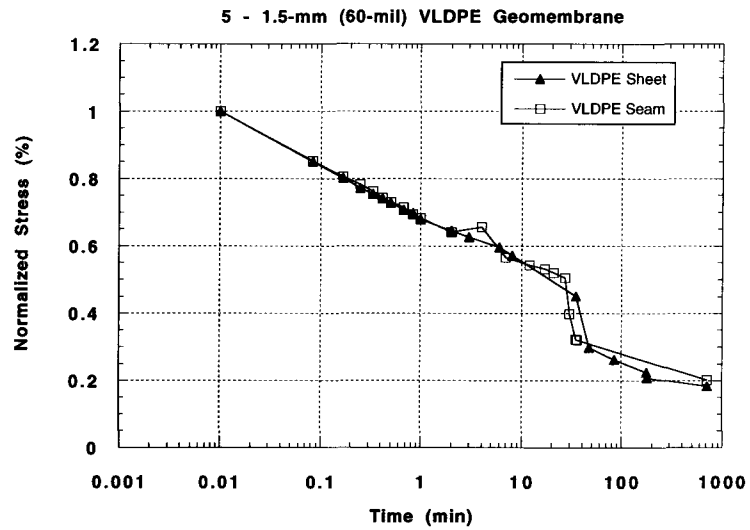
Stress Relaxation Plots

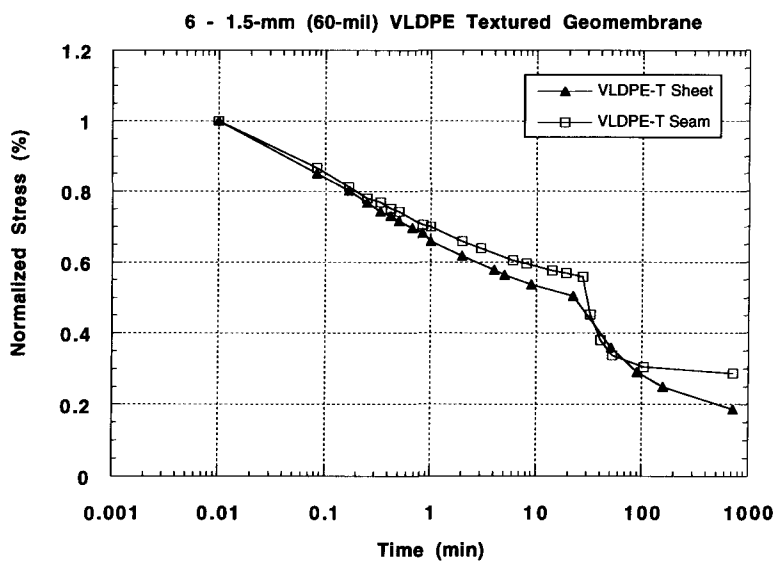

1 - 1.1-mm (45-mil) PVC-R Geomembrane Cold Temperature Formula
PVC-R Sheet
PVC-R Seam
Normalized Stress (%)
1.2
1
0.8
0.6
0.4
0.2
0.001
0.01
0.1
1
10
100
1000
Time (min)

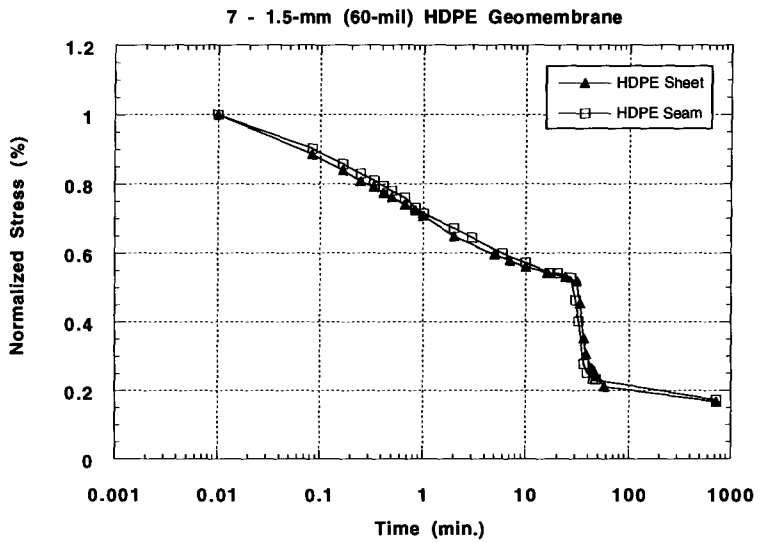

2 - 0.5-mm (20-mil) PVC Geomembrane
PVC Sheet
PVC Seam
Normalized Stress (%)
1.2
1
0.8
0.6
0.4
0.2
0.001
0.01
0.1
1
10
100
1000
Time (min)

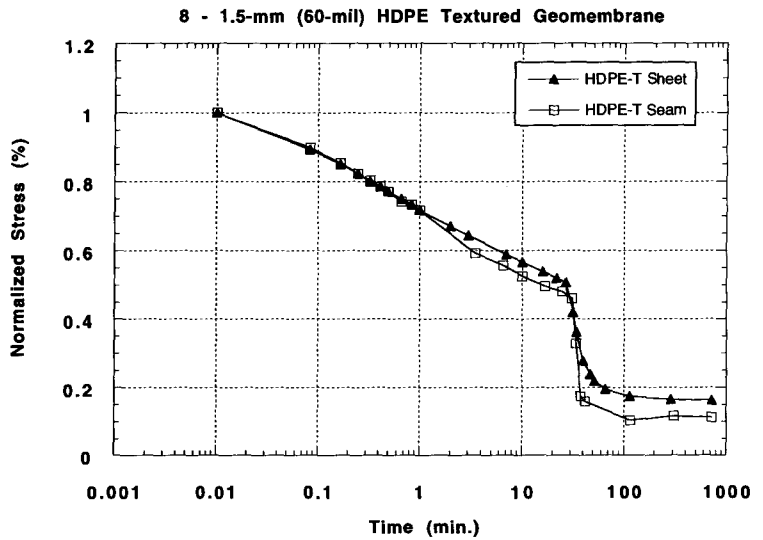

3 - 1.0-mm (40-mil) PVC Geomembrane
PVC Sheet
PVC Seam
Normalized Stress (%)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000
Time (min)

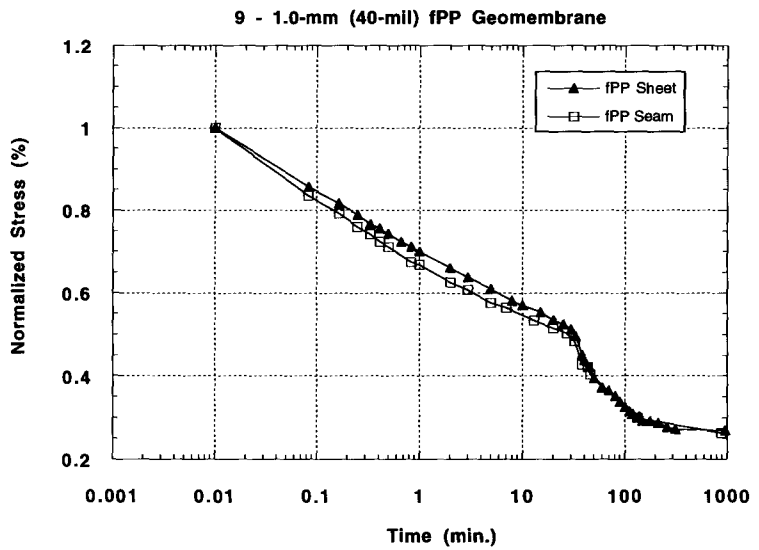

4 - 1.0-mm (40-mil) VLDPE Geomembrane
VLDPE Sheet
VLDPE Seam
Normalized Stress (%)
Time (min.)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000

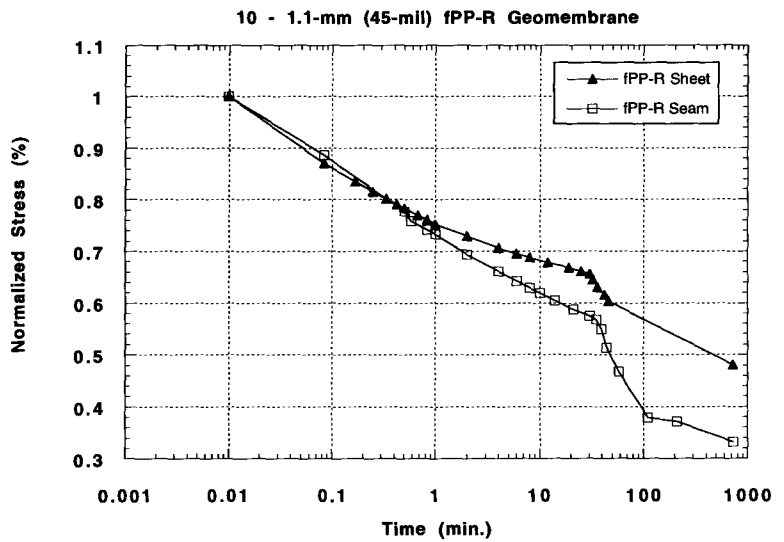

5 - 1.5-mm (60-mil) VLDPE Geomembrane
VLDPE Sheet
VLDPE Seam
Normalized Stress (%)
Time (min)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000

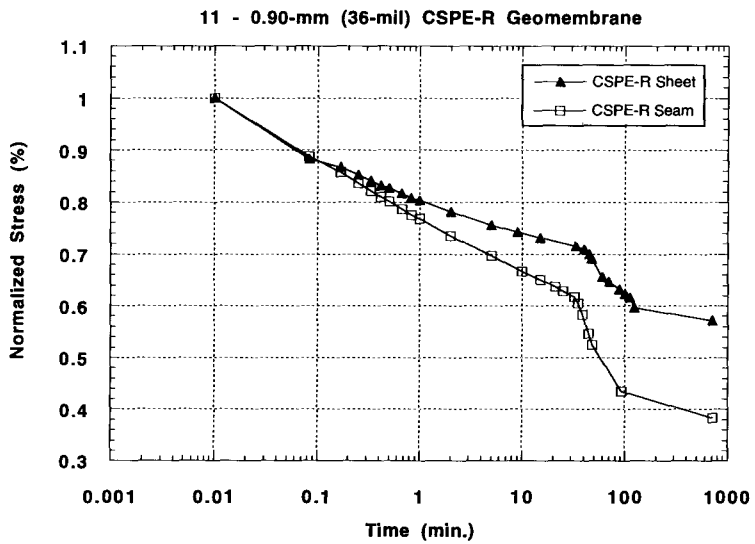

6 - 1.5-mm (60-mil) VLDPE Textured Geomembrane
VLDPE-T Sheet
VLDPE-T Seam
Normalized Stress (%)
Time (min)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000

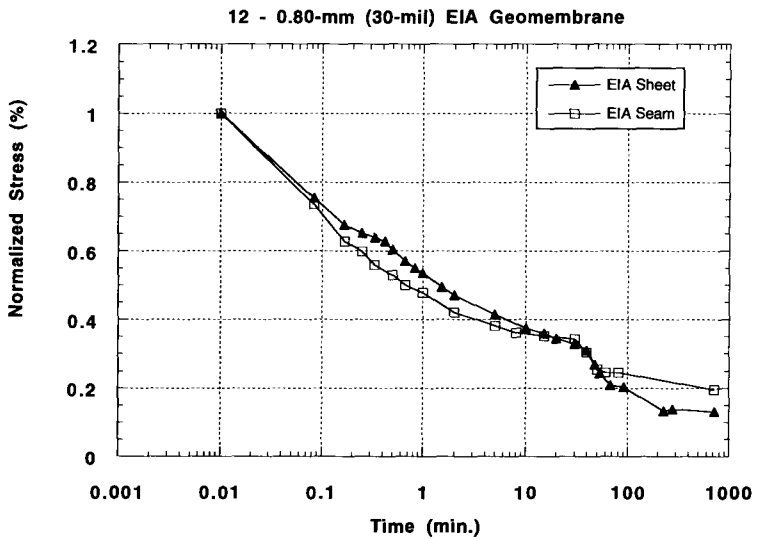

7 - 1.5-mm (60-mil) HDPE Geomembrane
HDPE Sheet
HDPE Seam
Normalized Stress (%)
Time (min.)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000


8 - 1.5-mm (60-mil) HDPE Textured Geomembrane
HDPE-T Sheet
HDPE-T Seam
Normalized Stress (%)
Time (min.)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000


9 - 1.0-mm (40-mil) fPP Geomembrane
fPP Sheet
fPP Seam
Normalized Stress (%)
Time (min.)
1.2
1
0.8
0.6
0.4
0.2
0.001
0.01
0.1
1
10
100
1000


10 - 1.1-mm (45-mil) fPP-R Geomembrane
fPP-R Sheet
fPP-R Seam
Normalized Stress (%)
Time (min.)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.001
0.01
0.1
1
10
100
1000

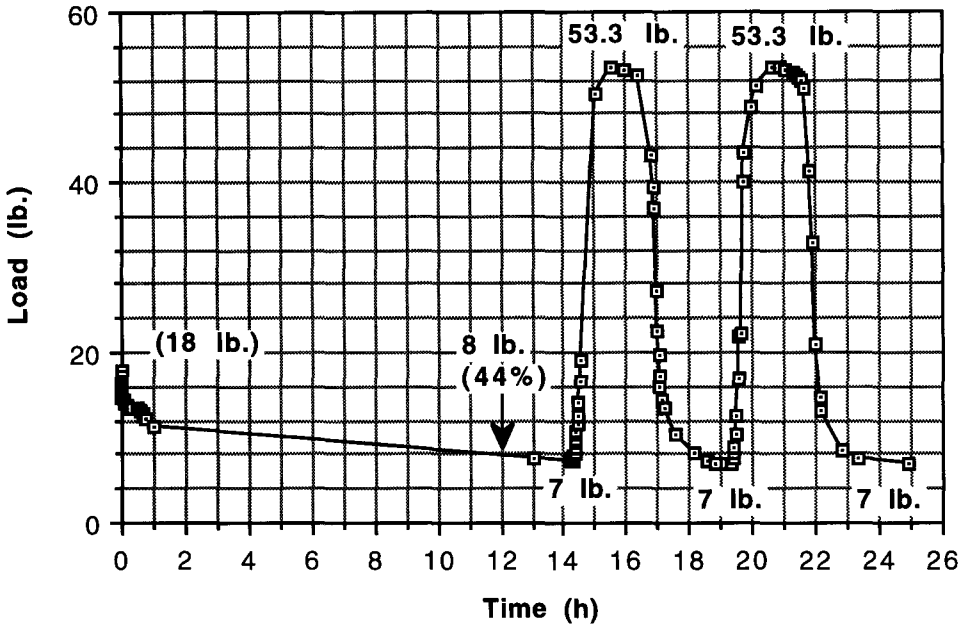

11 - 0.90-mm (36-mil) CSPE-R Geomembrane
CSPE-R Sheet
CSPE-R Seam
Normalized Stress (%)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.001
0.01
0.1
1
10
100
1000
Time (min.)


12 - 0.80-mm (30-mil) EIA Geomembrane
EIA Sheet
EIA Seam
Normalized Stress (%)
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.01
0.1
1
10
100
1000
Time (min.)

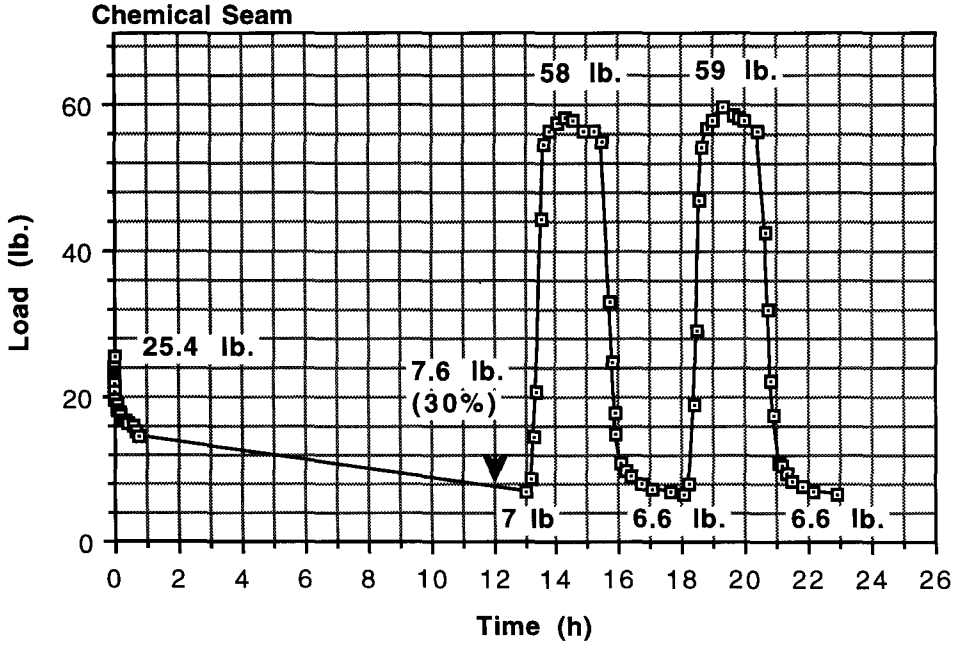
APPENDIX K

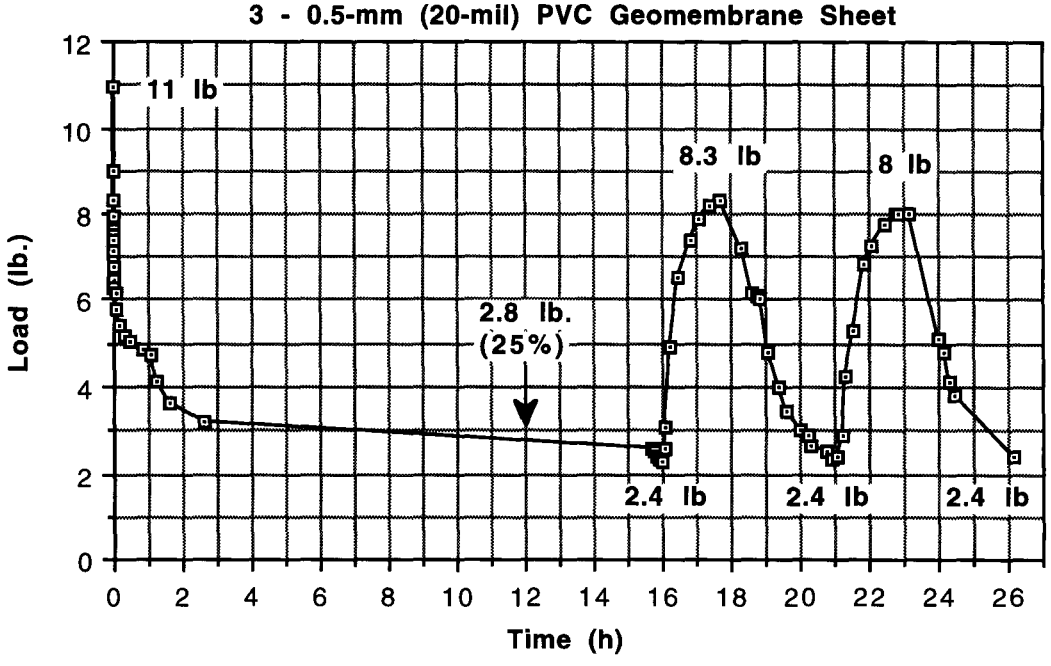
Cold Temperature Induced Tensile Stress

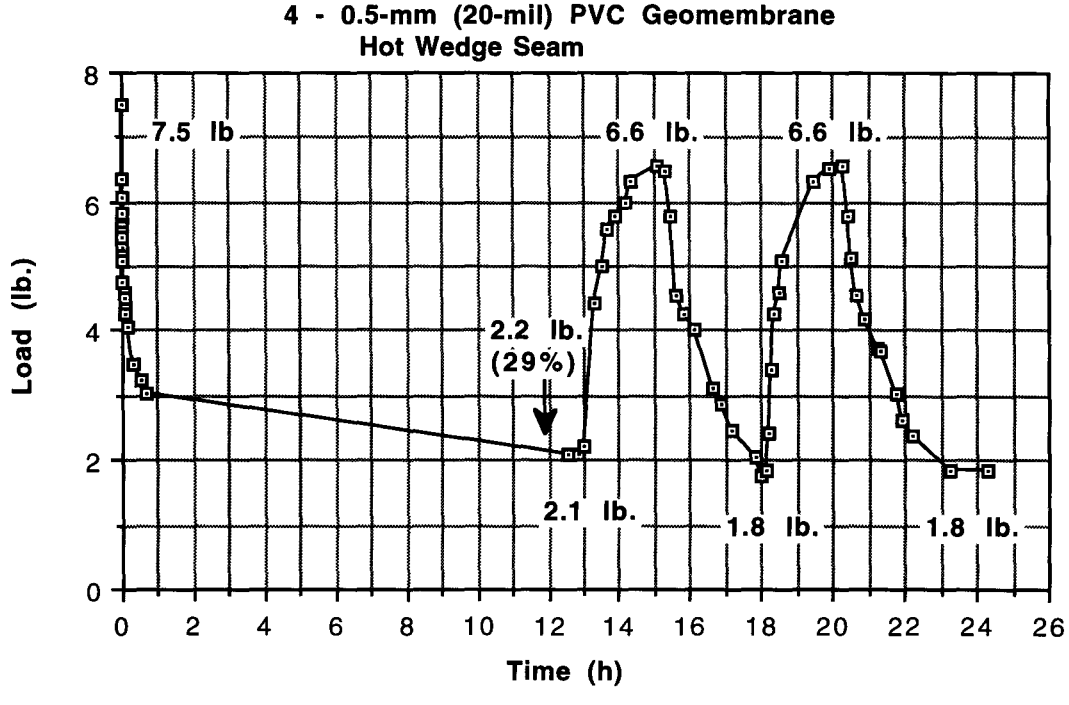
1 - 1.1 mm (45-mil) PVC-R Geomembrane Cold Temperature Formula



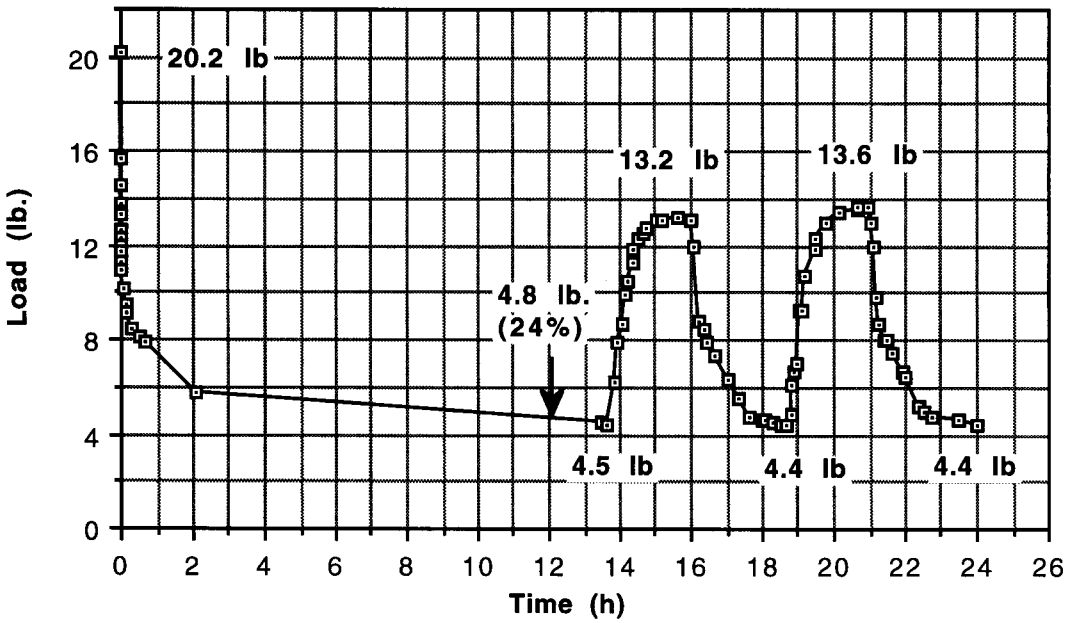
2 - 1.1 mm (45-mil) PVC-R Geomembrane Cold Temperature Formula
Chemical Seam



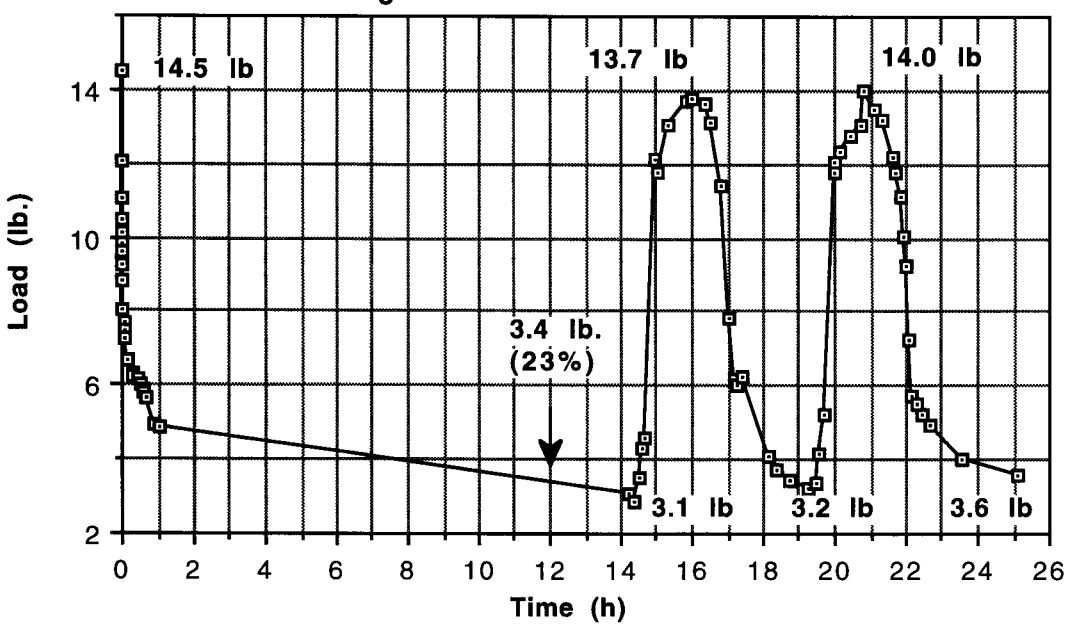

3 - 0.5-mm (20-mil) PVC Geomembrane Sheet
11 lb
8.3 lb
8 lb
2.8 lb.
(25%)
2.4 lb
2.4 lb
2.4 lb
Load (lb.)
Time (h)

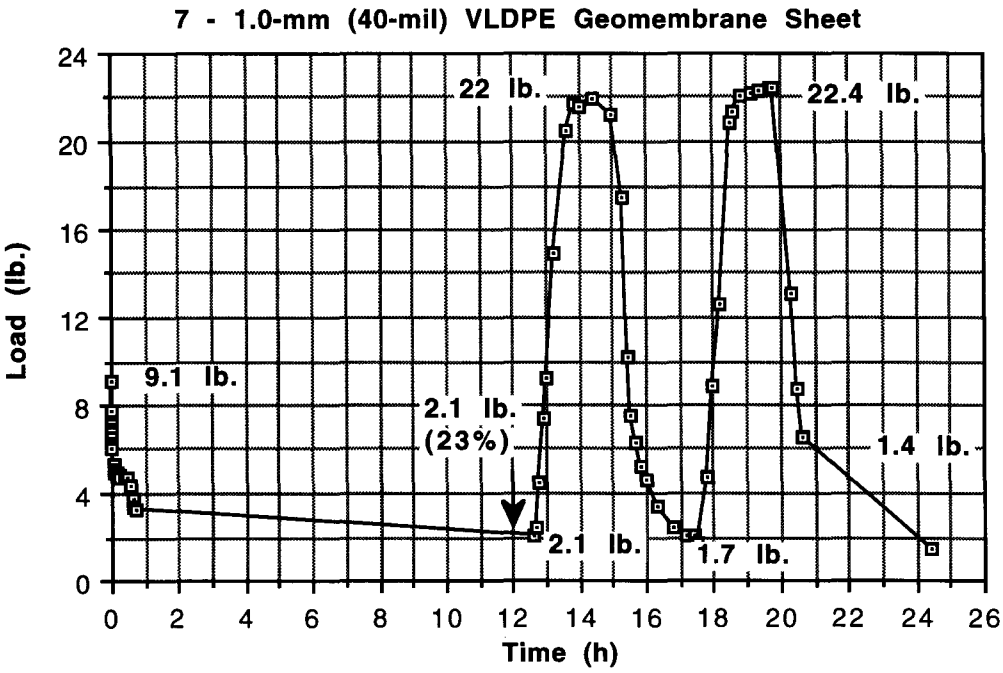

4 - 0.5-mm (20-mil) PVC Geomembrane
Hot Wedge Seam
7.5 lb
6.6 lb.
6.6 lb.
2.2 lb.
(29%)
2.1 lb.
1.8 lb.
1.8 lb.
Load (lb.)
Time (h)

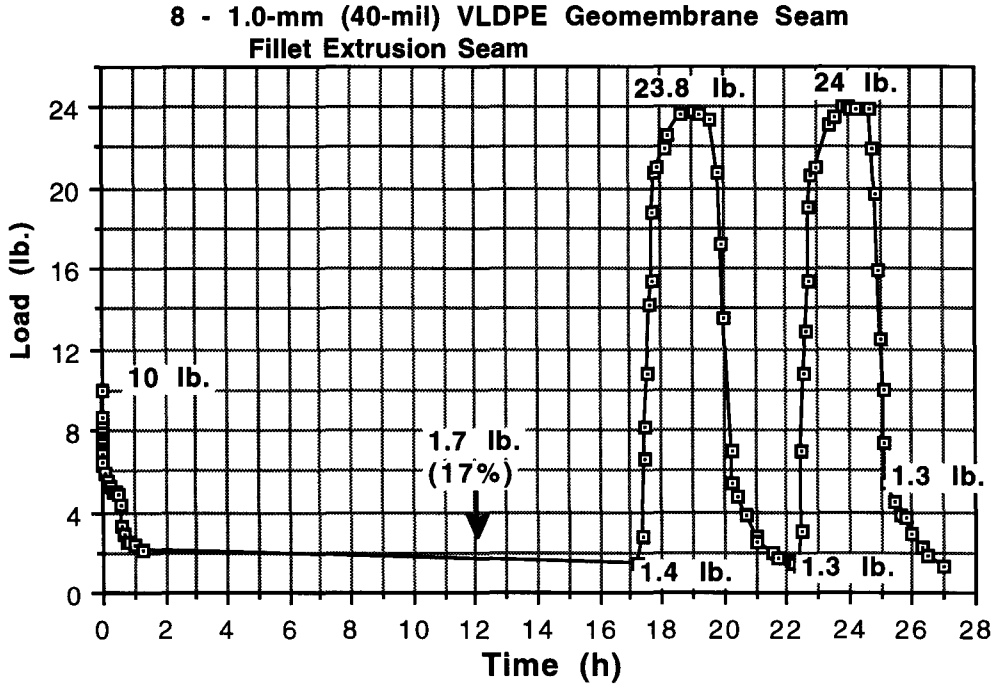
5 - 1.0-mm (40-mil) PVC Geomembrane Sheet

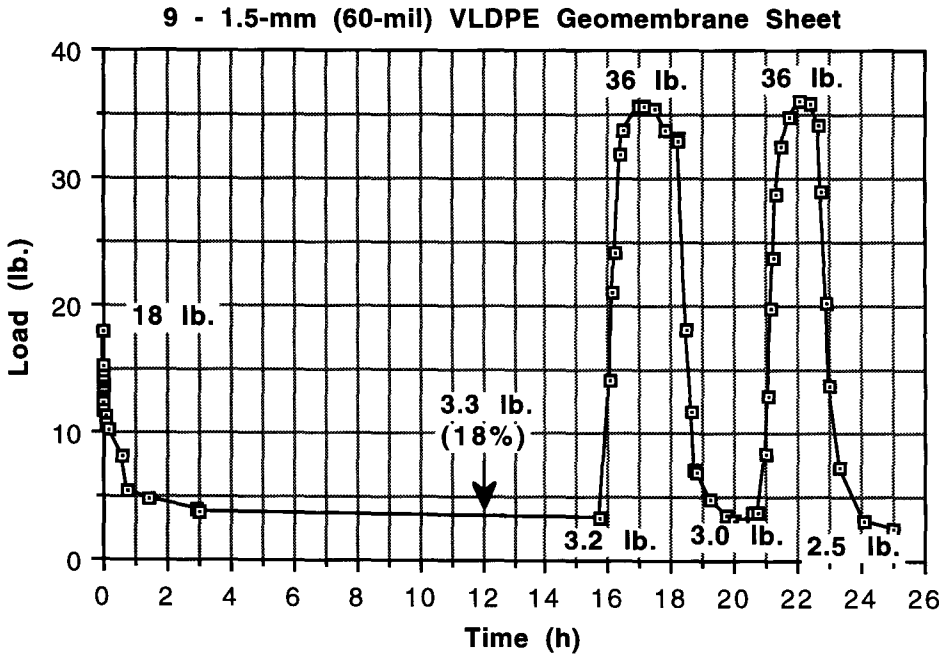


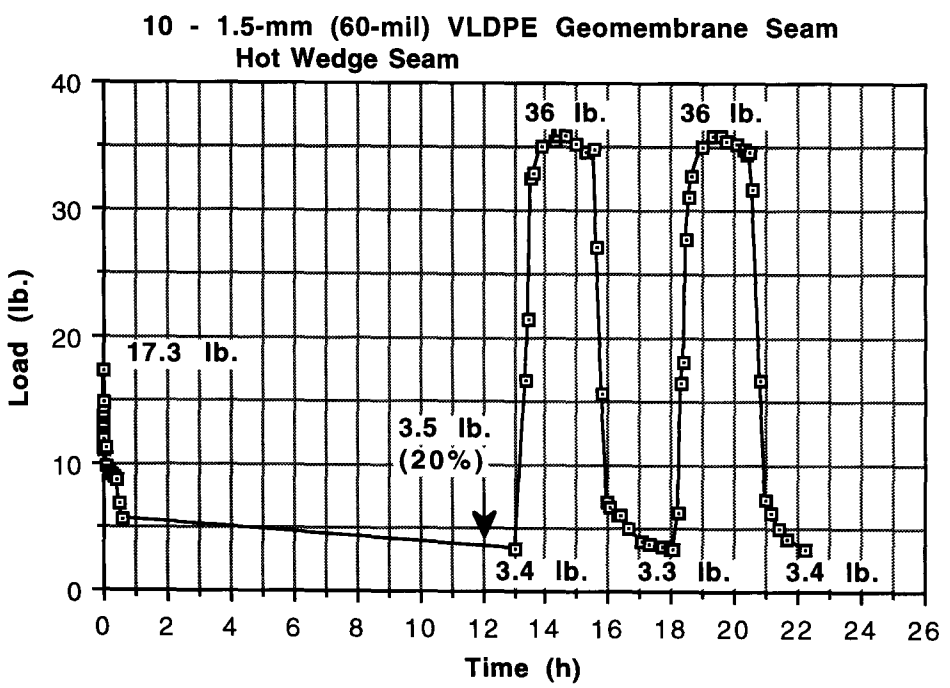
6 - 1.0-mm (40-mil) PVC Geomembrane Seam
Hot Wedge Seam

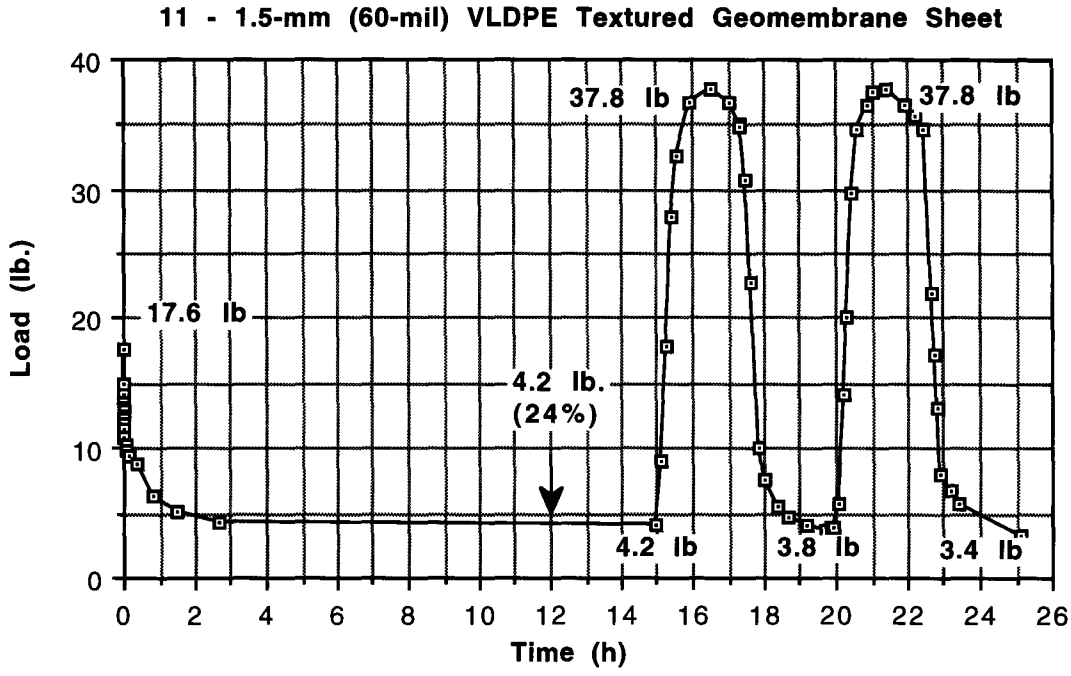


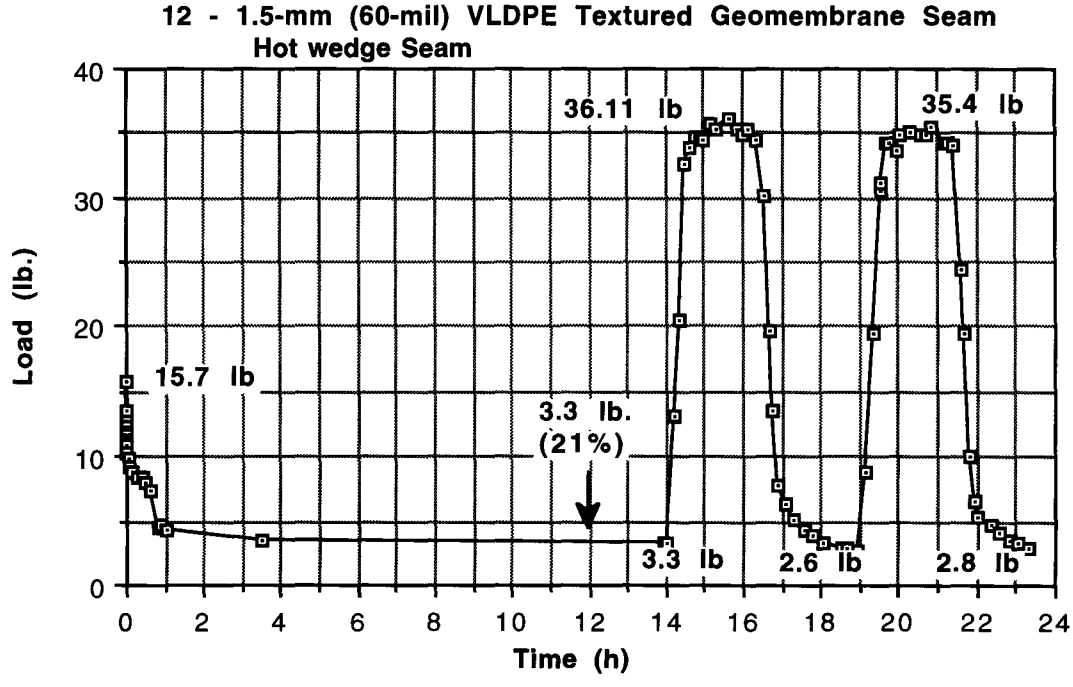

7 - 1.0-mm (40-mil) VLDPE Geomembrane Sheet
Load (lb.)
Time (h)
22 lb.
22.4 lb.
9.1 lb.
2.1 lb.
(23%)
1.4 lb.
2.1 lb.
1.7 lb.

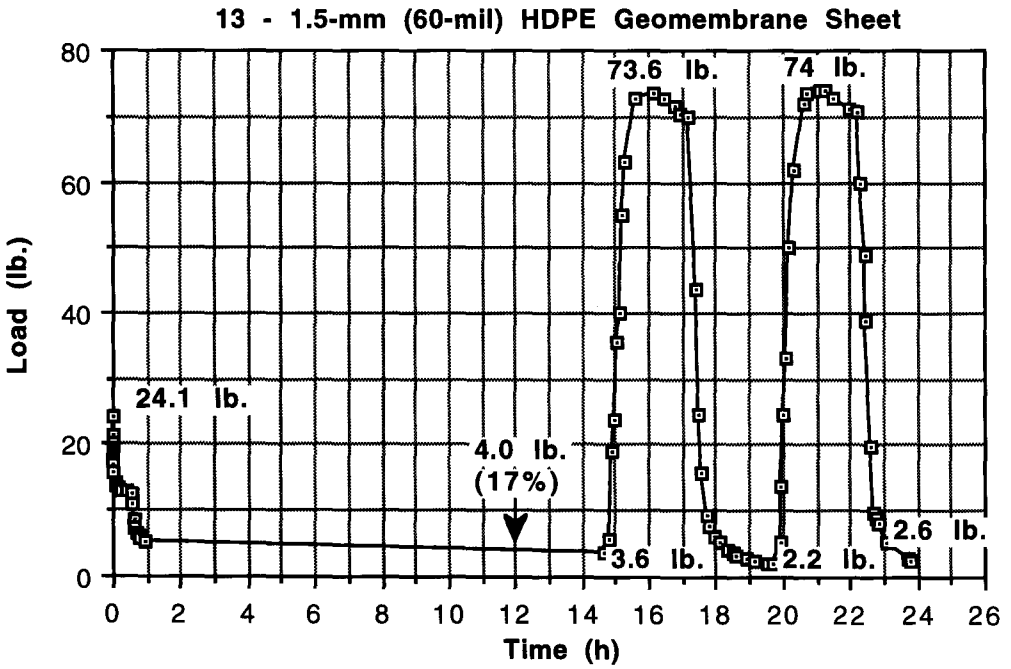

8 - 1.0-mm (40-mil) VLDPE Geomembrane Seam
Fillet Extrusion Seam
Load (lb.)
Time (h)
23.8 lb.
24 lb.
10 lb.
1.7 lb.
(17%)
1.3 lb.
1.4 lb.
1.3 lb.

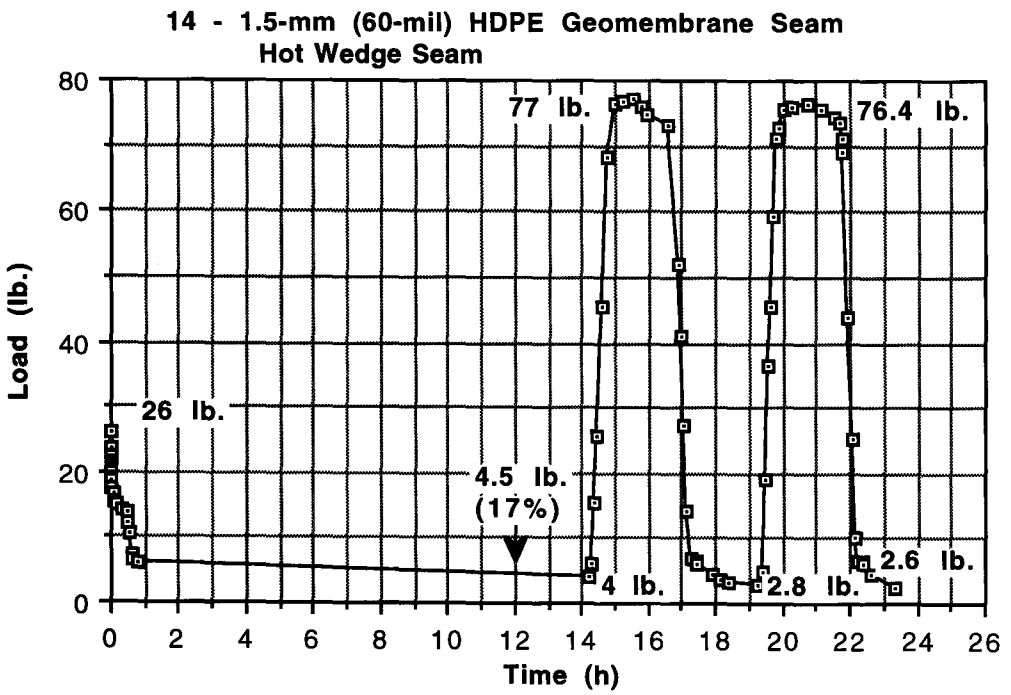

9 - 1.5-mm (60-mil) VLDPE Geomembrane Sheet
Load (lb.)
Time (h)
36 lb.
36 lb.
18 lb.
3.3 lb.
(18%)
3.2 lb.
3.0 lb.
2.5 lb.


10 - 1.5-mm (60-mil) VLDPE Geomembrane Seam
Hot Wedge Seam
Load (lb.)
Time (h)
36 lb.
36 lb.
17.3 lb.
3.5 lb.
(20%)
3.4 lb.
3.3 lb.
3.4 lb.

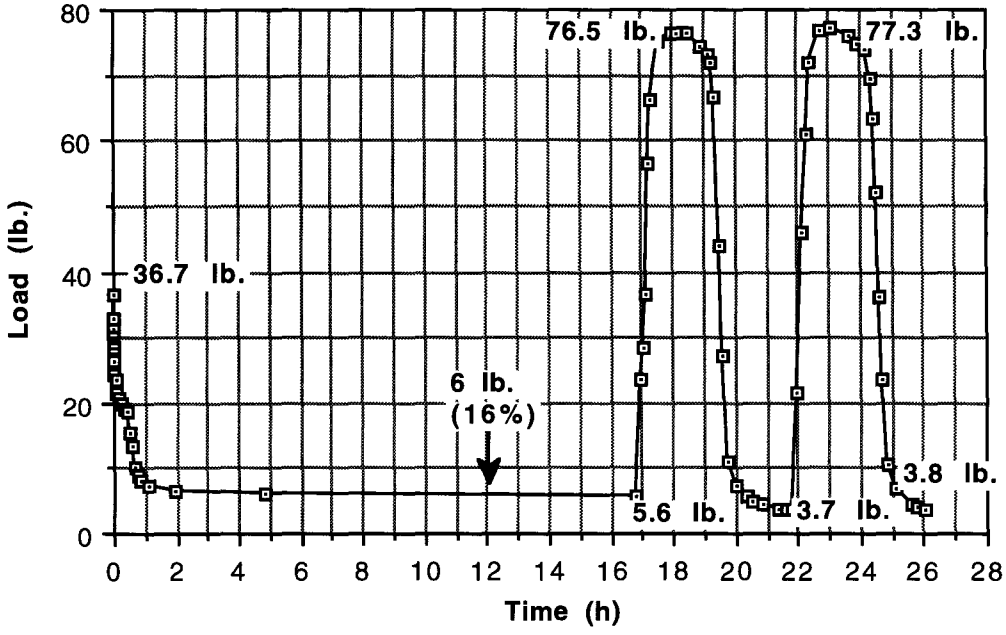

11 - 1.5-mm (60-mil) VLDPE Textured Geomembrane Sheet
Load (lb.)
Time (h)
37.8 lb
37.8 lb
17.6 lb
4.2 lb.
(24%)
4.2 lb
3.8 lb
3.4 lb
0
10
20
30
40
0
2
4
6
8
10
12
14
16
18
20
22
24
26


12 - 1.5-mm (60-mil) VLDPE Textured Geomembrane Seam
Hot wedge Seam
Load (lb.)
Time (h)
36.11 lb
35.4 lb
15.7 lb
3.3 lb.
(21%)
3.3 lb
2.6 lb
2.8 lb
0
10
20
30
40
0
2
4
6
8
10
12
14
16
18
20
22
24

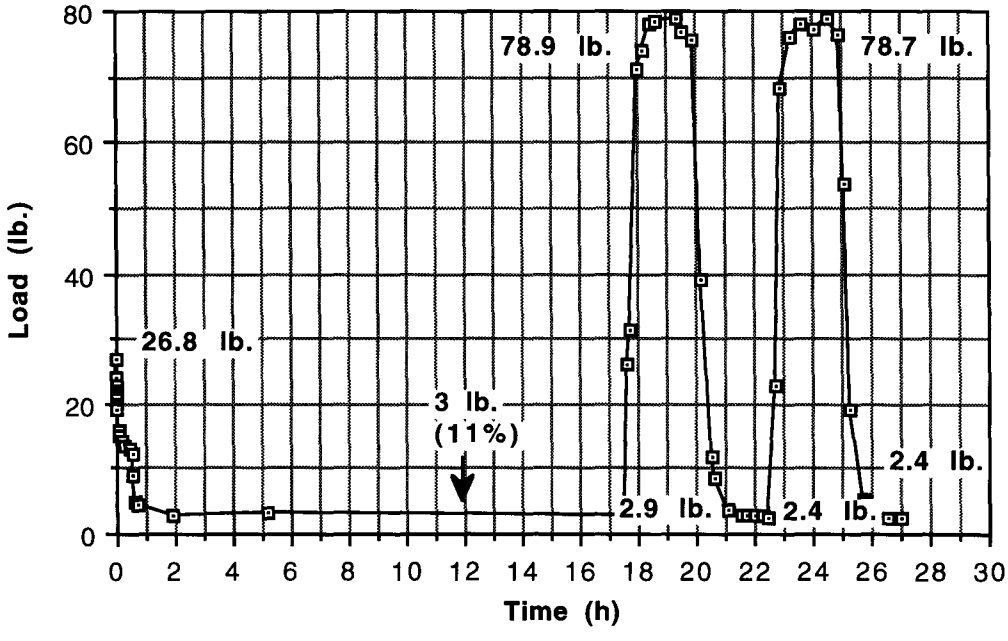

13 - 1.5-mm (60-mil) HDPE Geomembrane Sheet
Load (lb.)
Time (h)
73.6 lb.
74 lb.
24.1 lb.
4.0 lb.
(17%)
3.6 lb.
2.2 lb.
2.6 lb.

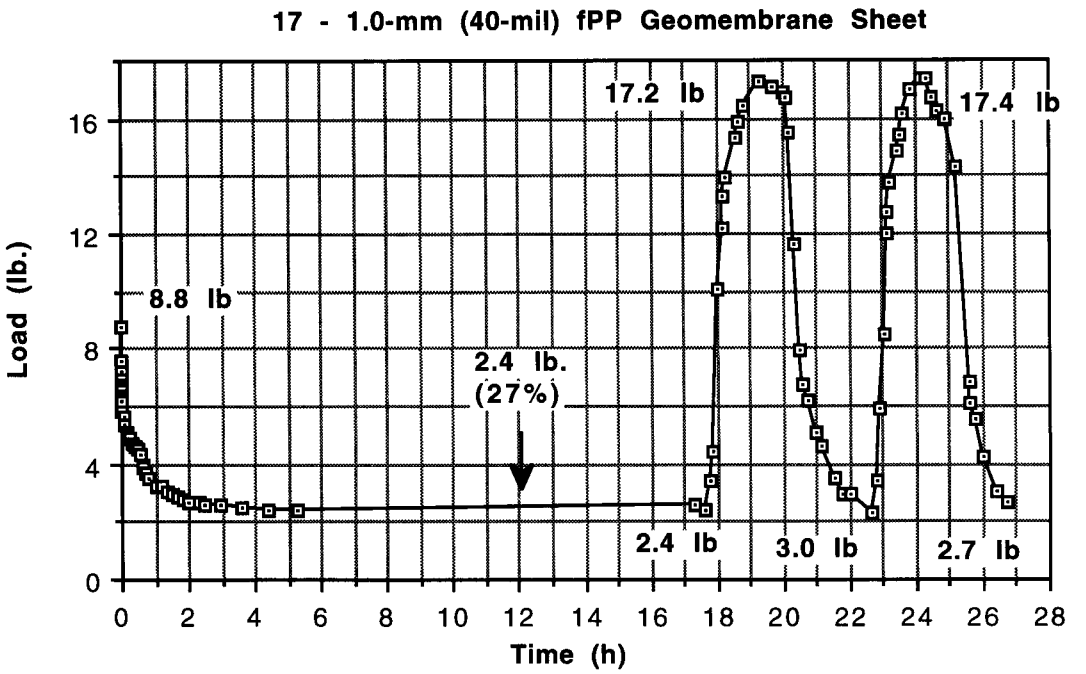

14 - 1.5-mm (60-mil) HDPE Geomembrane Seam
Hot Wedge Seam
Load (lb.)
Time (h)
77 lb.
76.4 lb.
26 lb.
4.5 lb.
(17%)
4 lb.
2.8 lb.
2.6 lb.

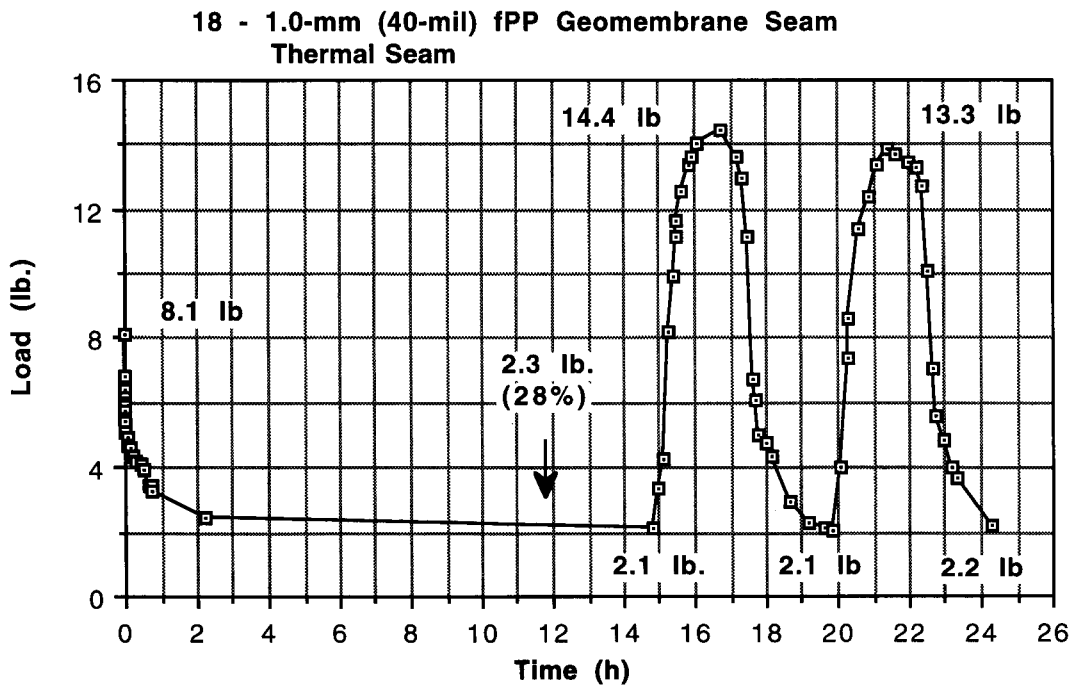
15 - 1.5-mm (60-mil) HDPE Textured Geomembrane Sheet



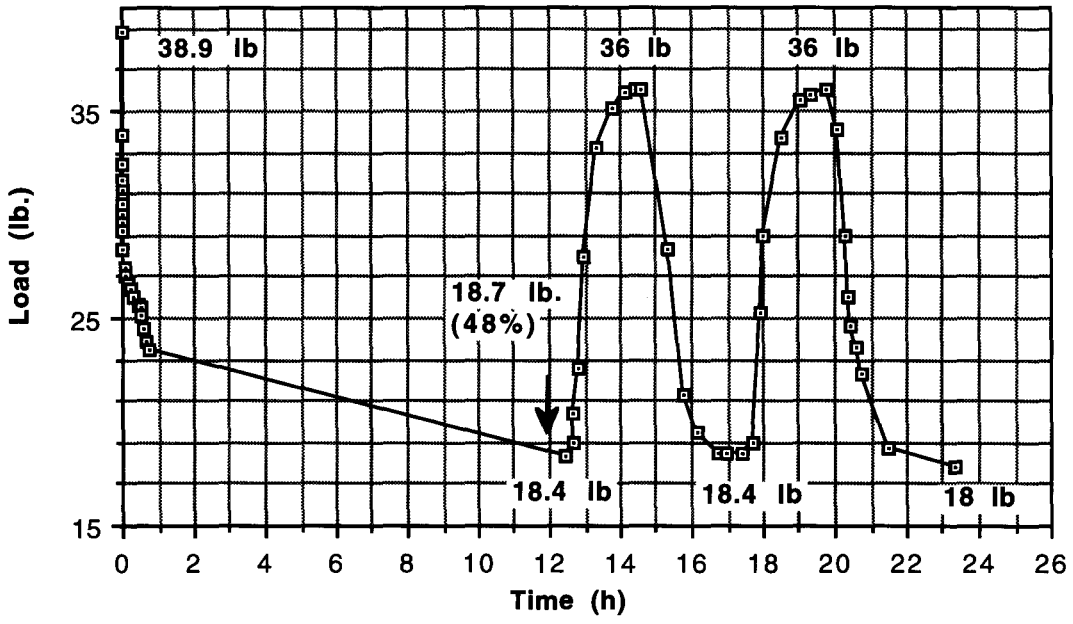
16 - 1.5-mm (60-mil) HDPE Textured Geomembrane Seam
Hot Wedge Seam



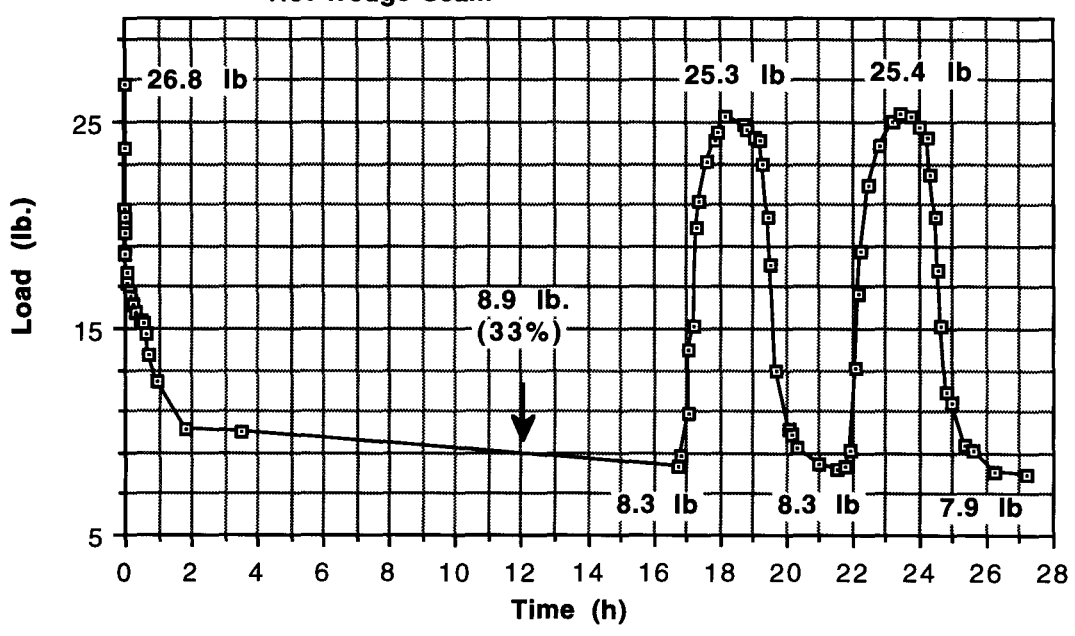

17 - 1.0-mm (40-mil) fPP Geomembrane Sheet
Load (lb.)
Time (h)
8.8 lb
2.4 lb.
(27%)
17.2 lb
17.4 lb
2.4 lb
3.0 lb
2.7 lb

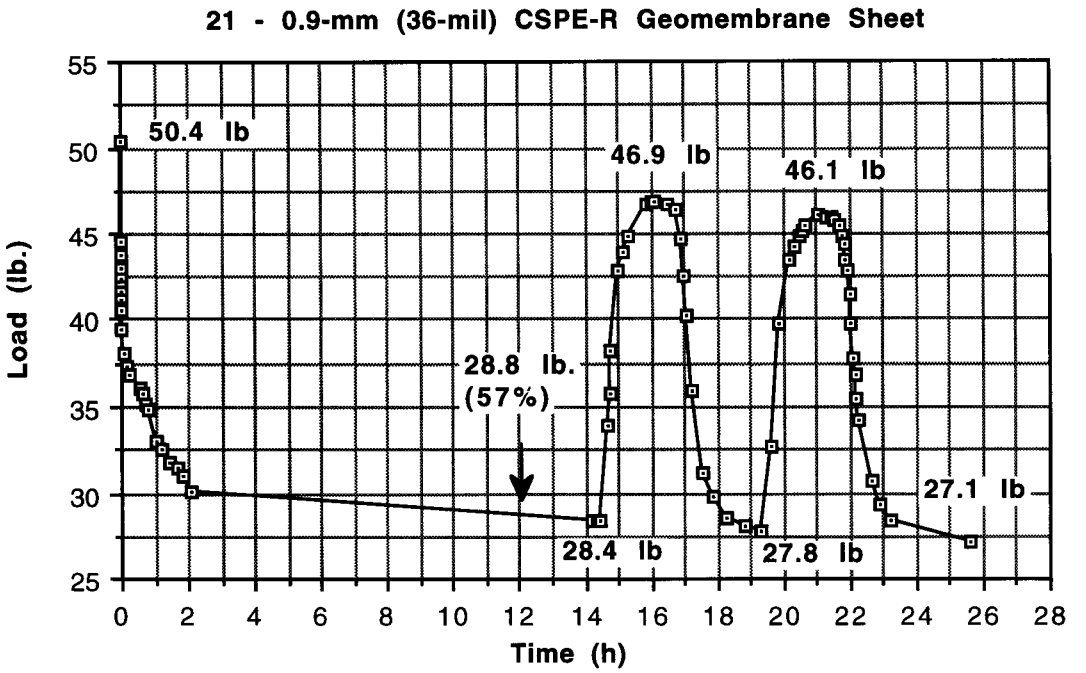

18 - 1.0-mm (40-mil) fPP Geomembrane Seam
Thermal Seam
Load (lb.)
Time (h)
8.1 lb
2.3 lb.
(28%)
14.4 lb
13.3 lb
2.1 lb.
2.1 lb
2.2 lb

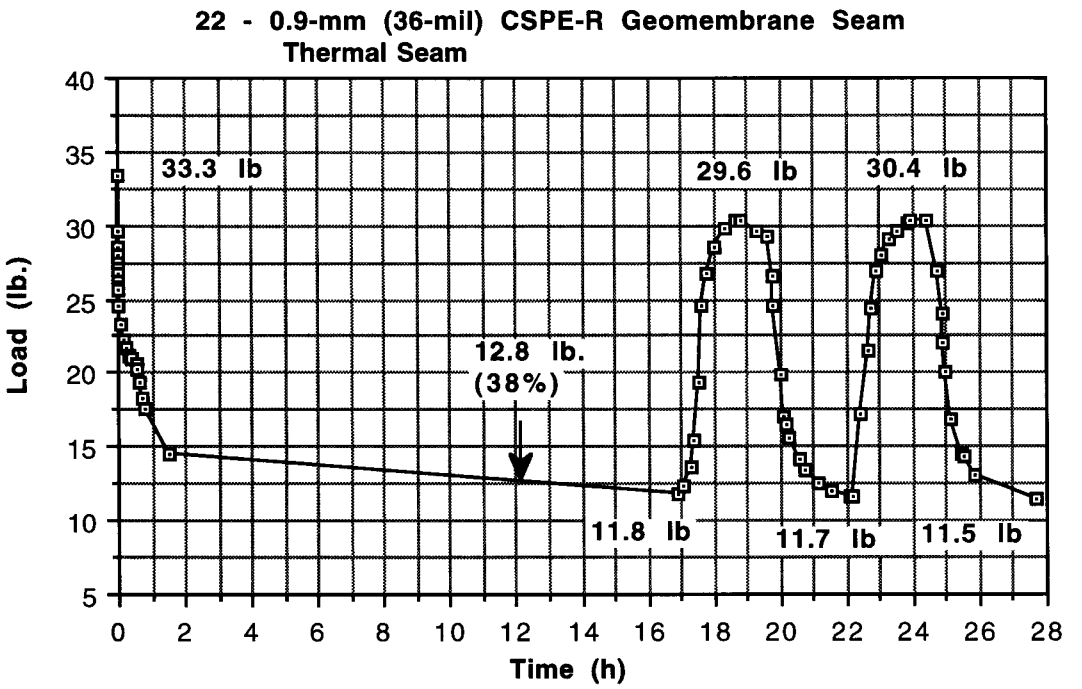
19 - 1.1-mm (45-mil) fPP-R Geomembrane Sheet



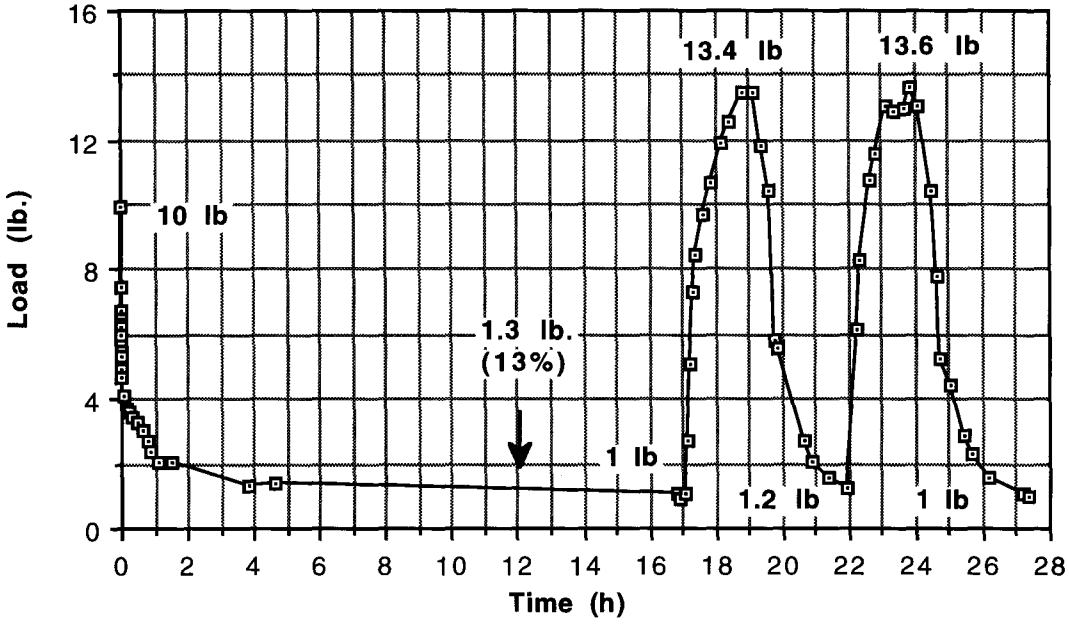
20 - 1.1-mm (45-mil) fPP-R Geomembrane Seam
Hot Wedge Seam



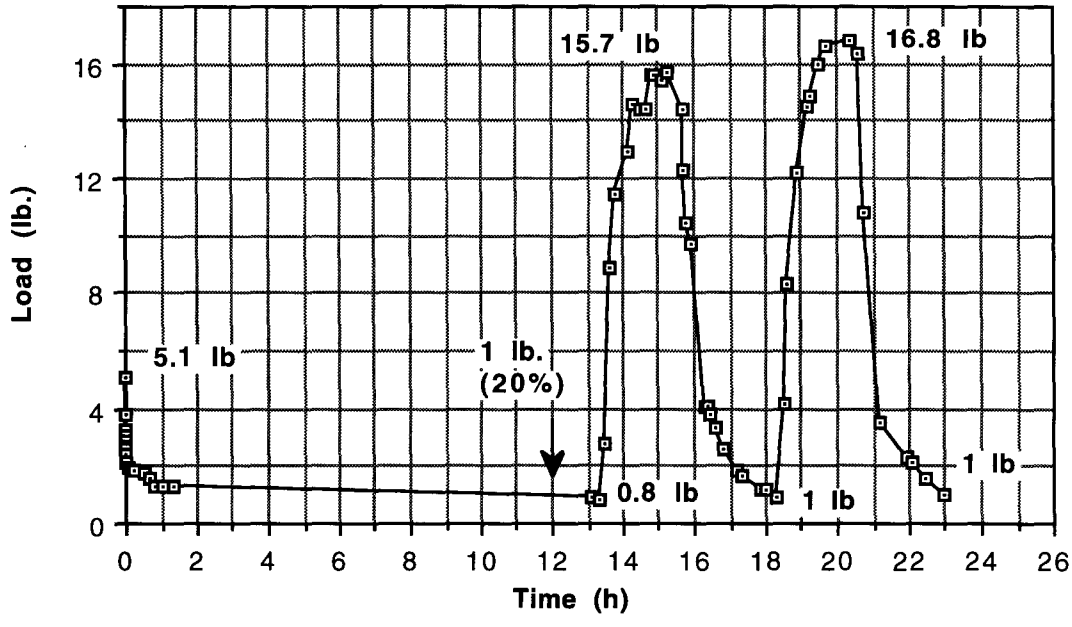

21 - 0.9-mm (36-mil) CSPE-R Geomembrane Sheet
Load (lb.)
Time (h)
50.4 lb
46.9 lb
46.1 lb
28.8 lb.
(57%)
28.4 lb
27.8 lb
27.1 lb


22 - 0.9-mm (36-mil) CSPE-R Geomembrane Seam
Thermal Seam
Load (lb.)
Time (h)
33.3 lb
29.6 lb
30.4 lb
12.8 lb.
(38%)
11.8 lb
11.7 lb
11.5 lb

23 - 0.8-mm (30-mil) EIA Geomembrane Sheet



24 - 0.8-mm (30-mil) EIA Geomembrane Seam
Chemical Seam



Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.