Air channel testing of thermally bonded PVC geomembrane seams

R. W. Thomas[1], T. D. Stark[2] and H. Choi[3]

[1]*TRI/Environmental, Inc., 9063 Bee Caves Road, Austin, TX 78733–6201, USA, Telephone: +1 512 263 2101, Telefax: +1 512 263 2558, E-mail: Rthomas@tri-env.com*
[2]*Professor of Civil and Environmental Engineering, University of Illinois, 2217 Newmark Civil Engineering Laboratory, 205 N. Mathews Ave., Urbana, IL 61801–2352, USA, Telephone: +1 217 333 7394, Telefax: +1 217 333 9464, E-mail: tstark@uiuc.edu*
[3]*Post-doctoral Research Associate of Civil and Environmental Engineering, University of Illinois, B156 Newmark Civil Engineering Laboratory, 205 N. Mathews Ave., Urbana, IL 61801–2352, USA, Telephone: +1 217 333 1773, Telefax: 1 217 333 9464 E-mail: hchoi2@uiuc.edu*

Received 9 September 2002, revised 12 August 2003, accepted 26 August 2003

ABSTRACT: Polyvinyl chloride (PVC) possesses excellent thermal welding characteristics, such as a wide thermal seaming range and the absence of a need for surface preparation such as grinding. The focus of this study was to utilise these welding characteristics to develop a procedure for air channel testing of dual track thermal seams and recommend that destructive testing of PVC geomembranes be reduced and possibly discontinued. This is possible because of the development of a relationship between thermally welded seam burst strength and seam peel strength for a given sheet temperature. To develop this relationship, test welds were created using hot air and wedge welders at two different geomembrane temperatures, two different geomembrane thicknesses, three welding speeds, and three welding temperatures. The 72 seams created were evaluated by conducting ASTM D 6392 peel strength tests at room temperature (22.8°C) and a burst test developed herein at three different sheet temperatures. This paper presents the test results, which illustrate the importance of welding temperature and speed. The test results are also used to develop a relationship between seam peel strength and burst pressure, which can then be used to conduct field burst tests to ensure the specified seam peel strength(s) are satisfied along the entire seam length instead of over the limited seam length used in destructive tests.

KEYWORDS: Geosynthetics, Peel strength, PVC geomembrane, Quality assurance, Quality control, Seams, Thermal welding

REFERENCE: Thomas, R. W., Stark, T. D. & Choi, H. (2003). Air channel testing of thermally bonded PVC geomembrane seams. *Geosynthetics International*, **10**, No. 2, 56–69

1. INTRODUCTION

The need to have field seams that can be checked quickly with measurable results has caused geosynthetic engineers and quality assurance/quality control (QA/QC) technicians not to prefer field chemical seams for polyvinyl chloride (PVC) geomembranes. In recent years, thermal welding has proved to be an efficient and cost-effective method of field-seaming PVC geomembrane liners. The use of thermal welding also allows prevalent QA/QC techniques to be used for PVC geomembranes.

Before the advent of thermal welding, field PVC seams were made using either an adhesive or a chemical fusion agent. Adhesive seams utilise a bonding agent that remains as an additional element in the seam after curing. Chemical fusion seams employ a solvent that actually dissolves the surface of the materials to be joined, allowing them to be fused together. These methods are still suitable for detail work but are inefficient for large field applications. In addition, QA/QC procedures for chemical welds can be difficult, owing to long curing times. This can delay peel and shear testing of seams up to 24 h and also delay non-destructive testing, such as air lance testing, until the seam has cured properly. This can result in a delay in placing cover material and meeting project deadlines. The surface temperature of the geomembrane needs to be monitored to ensure that the temperature is not too low or too high to ensure good chemical bonding. Thermal welding of PVC geomembranes, on the other hand, does have the benefit that it can extend liner construction into the cooler weather when chemical seams would not be possible.

In light of the limitations of large-scale field chemical welds, the benefits of thermal welding of PVC became apparent. PVC possesses excellent thermal welding characteristics, such as a wide thermal seaming range and no required surface preparation such as grinding. Fully automated thermal systems can thermally weld PVC geomembrane as thin as 0.5 mm in 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. It should also be adjusted to account for large variations in ambient temperature. Depending upon the manufacturer, welding temperatures vary from 315°C to 480°C.

At present, two types of 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, which is quickly. This rapid assessment of quality allows immediate changes to be made in the seaming process to ensure optimal productivity. This article focuses on the use of dual track seams and in particular the test procedures that should be utilised to air-channel test dual track PVC seams. Based on the success of dual track welding and air channel testing presented herein, the paper recommends that destructive testing of PVC geomembranes be significantly reduced, if not discontinued. This is accomplished by presenting relationships between the seam strength, measured by an air channel burst test, and the seam peel strength for a given seam temperature and welding type. To achieve this objective a study of the thermal welding process of PVC geomembranes was conducted to develop a window of appropriate conditions for welding, including sheet temperature, welder temperature and speed.

2. THERMAL SEAM PREPARATION

The seams used in this study were created in a single day in Austin, Texas, at TRI/Environmental on an asphalt subgrade. Two crews from two different companies, one using a hot air welder and the other using a hot wedge welding machine, created the 72 thermal seams, 9.2 m long, used in this study. The hot air machine was a Leister Twinnie model CH6056. The hot wedge machine was a Mini-Wedge made by Plastic Welding Technologies (formerly Columbine, Inc.). The 0.75 mm and 1.00 mm-thick PVC geomembranes used in the thermal seam testing were provided by Canadian General-Tower, Ltd. of Cambridge, Ontario, Canada.

The crews each used three welding temperatures and three welder speeds based on their normal operating conditions and their experience. Each crew made a set of 0.75 mm and 1.00 mm seams in the shade in the morning. Then each crew made an identical set of seams in the sun in the afternoon. The sheet temperatures ranged from 10°C to 38°C for these two conditions. The sheet temperature, i.e. temperature of the geomembrane, was monitored by a thermocouple attached to the sheet. During the study, the welder temperature and sheet temperature were varied but the nip roller pressure was held constant. 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.

Table 1. Range of seaming parameters used in study

Welder type	Sheet thickness (mm)	Sheet temperature (°C)	Welder speed (m/min)	Welder temperature (°C)
Hot air	0.75	10.0, 26.7	1.2, 2.1, 3.1	320, 360, 390
	1.00	15.6, 32.2	1.2, 2.1, 3.1	360, 390, 440
Hot wedge	0.75	10.0, 32.2	0.9, 3.1, 5.8	371, 427, 482
	1.00	15.6, 37.8	0.9, 3.1, 5.8	399, 427, 482

3. THERMAL SEAM EVALUATION

The seams were evaluated by the standard peel test at 50 mm/min at 22.8°C (ASTM D 6392) and by a seam burst test developed during this project. The seam burst test was performed by sealing off one end of a seam length and pressurising the other end with compressed air. The seam length tested in the burst test was 2 m. The basic test procedure involved selecting a starting air pressure, holding that air pressure constant for 30 s, then increasing the air pressure by 34.4 kPa at a time, and holding the new air pressure constant for another 30 s. This was repeated for each 34.4 kPa air pressure increment. The 34.4 kPa air pressure increment was achieved in a 5 s time period. This procedure of increasing the air channel pressure, holding the air pressure, and then increasing the air pressure by 34.4 kPa continued until the seam "burst". Most of the burst failures occurred during the 30 s holding period and involved the peel mode. However, some seams burst during the 34.4 kPa air pressure increase step.

The seam peel strength is compared to the burst pressure because pressurising the air channel results in the seam being challenged more in a peel mode than in a shear mode. The failure modes during the peel test included 100% seam peeling, some partial peeling, and some seam film tearing bond (FTB) failures. For simplicity, the partial peels and FTBs were grouped and called FTB. Identical failure modes were seen during the burst tests. In every case, the failures occurred in the seam (peel) or at the edge of a seam (FTB). The specific failure modes for hot air, hot wedge, 0.75 mm sheet and 1.0 mm sheet will be discussed in Section 6. It is important to note that the burst 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. The impact of this difference was not investigated because PVC seam requirements are specified in terms of peel strength, and the burst pressure is simply being correlated to this specified parameter. The specified value for the peel strength of both 0.75 mm and 1.00 mm thick PVC seams according to the material specification available through the PVC Geomembrane Institute (PGI 2003) is 2.6 N/mm.

Each burst test was conducted at room temperature (22.8°C) using a 2 m-long seam to determine a relation-

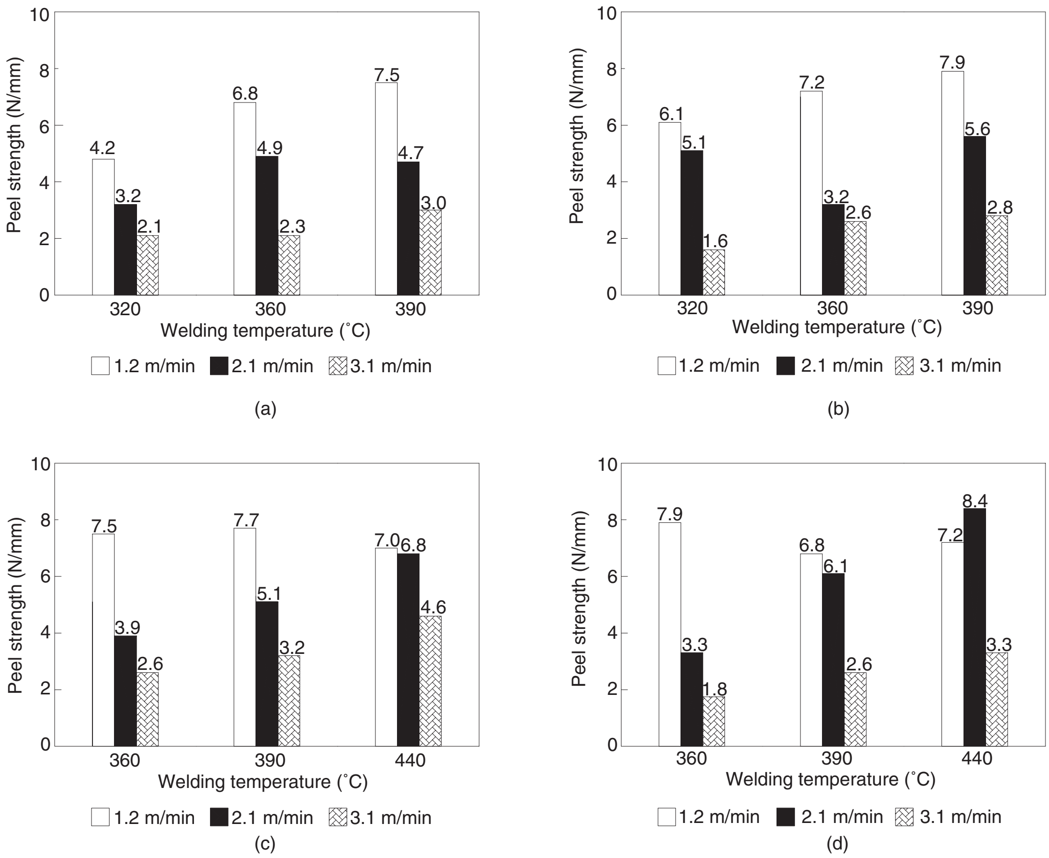

Figure 1. Seam peel strengths for 36 hot air welded seams: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 26.7°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 32.2°C

ship between seam peel strength and seam burst pressure. The burst test was also performed at two higher temperatures. These tests were performed in a constant-temperature room set at 37.8°C and 48.9°C. The actual sheet temperatures in these constant-temperature room tests were 35°C and 46.7°C. These elevated temperature tests were performed on 1.2 m-lengths of seam. The seam was clamped in the center, and then both 0.6 m halves were tested to produce duplicate results. None of the individual test strips that were pressurised in a burst test was also used for the peel strength testing. The peel strength test specimens were obtained from the seam adjacent to the burst test specimen. All peel and burst tests were performed on the same seam from the original 9.2 m-long seams.

4. EFFECT OF SHEET TEMPERATURE, WELDING SPEED AND WELDING TEMPERATURE ON SEAM PEEL STRENGTH

4.1. Hot air welded seams

A series of bar graphs of test results are used to illustrate the effect of sheet temperature, welding speed and welding temperature on seam peel strength. Figure 1 presents the measured peel strengths for the hot air welded seams. The temperature above each graph is the sheet temperature that was measured using a thermocouple attached to the sheet at the time of testing. The numbers above the top of each bar inside the graph represent the minimum peel strength between test results of the two weld tracks. Comparison of these bar graphs reveals a number of trends between seam peel strength and the three welding variables for a hot air welder.

First, the effect of welding speed appears to be greater than the effect of welding temperature because, comparing Figures 1a and 1b, it can be seen that the 1.2 m/min welding speed yields a significantly higher seam peel strength regardless of the welding temperature for a 0.75 mm-thick geomembrane. A similar trend is observed in Figures 1c and 1d for a 1.00 mm-thick geomembrane even though the trend is less pronounced at the highest welding temperature. This comparison suggests that welding personnel can increase the seam peel strength for a given sheet temperature and welding temperature by simply reducing the speed of the welder.

Second, a welding speed of 3.1 m/min produced significantly weaker seams than those fabricated at 2.1 m/min for the same sheet temperature and welding temperature: compare Figures 1a and 1b, for example. This comparison also suggests that decreasing the welding speed will increase the seam peel strength for a given set of welding conditions.

Third, the effect of sheet temperature on seam peel strength (compare Figures 1a and 1b) was the greatest at the lowest welder temperature, 320°C, for the 0.75 mm

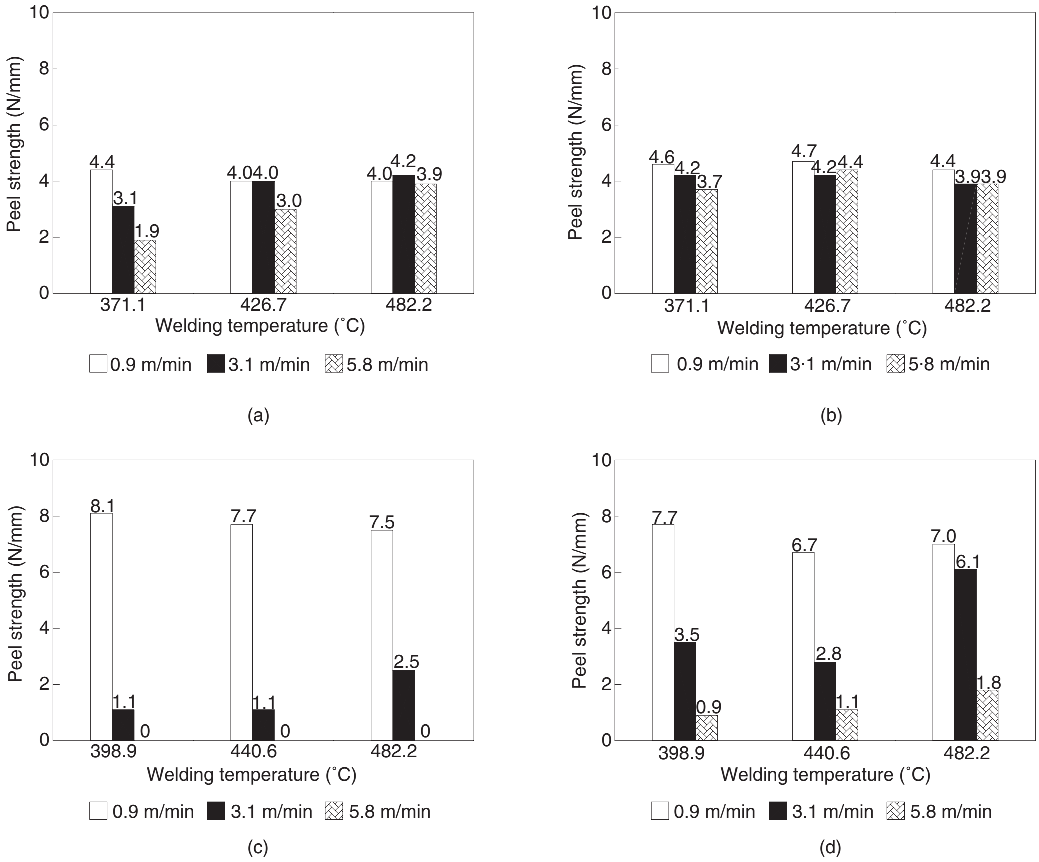

Figure 2. Seam peel strengths for 36 hot wedge welded seams: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 32.2°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 37.8°C

geomembrane. This suggests that a welding temperature of 320°C may be too low to consistently achieve welds that exceed the specified peel strength for a typical range of sheet temperature, i.e. 1–30°C.

Fourth, the 0.75 mm seams prepared at a welding temperature of 390°C exhibit similar peel strengths for a particular welding speed for the range of sheet temperature considered, i.e. 10–26.7°C. These results suggest that an optimal welding temperature for this 0.75 mm-thick PVC geomembrane is near 390°C, and thus a suitable starting point for a welding operation is probably a welding temperature around 390°C. The 1.00 mm-thick geomembrane seams prepared at a welding temperature of 440°C significantly exceed the specified value of 2.6 N/mm at the three welding speeds. However, the fastest speed (3.1 m/min) yielded the lowest peel strength, which suggests that the welding temperature could be raised to produce a stronger seam. A suitable welding temperature for 1.00 mm-thick PVC geomembrane might range from 454.4°C to 468.3°C for a welding speed of 3.1 m/min.

Finally, seams that did not peel during the peel test, i.e. exhibited FTB, were observed when the peel strength approached a value of 6.0 N/mm for the 0.75 mm sheet and 6.5 N/mm for the 1.0 mm sheet.

4.2. Wedge welded seams

A series of bar graphs are also used to present the effect of sheet temperature, welding speed and welding temperature on seam peel strength (Figure 2) for wedge welded seams. Comparison of these bar graphs reveals a number of trends between seam peel strength and the three welding variables for wedge welded seams.

First, the 0.75 mm-thick seams all yielded a peel strength of less than 4.7 N/mm, as shown in Figures 2a and 2b. The specified value of peel strength is 2.6 N/mm, based on the PGI 1103 specification (PGI 2003). In addition, the difference in peel strength for different welding temperatures and welder speeds is small. These results suggest that there is an upper limit to the value of peel strength that can be obtained for wedge welded 0.75 mm-thick seams. For example, the peel strengths for a sheet temperature of 32.2°C show a range of only 1.0 N/mm between the highest and lowest values. This is somewhat confusing because the burst pressures presented subsequently do not show a similar upper limit type of behavior.

Second, as observed in Figure 1, the effect of welding speed is greater than the effect of welding temperature. It can be seen from Figures 2c and 2d that a welding speed of 5.8 m/min is too fast for a 1.00 mm-thick seam, because the peel strengths are well below the specified value of 2.6 N/mm, but a speed of 5.8 m/min appears suitable for 0.75 mm seams.

Third, the effect of ambient temperature on seam peel strength is the greatest for the 1.00 mm-thick seams (see Figures 2c and 2d), except for the slowest speed, which showed extremely high peel strengths. These results also suggest that an optimal welding temperature for 1.00 mm-thick seams might range from 454°C to 468°C for a welding speed of 3.1 m/min. However, the higher temperature could also facilitate "burn-through" and acidic corrosion of the wedge. During the welding process, an acidic environment can be created by the degradation of PVC material that may accumulate on the wedge welding equipment. Traditional copper wedges are susceptible to attack by this acidic environment, which can result in a rough wedge surface. This problem has long been recognised, and several alternatives are available to prevent damage to the wedge. For example, protective coatings have been used to shield copper wedges from acidic by-products of welding; or a polished stainless steel wedge can be used.

Fourth, the only 1.00 mm seams that produced acceptable peel strengths at the lowest sheet temperature were created at the slowest speed of 0.9 mm/min. This suggests that the thicker sheet may be stiffer and less able to deform to contact the surface of the wedge at low sheet temperatures. This situation was not observed with the hot air welder, which seems to verify that the sheet may be stiffer and receiving less contact with the wedge than with hot air.

Another observation from the results on hot wedge welded seams was that FTB failures were observed at peel strengths of 3.7 N/mm for 0.75 mm sheet and 6.5 N/mm for 1.0 mm sheet.

5. EFFECT OF SHEET TEMPERATURE, WELDING SPEED AND WELDING TEMPERATURE ON SEAM BURST STRENGTH

5.1. General

This section of the paper presents the effect of sheet temperature, welding speed and welding temperature on seam burst pressure instead of seam peel strength, which was discussed in the preceding section. As mentioned previously, the burst test is analogous to a peel test except that the failure occurs from the inside towards the outside of the channel. This is different from a peel test, which challenges the seam from the outside towards the inside of the weld, but it is anticipated that the factors affecting peel strength will also affect the burst pressure. However, in the field the burst test will be more beneficial to quality assurance/quality control personnel because the test challenges the entire length of the seam and can be visually inspected to ensure identification of any weak or substandard weld.

5.2. Hot air welded seams

A series of bar graphs of test results are used to present the effect of sheet temperature, welding speed and welding temperature on seam burst pressure for hot air seams. The numbers above the top of each bar inside the graphs represent the maximum burst strength. Figures 3,

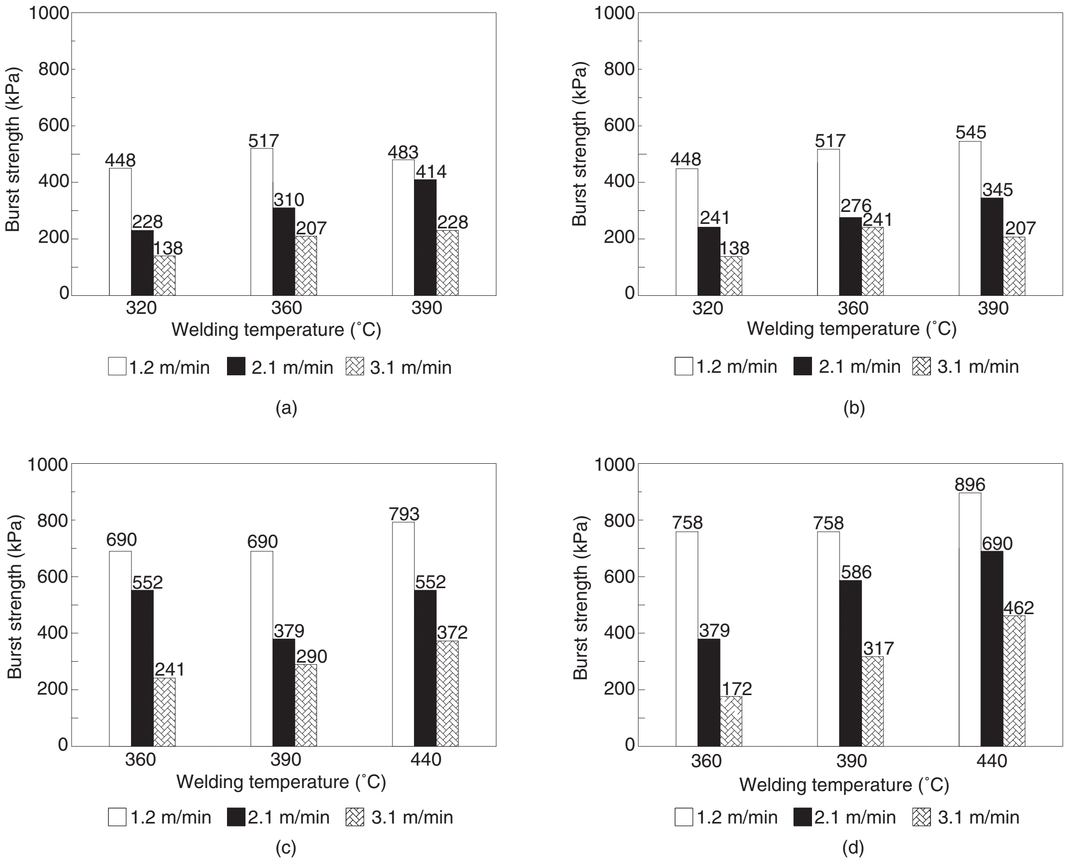

Figure 3. Seam burst pressures for 36 hot air welded seams, burst at 22.8°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 26.7°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 32.2°C

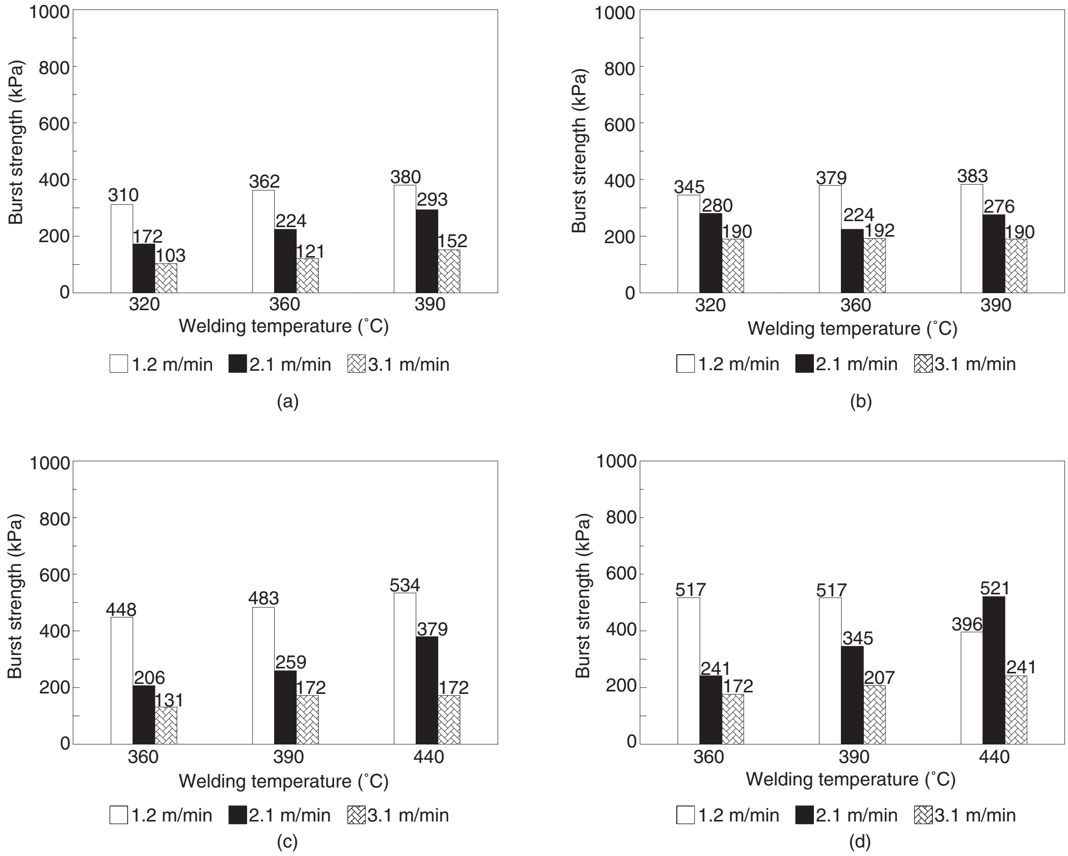

Figure 4. Seam burst pressures for 36 hot air welded seams, burst at 35.0°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 26.7°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 32.2°C

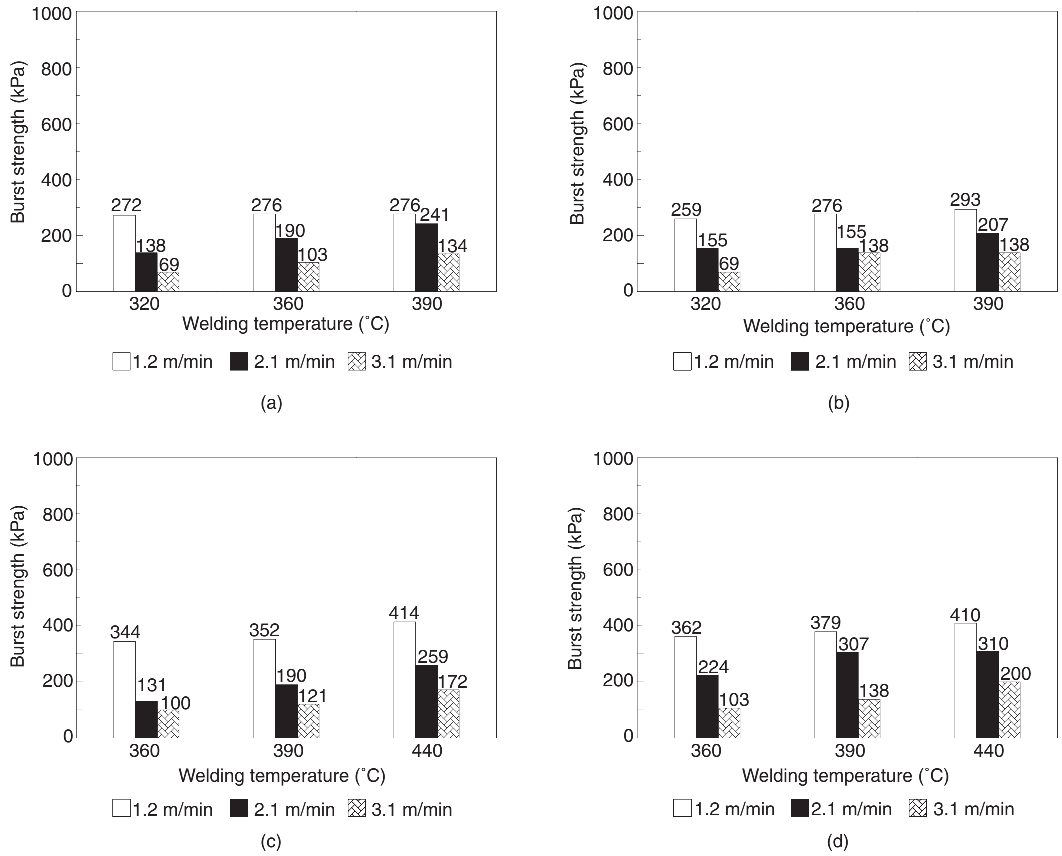

Figure 5. Seam burst pressures for 36 hot air welded seams, burst at 46.7°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 26.7°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 32.2°C

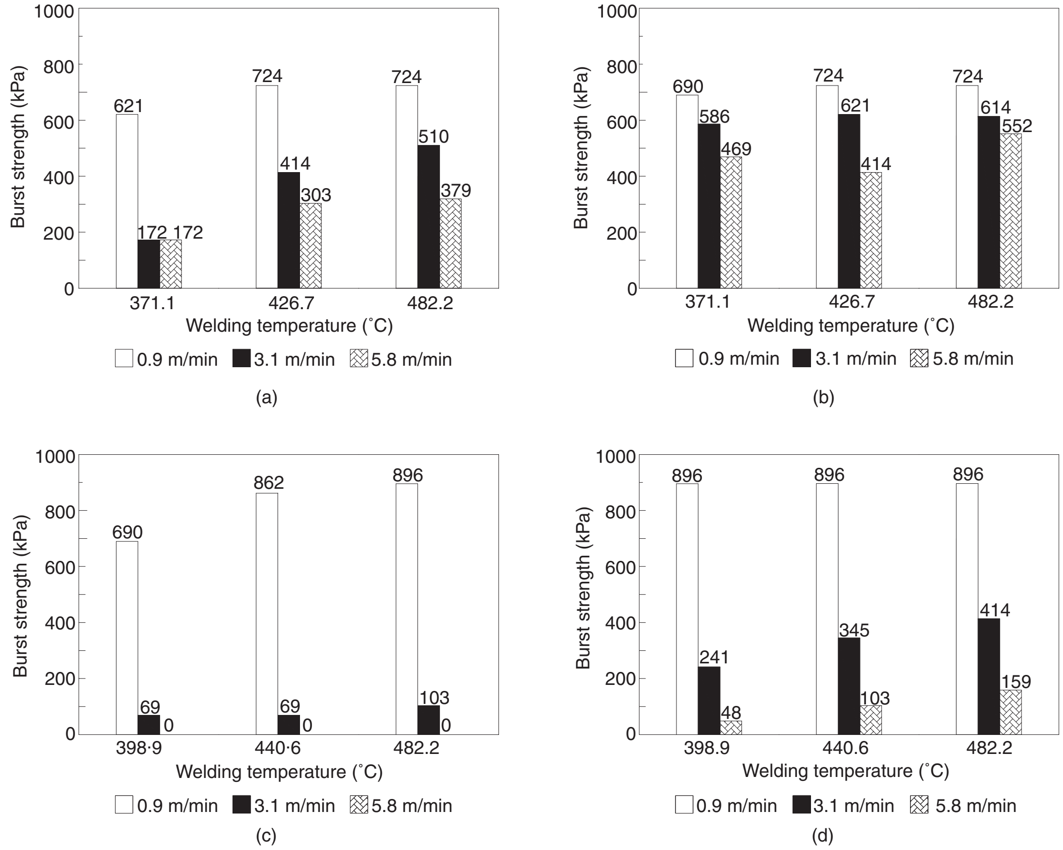

Figure 6. Seam burst pressures for 36 hot wedge welded seams, burst at 22.8°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 32.2°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 37.8°C

4 and 5 present the measured burst pressures for the hot air welded seams tested at sheet temperatures of 22.8, 35.0 and 46.7°C respectively. The burst tests conducted at a sheet temperature of 22.8°C were performed only once, whereas the burst tests at higher temperatures (35.0°C and 46.7°C) were performed in duplicate and averaged. The temperature above each bar graph is the sheet temperature that was measured using a thermocouple attached to the sheet. Comparison of these bar graphs reveals a number of trends between seam peel strength and the three welding variables of welding speed, welding temperature and sheet temperature for hot air welded seams. The results are similar to those seen with the peel test results. In particular, welding speed has a greater impact on seam burst pressure than welding temperature when the sheet temperature varies from 10°C to 26.7°C: compare Figures 3a and 3b, for example. Second, the burst pressure for the 1.00 mm-thick seams is significantly greater than the burst pressure for the 0.75 mm seams: compare Figures 3a and 3c, for example. Third, comparing Figures 3, 4 and 5, it can be seen that the burst pressure decreases as the sheet temperature increases.

5.3. Wedge welded seams

A series of bar graphs also are used to present the effect of sheet temperature, welding speed and welding temperature on seam burst pressure for wedge welded seams. Figures 6, 7 and 8 present the measured burst pressures for wedge welded seams when the burst test was performed at three different sheet temperatures, 22.8, 35.0 and 46.7°C, respectively. Comparison of these bar graphs reveals a few different trends between seam burst pressure and the three welding variables of welding speed, welding temperature and sheet temperature for the 0.75 mm-thick seams. Otherwise similar trends were obtained as described previously for peel strengths from wedge welded seams, such as welding speed having the largest effect on measured burst pressure and the weakest seams being created at lower welding temperatures and faster welding speeds regardless of the sheet temperature.

An important difference for the 0.75 mm seams is that the wedge welded seams exhibit significantly higher burst strengths than the hot air welded seams. This contrasts with the hot air welded seams yielding higher peel strengths than the wedge welded 0.75 mm seams. In particular, for the burst tests at the sheet temperature of 22.8°C (Figure 6), the test results for the 0.75 mm seams showed that the wedge welded seams exhibit maximum peel strengths around 4.4 N/mm whereas the hot air welded seams exhibit maximum peel strengths around 7.9 N/mm. Conversely, the hot air seams exhibit maximum burst pressures less than 552 kPa whereas the wedge welded seams exhibit maximum burst pressures greater than 690 kPa.

These data suggest that bursting the seam, i.e. failing it from the inside out, results in a different failure mechanism than the peel test, which fails the seam from

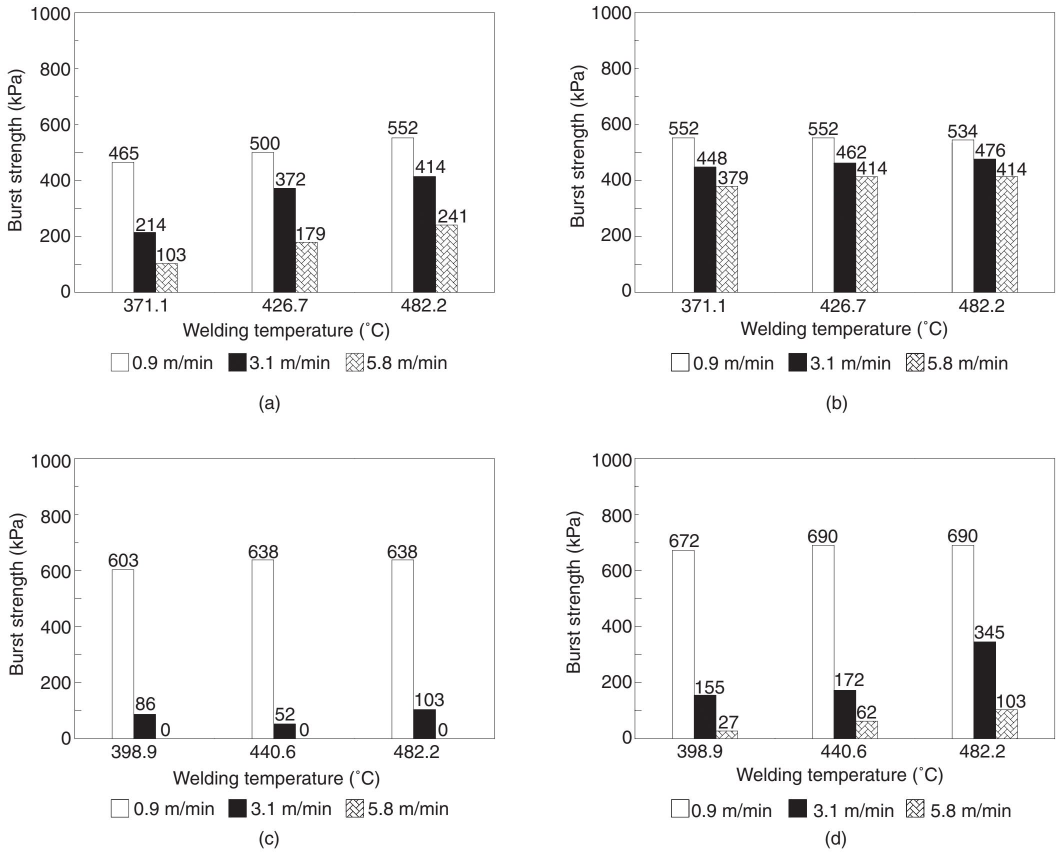

Figure 7. Seam burst pressures for 36 hot wedge welded seams, burst at 35.0°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 32.2°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 37.8°C

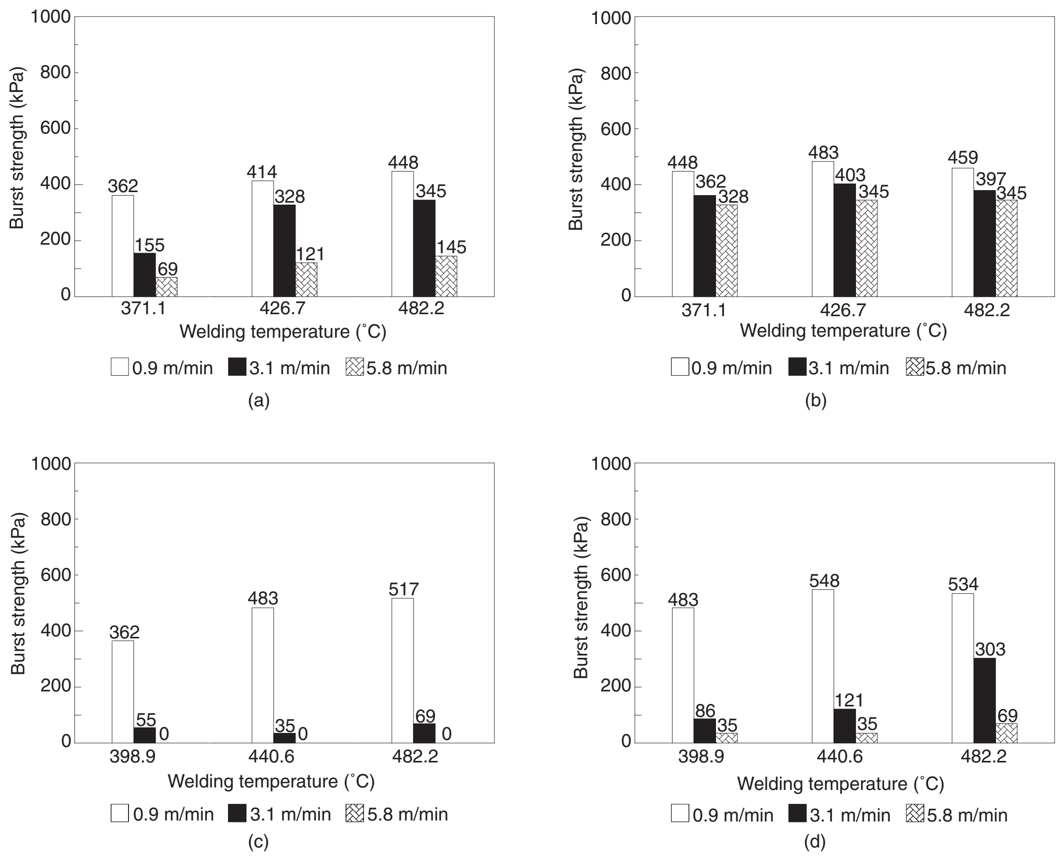

Figure 8. Seam burst pressures for 36 hot wedge welded seams, burst at 46.7°C: (a) 0.75 mm, sheet temperature 10°C; (b) 0.75 mm, sheet temperature 32.2°C; (c) 1.00 mm, sheet temperature 15.6°C; (d) 1.00 mm, sheet temperature 37.8°C

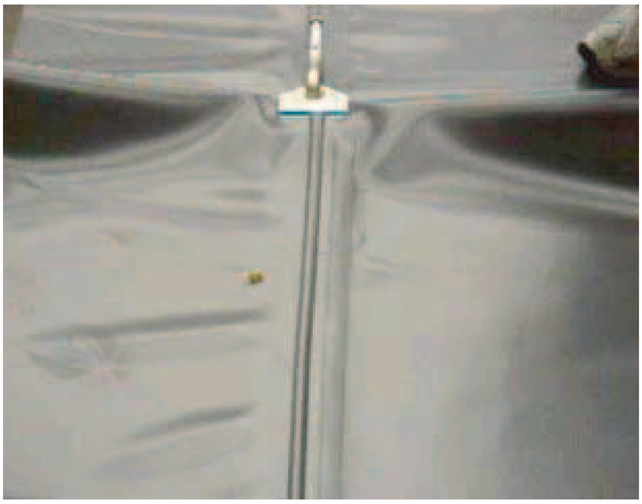

Figure 9. Inflated air channel in 0.75 mm-thick geomembrane in the field (photo courtesy of Fred Rohe, Environmental Protection, Inc.)

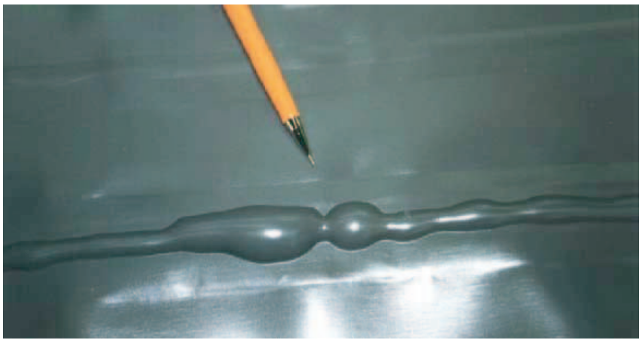

Figure 10. Inflated air channel in 0.75 mm-thick geomembrane at room temperature (22.8°C) with a problematic seam (photo courtesy of Fred Rohe, Environmental Protection, Inc.)

the outside in, or there is a difference in the weld from the inside to the outside. These different strengths, both peel and burst, will be discussed in more detail in Section 6.

As a practical matter, two of the seams burst at an extremely low pressure because of a specific weak spot in the seam. These two instances occurred at hot air welder temperatures of 441–482°C. Inspection of the weak spots appeared to have occurred because of the hot air welder ‘‘burning through’’ a portion of the geomembrane. The presence of weak spots may occur in the field at the full length of the seam will be tested by the air channel burst test. If the air channel fails to hold the required burst pressure, the area will be patched. More importantly, a major difference between air channel testing with PVC geomembranes and with high-density polyethylene (HDPE) is the flexible nature of a PVC geomembrane, which allows the technician to see the air channel inflate as the air pressure migrates down the seam. The inflated air channel somewhat resembles an inflated inner tube, and this distinctive behavior has been referred to as ‘‘inner tubing’’ of PVC seams. If a weak spot is encountered and leaks, the air channel may not be fully inflated at this weak spot. Figure 9 shows a 0.75 mm geomembrane with an inflated air channel in the field. It can be readily seen that the air channel is inflated along the seam.

Another benefit of air-channel testing of PVC seams is that problematic seams are readily visible. For example, Figure 10 shows a 0.75 mm geomembrane with an inflated air channel at a sheet temperature on the burst test (22.8°C) but the seam is problematic. It can be seen that the normally cylindrical seam or inner tube is irregular in shape, indicating weakness in the seam. However, it is important to note that the seam in Figure 10 is still maintaining air pressure even though the seam is problematic. This visual inspection would probably result in patching of the area in the field. Therefore, if ‘‘burn-through’’ occurs in the field because of high welder temperature, the inability to pressurise the seam near the weak spot will be measurable and visible in the field.

In general, increasing the welding temperature increased the peel strengths and burst pressures. Welding personnel can introduce greater temperature into a PVC seam by using a higher welding temperature, decreasing welder speed, and/or a higher sheet temperature. Welding personnel often adjust the welding speed to accommodate ambient conditions, which are reflected in the sheet temperature. For example, welders can increase welding speed during the afternoon as the air temperature and sheet temperature increase. Conversely, if clouds appear and a decrease in air temperature occurs, welders can reduce welding speed to counteract the decrease in sheet temperature resulting from the shade provided by the clouds.

6. RELATIONSHIP BETWEEN SEAM PEEL STRENGTH AND BURST PRESSURE

The main impetus for this study was to develop a relationship between air channel pressure, i.e. the burst test, and seam peel strength so that field destructive sampling could be reduced and possibly eliminated. This goal was derived from the hypothesis that a relationship between burst pressure and peel strength exists because both tests involve peeling the seam apart, albeit in different directions. This section of the paper presents the development of a relationship between burst pressure and peel strength. The relationships between burst pressure and peel strength for all of the 72 prepared seams, at three sheet temperatures in the burst test (22.8, 35.0 and 46.7°C) and both peel and FTB failure mode, are shown in Figure 11. The data plotted correspond to the lowest peel value measured for the two welded tracks and the average burst pressure of the seam to ensure a conservative relationship between peel strength and burst pressure. Notice that there are two or three cases where the relationship between peel strength and burst strength becomes non-linear. The most dramatic example is seen with the 0.75 mm seams made with the hot

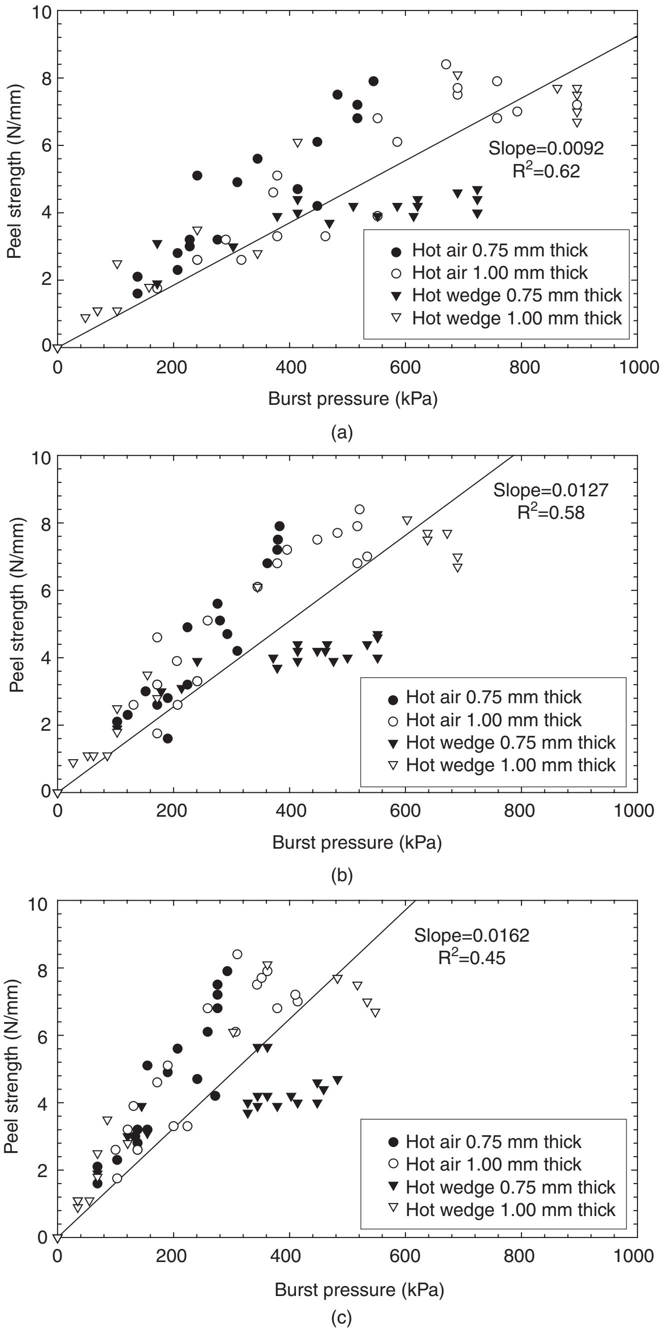

Figure 11. Relationship between burst pressure and peel strength for hot air welded seam. Sheet temperature: (a) 22.8°C; (b) 35.0°C; (c) 46.7°C

wedge welder. Notice that the relationship is linear until the peel strength approaches 3.7 N/mm. Then the peel strength stays constant while the burst strength varies over 200 kPa. This limit occurs right around the peel strength where the failure mode changes from peel to FTB. Clearly, the peel test creates a failure opportunity not present in the burst test. The simplest explanation is the fact that peel coupons have edges whereas the burst test does not. It is likely that the peel test failure is initiated by a tear at the edge of the 25 mm coupon. This is a common occurrence in peel testing because the outside edge of the seam being tested is almost never exactly perpendicular to the applied force. One edge is almost always slightly higher than the other, causing a stress concentration at the higher edge, initiating a tear. In fact, this phenomenon is where the term "film tear bond" came from. In seams that do not peel, the failure is largely a tearing of the sheet from one side of the test coupon to the other. A clear upper limit on peel strength is also seen in the results for the 1.0 mm wedge welded seams. There also may be an upper limit on the 1.0 mm hot-air welded seams, but in this case it is more obscure. Interestingly, the relationship between peel strength and burst strength remained linear for the 0.75 mm seams made by hot air, even when the seam failed by FTB. There is no obvious explanation for this. One additional point should be made. In every case of non-linearity, the burst results show that the seam is stronger, and in some cases much stronger, than the peel tests suggest. This might suggest that the burst test is actually a better test method for evaluating seam strength.

The significance of reaching a maximum peel strength for developing a relationship between peel strength and burst strength is huge. 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 strength. The resulting linear relationship is shown in Figure 12. A significant aspect of this relationship is that results for both sheet thickness and both seaming methods are described by this relationship, which suggests a generalised model.

The relationship between burst pressure and peel strength 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 12, using a regression analysis for the hot air welded seam and wedge welded seam, respectively. The ratios from Figure 12 are summarised in Table 2. It can be seen from Table 2 that, with an increase in sheet temperature, the ratio of peel strength to burst pressure increases. In other words, for a given peel strength, a lower burst pressure is expected as the sheet temperature increases. Because Figure 12 incorporates both sheet thickness and welding types, the relationship in Figure 13 can be used for sheet thicknesses of 0.75 mm and 1.00 mm and hot air and hot wedge welding.

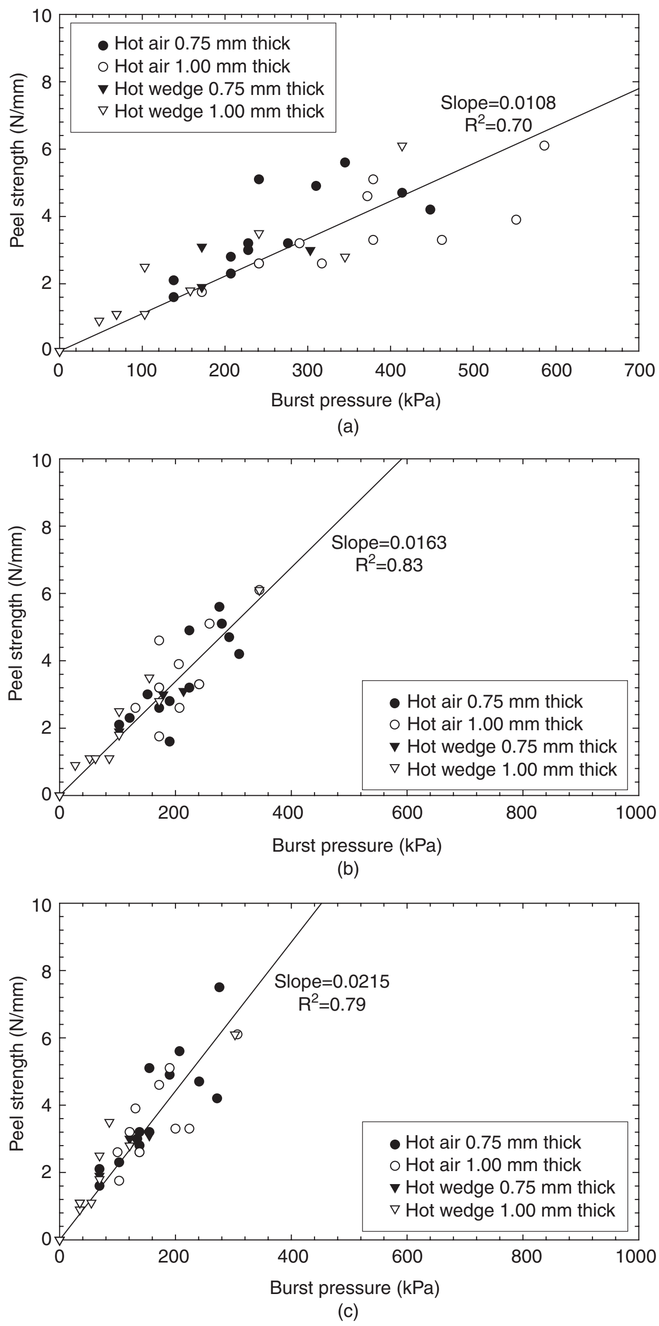

Figure 12. Relationship between burst pressure and peel strength for all non-FTB seams and 0.75 mm and 1.00 mm-thick geomembrane and hot air and hot wedge welding: (a) 22.8°C; (b) 35.0°C; (c) 46.7°C

Table 2. Relationship between burst pressure and peel strength for hot air and wedge welded seams

Sheet temperature during burst test (°C)	Peel strength (N/mm) / Burst pressure (kPa)
22.8	0.0108
35.0	0.0163
46.7	0.0215

7. RELATIONSHIP BETWEEN SHEET TEMPERATURE AND SEAM BURST PRESSURE

7.1. Background

Another impetus for this analysis was to investigate the effect of sheet temperature on burst pressure. This is an important topic because it has been reported that extremely high sheet temperatures may affect the performance and results of air channel testing in PVC geomembranes. As with all plastics and all geomembranes, PVC exhibits increased flexibility as the temperature increases. An increase in temperature also causes a lowering of the tensile strength of the parent material and a reduction in seam peel strength and seam burst pressure. Because it is proposed herein that the burst test be used as a field quality assurance/quality control test instead of destructively testing PVC geomembranes, it is necessary to determine a relationship between sheet temperature, burst pressure and peel strength. This relationship will allow field personnel to determine the burst pressure that is required for a particular sheet temperature during the burst test to ensure that the specified seam peel strength, e.g. 2.6 N/mm for 0.75 mm and 1.00 mm-thick seams, is satisfied.

7.2. Arrhenius model of seam burst pressure and peel strength relationship

As can be seen in Table 2, the slope of the burst pressure to peel strength relationship is a function of the sheet temperature during the burst test. With the use of the three slopes for the three sheet temperatures and a specified peel strength of 2.6 N/mm, the minimum burst pressure required to achieve the specified peel strength at sheet temperatures ranging from 22.8°C to 46.7°C can be estimated. Each of the data points in Figure 13 as a measured value was obtained by dividing the specified peel strength of 2.6 N/mm by the slopes in Table 2 and plotting the resulting burst pressure at the corresponding sheet temperature.

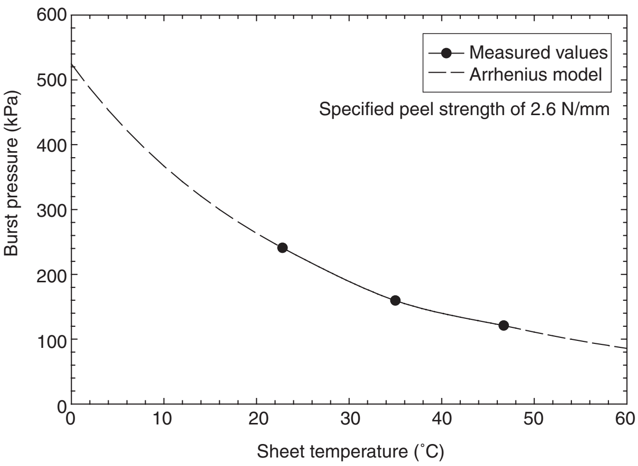

Figure 13. Burst pressure required to verify a specified peel strength of 2.6 N/mm at various sheet temperatures

To augment these data and extend the applicable temperature range beyond the 22.8–46.7°C range used in the testing, Arrehenius modelling was utilised (Koerner *et al.* 1992; Shelton and Bright 1993). Nearly all temperature-dependent properties change exponentially: therefore the Arrhenius model can be used to extend the measured relationship between burst pressure and peel strength 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. One would normally determine rate constants at elevated temperatures and extrapolate the rates to lower temperatures typical of service temperatures. The Arrhenius model has been frequently used to estimate the service lifetime of geosynthetic products (Koerner *et al.* 1992; Risseeuw and Schmidt 1990; Salman and DiMillio 1998; Shelton and Bright 1993; Thomas 2002). It is common to obtain data at temperatures approaching 100°C and use the data to predict behavior at 25°C. In this study, this model was used to extend the range of collected data (22.8–46.7°C) to a range of geomembrane temperatures that might be encountered in the field (0–60°C).

Figure 14 shows the Arrhenius plot for the effect of sheet temperature on the relationship of peel strength to burst strength. The plot presents the natural logarithm of the slopes from Table 2 against the inverse of temperature in absolute units. The resulting trend line (i.e. slope = 2.758) can be used to predict the value of the slope of a peel strength against burst pressure line for other sheet temperatures. When the slope is known, one can then calculate the required burst pressure at a particular temperature to ensure that a specific peel strength, e.g. 2.6 N/mm, is achieved. Figure 13 presents the results of this analysis for temperatures ranging from 0°C to 22.8°C and from 46.7°C to 60.0°C. The solid symbols in Figure 13 represent the data/values measured during this study, and the dashed lines represent the extrapolation of the measured data using the Arrhenius modelling for the hot air welded seam and wedge welded seam. It is anticipated that the relationships in Figure 13 can be used for field quality assurance/quality control purposes for thermally welded seams. Welding personnel could simply measure the sheet temperature, apply the required burst pressure 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. It is proposed that this procedure could be used instead of destructive seam testing, which has the disadvantages of cutting holes in the geomembrane, patching the resulting

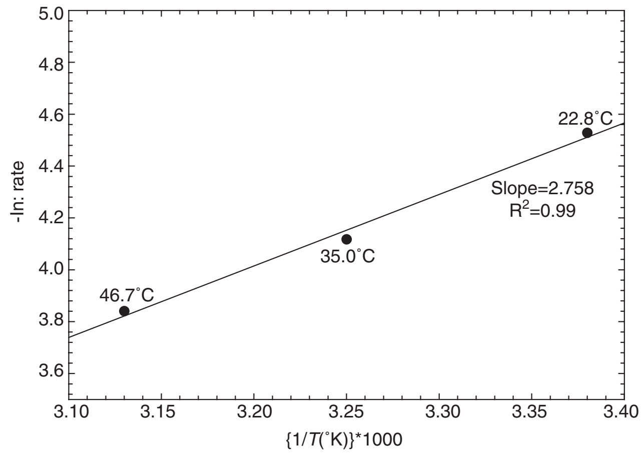

Figure 14. Arrhenius relationship between the ratio of peel strength and burst pressure to sheet temperature

geomembrane, and not testing 100% of the seam. The current practice of cutting a 1 m section each 152 m of field seam means that less than 1% of the seam is actually evaluated. The technique proposed herein evaluates 100% of the seam length. In addition, the proposed burst test for the air channel can be performed onsite regardless of the sheet temperature. Additional relationships can be developed for other values of specified peel strength using the information reported herein.

8. EVALUATION OF AIR CHANNEL TEST PROCEDURE

Before using the relationship in Figure 13 for field quality assurance/quality control (QA/QC) for 0.75 mm and 1.00 mm thermally welded PVC seams, it is important to verify the relationship. This was accomplished by predicting the burst pressure for the 72 seams created and tested during this study at the three sheet temperatures on the burst test, and comparing the predicted values with the measured values. This verification utilised a pass/fail criterion to simulate typical QA/QC procedures. Table 3 summarises the verification procedure and the number of seams that would have failed the required burst pressure from Figure 13 and thus the specified peel strength. For example, 11 of the 72 thermally welded seams failed to achieve the specified peel strength of 2.6 N/mm in standard seam testing. The burst pressure corresponding to the specified peel strength was estimated from Figure 13 for the three

Table 3. Numbers of failures predicted, using the specified value of 2.6 N/mm and Figure 13

Test method		Requirement	Number of failures
Peel strength		2.6 N/mm	11
	at 22.8°C	240.7 kPa	15
Burst pressure	at 35.0°C	159.5 kPa	13
	at 46.7°C	120.9 kPa	13

sheet temperatures, and these burst pressures were compared with the actual burst pressures for each sheet temperature. It can be seen that more seams failed the burst pressure requirement for each of the three sheet temperatures. For example, there were a total of 15, 13 and 13 failures for the burst test at the sheet temperatures of 22.8, 35.0 and 46.7°C, respectively. Therefore the burst 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.

An important observation concerning the seams that failed the burst requirement but passed the peel requirement was that most of them had peel values of 2.6 or 2.8 N/mm, which means the seams were near the pass/fail boundary. When this occurs it is likely that differences will develop between the measured and predicted values.

9. CONCLUSIONS

This paper describes an extensive study on the thermal welding of PVC geomembranes. The effects of welding temperature, welding speed and sheet temperature were evaluated for two geomembrane thicknesses and two types of welder, i.e. hot air and wedge welders, and a range of sheet temperature. The following conclusions are based on the data and interpretations presented in this paper.

- The test results show that welding speed has a greater impact on the measured peel strength than welding temperature. Therefore welding personnel can increase the seam peel strength for a given sheet temperature and welding temperature simply by reducing the speed of the welder. A welding speed in the range 0.9–2.1 m/min provides the best seams under the widest range of sheet temperature, geomembrane thickness and welding temperature. Welding speeds as high as 3.1 m/min can produce good seams, especially if the sheet temperature or welding temperature is high.
- The test results show that a welding temperature of 316°C is too low and a welding temperature of 482°C is too high for this 0.75 mm-thick PVC geomembrane. Therefore an optimal welding temperature to initiate welding of this geomembrane is about 400°C. The test results also suggest that an optimal welding temperature might range from 455°C to 468°C for a welding speed of 3.1 m/min for 1.00 mm-thick seams.
- The main contribution of this research is the development of a relationship between peel strength at room temperature (22.8°C) and the burst pressure at sheet temperatures ranging from 22.8°C to 46.7°C. This relationship will allow field personnel to perform seam QA/QC operations without conducting destructive tests. This relationship (see Figure 13) allows the seam peel strength to be measured indirectly by applying air pressure to the air channel in a dual-track weld. This field air channel test can be used instead of destructive

seam testing, which has the disadvantages of cutting holes in the geomembrane, geomembrane surface preparation such as grinding, patching the resulting geomembrane, and not testing 100% of the seam. The main advantage of the peel strength/burst pressure relationship is the ability to test the entire seam length instead of a 1 m-long coupon.

ACKNOWLEDGEMENTS

Colorado Lining of Denver, Colorado, and Environmental Protection, Inc. of Mancelona, Michigan, fabricated the thermal seams used in this study. The support of these organisations and the PVC Geomembrane Institute is gratefully acknowledged.

REFERENCES

ASTM D 6392. *Standard Test Method for Determining the Geomembrane Seams Produced using Thermo-Fusion Methods*, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

Geosynthetic Research Institute (GRI) (1994). *Standard Test Method GM-6: Testing of Geomembrane Materials*, Drexel University, Philadelphia, PA.

Koerner, R. M., Lord, A. & Hsuan, Y. H. (1992). Arrhenius modeling to predict geosynthetic degradation. *Geotextiles and Geomembranes*, **11**, 151–183.

Koerner, R. M. (1998). *Designing with Geosynthetics*, 4th edn, Prentice Hall, Upper Saddle River, New Jersey, 761 pp.

PVC Geomembrane Institute (PGI) (2003). *PVC Geomembrane Material Specification 1103*, University of Illinois, Urbana, IL.

Risseeuw, P. & Schmidt, H. M. (1990). Hydrolysis of HT polyester yarn in water at moderate temperatures. *Proceedings of the 4th International Conference on Geotextiles, Geomembranes, and Related Products*, The Hague, Netherlands, pp. 691–696.

Salman, A., Elias, V. & DiMillio, A. (1998). The effect of oxygen pressure, temperature and manufacturing processes on laboratory degradation of polypropylene geosynthetics. *Proceedings of the Sixth International Conference on Geosynthetics*, Atlanta, pp. 683–690.

Shelton, W. S. & Bright, D. G. (1993). Using the Arrhenius equation and rate expressions to predict the long-term behavior of geosynthetic polymers. *Proceedings of the Geosynthetics '93 Conference*, Vancouver, pp. 789–802.

Thomas, R. W. (2002). Thermal oxidation of a polypropylene geotextile used in a geosynthetic clay liner. *Proceedings of the International Symposium on Clay Geosynthetic Barriers, IS Nuremberg 2002*, Nuremberg, Germany, pp. 87–96.

The Editors welcome discussion on all papers published in Geosynthetics International. Please email your contribution to discussion@geosynthetics-international.com by 15 August 2004.