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Low-temperature air channel testing of thermally bonded PVC geomembrane seams

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ABSTRACT: The objective of this paper is to develop a procedure for air channel testing of dual-track thermal seams at low sheet temperatures and recommendations for reducing destructive testing of field PVC geomembrane seams. This objective is accomplished by developing relationships between seam peel strength and seam burst pressure for sheet temperatures ranging from 0.6°C to 25.6°C during field air channel testing. This paper refines the original correlation presented by Thomas *et al.* using data for low sheet temperatures, and develops a polynomial equation that can be used to convert the sheet temperature during field air channel testing to the air channel pressure required to satisfy the specified seam peel strength instead of graphically finding the air channel pressure from an Arrhenius analysis. Thus the proposed relationship and equation allow the seam peel strength to be determined from the field air channel testing without conducting destructive tests.

KEYWORDS: Geosynthetics, PVC geomembrane, Air channel testing, Seams, Quality assurance, Quality control, Thermal welding, Peel strength, Burst pressure, Low temperature

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1. INTRODUCTION

Thermal welding has proven to be a cost-effective method of field seaming PVC geomembrane liners because PVC possesses excellent thermal welding characteristics such as a wide thermal seaming range and surface preparation/grinding is not required. The thermal welding technique allows PVC geomembranes to be constructed in cold weather when chemical seams are not applicable and utilises prevalent QA/QC techniques. Thomas *et al.* (2003) show that fully automated thermal welding systems can weld PVC geomembranes as thin as 0.5 mm at temperatures as low as −8°C. These systems allow the operator to adjust welder speed, nip-roller pressure and welding temperature to create the best-quality seam. During installation, welder speed is set according to geomembrane thickness. The welder should also be adjusted to account for large variations in ambient temperature. Depending upon the manufacturer of the welder, PVC welding temperatures vary from 315 to 480°C. The use of thermal welding also allows common QA/QC techniques to be used for PVC geomembranes, such as air channel testing.

Thomas *et al.* (2003) present relationships between seam peel strength and seam burst pressure at three different sheet temperatures (22.8, 35.0, and 46.7°C) during field air channel testing. These relationships are used to construct a correlation between the field air channel pressure required to satisfy the specified seam peel strength of 2.6 N/mm and a range of sheet temperatures during air channel testing. The correlation is extended using an Arrhenius analysis of the test results. This correlation can be used to convert the sheet temperature during field air channel testing into the air channel pressure required to satisfy the specified seam peel strength. More importantly, the flexible nature of PVC allows the inflated air channel to be visible, and thus the integrity of the seam can be investigated along the entire seam length. In addition, the air channel test is challenging the peel strength along the entire length of the seam instead of a limited seam length that is used in conventional destructive tests.

In this study, 37 sets of seam peel strength and seam burst pressure data are used in addition to the data presented by Thomas *et al.* (2003). The new data correspond to low sheet temperatures, 0.6°C to 25.6°C, during field air channel testing. The data presented by Thomas *et al.* (2003) correspond to sheet temperatures ranging from 22.8°C to 46.7°C. The main objective of this paper is to develop a relationship between seam peel strength and burst pressure at low sheet temperatures. These data are also used to refine the correlation developed by Thomas *et al.* (2003), which relates the field air channel pressure required to satisfy the specified seam peel strength of 2.6 N/mm to sheet temperatures ranging from 0°C to 60°C.

2. THERMAL SEAM EVALUATION

To make field thermal seams, it is necessary to melt the polymer at the sheet surface using a heat source. The heat can be transferred to the sheets to be welded from hot air or a hot wedge. A hot air welder uses an air blower that blows heated air from an electrical element between the two sheets to be bonded by melting an interface strip. A hot wedge welder generates the heat energy necessary to melt the sheets at the interface by electrical elements placed directly between two sheets. Rollers are used to drive the heating machine and to apply pressure on the heated strip of the sheets.

At present, two types of PVC thermal seam are used in practice: dual-track and single-track seams. Both types of seam can be created with a hot air or a hot wedge, and allow destructive and non-destructive testing to be carried out as soon as the seam has cooled. This rapid assessment of quality allows immediate changes to be made in the seaming process to ensure optimal productivity. This paper focuses on non-destructive air channel testing of dual-track seams.

The seams used in this study were created at two different locations and using two different welders. This first location is TRI/Environmental in Austin, Texas, on an asphalt subgrade. The other location is Environmental Protection, Inc. (EPI) in Mancelona, Michigan. The two welders are hot air and hot wedge. The hot air machine is a Leister Twinnie Model CH6056. The hot wedge machine is a Mini-Wedge made by Plastic Welding Technologies (formerly Columbine, Inc.). The sheet temperatures range from 10 to 38°C during thermal welding. The 0.75 and 1.00 mm-thick PVC geomembranes used in the thermal seam testing were provided by Canadian General-Tower Ltd of Cambridge, Ontario, Canada. Both welders have a typical, pre-set nip pressure, and this was maintained throughout the seaming operation. Table 1 shows the different welding conditions used.

After eliminating test results corresponding to a film tearing bond (FTB) failure mode, 24 data sets were selected from 9.2 m long thermal seams using a hot air welder and a hot wedge welding machine, which were created at TRI/Environmental. The exclusion of the FTB failure mode is recommended by Thomas *et al.* (2003), so the peel strength and burst pressure of the seams correspond to a similar failure mode and thus are comparable.

Thirteen data sets from the nine thermal seams constructed by EPI at low-temperature conditions are also used. A hot air welder was used to thermally weld the 0.75 mm-thick PVC geomembranes. The sheet temperatures range from −3.9°C to 2.8°C during thermal welding.

A total of 37 sets of peel strength and burst pressure data, 24 sets from the TRI/Environmental seams and 13 sets from the EPI seams, are used to develop the correlation between sheet temperature, burst pressure, and peel strength. The 37 data sets are divided into four sub-groups according to the sheet temperature at the time of the air channel test, as shown in Table 1. The 37 data sets are summarised in descending order of sheet temperature during field air channel testing. Seven data sets are included in Group 1, which has sheet temperatures ranging from 24.4°C to 25.6°C with an average value of 25.1°C. Seven data sets are included in Group 2, which has sheet temperatures ranging from 12.8°C to 18.3°C with an average value of 14.8°C. Eleven data sets are included in Group 3, which has sheet temperatures ranging from 7.8°C to 11.7°C with an average value of 9.7°C. Finally, 12 data sets are included in Group 4, which has sheet temperatures ranging from 0.6°C to 7.2°C with an average value of 5.3°C.

The seams were evaluated by the standard peel test at 50 mm/min at 22.8°C (ASTM D 6392) and by an air channel test developed during this project. The air channel test is performed by sealing off one end of a seam length and pressurising the other end with compressed air. The air channel test procedure used herein is different from the ASTM D 5820 procedure for pressurised air channel evaluation of dual-track seamed geomembranes. All of the equipment used herein is the same as in ASTM D 5820 but the test procedure is different. In ASTM D 5820, the test procedure involves measuring a pressure drop in the air channel for a minimum of 2 min and comparing this drop with the maximum allowable pressure drop to decide whether the seam is acceptable or not. In contrast, the air channel test used herein to develop relationships between sheet temperature, burst pressure and seam peel strength involves selecting a starting air pressure and holding that air pressure constant for 30 s, then increasing the air pressure by 34.4 kPa, and holding the new air pressure constant for another 30 s. This multi-stage test procedure continues with air pressure increments of 34.4 kPa until the seam bursts. The full procedure of the air channel test is described in Thomas *et al.* (2003).

Thomas *et al.* (2003) show that the air channel test fails the seam from the inside towards the outside of the seam, whereas the peel test fails the seam from the outside towards the inside of the seam. This difference is not deemed significant because PVC seam requirements are specified in terms of peel strength, and the burst pressure during air channel testing is simply being correlated to this specified parameter. The specified value for the peel strength of both 0.75 and 1.00 mm-thick PVC seams according to the material specification

Table 1. PVC seam testing data summary

Group	Test ID	Burst temp. (°C)	Average burst temp. (°C)	Burst pressure (kPa)	Peel strength (N/mm)	PVC thickness (mm)	Welding details				Data source
							Welder type	Welder temp. (°C)	Welder speed (m/min)	Sheet temp. (°C)	
1	1	25.6	25.1	482.3	5.60	1.00	H/A	390	1.9	1.7	EPI
	2	25.6		172.3	3.00	1.00	H/A	390	2.8	1.7	EPI
	3	25.0		482.3	5.95	1.00	H/A	320	1.1	−3.9	EPI
	4	25.0		137.8	1.23	1.00	H/A	320	1.9	−2.2	EPI
	5	25.0		34.5	0.70	1.00	H/A	320	2.8	−1.1	EPI
	6	25.0		537.4	5.95	1.00	H/A	482	2.8	2.8	EPI
	7	24.4		551.2	7.35	1.00	H/A	482	1.9	2.8	EPI
2	8	18.3	14.8	861.3	8.05	1.00	H/W	399	0.9	15.6	TRI/Envir.
	9	15.6		82.7	0.88	1.00	H/A	320	1.9	−2.2	EPI
	10	15.6		20.7	0.35	1.00	H/A	320	2.8	−1.1	EPI
	11	14.4		585.7	4.20	0.75	H/W	371	3.0	32.2	TRI/Envir.
	12	13.9		592.5	5.78	1.00	H/A	390	1.9	1.7	EPI
	13	13.3		689.0	6.48	1.00	H/A	482	2.8	2.8	EPI
	14	12.8		757.9	7.18	1.00	H/A	482	1.9	2.8	EPI
3	15	11.7	9.7	275.6	2.63	0.75	H/A	360	3.0	26.7	TRI/Envir.
	16	11.1		516.8	4.73	0.75	H/A	390	2.1	10.0	TRI/Envir.
	17	11.1		172.3	1.58	0.75	H/A	320	3.0	26.7	TRI/Envir.
	18	10.0		413.4	5.08	0.75	H/A	320	2.1	26.7	TRI/Envir.
	19	10.0		482.3	3.15	0.75	H/A	360	2.1	26.7	TRI/Envir.
	20	9.4		275.6	2.28	1.00	H/A	390	2.8	1.7	EPI
	21	9.4		530.5	3.33	1.00	H/A	360	2.1	32.2	TRI/Envir.
	22	8.9		702.8	4.38	0.75	H/W	427	5.8	32.2	TRI/Envir.
	23	8.9		268.7	3.50	1.00	H/W	399	3.0	37.8	TRI/Envir.
	24	7.8		475.4	2.98	0.75	H/W	427	5.8	10.0	TRI/Envir.
	25	7.8		757.9	4.20	0.75	H/W	427	3.0	32.2	TRI/Envir.
4	26	7.2	5.3	413.4	2.98	0.75	H/A	390	3.0	10.0	TRI/Envir.
	27	6.7		723.5	3.85	0.75	H/W	482	3.0	32.2	TRI/Envir.
	28	6.1		254.9	2.80	0.75	H/A	390	3.0	26.7	TRI/Envir.
	29	6.1		620.1	5.08	1.00	H/A	390	2.1	15.6	TRI/Envir.
	30	6.1		213.6	1.75	1.00	H/A	360	3.0	32.2	TRI/Envir.
	31	6.1		551.2	3.33	1.00	H/A	440	3.0	32.2	TRI/Envir.
	32	5.6		254.9	2.28	0.75	H/A	360	3.0	10.0	TRI/Envir.
	33	5.0		261.8	3.15	1.00	H/A	390	3.0	15.6	TRI/Envir.
	34	5.0		475.4	2.45	1.00	H/W	482	3.0	15.6	TRI/Envir.
	35	4.4		551.2	2.63	1.00	H/A	390	3.0	32.2	TRI/Envir.
	36	4.4		620.1	2.80	1.00	H/W	441	3.0	37.8	TRI/Envir.
	37	0.6		551.2	3.68	0.75	H/W	371	5.8	32.2	TRI/Envir.

Note: Welder type H/A = hot air welder and H/W = hot wedge welder

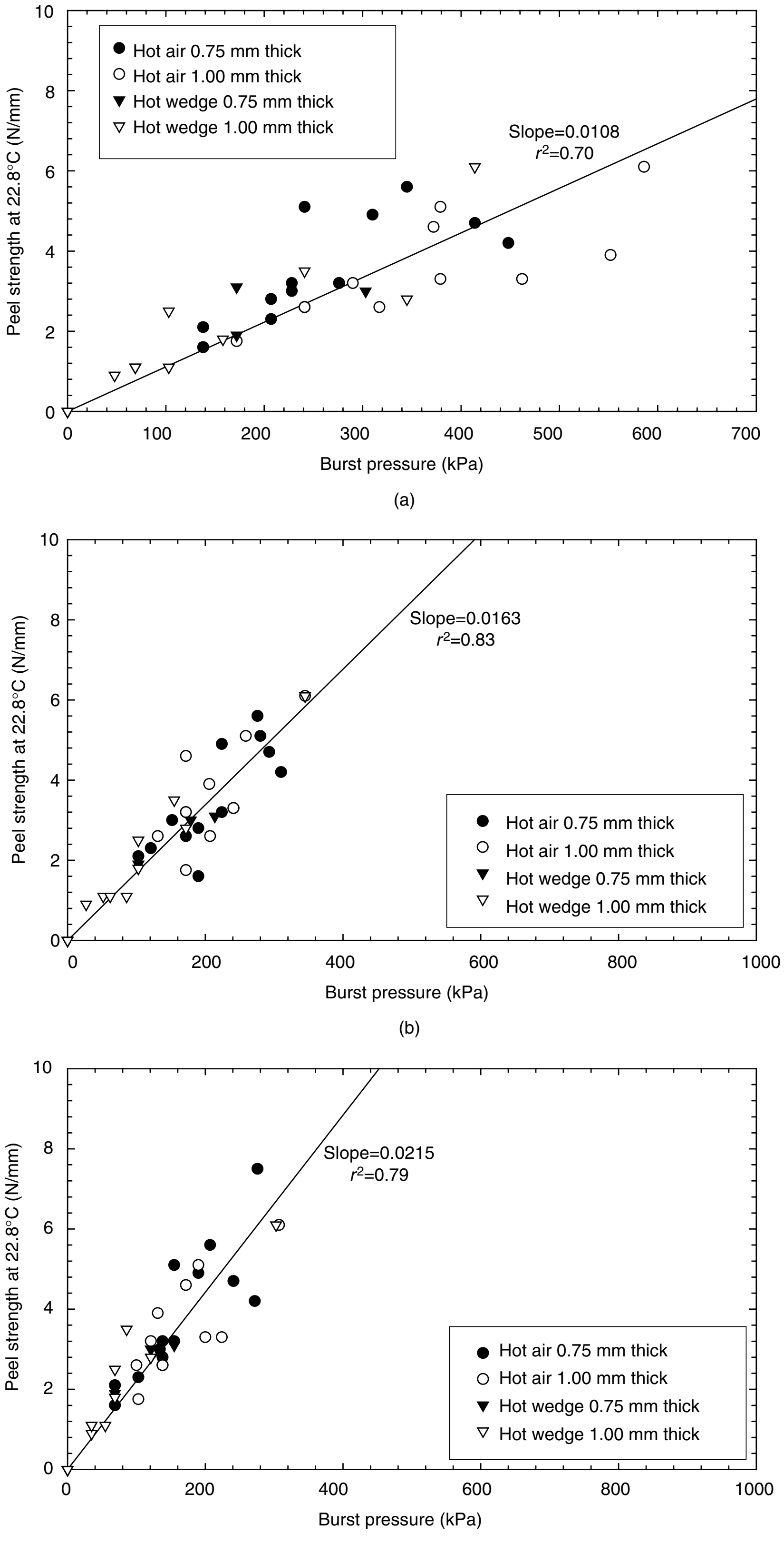
available through the PVC Geomembrane Institute (2004) is 2.6 N/mm.

In the field, the relationships developed herein and a slightly different air channel test procedure than ASTM D 5820, described above, are used to determine whether the field seam is acceptable or not. The relationships between sheet temperature, burst pressure and seam peel strength developed herein are used to determine the air pressure required to ensure a field seam peel strength of 2.6 N/mm. The air channel is pressurised to the pressure required for a peel strength of 2.6 N/mm, which is obtained from the relationships presented herein, and this pressure is held for 30 s. If the seam maintains this pressure for 30 s, the peel strength is greater than 2.6 N/mm.

3. RELATIONSHIP BETWEEN SEAM PEEL STRENGTH AND BURST PRESSURE

3.1. Verification of previous relationships

Thomas *et al.* (2003) present relationships between seam peel strength and seam burst pressure during air channel testing for three sheet temperatures. These relationships use the hypothesis that a correlation exists between peel strength and burst pressure because both tests involve peeling apart the seam, albeit in different directions. Figure 1 shows the Thomas *et al.* (2003) relationships between peel strength and burst pressure for the 72 seams welded at TRI/Environmental, which exhibit a peel failure



(a)

(b)

(c)

Figure 1. Relationship between peel strength and burst pressure for all non-FTB seams, 0.75 and 1.00 mm-thick geomembranes and hot air and hot wedge welded seams (from Thomas *et al.* 2003): (a) 22.8°C; (b) 35.0°C; (c) 46.7°C

mode (i.e. non-FTB failure mode), at three sheet temperatures (i.e. 22.8, 35.0 and 46.7°C). To be useful, this relationship should be linear and should include seams that fail in identical ways, i.e. peel versus FTB. Therefore the non-linear data points, i.e. FTB failure mode, were omitted to develop a relationship between peel strength and burst pressure (Thomas *et al.* 2003).

The relationship between peel strength and burst pressure can be expressed in terms of a ratio of peel strength (N/mm) to burst pressure (kPa), and the ratio is obtained from the slope of each trend line in Figure 1, using a linear regression analysis. Figure 1 shows that, with an increase in sheet temperature, the ratio of peel strength to burst pressure, or slope of the trend line, increases. In other words, for a given peel strength, a lower burst pressure is expected as the sheet temperature increases.

To confirm the accuracy of the relationship presented by Thomas *et al.* (2003) between peel strength and burst pressure at a sheet temperature of 22.8°C (see Figure 1a), this ratio between peel strength and burst pressure of 0.0108 is plotted along with the Group 1 data sets in Figure 2. Group 1 data sets have sheet temperatures ranging from 24.4°C to 25.6°C with an average value of 25.1°C, whereas the data from Figure 1a correspond to a sheet temperature of 22.8°C.

In general, the relationship between peel strength and burst pressure at a sheet temperature of 22.8°C (i.e. the ratio of peel strength to burst pressure of 0.0108) is in agreement with the trend of the Group 1 data. The trend line with a slope of 0.0108 lies slightly below most data sets that have sheet temperature greater than 22.8°C. One data point does not satisfy this trend, which is at 25°C and is plotted below the line. The data show that, with a sheet temperature greater than 22.8°C, the ratio of peel strength to burst pressure must be greater than 0.0108. This trend that higher sheet temperature results in the greater ratio of peel strength to burst pressure is also observed in the relationships presented by Thomas *et al.* (2003) between the ratio of peel strength to burst pressure and sheet temperature as shown in Figure 1. Thus the accuracy of the relationship presented by Thomas *et al.* (2003) is reinforced.

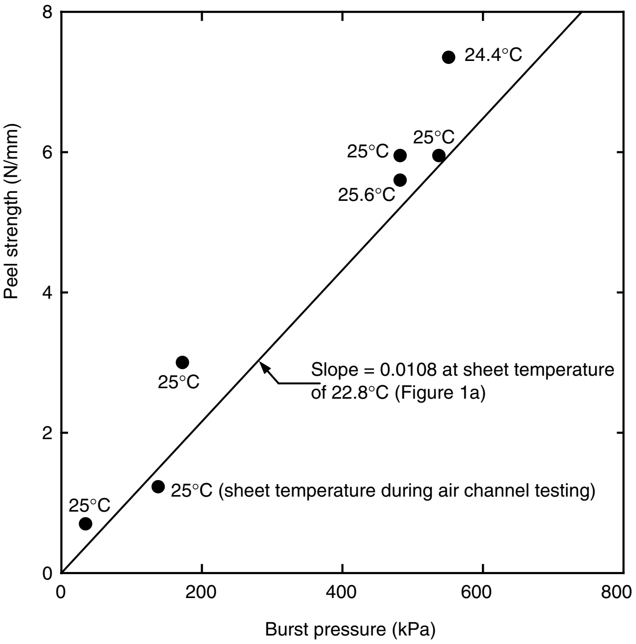


Figure 2. Verification of peel strength/burst pressure ratio (= 0.0108 from Figure 1a) at sheet temperature of 22.8°C

3.2. Development of new relationships for low temperature

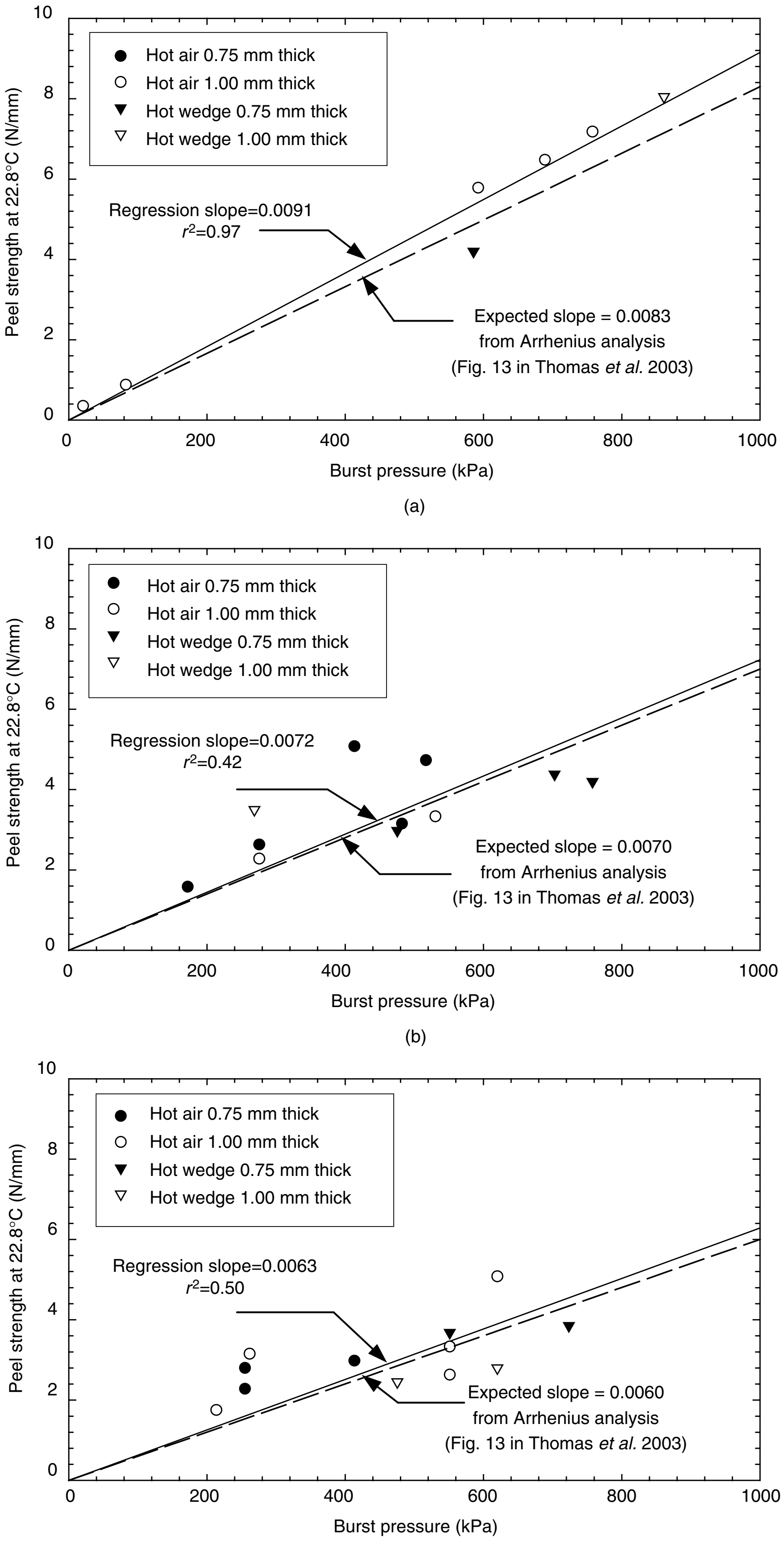
In this paper, new relationships between peel strength and burst pressure for air channel testing at temperatures ranging from 0.6°C to 18.3°C are developed to complement the prior relationships for sheet temperatures of 22.8°C, 35.0°C and 46.7°C presented by Thomas *et al.* (2003). Thirty data sets, which are designated Groups 2, 3 and 4 in Table 1, are used to develop the relationships for low sheet temperatures. Average sheet temperatures for Group 2, 3 and 4 data sets are 14.8°C, 9.7°C and 5.3°C respectively, as shown in Table 1. As recommended by Thomas *et al.* (2003), only the peel failure mode is considered in this analysis.

The results of linear regression analyses for each data set are plotted in Figure 3. The solid line in Figure 3 represents the relationship between peel strength and burst pressure from the low-temperature data and can be expressed in terms of a ratio of peel strength (N/mm) to burst pressure (kPa). Compared with the r^2 value for a sheet temperature of 14.8°C (i.e. $r^2 = 0.97$), the r^2 values of 0.42 and 0.50 at sheet temperatures of 9.7°C and 5.3°C respectively indicate a weaker correlation between peel strength and burst pressure. The poor correlation may result from a smaller number of data points and greater scatter. Thus it is concluded that a correlation between peel strength and burst pressure does exist in this temperature range. To confirm this conclusion, it is recommended that additional data for various PVC geomembranes be developed and added to this dataset in the future.

The ratio is obtained from the slope of each trend line in Figure 3. The slopes are calculated as 0.0091, 0.0072 and 0.0063 for average sheet temperatures of 14.8°C, 9.7°C and 5.3°C respectively. The trend lines show that a ratio of peel strength to burst pressure decreases with a decrease in sheet temperature during air channel testing. In other words, for a given peel strength, a greater burst pressure is expected as the sheet temperature decreases and the PVC geomembrane becomes stiffer. The ratios of peel strength to burst pressure from Figure 3 are summarised in Table 2 together with the ratios for sheet temperatures of 22.8°C, 35.0°C and 46.7°C presented by Thomas *et al.* (2003).

The dashed line in Figure 3 represents the expected relationship between peel strength and burst pressure from the Arrhenius analysis performed by Thomas *et al.* (2003). The expected slopes are 0.0083, 0.0070 and 0.0060 for sheet temperatures of 14.8°C, 9.7°C and 5.3°C respectively. Comparing the measured and estimated slopes at each sheet temperature, the expected slope from the Arrhenius analysis underestimates the slope obtained by a linear regression analysis. The degree of difference between the two slopes is expressed as follows:

$$\text{Degree of difference (\%)} = \frac{(\text{Regression slope} - \text{Expected slope})}{\text{Regression slope}} \times 100 \quad (1)$$



(a)

(b)

(c)

Figure 3. Relationship between peel strength and burst pressure of 0.75 and 1.00 mm-thick PVC geomembrane and hot air and hot wedge welding for low sheet temperatures during air channel testing at: (a) 14.8°C; (b) 9.7°C; (c) 5.3°C

Using Equation 1, the degree of difference is calculated to be 8.8%, 2.8% and 4.8% for sheet temperatures of 14.8°C, 9.7°C and 5.3°C respectively. Thus the results of the Arrhenius analysis performed by Thomas *et al.* (2003) do not correctly represent the measured relationship between sheet temperature, burst pressure and peel strength, and thus a new relationship is presented herein.

Table 2. Relationship between peel strength and burst pressure

Sheet temperature during burst test (°C)	Peel strength (N/mm) / Burst pressure (kPa)	
	Measured value by regression	Expected value by Arrhenius analysis (Thomas *et al.* 2003)
5.3	0.0063	0.0060
9.7	0.0072	0.0070
14.8	0.0091	0.0083
22.8	0.0108(a)	–
35.0	0.0163(a)	–
46.7	0.0215(a)	–

(a)Data from Thomas *et al.* (2003)

4. RELATIONSHIP BETWEEN SHEET TEMPERATURE AND REQUIRED AIR CHANNEL PRESSURE

It is proposed that the air channel test can be used as a field quality assurance/quality control test instead of destructive testing of PVC geomembrane seams. Therefore it is necessary to develop a relationship between sheet temperature, burst pressure and peel strength. This relationship allows field personnel to determine the air channel pressure that is required for a particular sheet temperature to ensure that the specified seam peel strength, e.g. 2.6 N/mm, is satisfied.

Table 2 shows that the ratio of peel strength to burst pressure is a function of a sheet temperature during air channel testing. Thomas *et al.* (2003) use the three ratios for the three sheet temperatures (i.e. 22.8°C, 35.0°C and 46.7°C) and the specified peel strength of 2.6 N/mm to calculate the minimum air channel pressure required to achieve the specified peel strength at sheet temperatures ranging from 22.8°C to 46.7°C. Three data points (solid circles) in Figure 4 denoted as a measured value were obtained by dividing the specified peel strength of 2.6 N/mm by the ratios at the three sheet temperatures (i.e. 22.8°C, 35.0°C and 46.7°C). These three data points are from Thomas *et al.* (2003).

Thomas *et al.* (2003) utilise Arrhenius modelling (Koerner *et al.* 1992; Shelton and Bright 1993) to augment these three data points and extend the applicable temperature range beyond the range of 22.8–46.7°C used in the testing. Because it is assumed that most temperature-dependent properties vary exponentially, the Arrhenius model was used to extend the measured relationship between peel strength and burst pressure to other sheet temperatures. Arrhenius modelling is typically used to determine the temperature dependence of chemical reactions, including deleterious reactions such as hydrolysis or oxidation, and it has been frequently used to estimate the service lifetime of geosynthetic products (Risseeuw and Schmidt 1990; Koerner *et al.* 1992; Shelton and Bright 1993; Salman *et al.* 1998; Thomas 2002). The results of the Arrhenius analysis performed by Thomas *et al.* (2003) were used to extend the relationship between sheet

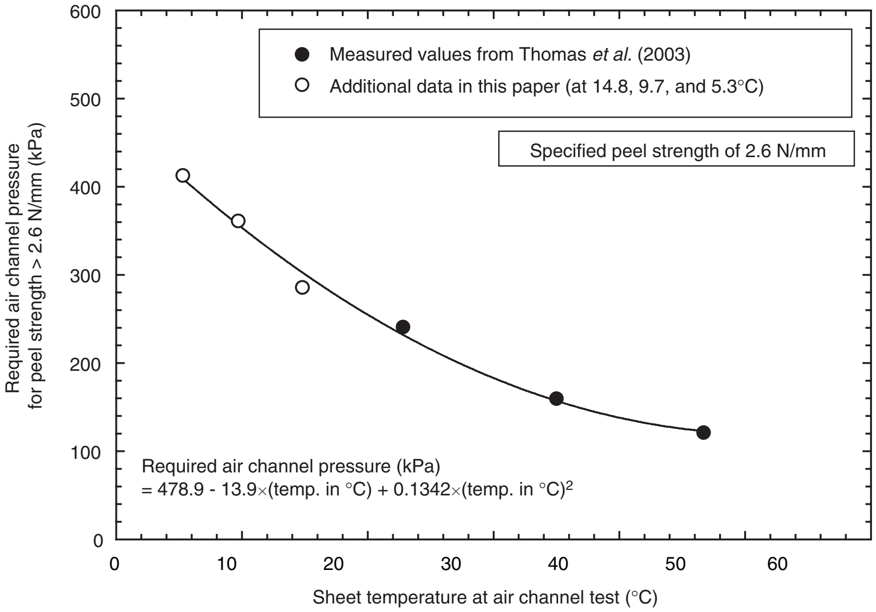


Figure 4. Recommended relationship between air channel pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures (in SI units)

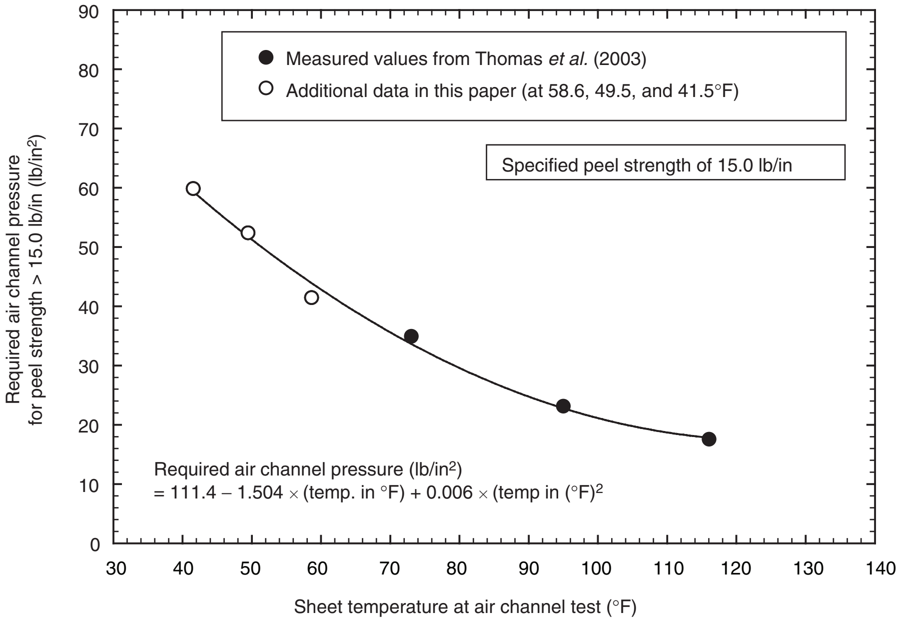


Figure 5. Recommended relationship between air channel pressure required to verify a specified peel strength of 15.0 lb/in at various sheet temperatures (in English units)

temperature, burst pressure and peel strength to sheet temperatures ranging from 0 to 22.8°C and from 46.7 to 60.0°C.

Considering the three measured ratios for low sheet temperatures in Table 2, three data points (open circles) are added to Figure 4, which represent the air channel pressure required to satisfy the specified peel strength of 2.6 N/mm for sheet temperatures of 14.8°C, 9.7°C and 5.3°C.

Instead of performing an Arrhenius analysis, all of the six slopes in Table 2 for sheet temperatures of 5.3, 9.7, 14.8, 22.8, 35.0 and 46.7°C are used to construct the new relationship in Figure 4 between the air channel pressure required to satisfy the specified seam peel strength of 2.6 N/mm and the sheet temperature during air channel testing. The six data points correspond to the following polynomial equation for temperatures between 5.3°C and 46.7°C:

$$\text{Required air channel pressure (kPa)} = 478.9 - 13.9 \times (\text{temp. in } ^\circ\text{C}) + 0.1342 \times (\text{temp. in } ^\circ\text{C})^2 \quad (2)$$

It is useful to express Figure 4 and Equation 2 in English units because there is still a tendency to use English units in field welding operation. Figure 5 shows the air channel pressures (lb/in^2) required to satisfy the specified peel strength of 15.0 lb/in, corresponding to 2.6 N/mm in SI units, for sheet temperatures of 41.5, 49.5, 58.6, 73.0, 95.0 and 116.1°F. The six data points correspond to the following polynomial equation in English units for temperatures between 41.5°F and 116.1°F:

$$\text{Required air channel pressure (lb/in}^2\text{)} = 111.4 - 1.504 \times (\text{temp. in } ^\circ\text{F}) + 0.006 \times (\text{temp. in } ^\circ\text{F})^2 \quad (3)$$

These equations can be used to convert a sheet temperature to the air channel pressure required to satisfy the specified seam peel strength instead of graphically estimating the required air channel pressure or performing an Arrhenius analysis.

Welding personnel can simply measure a sheet temperature during air channel testing, apply the required air channel pressure calculated from Equation 2 or 3 to the air channel for 30 s, and if the air channel maintains this pressure without peeling, it can be assumed that the seam peel strength is greater than or equal to the specified value of 2.6 N/mm (15.0 lb/in). It is proposed that this procedure can be used instead of destructive seam testing, which has the disadvantages of cutting holes in the geomembrane, patching the resulting geomembrane, and not testing 100% of the seam. The technique proposed herein evaluates 100% of the seam length, and the flexible nature of a PVC geomembrane allows the inflated seam to be visually inspected over the entire length for defects. The proposed air channel test can be performed on-site at sheet temperatures ranging from 5.3°C to 46.7°C.

It is recommended that the relationships presented herein be augmented with additional data for various PVC geomembranes. However, the PVC Geomembrane Institute (PGI) specification ensures a flexible PVC geomembrane. Thus it is anticipated that the proposed relationships between sheet temperature, burst pressure and peel strength are applicable to other PVC geomem-

Table 3. Number of failures predicted using the specified seam peel strength of 2.6 N/mm and Figure 4

Sheet temperature during air channel test (°C)	Data set ID (Number of data sets)	Peel strength			Air channel pressure		
		Requirement (N/mm)	Failure number	Failure rate (%)	Requirement (kPa)	Failure number	Failure rate (%)
14.8	Group 2 (7)	2.6	2	28.6	285.7	2	28.6
9.7	Group 3 (11)	2.6	2	18.2	361.1	4	36.4
5.3	Group 4 (12)	2.6	3	25.0	412.7	4	33.3

branes that meet the PGI 1104 specification (PVC Geomembrane Institute 2004).

5. EVALUATION OF RECOMMENDED RELATIONSHIP FOR AIR CHANNEL TEST

This section evaluates the accuracy of the proposed relationship in Figure 4 between required air channel pressure to satisfy the specified seam peel strength (i.e. 2.6 N/mm) and sheet temperature during air channel testing. Thomas *et al.* (2003) performed the verification by predicting the burst pressure for the 72 seams created and tested at the three sheet temperatures during air channel testing (i.e. 22.8°C, 35.0°C and 46.7°C) and comparing the predicted values with the measured values. This verification utilised a pass/fail criterion to simulate typical QA/QC procedures.

In this paper, the same verification procedure is adopted for the additional three average sheet temperatures (i.e. 14.8°C, 9.7°C and 5.3°C). Table 3 summarises the verification procedure and the number of seams that would have failed the requirement of peel strength (i.e. 2.6 N/mm) and air channel pressure. The air channel pressure required for a peel strength of 2.6 N/mm is calculated from Figure 4 and Equation 2 at each sheet temperature. For example, two welded seams out of eleven in Group 3 with an average sheet temperature of 9.7°C fail to satisfy the requirement of peel strength of 2.6 N/mm in standard seam testing. Requirement of air channel pressure corresponding to the specified peel strength is calculated from Equation 2 to be 361.1 kPa for a sheet temperature of 9.7°C. This required air channel pressure is compared with the actually measured burst pressures in Group 3. Four welded seams out of eleven in Group 3 fail the air channel pressure requirement (see Table 3). Thus more seams fail the air channel pressure requirement for each of the low sheet temperatures (i.e. 14.8°C, 9.7°C and 5.3°C) than a destructive seam peel test. Therefore the result of the air channel test is conservative because it will classify more seams as failed than the conventional peel test. It is anticipated that the extra failures were identified because the burst test challenges the entire seam and not only a limited portion of the seam.

6. CONCLUSIONS

The purpose of this study is to develop three relationships between seam peel strength and burst pressure for sheet temperatures of 14.8°C, 9.7°C and 5.3°C during field air channel testing. With these relationships, the correlation presented by Thomas *et al.* (2003) between the required air channel pressure to satisfy the specified peel strength (i.e. 2.6 N/mm) and the sheet temperature during air channel testing is refined and extended to a sheet temperature of 5.3°C. The following conclusions are based on the data and interpretation presented in this paper.

- The ratios of peel strength to burst pressure are measured to be 0.0091, 0.0072 and 0.0063 for average sheet temperatures of 14.8°C, 9.7°C and 5.3°C respectively. The expected ratios of peel strength to burst pressure from the Arrhenius analysis presented by Thomas *et al.* (2003) are 0.0083, 0.0070 and 0.0060 for these sheet temperatures. Comparing these ratios at each sheet temperature indicates that the Arrhenius analysis does not predict the measured relationship between peel strength, burst pressure and sheet temperature at the low sheet temperatures, 5.3–14.8°C.
- The Arrhenius analysis presented by Thomas *et al.* (2003) slightly overestimates the air channel pressure required to satisfy the specified seam peel strength of 2.6 N/mm at low sheet temperatures. The error is measured to be 8.8%, 2.8% and 4.8% for sheet temperatures of 14.8°C, 9.7°C and 5.3°C respectively. The data presented herein are used to develop a polynomial equation to refine the relationship presented by Thomas *et al.* (2003) for a range of sheet temperature of 5.3–46.7°C. The equation can be used to convert a sheet temperature during field air channel testing to the air channel pressure required to satisfy the specified seam peel strength of 2.6 N/mm instead of graphically finding the required air channel pressure or performing an Arrhenius analysis.
- Verification of the proposed equation was performed by comparing the predicted value with the measured value along with a pass/fail criterion to simulate typical QA/QC procedures. Equal or more seams fail the requirement of air channel pressure compared with the requirement of peel strength. Therefore the air channel test is conservative, and it will classify more

seams as failed than the conventional peel test. The proposed relationship in this paper will allow field personnel to perform seam QA/QC operations without conducting destructive tests. This relationship (see Figure 4 and/or Equation 2, and Figure 5 and/or Equation 3 in English units) allows the seam peel strength to be measured indirectly by applying air pressure to the air channel in a dual-track weld, which reduces if not eliminates the need for destructive testing. This, coupled with the visibility of an inflated air channel, provides assurance of the integrity of the seam.

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