Technical Paper by T.D. Stark and L.F. Pazmino

HIGH TEMPERATURE AIR CHANNEL TESTING OF THERMALLY BONDED PVC GEOMEMBRANE SEAMS

ABSTRACT: The objective of this paper is to present a procedure for high sheet temperature air channel testing of dual track thermal seams for 0.75 mm thick PVC geomembranes. This objective is accomplished by developing relationships between seam peel strength and seam burst pressure for sheet temperatures ranging from 46.7°C to 62.8°C during field air channel testing. This paper extends the original relationships presented by Thomas et al. (2003a) and Stark et al. (2004) that only extend to 46.7°C because a sheet temperature greater than 46.7°C is frequently encountered during hot summer months. The original relationship is extended to 62.8°C using the Arrhenius model and a polynomial equation is presented that can be used to convert the sheet temperature during field air channel testing to the air channel pressure required to ensure the specified seam peel strength of 2.6 N/mm (15 lb/in) is met or exceeded. Thus, the proposed relationship and equation allow the seam peel strength to be verified by field air channel testing without conducting destructive tests.

KEYWORDS: PVC Geomembrane, Air Channel Testing, Seams, Quality Assurance, Quality Control, Thermal Welding, Peel Strength, Burst Pressure, High Temperature

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1. INTRODUCTION

Thermal welding has proven to be a cost-effective method of field seaming PVC geomembranes because PVC possesses excellent thermal welding characteristics such as a wide thermal seaming range and surface preparation/grinding is not required. Thomas et al. (2003a) show that fully automated thermal welding systems can allow the operator to adjust welder speed, nip-roller pressure, and welding temperature to create high quality seams for a range of geomembrane thicknesses. The welder should also be adjusted to account for 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 which is the focus of this paper.

Field seaming is performed under a wide range of varying weather conditions, where sheet temperatures can easily reach high temperatures. Thus, the prior relationship between sheet temperature and air channel pressure required to verify a seam peel strength of 2.6 N/mm (15 lbs/in) for 0.75 mm thick PVC geomembranes presented by Stark et al (2004) needed to be extended to sheet temperatures greater than 46.7°C. The main objective of this technical paper is to present a relationship between seam peel strength and burst pressure at sheet temperatures greater than 46.7°C for 0.75 mm thick PVC geomembranes.

Stark et al. (2004) present relationships between seam peel strength and seam burst pressure at the following six different sheet temperatures, 5.3, 9.7, 14.8, 22.8, 35.0, and 46.7°C, during field air channel testing. These relationships were used to construct a correlation between the field air channel pressure required to satisfy the required seam peel strength of 2.6 N/mm and a range of sheet temperatures during air channel testing. The correlation is extended herein to 62.8°C 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 of 2.6 N/mm without taking, or at least reducing the number of, destructive samples (Thomas et al., 2003b). The air channel test also challenges the peel strength along the entire length of the seam instead of a limited seam length that is used in conventional destructive tests. Most importantly, the air channel test inflates the flexible PVC geomembrane so the air channel is visible and the integrity of the seam can be visually inspected along the entire seam length as shown in Figure 1.

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 and/or a hot wedge welder. A hot air welder uses an air blower that blows heated air from an electrical element between the two sheets to be bonded and melts an interface strip. The use of hot air also helps prepare or clean the seam area prior to seaming. A hot wedge welder generates the heat necessary to melt the sheets at the interface by electrical elements placed directly between two sheets. Nip rollers are used to drive the heating machine and to apply pressure on the heated strip of the sheets (Mills and Stang, 1997).

At present, two types of PVC thermal seams 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 nondestructive testing to be performed 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 thermally-welded 0.75 mm thick PVC geomembrane seams presented by Stark et al. (2004) and used herein to extend the correlation were evaluated by the standard peel test at 50 mm/min at 22.8°C (ASTM D 6392, 1999) and by an air channel test developed by Thomas et al. (2003 a and b). The air channel test is performed by sealing off one end of a seam length and pressurizing the other end with compressed air. The air channel test procedure used is different than the ASTM D 5820 procedure for pressurized air channel evaluation of dual-track seamed geomembranes. All of the equipment 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 minutes 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 by Stark et al. (2004) to develop relationships between sheet temperature, burst pressure, and seam peel strength involves selecting a starting air channel pressure and holding that air pressure constant for 30 seconds, then increasing the air pressure by 34.4 kPa, and holding the new air channel pressure constant for another 30 seconds. This multi-stage test procedure continues with air pressure increments of 34.4 kPa until the seam bursts. This allows a relationship between peel strength and burst pressure to be developed. The full procedure of the air channel test is described in Thomas et al. (2003a). This procedure is the basis for the field air channel test procedure described in ASTM D7177 (ASTM D 7177, 2010).

Thomas et al. (2003a) 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 geomembrane seams according to the material specification available through ASTM D 7408 and the Fabricated 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 (see ASTM D7177). 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 meets and/or exceeds a peel strength of 2.6 N/mm for sheet temperatures up to 62.8°C. The air channel is pressurized 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 seconds. If the seam maintains this pressure for 30 seconds, the peel strength is greater than 2.6 N/mm as discussed in more detail below. The extended relationship for high sheet temperatures can be used with ASTM D7177.

3. RELATIONSHIP BETWEEN SEAM PEEL STREGNTH AND BURST PRESSURE AT HIGH TEMPERATURES

New relationships between peel strength and burst pressure for air channel testing at sheet temperatures ranging from 46.7 °C to 62.8 °C are developed herein to extend the prior air channel testing relationship presented by Stark et al. (2004) and used in ASTM D7177 for sheet temperatures ranging from 14.8 °C to 46.7 °C for 0.75 mm thick PVC geomembranes. The results of the Arrhenius analysis performed are plotted in Figure 2. The vertical axis is the natural logarithm (ln) of the slope of the relationships between peel strength and burst pressure for a given sheet temperature as presented in Thomas et al. (2003a) and Stark et al. (2004) which happens to negative. Thus, the vertical axis is labeled “Rate” which means rate of change in peel strength with burst pressure. The horizontal axis is the inverse of the sheet temperature. The data collected by Stark et al. (2004) are shown in solid circles and fit a nearly linear trend line. This linear relationship supports validation of the use of the Arrhenius model for air channel testing. The extension to three new sheet temperatures, 54.4 °C, 60.0 °C, and 62.8 °C is also shown (open circles) in Figure 2. The three points were selected to continue the linear relationship established by the prior data.

An important aspect of the linear relationship in Figure 2 is the linear relationship is used extend to sheet temperatures of 54.4, 60.0, and 62.8°C. The extension maintains an R^2 value of 0.996. This is R^2 value indicates a well defined linear relationship and it was deemed appropriate to extend the existing data from 46.7 to 54.4°C. Based on this excellent agreement and only extending the relationship from 46.7 to 54.4°C, or 8.3°C, compared to the entire relationship which extends from 5.3 to 46.7°C, i.e., 41.4°C, additional testing to prove this small extension was deemed unnecessary.

The relationships between burst pressure and peel strength for the seams evaluated by Stark et al. (2004) are presented in Figure 3 as continuous lines, as well as the expected relationships from the Arrhenius analysis in Figure 2 as dashed lines. The slope of the trend lines for sheet temperatures of 54.4, 60.0 and 62.8 °C were obtained by extending the linear relationship in Figure 2. The trend lines in Figure 3 show that a ratio of peel strength to burst pressure decreases with decreasing 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 for 0.75 mm thick PVC geomembranes from Stark et al. (2004) are summarized in Table 1 together with the ratios for sheet temperatures determined herein.

4. RELATIONSHIP BETWEEN SHEET TEMPERATURE AND REQUIRED AIR CHANNEL PRESSURE

It is proposed that the air channel test can be used as a nondestructive field quality assurance/quality control test instead of destructive sampling and testing of PVC geomembrane seams (Thomas et al., 2003b). 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 measured seam peel strength exceeds 2.6 N/mm.

Table 1 shows that the ratio of peel strength to burst pressure is a function of a sheet temperature during air channel testing. Thomas et al. (2003a) and Stark et al. (2004) use the ratios for six sheet temperatures 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 5.3 °C to 46.7 °C for 0.75 mm thick PVC geomembranes. Six data points (solid circles) in Figure 4 denote these values and were obtained by dividing the specified peel strength of 2.6 N/mm by the ratios of peel strength to burst pressure (shown in Table 1) at the six sheet temperatures. These six data points are from Stark et al. (2004).

To augment these data and extend the sheet temperature range beyond 46.7°C, the previously shown Arrhenius model (Koerner et al. 1992, Shelton and Bright 1993) was utilized to extend the non-linear relationship shown in Figure 4. Arrhenius modeling is typically used to determine the temperature dependence of chemical reactions, including deleterious reactions such as hydrolysis or oxidation, and has been frequently used to estimate the service lifetime of geosynthetics (Koerner et al. 1992, Shelton and Bright 1993, Risseeuw and Schmidt 1990, Salman et al. 1998, Thomas 2002). The results of the Arrhenius analysis were used to extend the relationship between sheet temperature, burst pressure, and peel strength to sheet temperatures ranging from 46.7 to 62.8 °C. From Figure 4, the extension looks reasonable based on the data for sheet temperatures below 46.7°C.

Considering the three new peel strength to burst pressure ratios for high sheet temperatures in Table 1, three data points (open circles) were 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 54.4 °C, 60.0 °C, and 62.8 °C for 0.75 mm thick PVC geomembranes. The result is the nine data points that correspond to the following polynomial equation for temperatures between 5.3 °C and 62.8 °C:

$$\text{Required air channel pressure (kPa) to meet or exceed a peel strength of 2.6N/mm} = 0.0963 \times \left(\text{temp. in °C}\right)^2 - 12.061 \times \left(\text{temp. in °C}\right) + 464.39 \qquad (1)$$

This equation 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. Table 2 presents the nine data points in Figure 4 in tabular form which may be easier to utilize in the field.

For comparison purposes, the relationship between sheet temperature and required air channel pressure required to meet or exceed a peel strength of 2.6 N/mm is compared to the values included in ASTM D7177 in Figure 5. Figure 5 shows excellent agreement between the recommended relationship and ASTM D7177 for sheet temperatures less than 46.7°C. Figure 5 also shows the proposed extension is reasonable and fits the existing relationships (Stark et al., 2004 and ASTM D7177). It is also important to note that the six data points from Stark et al. (2004) were used to generate many intermediate points for use in ASTM D7177 because Figure 5 shows many more data points from ASTM D7177 than .Stark et al. (2004) report. This reinforces using the six data points from Stark et al. (2004) to extend the relationship to sheet temperatures greater than 46.7°C.

5. FIELD TEST PROCEDURE

To utilize the relationship proposed in Figure 4, field welding personnel can simply measure sheet temperature during air channel testing, apply the required air channel pressure calculated from Equation (1) to the air channel or estimated from Figure 4, and if the air channel maintains or holds the required air pressure for 30 seconds the seam peel strength exceeds the specified peel strength of 2.6 N/mm for 0.75 mm thick PVC geomembranes. It is proposed that this procedure can be used instead of destructive seam testing, which has the disadvantage of cutting holes in the production geomembrane, patching the production 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 (see Figure 1). The proposed air channel test can be performed onsite at sheet temperatures ranging from 5.3 °C to 62.8°C. Even though the data used herein was developed for 0.75 mm thick PVC geomembranes, it is anticipated that Equation (1) can be used for PVC geomembrane thicknesses of 0.75 mm or thicker.

While the air channel is inflated, the entire length of the seam should be inspected to ensure there is no blockage in the seam. If the seam inflates the entire length, there is no audible or visible evidence of air leakage, and the seam holds the pressure required in Figure 4 or Equation (1), the peel strength of the seam exceeds 2.6 N/mm and the seam passes the test. If the seam does not hold the required pressure, the seam fails and the leak should be located by sound of the leakage or isolating portions of the seam with another clamp. Portions of the failed seam can be isolated by folding the seam over itself and clamping the fold.

One other benefit of air channel testing of flexible PVC geomembranes is the presence of aneurysms or slight seam defects can be detected (see Figure 6). An aneurysm is an area of the weld that did not seam completely because of dirt, moisture, wrinkle, or other deleterious material was present in the weld area that prevented the bonding of the geomembrane sheets in that area. It is recommended that a patch be placed over the aneurysm if greater than or equal to 50% of the seam width is unbounded. The percentage is calculated by dividing the length of the intrusion by the width of the unimpacted weld. The patch should extend 15 cm on all the sides of the aneurysm, parallel and perpendicular to the seam. If the seam has a flap, i.e., the weld does not extend to the edge of the top geomembrane as shown in Figures 1 and 6, the flap should be welded to the under geomembrane before patching. The flap can be welded easily and quickly in the field using a solvent or an adhesive. After welding the flap in the area of the patch, the patch can be applied using hot air, solvent, or adhesive. If less than 50% of the seam is unbounded by the aneurysm and the air channel maintains the required air pressure for a peel strength of 2.6 N/mm, the seam is acceptable.

The air channel test presented herein is based on air channel width of 15.9 ± 3.2 mm. For air channels greater or lesser in lay flat width, the hoop stress equation can be used to calculate the new air channel pressure to generate the same hoop stress (ASTM D 7177, 2010). The hoop stress equation is:

$$S = \frac{PD}{2t} \qquad (2)$$

Where:

S = hoop stress (kPa)

P = internal pressure (kPa)

D = outside diameter (mm) and

t = normal wall thickness (mm)

6. CONCLUSIONS

The purpose of this study is to extend the relationship between 0.75 mm thick PVC geomembrane sheet temperature and air channel pressure required to ensure a seam peel strength of 2.6 N/mm is satisfied for sheet temperatures up to 62.8 °C. The following conclusions are based on the data and interpretation presented in this paper.

1. The Arrhenius analysis performed shows a R^2 value of 0.996 which reinforces the use of this approach to develop a relationship between peel strength and burst pressure for the extended range of sheet temperatures.

2. The analysis presented herein is used to develop a polynomial equation to refine the relationship presented by Stark et al. (2004) and extend the range of sheet temperature from 46.7 °C to 62.8 °C. The polynomial 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. Alternatively, the graph in Figure 4 or the tabulated values in Table 2 can be used in the field by welding personnel.

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HIGH TEMPERATURE AIR CHANNEL TESTING OF THERMALLY BONDED PVC GEOMEMBRANE SEAMS

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Table caption:

Table 1. Relationship between peel strength and burst pressure for various sheet temperatures.

Table 2. Air channel pressure required to verify 2.6 N/mm (15 lb/in) seam peel strength for 0.75 mm and thicker PVC geomembranes.

Figure caption:

Figure 1. Air channel test performed in 0.75 mm PVC geomembrane seam.

Figure 2. Arrhenius relationship between peel and burst pressure ration to the inverse sheet temperature.

Figure 3. Relationships between burst pressure and peel strength for all non-FTB seams for various sheet temperatures.

Figure 4. Recommend Relationship between air channel pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures.

Figure 5. Comparison of recommend relationship between air channel pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures with relationship included in ASTM D7177.

Figure 6. Aneurysm in 0.75 mm PVC geomembrane seam.

Table 1. Relationship between peel strength and burst pressure for various sheet temperatures.

Sheet temperature during burst test	Peel Strength (N/mm) / Burst Pressure (kPa)	
°C	Measured slope from Stark et al. (2004)	Expected slope from Arrhenius analysis
5.3	0.0063	-
9.7	0.0072	-
14.8	0.0091	-
22.8	0.0108	-
35	0.0163	-
46.7	0.0215	-
54.4	-	0.0265
60	-	0.0304
62.8	-	0.0324

Table 2. Air channel pressure required to verify 2.6 N/mm (15 lb/in) seam peel strength for 0.75 mm and thicker PVC geomembranes.

Sheet Temperature	Air Pressure	Pressure Hold Time (sec)
ºC	kPa	
5.3	412.7	30 Seconds
9.7	361.1	30 Seconds
14.8	285.7	30 Seconds
22.8	240.7	30 Seconds
35	159.5	30 Seconds
46.7	120.9	30 Seconds
54.4	98	30 Seconds
60	85.6	30 Seconds
62.8	80.2	30 Seconds

Figure 1. Air channel test performed in 0.75 mm PVC geomembrane seam

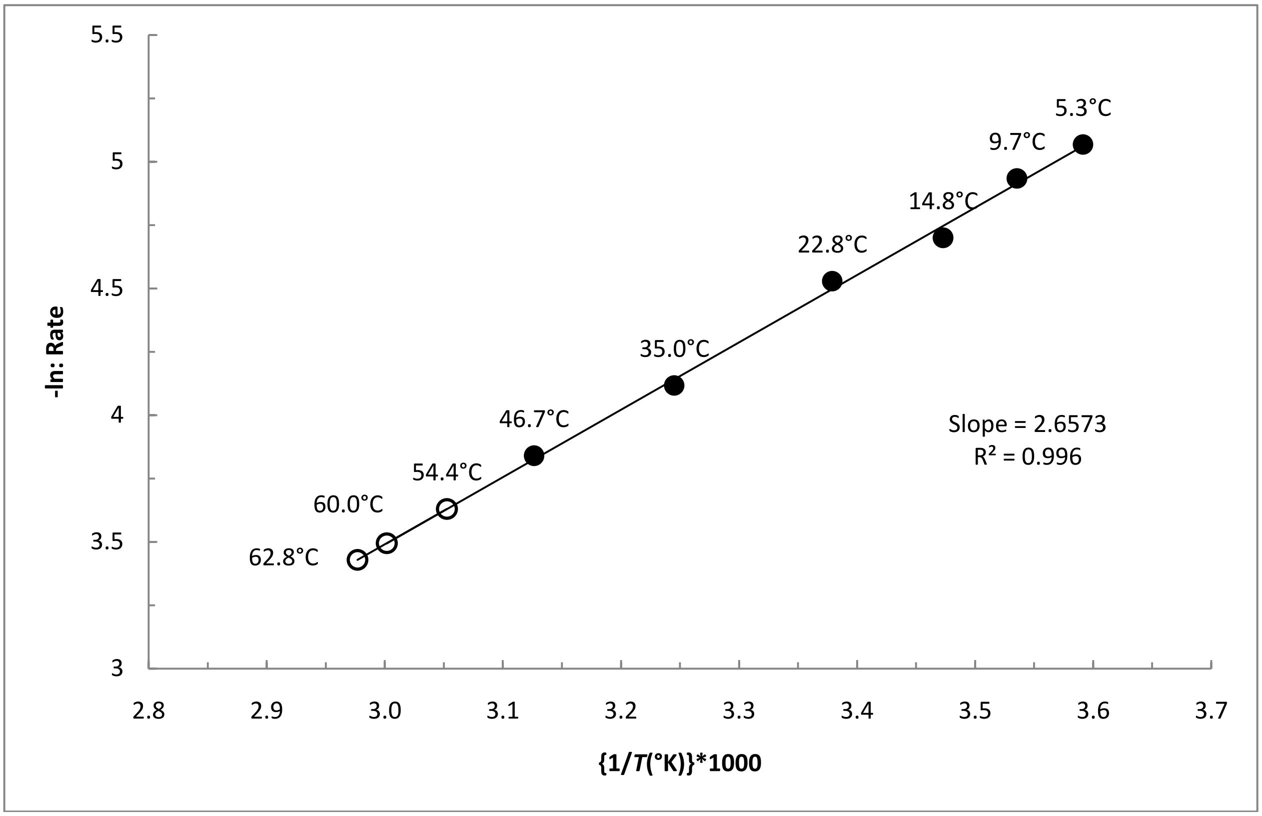

Figure 2. Arrhenius relationship between peel and burst pressure ration to the inverse sheet temperature.

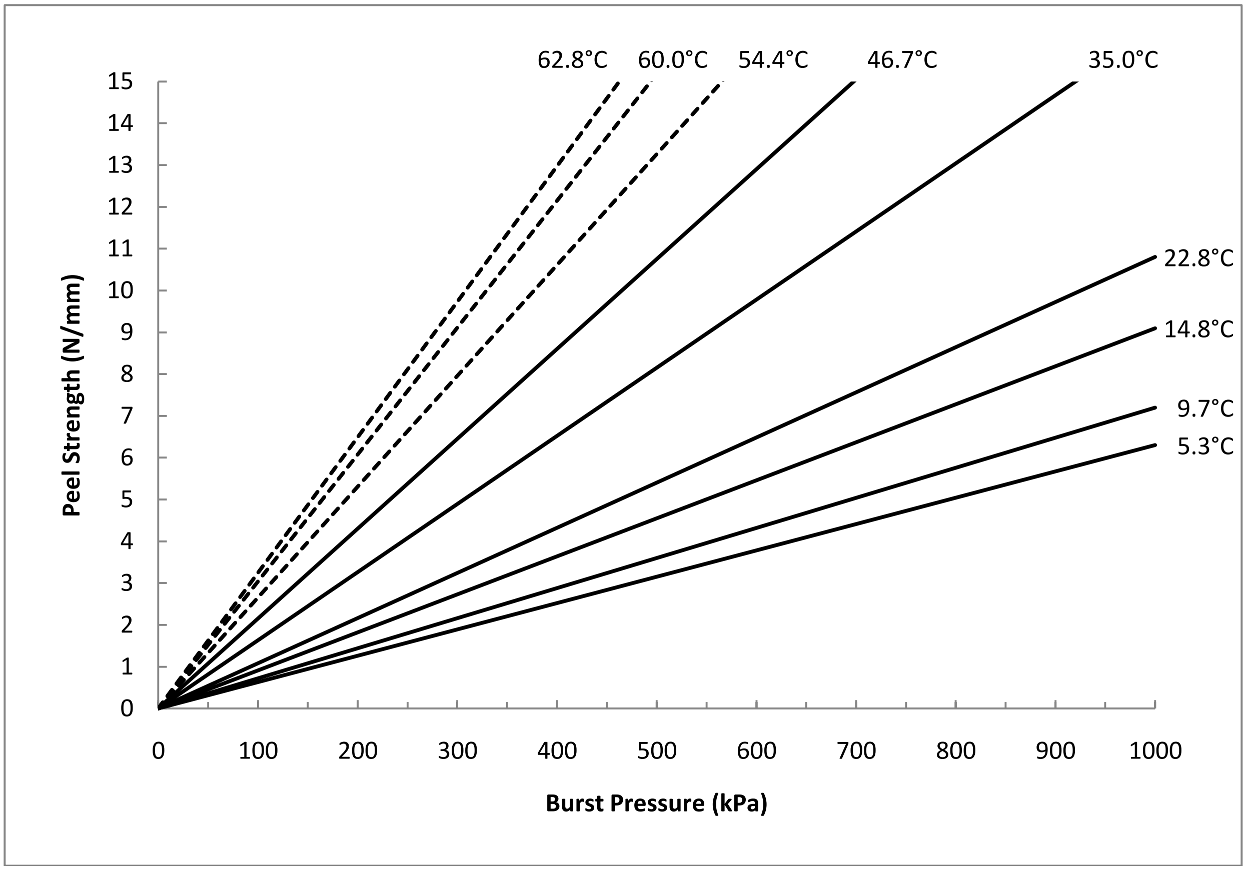

Figure 3. Relationships between burst pressure and peel strength for all non-FTB seams for various sheet temperatures.

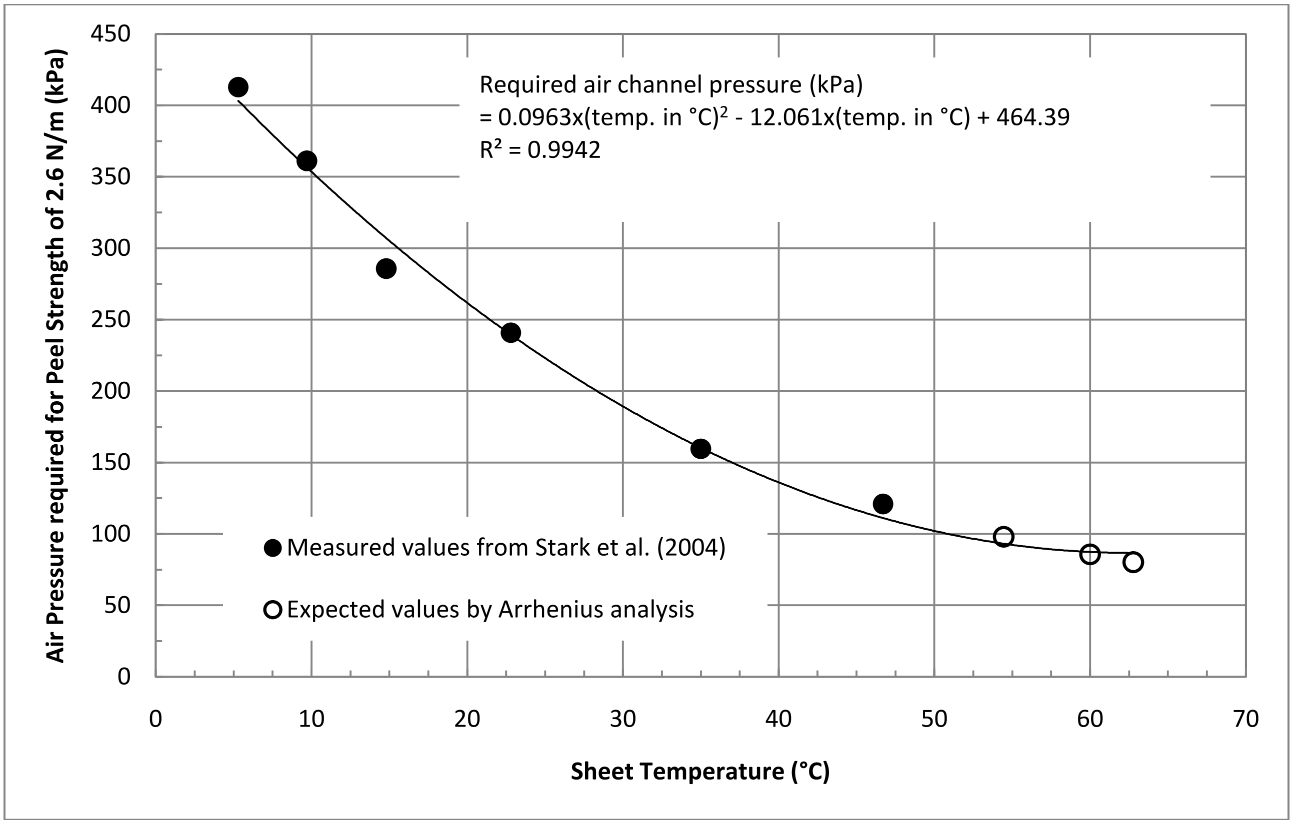

Figure 4. Recommend Relationship between air channel pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures for 0.75 PVC geomembranes.

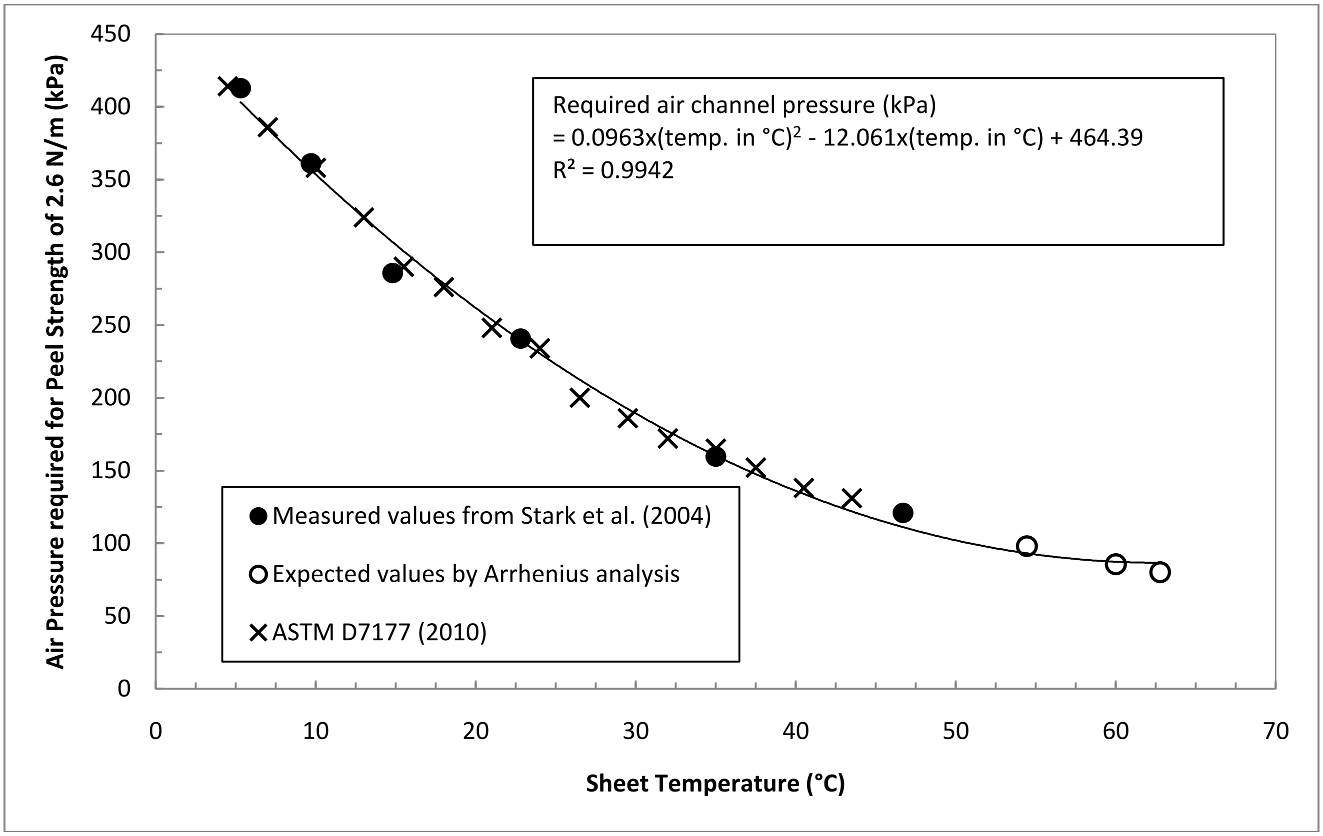

Figure 5. Comparison of recommend relationship between air channel pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures with relationship included in ASTM D7177.

Figure 6. Aneurysm in 0.75 mm PVC geomembrane seam.