The Durability and Development of Optimum Seaming Parameters for an FCEA Geomembrane

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ABSTRACT

A new polymeric material proposed for geomembrane applications must be carefully evaluated. The material must have adequate chemical resistance to the liquids and leachates it is intended to contain. Likewise, it must have adequate mechanical durability, and be easily installed under a wide range of ambient conditions so that seam integrity can be assured at the time of installation and throughout the liner's service life.

Tuff-Ply is a fully cross-linked elastomeric alloy that has been proposed for, and used in, geomembrane applications. An international testing program is described that confirms the suitability of using this thermoplastic elastomer as a geomembrane.

INTRODUCTION

As the geomembrane market grows rapidly and as our technological understanding of existing geomembranes increases, the demand for new geomembrane materials also increases. New materials must provide advantages over conventional materials. They must be easier to handle in the field, they must be more durable, have significant improvements in some properties without displaying reductions in others, be easier to seam, suffer less installation damage, or simply provide the same performance at a significantly reduced installed cost.

High density polyethylene (HDPE) made such an impact on the geomembrane market several years ago because of its excellent chemical resistance, low cost, weathering resistance, and ability to be essentially homogeneously seamed among other properties. But, like all materials, it has undesirable properties, which, with time, have been identified. Not surprisingly, since technological advancements never cease, there is now a window of opportunity for new materials to meet the challenges that HDPE cannot. Such a material may be Tuff-Ply (TP), a fully cross-linked elastomeric alloy (ASTM D5046-90, "Standard Specification for Fully Cross-linked Elastomeric Alloys (FCEAs)") of polypropylene (PP) and ethylene propylene diene monomer (EPDM). However, before any claim can be made that a new material is a candidate for geomembrane applications, a significant amount of testing must be done. Such a program of testing is described.

In addition to the basic mechanical and physical property requirements that all construction materials must meet, there are three predominant characteristics required by geomembranes: they must be chemically resistant to the chemicals and leachates they will contain, they must have adequate mechanical durability, and their seaming characteristics must be known and understood.

This paper reviews the testing program performed to assess the performance of TP in these three critical areas, with most emphasis being placed on the development of optimum seaming parameters and the definition of seam specifications. The testing program was devised in light of 1991/1992 geomembrane technology and concerns expressed at that time about the performance of conventional geomembranes such as PVC, VLDPE, and HDPE.

The emphasis was placed on seams because they are frequently the weak link of field installation and long-term performance. In practical terms, it is therefore essential that seaming performance be understood in order to provide adequate guidelines to field seaming crews dealing with new materials for the first time, and thus to assure the integrity and durability of field seams; the latter is often completely ignored during installation.

SCOPE OF WORK

The testing program discussed in the paper covers the following items:

- A comparison of the stress cracking rates between a typical HDPE and TP.
- The chemical resistance of TP to a municipal solid waste leachate and to a pulp mill black liquor; the latter is an environment in which HDPE does not perform well.
- Seams fabricated by hot wedge and hot air equipment over a range of machine temperatures and speed settings and over a range of ambient temperatures (-9 to 40°C).

MATERIAL EVALUATION - DURABILITY

Stress Cracking Resistance. Since it has been determined that medium and high density polyethylenes (PE) are subject to stress cracking (SC), significant advances have been made in developing PE resins that have a high resistance to stress cracking. Stress cracking is a brittle fracture phenomenon that occurs at a constant applied stress below the yield stress. It occurs in many materials, even in some stainless steels. Since it can be accelerated, for instance by chemical environments (environmental stress cracking), overheated seams, notch geometries (seams and scratches), and high service stresses (low temperature contraction), it will remain one of the less desirable properties of HDPE. New materials will have to be assessed for stress cracking resistance (SCR) in comparison to HDPE, since SC is the Achilles heel of HDPE and since most engineers use HDPE performance as the reference against which new materials are judged. Shortly there will be a method to relate laboratory stress cracking characteristics to mechanical durability in the field (Kanninen et al).

In this project, the stress crack growth rate of TP was compared to that of a frequently used HDPE with higher than average SCR. The work was performed at GeoSyntec Consultants' Materials Testing Laboratory according to the basic procedure of GRI standard GM5.

Dogbone specimens of 1.5 mm TP and PE were notched and placed in water at 50°C at a constant load providing an initial stress equivalent to 25% of each material's room temperature yield stress (TP at 11.5 MPa, PE at 17.7 MPa). Igepal, normally used to accelerate the stress cracking process in PE, would not necessarily accelerate the process in TP. It was, therefore, decided to expose both materials in water. Since the SC process would not be accelerated, except by temperature, times to failure would be long. Crack growth rates were, therefore, monitored by removing specimens from the test rig after various exposure times, preparing thin slice microsections, and measuring the extension of the notch initially placed in the specimen. The crack growth rates are summarized in Table 1 which shows that after 736 hours there was no crack growth in TP. In fact, the notch in TP was clearly blunted. TP is clearly not susceptible to stress cracking in its as-manufactured state.

Table 1. Results of Notched Constant Tensile Load Testing in Water
GRI Standard GM-5

HDPE @ 25% Yield Strength Time (hr)	 Craze Length (μm)	TUFF-PLY @ 25% Yield Strength Time (hr)	 Craze Length (μm)
4	37	5	0
12	52	26	0
98	58	121	0
548	58	170	0
750	64	406	0
835	65	736	0

While geomembranes such as PVC and VLDPE may become susceptible to stress cracking as they age (by loss of additives or oxidation), it is expected that the elastomeric component of TP and its non-phthalate, non-volatile additive content will minimize the aging-induced initiation of SC.

It is encouraging to note that TP is not susceptible to stress cracking; it does not, therefore, require measurement of seam elongation in the shear test and seam separation in the peel test as does HDPE.

Chemical Resistance. The polymer from which TP is extruded consists of cross-linked EPDM suspended in a PP matrix during a dynamic vulcanization process. The two polymer systems interact synergistically, giving rise to properties and performance above and beyond what would rationally be expected from a physical blend of the systems. For many years this polymer had been used in high temperature applications for gaskets and seals in automobiles. It has also been used on a regional basis in the United States as an extruded membrane in roofing applications.

Some of the same characteristics that made it an ideal product for high temperature and for roofing applications naturally make it a logical candidate for geomembrane applications. It became necessary to demonstrate that TP was compatible with municipal solid waste leachate (MSW) before any designer would even consider it as a candidate geomembrane for waste containment.

In an independent EPA Method 9090 laboratory study (conducted by GeoSyntec Consultants), TP was immersed for 120 days at 23°C and 50°C in a MSW leachate that had some aggressive organic traces. The results showed that increases in mass were generally less than 1.5%, indicating that the TP geomembrane did not significantly absorb constituents from the leachate. According to the laboratory, lower variability in mechanical property values of the TP was observed than were typically measured in other families of geomembranes immersed in leachate of a similar composition.

These initial data suggest that TP may be a viable alternative to HDPE as a material for spent sulfite (low pH) and black liquor (high pH) pond liners (in the pulp and paper industry), since it appears not to suffer from stress cracking, and has been shown to be chemically resistant to the liquors, even at their elevated operating and inlet temperatures. For example, in a two-year test in spent sulfite liquor (pH 1.3-2.4), TP showed little interaction and retained over 92% of its original mechanical property values, as shown in Table 2 (Akzo).

In a parallel immersion test (Akzo) at an elevated temperature of 70°C, TP showed no significant degradation of mechanical properties over 90 days (Table 3). A three-week test during which TP, VLDPE, HDPE, XR-5, and Hypalon were exposed to black liquor at 70°C (Peggs et al), then examined by structural and thermal analytical methods, showed TP to offer excellent resistance to the high pH, high temperature black liquor.

In a 60-day immersion test in NaOH at 100°C, TP showed no appreciable change in physical or mechanical properties (Table 4).

Table 2. Resistance of Tuff-Ply to Spent Sulfite Liquors (pH 1.3-2.4) at 23° for 24 months

Property	Procedure	1 Month	6 Months	12 Months	24 Months
Hardness, Shore D (Units Change)	ASTM D2240	-1	-1	-2	-2
Ultimate Tensile Strength (% Retention)	ASTM D412	102	103	101	92
Ultimate Elongation (% Retention)	ASTM D412	99	103	101	93
Modulus @100% Strain (% Retention)	ASTM D412	98	99	99	98
Volume Swell (%)	ASTM D471	1.09	3.6	5.5	7.7

Table 3. Resistance of Tuff-Ply to Spent Sulfite Liquors (pH 1.3-2.4) at 70°C for 90 days

Property	Procedure	6 Days	24 Days	90 Days
Hardness, Shore D (Units Change)	ASTM D2240	-1	-1	-2
Ultimate Tensile Strength (% Retention)	ASTM D412	102	102	99
Ultimate Elongation (% Retention)	ASTM D412	97	100	99
Modulus @100% Strain (% Retention)	ASTM D412	99	100	97
Volume Swell (%)	ASTM D471	2.8	3.4	5.3

Table 4. Resistance of Tuff-Ply to -50% NaOH at 100°C for 1440 hours

Property	Procedure	168 Hours	360 Hours	720 Hours	1440 Hours
Hardness, Shore D (Units Change)	ASTM D2240	-2	-2	-4	-5
Ultimate Tensile Strength (% Retention)	ASTM D412	106	102	102	111
Ultimate Elongation (% Retention)	ASTM D412	98	96	93	100
Modulus @100% Strain (% Retention)	ASTM D412	101	101	105	100
Weight Change (%)	ASTM D471	0.02	0.20	0.45	2.10

SEAMING

Uniaxial Tensile Properties. Since seam acceptance criteria are generally related to the uniaxial yield stress of the material, it is necessary to establish the index uniaxial tensile properties of the material. Typical uniaxial stress/strain curves for TP and HDPE are shown in Figure 1.

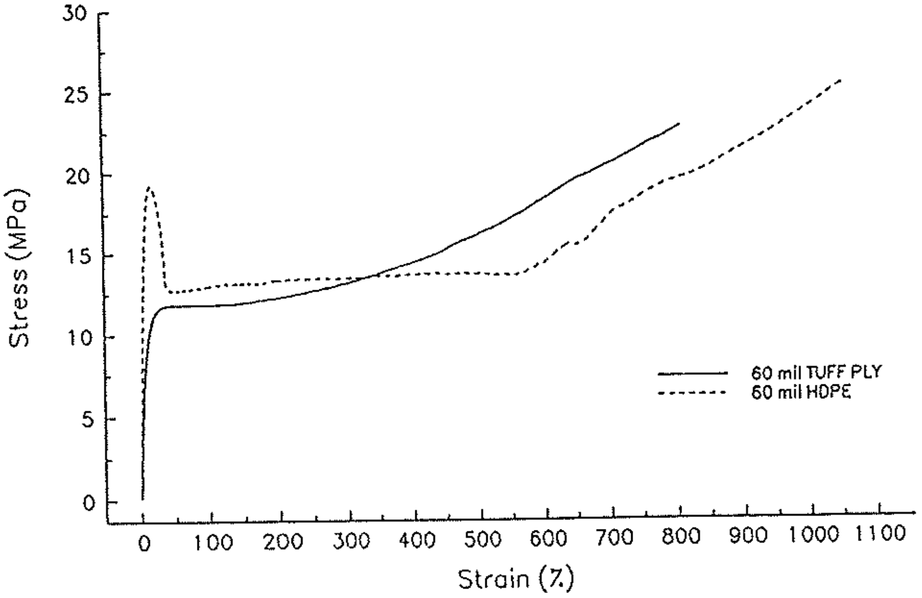

Figure 1. Uniaxial Stress-Strain Curves of Tuff-Ply and HDPE geomembranes.

The yield and break parameters (stress, elongation) are 11.8 MPa and 34%, and 23.1 MPa and 810%, respectively. The yield point of HDPE occurs at a higher stress (17.7 MPa), but at a lower elongation (13%). This pronounced yield point is a point of instability and is a restrictive feature for designers to accommodate. The higher the strain at which the yield point occurs, and the smoother the curve (provided it does not become horizontal), the better. TP's other mechanical properties are in line with those required for geomembranes in National Sanitation Foundation International Standard 54.

It is evident that TP, with its identifiable yield point that provides a basic material reference point, has satisfactory uniaxial tensile mechanical properties for use as a geomembrane.

Hot Air Seaming. Hot air seaming methods are not often used. Hot air seaming is probably felt not to be as controllable as the similar hot wedge technique due to the perceived difficulty of maintaining a constant geomembrane heating/cooling profile in windy conditions. It is also somewhat slower than hot wedge techniques for seaming HDPE. However, one of its advantages may be that the temperature profile of the heat-affected zone in the parent geomembrane (at the edge of the melted and solidified material) is less sharp than in hot wedge seams, and, therefore, capable of providing an "easier" transition of service stresses from geomembrane to seam. FCEA materials similar to TP have a long history of successful hot air seaming, so it was felt appropriate to take advantage of this proven technology in this study.

In order to be able to seam at sub-zero temperatures, the seam fabrication program was performed by Matériaux Techniques Côté in Montreal, Canada. A Leister X-10 machine was used to make the seams. The hot air temperature was measured by placing the thermocouple supplied by the manufacturer through the slots at the nozzle exit back into the supplied air stream (Figure 2). The speed of the machine was determined on each sample by measuring the distance traveled in a known time. When temperatures were reset, the hot air was allowed to reach an equilibrium temperature before seaming was initiated. At specific machine temperatures, the speed was adjusted to different settings, approximately each meter of seam. The peel and shear specimens were always cut from the last 65 cm of each 1 m test length. In both cases, double track seams were made over a range of machine temperature settings from 200 to 500°C and speed settings from 0.5 to 2.5 m/min. Seaming was performed in the plant at a temperature of 20°C and outside at -9°C.

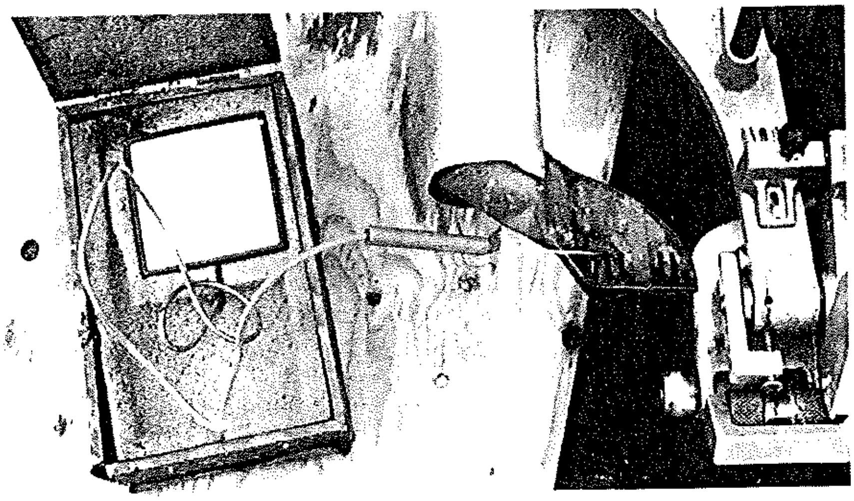

Figure 2. Measuring hot air temperature.

When seaming at the low temperature it was snowing and windy, the wind blowing directly into the gap between the two sheets being joined. Unsuccessful attempts were made to clean the snow from the areas to be joined. Subsequently, the hot air was allowed to melt the snow and blow the water away from the surfaces to be seamed.

All samples were peel-tested on an instrumented field tensiometer at a cross head displacement rate of 50 mm/min. Only the inside track of the double track seam was tested. A number of specimens were also tested on a calibrated tensile machine in a temperature and humidity-controlled, independent testing laboratory (GeoSyntec Consultants MTL). Seam samples made in U.S. were sent to Belgium for confirmatory testing.

A few seamed and tested specimens were cut on a microtome to produce thin-slice microsections for viewing by light transmission microscopy, in order to assess the homogeneity and quality of the seam and to define the characteristics of peel test breaks.

It appeared, quite early in the testing program, that the seams were either good or bad: there appeared to be very little grey area in which their quality was uncertain. Peel strength would be very low or very high: optimally within 90% of the measured yield strength. At high peel strengths, there were two characteristic breaks: break would occur at an angle of approximately 45° (Figure 3) from the root of the squeeze-out bead through the geomembrane, or the seam would appear to peel completely (Figure 4). However, this latter figure and a microsection (Figure 5) do show that separation does not occur along the joined interface but, in fact, occurs along the edge of the heat-affected zone (HAZ) in the parent geomembrane. Break is, therefore, occurring in solid material, hence the high strength. The results of testing are summarized in Figure 6.

Figures 6 b, d, f, and h show that at any hot air temperature, between 200°C and 500°C, there is an optimum speed range over which there is a minimum "apparent peel separation". (We will use the term "apparent" since the seam interface itself is not separating). At higher and lower speeds, the peel strength is still high but the apparent peel separation increases to 100%. Only at very low speeds would the peel tension fall sharply to zero. Although it is clear that there will be a high speed at which a weld will not be effected, it is higher than the maximum speed of 2.5 m/min. used in this study. At a constant seaming machine speed, there is also an optimum temperature range that produces a sweet spot seam with minimum apparent peel separation (Figure 6).

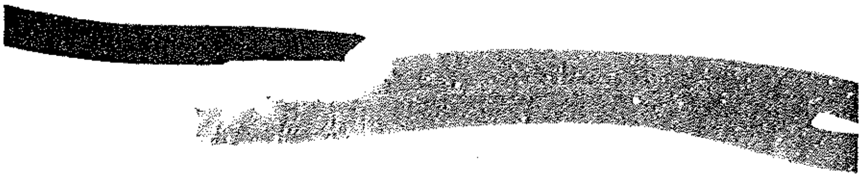

Figure 3. Peel test break at 45° at edge of seam. (x3.5)

Figure 4. Peel test apparent separation. Top part is thinner than lower part. (x3.5)

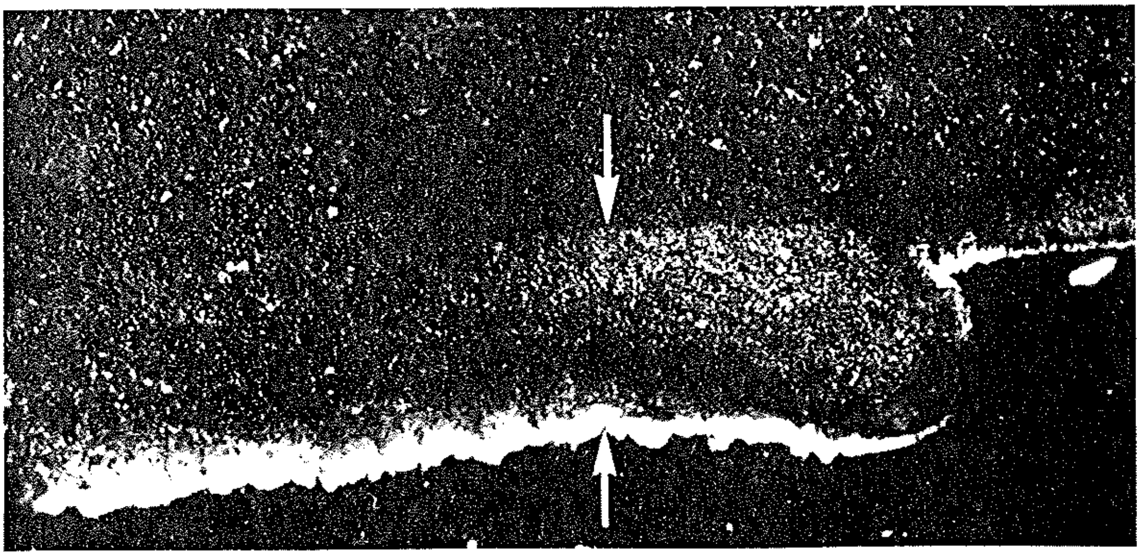

Figure 5. Apparent separation along edge of HAZ. Weld zone is between arrows. (x65 polarized)

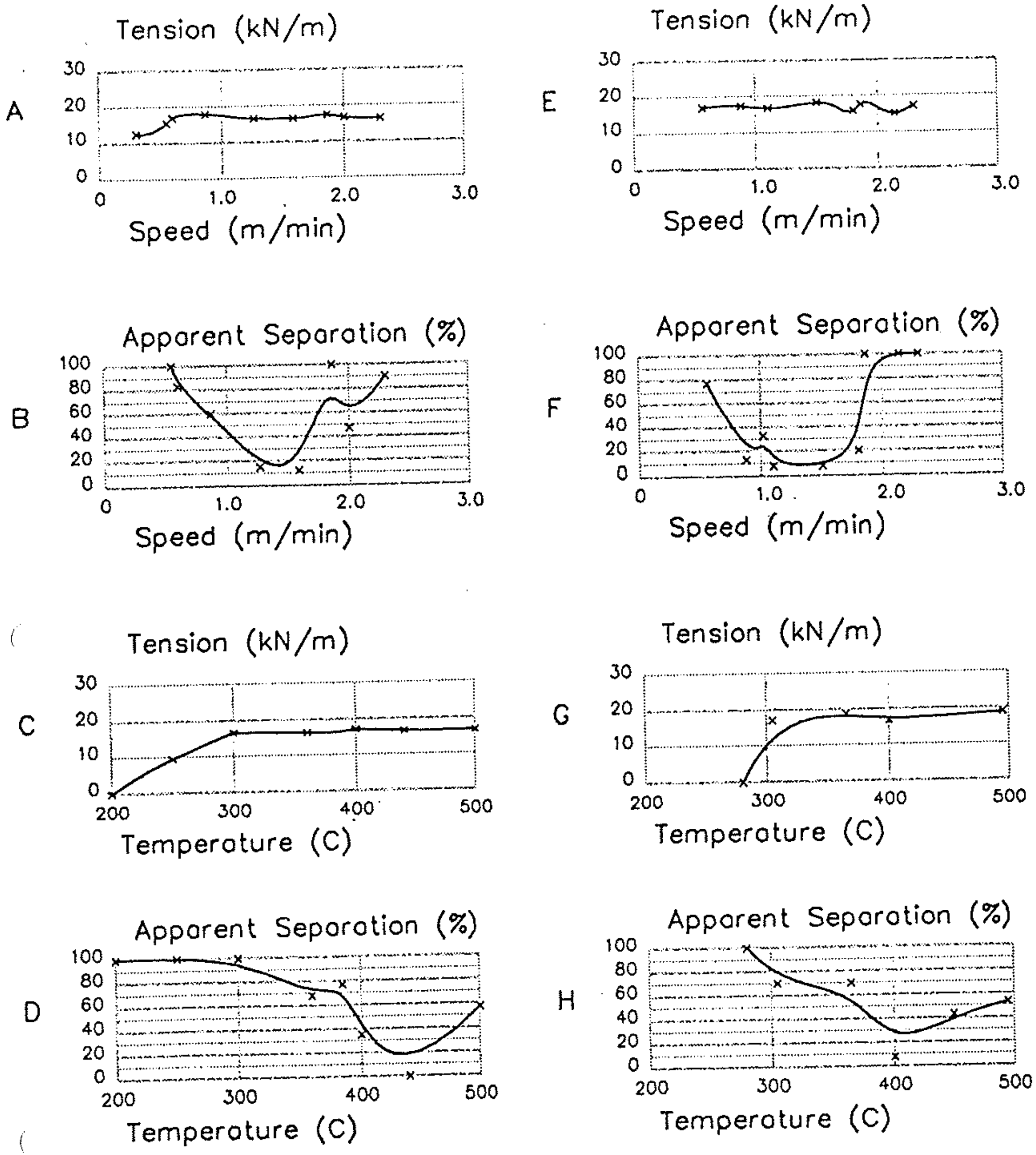

Figure 6. Seam Peel Tensions and Apparent Peel Separations at:

a,b) 410°C hot air, 20°C ambient
c,d) 1.56 m/min machine speed, 20°C ambient
e,f) 405°C hot air, -9°C ambient
g,h) 1.1 m/min machine speed, -9°C ambient

The minimum in curves b, d, f, and h is the sweet spot, or optimum seaming condition.

From Figure 6, it can be seen that there is very little difference between the tests performed at ambient temperatures of 20°C and -9°C, except that the optimum machine speeds are approximately 1.5 m/min. and 1.3 m/min., respectively. This would be expected since, at lower ambient temperatures, the machine speed would need to be a little slower in order to provide the required thermal energy input for effective seaming.

From the test results, appropriate conditions for producing good seams (that still provide room for error) in 1.5 mm thick TP geomembrane over a geomembrane temperature range from -10°C to 20°C are summarized in Table 5.

Table 5. Hot Air Seaming Parameters for 1.5 mm Tuff-Ply

LINER TEMP (°C)	HOT AIR TEMP (°C)	SPEED (m/min)
20	400	0.8 to 2.5
20	300 - 500	1.6
-9	400	0.5 to 2.5
-9	350 - 500	1.1

With additional testing it should be possible to generate, from a statistically treated set of data, a family of curves that relate optimum temperature and speed ranges. For thicknesses of 1.5 mm and above, these ranges will probably be approximately 1.5 to 2.0 m/min. and 400 to 450°C.

Apparent Peel Separation. When apparent peel separation occurs, it is clear from the full microsection, Figure 4, that separation does not occur along the original interface of the two geomembranes, but instead occurs along the edge of the heat affected zone (HAZ). The edge of the HAZ is not necessarily the edge of the molten pool, but is the boundary to which the parent geomembrane microstructure is modified by the input of thermal energy during seaming. One part of the separated seam is significantly thicker than the other. Separation along the edge of the HAZ is more clearly shown at higher magnification in Figure 5.

The microsections examined in this project revealed that the only apparent difference between those specimens that break in the geomembrane at the edge of the seam and those that apparently peel, is the sharpness of the boundary of the heat-affected zone. The specimens that fail at the edge of the seam have an almost undefinable transition (Figure 7), while those that appear to peel have a relatively distinct transition between the weld and the parent geomembrane (Figure 8).

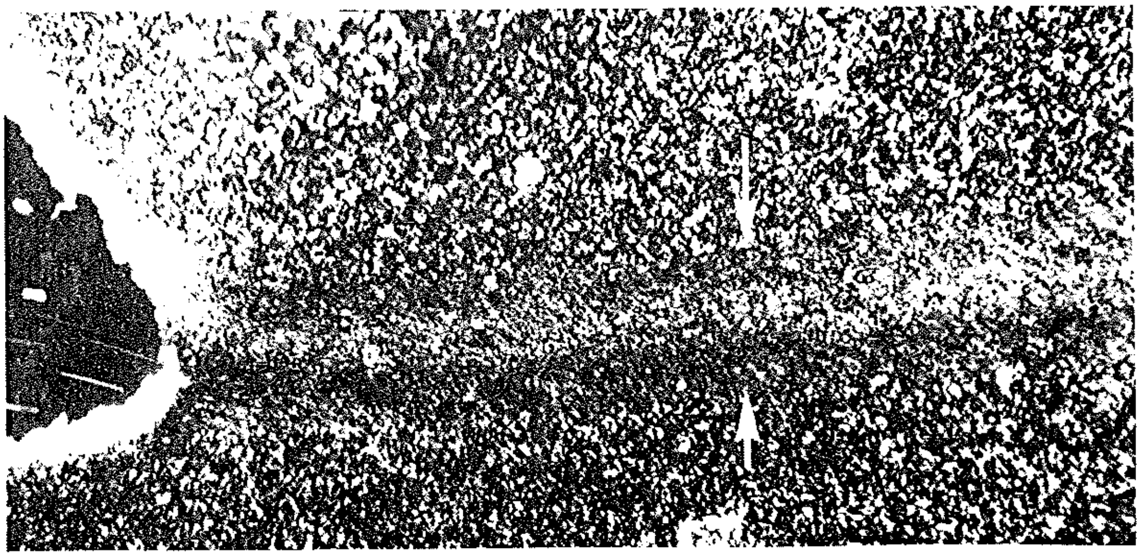

Figure 7. HAZ (arrowed) blends in to parent geomembrane. (x65 polarized)

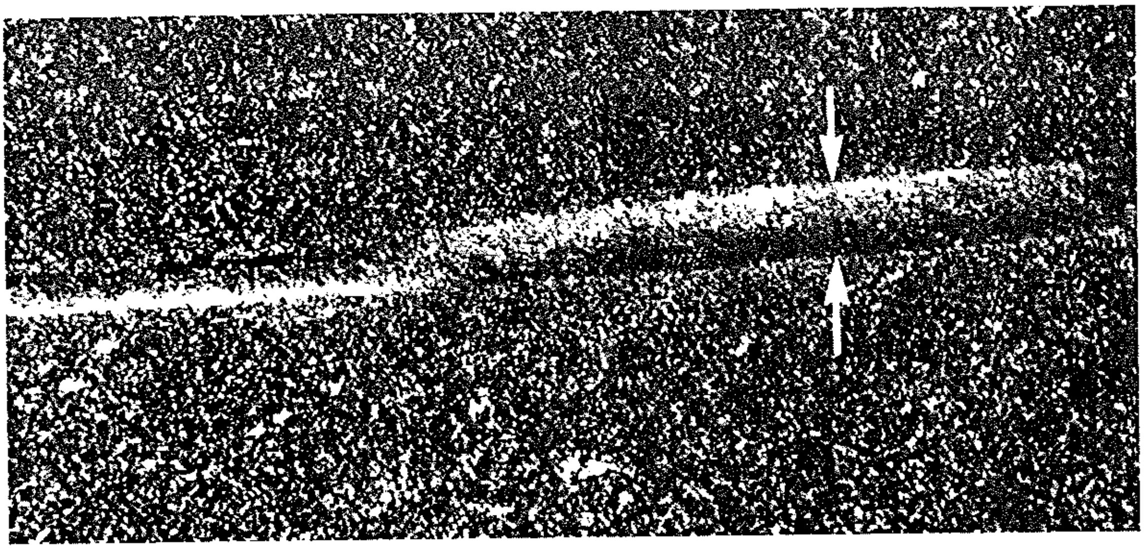

Figure 8. HAZ (arrowed) has distinct edges. (x65 polarized)

In comparison, the specimens that clearly separate in the conventional peeling mode along the original interface between the two geomembranes show a distinct interface line, clearly a lack of bonding across the interface. Seams that are extremely badly made contain very apparent defects (Figure 9).

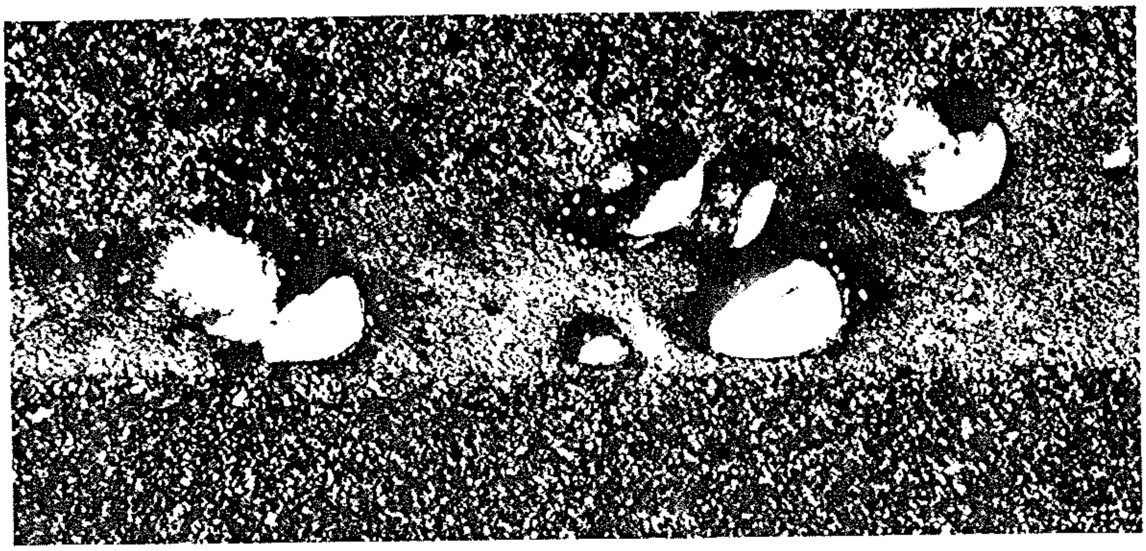

Figure 9. Voids in weld zone (across middle of photograph). (x65 partial polarization)

Hot Air Welding with a Hand Tool. Seam shear test data generated by GeoSyntec Consultants on seams in 0.75 mm, 1.0 mm, and 1.5 mm thick geomembrane made using a Leister Triac hand held hot air tool set at 600°C are shown in Table 6. The normal pressure was applied by a nylon roller. In all cases, the residual peel strengths were very high, exceeding 90%.

At patches, appurtenances, and wherever detailed seaming is required, hot air seaming using a hand-held tool could, apparently, produce seams of the same quality as the long-run seams.

Hot Wedge Seaming. Dual track hot wedge seams were constructed on 1.5 mm TP both in the USA and in Belgium at the University of Liege. A Pfaff type 8365/002 computerized hot wedge seaming machine was used in Belgium to run three series of seaming experiments.

Table 6. Hot Wedge Seam Test Results

Sample No.	No. Spcms	Thick. (mm)	Ambient Temp(°C)	Wedge Temp(°C)	Machine Speed(m/min)	Shear (kN/m)	Peel (kN/m)	Residual Yld Strength (%)		Sheet Yld Tension (kN/m)	Equip Mfg.	Welded/ Tested
								Shear	Peel			
1	13	1.0	20	260	3.7	12.43	10.51	103	87	12.08	Columbine	USA/USA
2	4	1.0	20	260	4.0	---	11.21	--	93	12.08	Columbine	USA/USA
3	8	1.0	19	260	3.0	---	11.38	--	94	12.08	Columbine	USA/USA
4	8	1.0	19	260	3.7	---	11.21	--	93	12.08	Columbine	USA/USA
5	8	1.0	19	260	4.0	---	10.51	--	87	12.08	Columbine	USA/USA
6	8	1.0	19	260	4.6	16.25	11.03	135	91	12.08	Columbine	USA/USA
7	4	1.0	19	260	3.7	13.13	11.25	105	90	12.50	Columbine	USA/USA
8	4	1.0	23	260	2.8	12.96	10.36	96	76	13.50	Pfaff	Bel/Bel
9	4	1.0	23	260	1.9	15.80	9.59	117	71	13.50	Pfaff	Bel/Bel
10	4	1.0	23	360	3.0	Material	Melted	--	--	13.50	Pfaff	Bel/Bel
11	4	1.0	23	183	1.9	18.43	13.30	97	70	19.00	Pfaff	Bel/Bel
12	4	1.5	20	300	3.7	20.88	14.58	106	74	19.7	Columbine	USA/Bel
13	4	1.5	20	260	3.7	19.70	13.40	100	68	19.7	Columbine	USA/Bel
14	4	1.5	20	300	4.6	20.88	13.59	106	69	19.7	Columbine	USA/Bel
15	4	1.5	23	300	1.5	19.95	13.68	105	72	19.0	Pfaff	Bel/Bel
16	4	1.5	23	260	1.5	20.33	14.06	107	74	19.0	Pfaff	Bel/Bel
17	4	1.5	23	260	2.5	19.38	14.63	102	77	19.0	Pfaff	Bel/Bel
18	4	1.5	23	292	2.4	22.61	14.75	119	75	19.0	Pfaff	Bel/Bel
19	4	1.5	23	200	2.3	19.00	14.82	100	78	19.0	Pfaff	Bel/Bel
20	4	1.5	23	200	1.5	22.99	14.25	125	75	19.0	Pfaff	Bel/Bel
21	4	1.5	-10	300	1.5	17.88	13.63	101	77	17.7	Pfaff	Bel/Bel
22	4	1.5	-10	260	1.5	17.88	14.16	101	80	17.7	Pfaff	Bel/Bel
23	4	1.5	-10	200	1.5	18.76	14.16	106	80	17.7	Pfaff	Bel/Bel
24	4	1.5	-10	200	2.5	18.76	12.21	106	69	17.7	Pfaff	Bel/Bel
25	4	1.5	23*	200	2.5	19.29	13.63	109	77	17.7	Pfaff	Bel/Bel
26	4	1.5	40	300	1.5	19.82	12.39	112	70	17.7	Pfaff	Bel/Bel
27	4	1.5	40	260	1.5	18.41	13.10	104	74	17.7	Pfaff	Bel/Bel
28	4	1.5	40	200	1.5	19.12	13.98	108	79	17.7	Pfaff	Bel/Bel
29	4	1.5	40	200	2.5	18.76	13.10	106	74	17.7	Pfaff	Bel/Bel
30	10	1.5	20	300	4.6	18.48	11.38	104	64	17.78	Columbine	USA/USA
31	10	1.5	20	260	3.7	17.58	10.31	99	58	17.78	Columbine	USA/USA
32	10	1.5	20	300	3.7	18.55	13.15	104	74	17.78	Columbine	USA/USA
33	10	1.5	20	365	1.5	---	15.24	--	90	16.87	Resicon	USA/USA
34	10	1.5	20	365	1.5	---	15.57	--	86	18.18	Resicon	USA/USA

*Sheet cooled at -10°C; seamed at +23°C with condensate from the air.

In the first series of tests, the seaming was done at room temperature (23 ± 2°C) with seaming speeds varied between 1.5 and 2.5 m/min. and hot wedge temperatures ranging from 200°C to 300°C.

The second series was executed on TP samples that had been previously conditioned at -10°C for three hours in a cold chamber. The seaming was done in the cold chamber at the same speeds and hot wedge temperatures as used in the first run. The third series was made in another chamber set a +40°C with the same parameters as the second series.

A seam was also constructed on 1 mm TP at 23°C with the wedge temperature varied between 183°C and 300°C and speeds adjusted to 1.9, 2.8, and 3.0 m/min.

Specimens for peel and shear testing were then cut from the last-seamed sections of the 1 m long double track test seams and tested according to ASTM D4545. Samples cut from test seams made at an ambient temperature of 23°C with a hot wedge temperature of 300°C and seaming speeds of 1.3 and 2.5 m/min were sent to the USA for cross-examination.

The results of all peel and shear testing conducted on dual track hot wedge welded seams are shown in Table 7, including the data from the seams effected in the USA. In order to account for any differences in tensile yield strength, the authors felt it important to also identify the peel strength as a residual percentage of the parent geomembrane tensile yield strength.

Table 7. Hot Air (Hand Gun) Seam Test Results

	SAMPLE/THICKNESS (mm)		
PARAMETERS	1.5	1.0	0.75
Ambient Temperature (°C)	20	20	20
Nozzle Temperature (°C)	600	600	600
Shear (kN/m)	16.08	12.47	9.74
Peel (kN/m)	18.09	12.00	9.53
Residual Shear Strength (%)	106	103	105
Residual Peel Strength (%)	90	99	102
Sheet Yield Strength (kN/m)	17.08	12.08	9.30

The hot-wedge seams made in the U.S.A. (except for samples 34 and 35) were constructed with Columbine International's Wedge-It, an automated hot wedge welder. All the peel and shear tests done in Belgium were conducted in a controlled atmosphere laboratory, whereas in the USA they were done on a portable field tensiometer at a strain rate of 50 mm/min. Samples 34 and 35 were done at an independent laboratory.

The seams constructed on the 1 mm geomembrane, consistently showed residual peel strengths between 87% and 94% at a constant wedge temperature of 260°C at speeds between 3.0 and 4.6 m/min. at room temperatures.

The seaming of the 1.5 mm TP identified some interesting trends. For example, at an ambient temperature of -10°C and seaming speed of 1.5 m/min., the peel strength values varied only slightly with wedge temperatures of 200, 260, and 300°C. The residual peel strengths of these three test seams were 80% at 200 and 260°C and 77% at the 300°C wedge temperatures.

Similarly, the seams produced at 23°C and wedge temperatures ranging from 200 to 292°C and seaming speeds between 1.5 and 2.5 m/min. consistently showed residual peel strengths greater than 75%. Thus, ambient temperature fluctuations that might be experienced during a working day in a high desert climate, may not necessitate the adjustment of the equipment settings for satisfactorily welding TP.

The tests conducted on material welded at an ambient temperature of 40°C (which is quite common in the southwestern part of the United States), provide very comparable data to those obtained at 23°C over a similar range of wedge temperatures and speeds.

Test seams 34 and 35 were made on material welded at an ambient temperature of

20°C by professional installers at a machine speed setting of 1.5 m/min. and a wedge temperature of 365°C. The material was seamed in both the roll and cross roll directions and showed excellent consistency in the peel strength values. The residual peel strength was 90% in the roll direction and 86% in the cross roll direction.

Although most of the results from the 23°C tests indicated satisfactory seams, the higher peel strength values obtained from samples 34 and 35 seem to indicate that the wedge temperature has not yet been optimized at a seaming speed of 1.5 m/min.

It should be noted that in all cases (except three) the seam shear values were equal to, or greater than, the yield strength of the parent geomembrane. Although a compilation was not made during the testing program, it qualitatively appeared that there were many more "apparent" separations during peel testing of hot wedge seams than there were in hot air seams.

Comparative Seam Tests. Table 8 summarizes the data generated when the uniaxial tensile yield properties and the seam peel and shear properties of TP geomembrane were measured on the different pieces of test equipment.

Table 8. Interlaboratory Test Results

SPECIMEN	TEST LOCATION/DETAILS	Yield Tension (kN/m)	Yield Elong. (%)
1.5 mm TP gmb	Montreal, Tensiometer, Strip	21.7	--
1.5 mm TP gmb	Belgium, Laboratory	17.7	20.4
1.5 mm TP gmb	GeoSyntec, Laboratory	17.6	24.6
1.5 mm TP gmb	Akzo, Laboratory	16.1	30.0
1.5 mm TP gmb	Brochure specification	17.5	31.0
		Average Peel Tension (kN/m)	
Montreal Seam	Montreal, Tensiometer	15.1	
Montreal Seam	GeoSyntec, Laboratory	14.9	
Belgian Seam	Belgium, Laboratory	13.8	
Belgian Seam	GeoSyntec, Laboratory	14.4	
Belgian Seam	Akzo, Laboratory	14.4	

The data in Table 8 show that when the geomembrane tensile properties are measured using the same (dogbone) type of specimens, the yield strength values are within 1% of each other. However, there can be a difference of about 25% between yield strength values measured on dogbone specimens and strip specimens. A large (>20%) variation in yield elongation measurements can occur, even when using the same specimen geometry. The seam peel strengths are surprisingly consistent: within approximately 5% of each other. If all parent geomembrane tests are performed using the same dogbone specimen geometry and all seam tests are done using strip specimens, the test data will be uniformly consistent.

DISCUSSION

The three most significant features of this seaming study are: a) the wide window of environmental conditions over which satisfactory seams can be made; b) the effectiveness of hot air seaming methods, even under adverse ambient conditions; and c) the apparent peel separation characteristic of the seams.

Unlike HDPE seams, which essentially break in a peel test through the geomembrane or by interface separation, TP breaks in an additional mode: by separation along the edge of the HAZ. It has been shown that this "apparent" peel behavior occurs through solid material and, therefore, occurs at a stress very close to the yield stress of the parent material. Such a breaking mode should be considered acceptable. For comparison, National Sanitation Foundation International Standard 54 specifies that a peel separation in PVC geomembrane is acceptable at 10% of the tensions measured in this study.

Within the range of seaming conditions that produce adequate peel strength values, and bounded by "apparent" separation characteristics, is a zone where peel break occurs through the geomembrane at the edge of the seam, without any apparent peel separation. This is the "sweet spot" (as in a tennis racquet) or the zone of optimum seam strength. It appears that in this region the weld zone has optimum homogeneity and blends smoothly into the parent geomembrane structure. As the seaming parameters move away from the sweet spot, apparent separation begins to occur as the boundary between the HAZ and the parent geomembrane becomes more distinct, i.e., the microstructural changes between one region and the next are less smooth. The orientation of the crystalline/amorphous microstructure apparently provides a plane of preferred failure, not necessarily a significantly weaker plane but one on which fracture can initiate and propagate more easily than elsewhere.

On a qualitative basis, there appeared to be more hot wedge specimens that failed by apparent peel separation than hot air specimens. This may simply be because the sweet spot for hot wedge seams was not identified, because the sweet spot is not as broad, or does not occur. If the latter is the case, this must be because the hot wedge, with its definite "footprint" produces a sharper transition between HAZ and parent geomembrane. The hot air seams, on the other hand, may have a more diffuse extremity that encourages the smooth transition from weld zone to parent geomembrane. Such a hypothesis requires further investigation. However, if it is found to be true, some geomembrane materials (depending on their microstructure) such as TP, may provide more durable seams by hot air seaming. Even though this seaming process may be a little slower than hot wedge seaming, the actual seam strength and durability may be better.

CONCLUSIONS

Preliminary fundamental stress cracking studies and chemical resistance studies performed on Tuff-Ply, a fully cross-linked elastomeric PP/EPDM alloy, in spent sulfite liquors and a municipal solid waste leachate indicate that the material may perform very well as a geomembrane for the containment of solid and liquid wastes. It has good resistance to high and low pH liquors at elevated temperatures.

A comprehensive series of hot air and hot wedge seaming tests over a wide range of machine parameters and seaming conditions show that the material is easy to seam in the field:

- It can be successfully seamed at -10°C in blowing snow.
- It can be successfully seamed over a wide range of machine speed and temperature settings.
- Hot air seaming techniques will probably produce the most durable seams.
- Seam test specimens may appear to peel apart, but if the peel stress is close to the yield stress, such seams are acceptable.

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