17

Welding of Geomembranes

Polymeric geomembranes can be welded or seamed by either thermal methods or chemical welding. Thermal methods rely on fusion of the surfaces to be joined using applied heat (this includes wedge welding, hot air welding, extrusion welding and less commonly, ultrasonic welding). Chemical seaming relies on the use of solvents to soften the bonded surfaces but this technique can only be used for those geomembranes that are softened by solvents.

17.1 WEDGE WELDING

Hot wedge welding is a thermal technique where the two opposing geomembrane surfaces to be welded are melted by passing a hot metal wedge or knife between them (see Figure 17.1 and Figure 17.2). Pressure is simultaneously applied to the top and/or bottom geomembranes to form an integral bond. Welds of this type can be made with dual (or 'split') bond tracks separated by a non-fused gap (known as the 'air channel') which is utilized for air pressure testing (see Figure 17.3). Such welds are referred to as dual hot wedge welds or double-track welds. Alternatively, a single hot wedge creates a solitary uniform width weld track (see Figure 17.4). Hot wedge welding is applicable for HDPE, LLDPE, fPP, PVC and EIA-R materials, but is generally not suited to EPDM and EPDM-R, although Trelleborg (Denmark) does make EPDM liners that are thermally weldable.

When hot wedge welding with dual wedges, two parallel seams are produced with an air channel in between that is used for field quality assessment via air pressure testing of the seam.

Hot wedge welding of geomembranes utilizes a wedge-shaped, electrically heated resistance element (see Figure 17.5) that travels between the two geomembrane sheets to be joined. As the surface of the two geomembrane sheets are being melted and seamed, a shear flow field is induced across the upper and lower surfaces of the wedge. Then, as the two sheets converge at the tip of the wedge, pressure is applied via nip rollers to form the weld (see Figure 17.6).

A Guide to Polymeric Geomembranes John Scheirs

Figure 17.1 Photograph of seaming of HDPE geomembranes liners using a wedge welder (side view). Reproduced by permission of Sotrafa

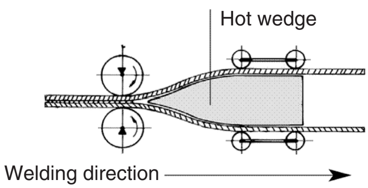

Figure 17.2 Schematic of the welding of two geomembrane sheets using a hot wedge. In hot wedge (or knife) welding a hot metal wedge is run between the two geomembrane surfaces to be seamed. Pressure is applied to the top or bottom geomembrane, or both, to form a continuous bond. Some seams of this kind are made with double weld tracks separated by a nonbonded gap. These seams are sometimes referred to as dual hot wedge seams or double-track seams. Reproduced by permission of Barry Smith, Plastic Welding Division, Plastral Pty Ltd

Modern hot wedge welding machines are largely automated and carefully control the key operating parameters of wedge temperature, travel rate and degree of pressure applied (see Figure 17.7). The non-bonded channel enables the integrity of the weld to be field assessed by pressuring the channel with compressed air and then observing whether the pressure remains constant. Any drop in air pressure can indicate there is a leak in the seam. The dual hot wedge welding methods are now recognized as the state-of-the-art in geomembrane welding.

17.1.1 THE WEDGE WELDING PROCESS

The wedge welder is a fixed overlap welder, where the welded seam is produced by the two edges of the liner going through the wedge welder (1 sheet over the wedge and one sheet under the wedge) at a fixed rate of travel (see Figure 17.8). This process melts the sheets, followed by clamping the liners together by rear pressure/drive wheels. The

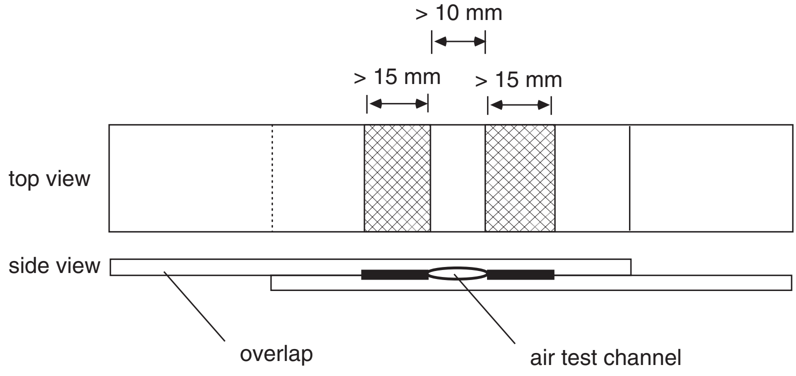

Figure 17.3 Schematic of an idealized dual wedge weld showing the optimum dimensions of the weld tracks and air channel

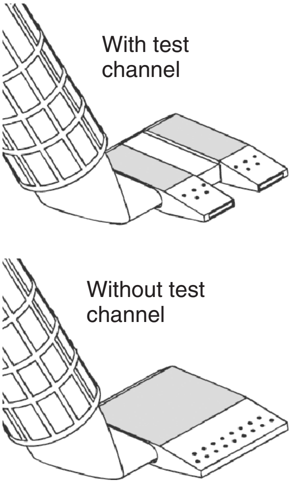

Figure 17.4 Diagrams of hot wedge designs: upper wedge produces a test channel for air testing while the lower wedge is without the test channel. Reproduced by permission of Leister

liner sections require a fixed overlap of between 8 cm to 10 cm. Trimming of the top sheet may be required to ensure that the 8–10 cm overlap is continuous along the length of the seam to be welded.

The welder travels forward with the drive wheels being at the rear of the machine (see Figure 17.9). The welder is loaded with the top liner (i.e. the sheet that will be loaded on the left-hand side when viewed from the rear of the machine) and the bottom liner (loading from the right).

The welder typically operates at a constant speed and temperature with a range between 400–430 °C once the machine is warmed up. Warmer weather will require the speed to

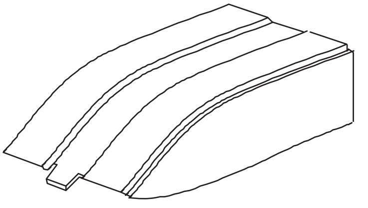

Figure 17.5 Picture of a double welding wedge for dual wedge welding of geomembranes. Note the gap in the centre which forms the air channel

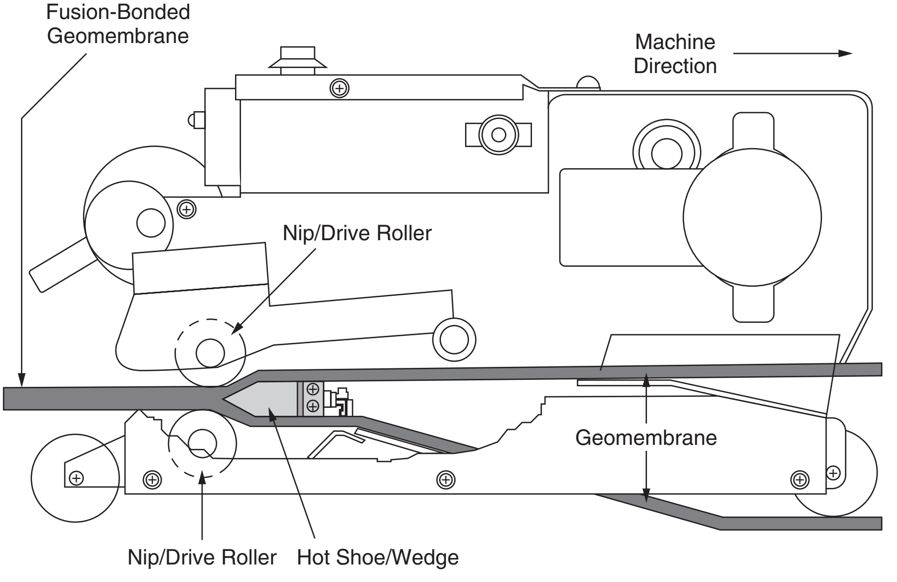

Figure 17.6 Schematic of a hot wedge welder showing the hot wedge positioned between the two geomembrane sheets and the nip/drive rollers positioned above and below the fusion-bonded sheets

be slightly adjusted upward while in colder/cooler weather it will be necessary to slow down the welding machine.

During hot wedge welding the machine runs automatically at speeds around 2.0–2.5 m/min (for HDPE) with temperatures as high as 460 °C. Considering the subgrade is often uneven, it is good practice to place one piece of a 30 cm wide HDPE strip underneath the track of the machine.

An HDPE liner of 1.00 mm or less is relatively easy to weld; however for thicknesses of 1.5–2.0 mm, welding becomes more challenging and a combination of experience, optimum welding conditions and care are required. It is important however to control the application of heat during welding of relatively thin geomembranes or else ‘burn though’ holes can result (see Figure 17.10).

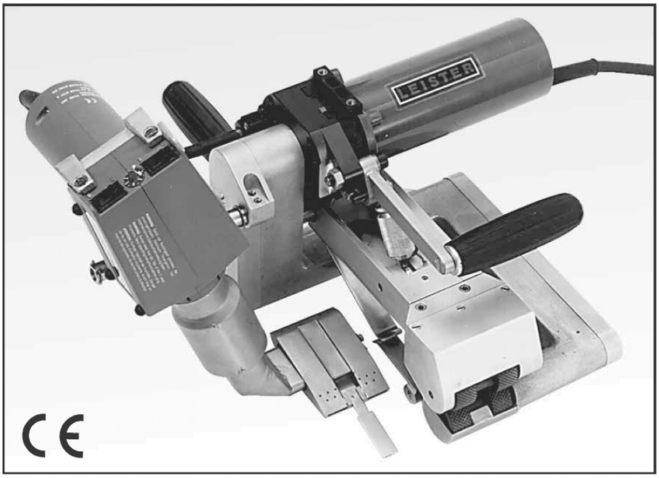

Figure 17.7 Photograph of a hot wedge welder. Reproduced by permission of Leister

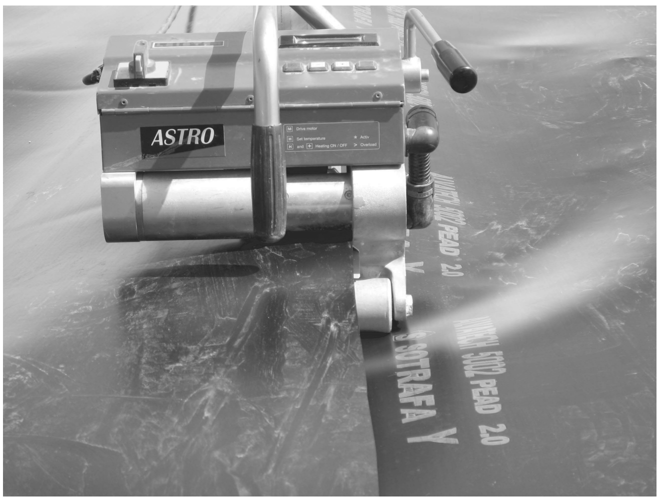

Figure 17.8 Photograph of seaming of HDPE geomembranes liners using a wedge welder (front view). Reproduced by permission of Sotrafa

Unreinforced PVC and LLDPE are lightweight materials that require careful welding. Wedge welding is not recommended for unreinforced PVC and LLDPE of a thickness less than 0.3 mm.

Reinforced PVC and CSPE (Hypalon™) are arguably the easiest geomembranes to weld as they are very compliant and forgiving. For CSPE it is important to ensure that the material has not partially cured prior to welding. Curing by exposure to heat and/or UV light will alter its structure from a thermoplastic to a thermoset material. It is impossible

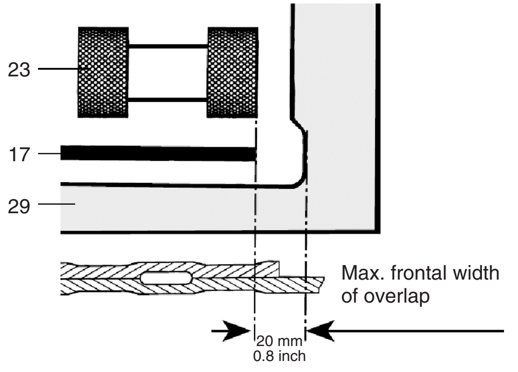

Figure 17.9 Schematic showing position of pressure roller relative to the edge of the seam. Reproduced by permission of Leister

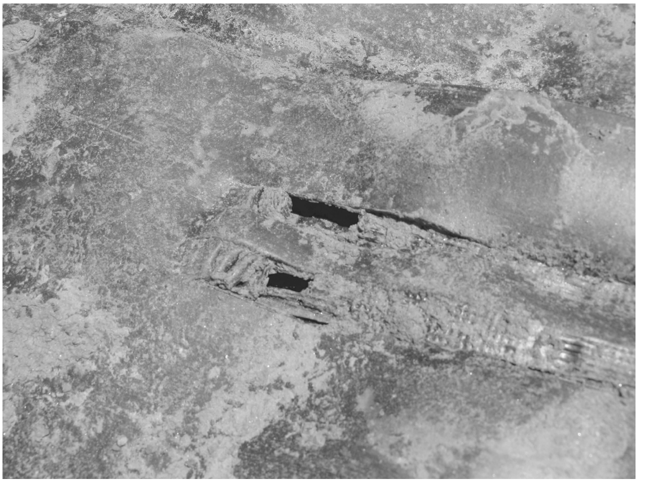

Figure 17.10 Photograph of burn-through marks on a 1 mm HDPE geomembrane (note holes in the weld tracks)

to weld thermoset materials because of their crosslinked nature. It is important to note that the manufacturers of CSPE supply a spray or liquid solvent that reverses the curing (crosslinking) process and prepares the material for wedge welding (Novaweld, 2008).

17.1.2 WEDGE WELDING CONDITIONS

Typical wedge welding parameters for common geomembranes are summarized in Table 17.1.

While the weld parameters shown in Table 17.1 are typically employed it is important to note that the welding temperature and the welder travel speed are dependent on the

Table 17.1 Typical fusion welding parameters (Agru)

Geomembrane type	Wedge temperature (°C)	Pressure (N/mm^2)	Welding speed (m/min)
HDPE	360–430	20–30	~1.6–2.8
Textured HDPE	380–420	20–30	~1.6–2.8
VLDPE	280–430	8–12	~0.8–3.5
fPP	250–480	8–12	~0.8–3.0

Table 17.2 Wedge welder temperature and speed settings (North American conditions)

Thickness/type[a]	Wedge temperature (°C)	Pressure knob (steps)	Speed (m/min)
0.75 mm HDPE	400	3	3.0
1.00 mm HDPE	400	4	2.5
1.50 mm HDPE	420	6	2.0
2.00 mm HDPE	430	8	1.3
2.50 mm HDPE	440	10	0.9
3.00 mm HDPE	450	12	0.6
1.50 mm HDPE-T	430	6	2.0
2.00 mm HDPE-T	450	8	1.3
2.50 mm HDPE-T	450	10	0.9
0.75 mm VLDPE	380	3	3.5
1.00 mm VLDPE	420	4	3.0
1.50 mm VLDPE	430	6	2.0

[a]HDPE-T, textured HDPE; VLDPE, = very low-density polyethylene.

geomembrane thickness (as shown in Table 17.2) and other factors such as the weather conditions.

Figure 17.11 shows the thermal welding temperature windows for various geomembrane types (note that fPP has a very wide seaming window).

The welding temperature and the welder travel speed are also dependent on the ambient weather conditions.

Typical wedge temperature ranges for hot wedge seaming of 0.75 mm sheet are shown in Table 17.3.

The welding temperature can be affected by ambient variations such as ambient temperature, cloud cover and wind speed. Thus it will be necessary to adjust and optimize the wedge temperature as the environmental conditions change.

Common practice when wedge welding 2.0 mm HDPE is to use a temperature of 420–430 °C and a speed of between 1.3 and 2.2 m/min depending on the ambient temperature.

17.1.3 MINIMUM REQUIREMENTS FOR A WEDGE WELDER

Wedge welding machines should have the following minimum capabilities:

- The temperature of the wedge needs to be adjustable up to 450 °C. To ensure optimal heating of the GML sheet the wedge needs to be of sufficient length. Note also that

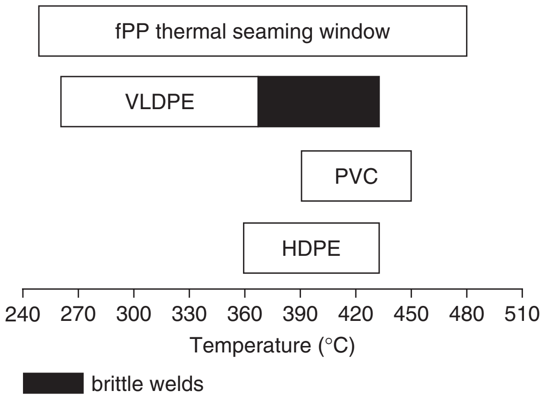

Figure 17.11 Thermal welding temperature windows for various geomembrane types

Table 17.3 Typical wedge temperature ranges for hot wedge welding of 0.75 mm polyolefin geomembranes

Liner type	Minimum warm weather temperature (°C)	Maximum cold weather temperature (°C)
HDPE	315	400
LLDPE	315	380

the gap between the wedge and the contact surface of the geomembrane liner has to be protected against direct side wind.

- The drive on the wedge welder needs to run at a constant speed of ±5 cm/min. It is necessary to ensure both nip rollers are tracking correctly or else defective welds can be created (see Figure 17.12).
- The welding pressure tolerance should be ±1 N/mm^2.

Figure 17.13 shows a schematic of a hot wedge welder. Figure 17.14 shows wedge welding occurring on a steep slope

The specifications and performance parameters of Leister wedge welders are listed in Tables 17.4 to 17.6.

It is advisable to turn off the welder drive motor when placing the geomembrane overlap in the wedge and roller assembly. After the overlap to be welded is properly positioned, the drive motor can be turned on and the seam locked in position.

17.1.4 WEDGE WELDING TIPS FOR SEAMING GEOMEMBRANES

The following are tips and hints to be mindful of during hot wedge welding of geomembranes.

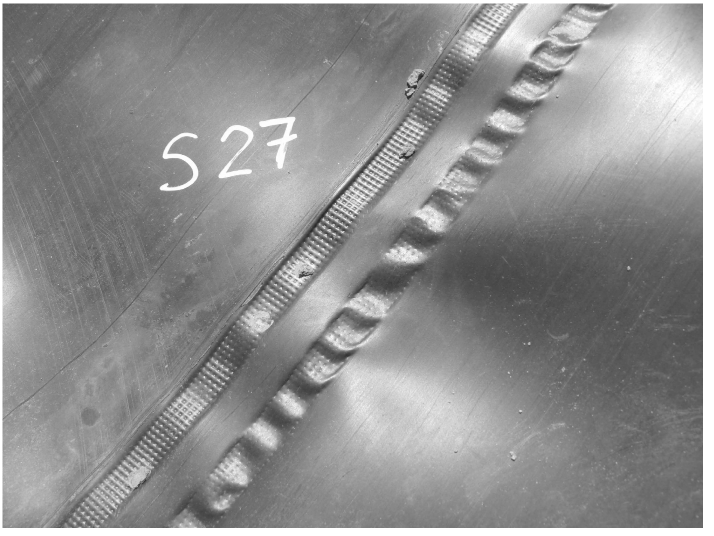

Figure 17.12 Photograph of weld tracks formed by hot wedge welding of 1 mm HDPE geomembranes. Note the poor tracking of the nip roller for the lower weld track

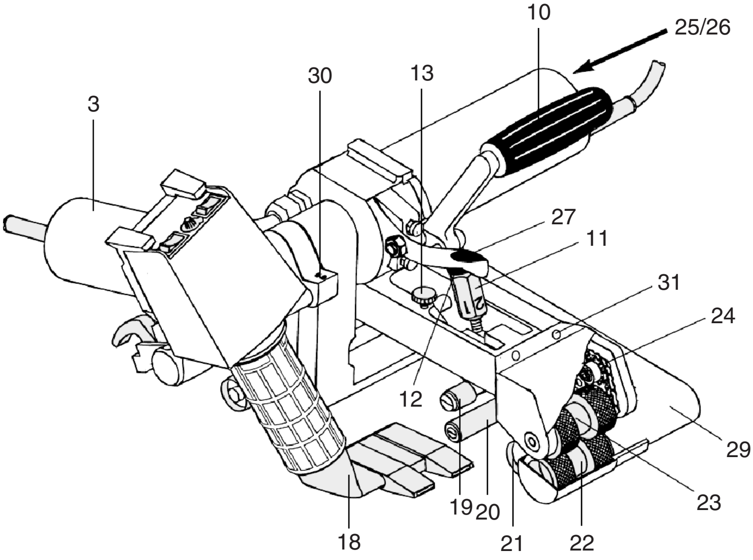

Figure 17.13 Schematic of a wedge welder (back view): hot wedge, position 18; pressure rollers, positions 22 and 23; hot air blower, position 3; lever for welding pressure, position 10; guide roller, position 20. Reproduced by permission of Leister

Figure 17.14 Photograph of a wedge welder seaming HDPE geomembranes on a steep slope. Reproduced by permission of NAUE

Table 17.4 Specifications and performance parameters of commonly used wedge welders for geomembranes (data from Leister)

Parameter	Leister Twinny T	Leister Astro	Leister Cosmo
Speed (m/min)	0.8–3.2	0.8–5.0	0.5–5.0
Temperature (°C)	20–560	20–420	20–450
Welding pressure (N) (maximum)	1000	1500	2500
Air flow (l/min)	150–190	No air flow	No air flow
Weight (kg)	7.9	23	32
Material thickness capability (mm)	1.5–3.0	1.5–3.0	1.5–3.0
Number of wedges	Single wedge	Single wedge	Double wedge
Self tracking	No	Self tracking	Self tracking

Table 17.5 Welding parameters for 1.0 mm HDPE (smooth) at 20 °C (ambient) (from Leister)

Machine	Temperature (°C)	Speed (m/min)	Pressure (N)
Leister Comet 50 mm	420	3.0	600
Leister Twinny S (short wedge)	550	3.2	500

Table 17.6 Welding parameters for 2.0 mm HDPE (smooth) at 20 °C (ambient)

Machine	Temperature (°C)	Speed (m/min)	Pressure (N)
Leister Comet 70 mm	420	1.5	1000
Leister Astro	420	2.8	1250
Leister Twinny T (long wedge)	550	1.3	1000

Note: the welding parameters shown in Tables 17.5 and 17.6 are for 'normal' weather conditions.

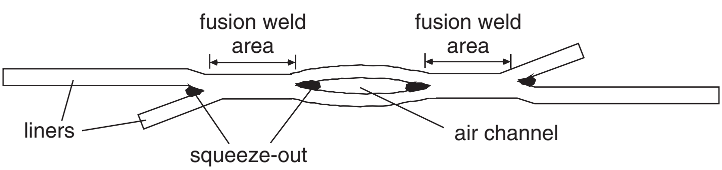

Figure 17.15 Cross-section of a dual wedge weld showing location of 'squeeze-outs' and air channel

'Squeeze-Out'

Analysis of the welds has demonstrated that there is a temperature gradient across the heated-track (i.e. the weld-track). The two edges are relatively the coolest, with the temperature increasing to a maximum at the mid-point of the track. Physically this translates into there being more molten material in the mid-region of the track. As the heated-track passes between the nip rollers which force the two molten surfaces together, a small portion of the molten material is squeezed out of the weld zone and forms what is referred to as 'squeeze-out' at each edge of the weld-track (see Figure 17.15).

In properly welded seams, the melted polymer will extrude out laterally from the seam area – referred to as 'squeeze-out'.

A small amount of 'squeeze-out' is a good sign that the proper welding temperature has been achieved. An excessive amount of extruded hot melt indicates that excessive heat and/or pressure were applied. The presence of excess 'squeeze-out' may also indicate that the seaming rate was too slow.

It should be noted that 'squeeze-out' (or 'flashing') is acceptable if it is equal on both sides and does not produce a notch effect at the edge of the weld (see Figure 17.16).

Wave Pattern

For a geomembrane with *a thickness less than or equal to* 1 mm, a long, low, sinusoidal wavelength pattern in the direction of the weld is indicative of proper welding (see Figure 17.17). If the wave peaks are too close together then the welding speed should be increased until an acceptable pattern appears. The absence of the wave pattern indicates that the welding speed is too fast and hence it should be decreased. There usually are no

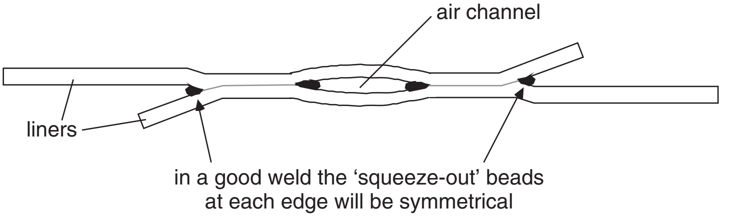

Figure 17.16 Schematic showing the 'squeeze-out' beads that occur during wedge welding and which are considered as a sign that the correct melting temperature was achieved during welding

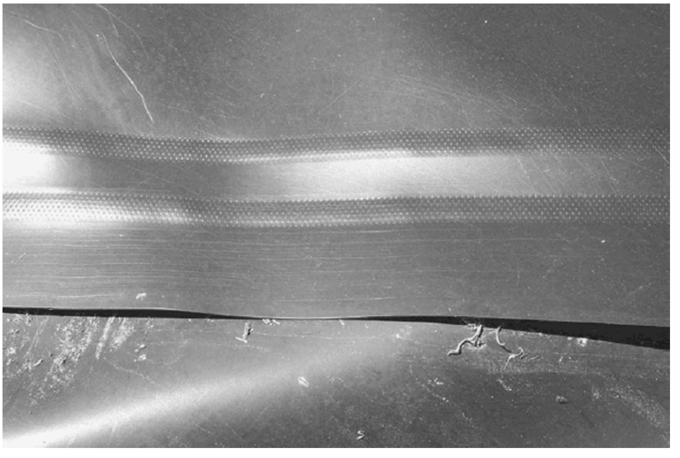

Figure 17.17 Photograph of a 'textbook' double wedge weld in an HDPE geomembrane (note the uniformity of the weld tracks and the slight undulation in the HDPE, both of which indicate good welding conditions were employed)

characteristic wave patterns evident for HDPE geomembranes with thicknesses greater than 1 mm because of the inherent stiffness of the material.

Nip Roller Marks

Nip/drive roller marks will always show on the welding track surface and are normal indicators of the wedge welding process. They should be noticeable and slightly embossed if welding pressures in the correct range were used.

Heat Distortion from Welding

If possible the underside of the lower liner should be inspected for heat distortion. This can be done at the end of seams, and wherever destructive weld samples are cut out of the seam. A small amount of heat distortion referred to as 'thermal puckering' is acceptable on relatively thin liners (e.g. 0.75–1.00 mm). A small degree of thermal puckering indicates

Figure 17.18 Photograph of a heat-affected weld in a 1 mm HDPE liner (note the buckling and distortion at the right side of the photograph)

that heat has penetrated through the entire sheet. On the other hand, if the lower liner is greatly distorted then too much heat has been applied and the corrective action is to either increase the welding speed or lower the welding temperature (see Figure 17.18). For geomembranes that are 2 mm or thicker, no thermal puckering should be observed.

17.2 HOT AIR FUSION WELDING

In hot air welding a high-temperature air or gas is introduced between the two geomembrane surfaces to facilitate localized surface melting (see Figure 17.19). Roller pressure is simultaneously applied to the top and/or bottom geomembrane, forcing together the two surfaces to form a continuous bond (see Figure 17.20). Hot air welding is applicable for thermoplastic geomembranes (e.g. HDPE, LLDPE, fPP, PVC and EIA-R) but cannot weld thermoset geomembranes (i.e. cured CSPE, CSPE-R, EPDM and EPDM-R).

Figure 17.21 shows a schematic of a combination hot air welder and wedge welder.

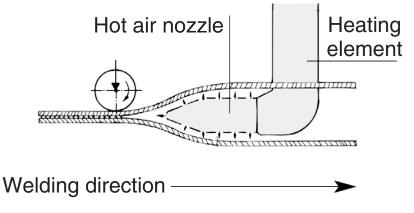

Figure 17.19 Schematic of hot air welding. Reproduced by permission of Leister

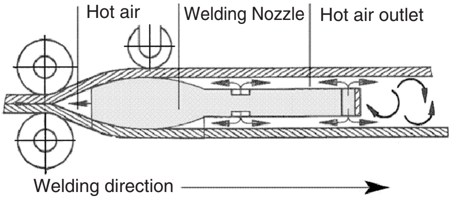

Figure 17.20 Schematic of the welding of two geomembrane sheets using hot air welding where high-temperature air is introduced between the two geomembrane surfaces to facilitate melting. Pressure is also applied to the top and bottom geomembranes, forcing together the two surfaces to form a continuous bond. Reproduced by permission of Barry Smith, Plastic Welding Division, Plastral Pty Ltd

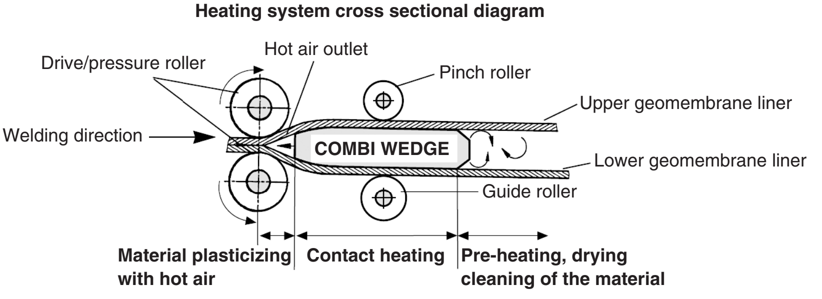

Figure 17.21 Schematic of combination wedge welding and hot-air welding. Notice that the nip rollers squeeze the weld area together. Reproduced by permission of Leister

Table 17.7 Manual hot air welding

Welding parameter	HDPE	fPP	PVC
Air temperature (°C)	280–320	270–500	450–500
Air flow (l/min)	ca. 230	Ca. 230	ca. 230
Pressure (joining force) (N/mm^2)	–	–	–
Welding speed (m/min)	0.1–0.2	0.1–0.2	0.2–0.4

17.2.1 HOT AIR FUSION WELDING CONDITIONS

The typical hot air fusion welding parameters for manual and automatic welding are shown in Tables 17.7 and 17.8, respectively. Note that in both tables, the results for fPP are obtained from SKZ[1] testing while the data for the other polymers are from the DVS Guidelines 225, Part 1.

Hot air fusion welders are generally used for thermally welded repair work. However these units require specialized operator training. Hand-held air fusion welders are capable

[1] SKZ = Sueddeutsches Kunststoffzentrum (South German Polymer Center), DVS = German Welding Society.

Table 17.8 Automatic air welding

Welding parameter	HDPE	fPP	PVC
Air temperature (°C)	350–500	230–480	450–550
Air flow (l/min)	400–600	400–600	400–600
Pressure (joining force) (N/mm^2)	25–40	20–40	10
Welding speed (m/min)	0.5–4.5	0.5–2.5	1.0–3.0

Table 17.9 Novaweld GT-100 seam strengths for geomembrane liners (Comer, 1997)

Material	Thickness (mm)	Heat setting	Shear strength (kgf)	Peel strength (kgf)	Comments
PVC	1.0	3	33	6.3	Good
CSPE	0.9	4	21.8	2.2	Poor
HDPE (smooth)	1.5	3.5	74.5	0.45	Poor
HDPE (smooth)	1.5	5	72.2	25	Good
HDPE (textured)	1.5	4.5	69	0.9	Poor
HDPE (smooth–textured)	1.5	4	60.9	1.8	Poor
VLDPE (smooth)	1.5	4	24	1.3	Poor
VLDPE (textured)	1.5	4	38.6	11.3	Good
VLDPE (smooth–textured	1.5	4	40	6.8	Good

of producing seams with good shear strength and peel strength; however the seam quality is highly dependent on operator skill and the temperature setting. Good peel strengths are not attained until the welding temperatures and pressures are high enough. If the welding temperature is too high then the geomembrane liner material begins to 'smoke' and gives off acrid fumes.

Table 17.9 highlights the importance of temperature optimization. For 1.5 mm HDPE, extremely low peel strength values are obtained when a temperature setting on the welder (Novaweld Model GT-100) of 3.5 was used. However when the temperature setting was increased to the heat setting of 5.0, excellent peel strength values were obtained. If the temperature settings on the other types of polyolefin liners were increased then their weld strengths would have increased as in the case of the smooth HDPE. The poor performance of the CSPE is likely to be due to the material being aged and the cured surface not being removed before seaming.

17.3 EXTRUSION WELDING

The extrusion fillet welding method involves extruding a ribbon of molten resin at the edge of overlapped geomembranes to form a continuous bond (see Figure 17.22). In extrusion welding the polymer substrate upon which the molten resin is deposited must be suitably prepared by slight grinding/buffing to clean the surface. The surface must be melted and mixed with the weld bead material in order to achieve a strong bond.

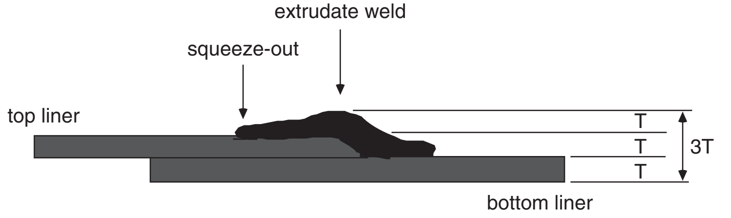

Figure 17.22 Dimensions of a typical extrusion fillet weld

Extrusion welding involves extruding a band/ribbon of molten polymer over the edges of (or in between) the two slightly roughened geomembrane sheet surfaces to be joined. The molten extrudate causes the surfaces of the sheets to fuse and after cooling the entire weld region cools and permanently bonds together. Extrusion welding is generally performed on polyolefin geomembranes such as HDPE, LLDPE, fPP and fPP-R.

Extrusion welding was the first welding technique developed for HDPE geomembranes. It is a thickness-dependant technique that requires a minimum material thickness to create an effective weld without distortion. Extrusion welds in sheets less than 1.0 mm thick are not recommended. Extrusion welds in 1.0 mm HDPE geomembranes can exhibit some distortion and can sometimes be very difficult to prepare around intricate pipe penetrations and mechanical attachments. However 1.5 mm HDPE can be reliably extrusion welded in most situations and is recommended in most applications. Welds in 2.0 and 2.5 mm geomembranes can be excellent and are recommended in applications that require exceptional durability.

Extrusion welding is very slow and is therefore typically used only for repairs and details. Extrusion welds are very difficult to prepare on vertical or overhead walls and require a minimum clearance of 1 m. This is especially important in sump details where a minimum clearance must be maintained underneath the lowest pipe penetration.

Extrusion fillet seaming is effectively the only method for welding patches on polyolefin geomembrane, as well as for seams around pipes and other appurtenances, and for difficult seams in poorly accessible areas such as sump bottoms which are difficult to access with a wedge welder. Therefore, these seams should be carefully inspected to ensure they are leak free.

The extrusion process is used primarily for detailed work around structures, pipes and other penetrations. It is also used for repair work. The hand-held extruder applies a molten layer of polyethylene material to the exposed edge of an overlapped section of liner. A large drill motor turns the extrusion screw (see Figure 17.23). Temperature is maintained by means of a temperature indicating controller which modulates the power to a heater band surrounding the barrel of the extruder. Typically, HDPE material is fed to the extruder as 4–5 mm rod. As it leaves the extruder, the molten extrudate passes through a Teflon™ and steel die (the 'welding shoe') and is deposited upon the seam in a layer about 25–40 mm wide.

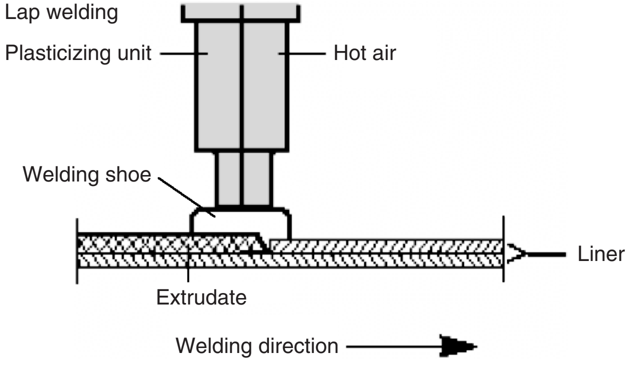

Figure 17.23 Schematic of extrusion welding. Reproduced by permission of Leister

Extrusion fillet welding is primarily used for detailed work and patching/repairs.

When the extrudate is placed over the leading edge of the seam it is termed 'extrusion fillet seaming'. When the extrudate is placed between the two sheets to be joined then it is termed 'extrusion flat seaming'. Extrusion flat seaming is seldom used today.

17.3.1 EXTRUSION WELDER REQUIREMENTS

The extrusion welder must have a calibrated temperature display (i.e. read-out) which shows the extrusion temperature.

Extrusion fillet welders employ Teflon™ dies through which the extrudate passes onto the liner. These dies must be regularly inspected for wear and notches.

17.3.2 EXTRUSION WELDING CONDITIONS

The critical parameters to be controlled in order to create an acceptable bond are temperature and welding speed. If the temperature is too high or the speed too slow then excessive melting can weaken the geomembrane or lead to excessive thinning. Localized thickness reductions can in turn lead to stress concentrations forming in those locations. Insufficient temperature on the other hand results in poor melting that causes inadequate flow of the extrudate across the weld interface and thus results in poor weld integrity and low seam strength (see Figure 17.24). Typical welding parameters for extrusion welding are shown in Table 17.10.

In extrusion welding a welding rod made of the same polymer as the liner material is fed into a hand-held extrusion gun and heated to above its melting point. The molten bead known as the 'extrudate' is then deposited onto an overlapped seam area that has been ground to remove oxidized surface material, pre-tacked and preheated by a hot air nozzle attached to the extrusion gun. A 4 or 5 mm diameter welding rod is generally used to produce an extrusion weld. The welding rod is applied as a molten bead at the edge of two overlapping liners and this produces an 'extrusion seam'.

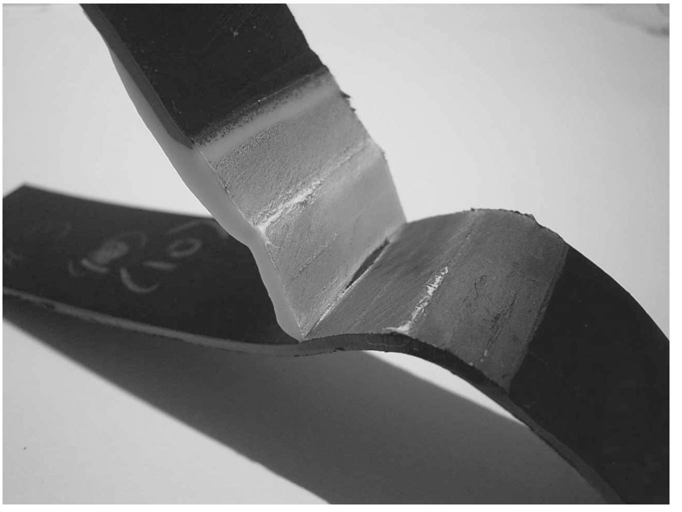

Figure 17.24 Photograph of total delamination of an extrusion fillet weld due to too low a hot air temperature (240 °C) whereas 250–260 °C is required for a good weld. Note that the extrudate weld is the lighter coloured material

Table 17.10 Typical welding parameters for extrusion welding (Agru)

Geomembrane material	Air temperature at preheating nozzle (°C)	Extrudate temperature (°C)	Welding speed (m/min)
HDPE	240–280	220	0.4 (up to 0.55)
LLDPE	240–280	220	0.4 (up to 0.55)
VLDPE	200–240	190–200	0.4 (up to 0.55)
fPP	200–240	190–200	0.4 (up to 0.55)
PVDF	260–280	225–240	0.4

Extrusion fillet welds are generally performed for patches and around details such as pipes, sumps, fittings, appurtenances (fixtures that penetrate the liner) and ‘T’- and ‘Y’-shaped seams. The butt seam at a ‘T’ intersection for example ensures integrity of the seam at an area where a wedge welder is not able to produce a uniform seam.

The two liners to be joined must be positioned to create an overlap of at least 150 mm (Agru recommends overlapping the geomembrane panels at a minimum of 75 mm). The same general guidelines as specified for liner preparation of hot wedge welding also apply to extrusion fillet welding. A hot air welder (capable of a temperature up to 600 °C) should be used to ‘tack’ the liners after they are properly positioned. The hot air gun thus prepares the seam for the extrusion welder by creating a light bond between the two sheets, thereby securing their position. It is important that no heat distortion is obvious on the surface of the upper sheet.

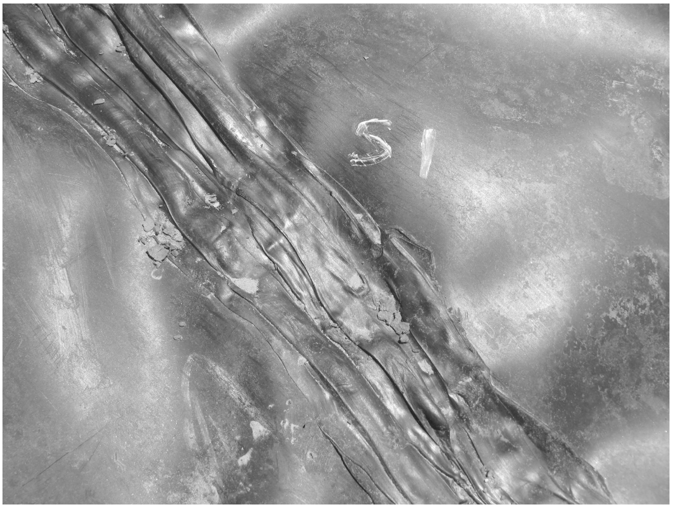

Figure 17.25 Photograph of a very poor example of an extrusion fillet weld

Extrusion fillet welding of geomembranes welding requires great operator skill and care for both the preparation step and the welding. Extrusion welding requires manual grinding of the weld area which can weaken the geomembrane due to the introduction of scores and notches. Figure 17.25 shows a 'poorly made' extrusion weld while Figure 17.26 is an example of a 'well made' extrusion weld.

When tapering the edge of the upper geomembrane, care must be taken that the lower geomembrane is not damaged by deep scoring or grooving.

Surveys of geomembrane liners have shown that extrusion welds have been found to be a significant source of small leaks when inspected by electrical leak location. The presence of a repair patch and the rigidness of an extrusion weld introduce sites for stress to accumulate under an applied load (Darilek and Laine, 2001).

Manual extrusion welds are known to fail at a far greater rate than double wedge welds.

Extrusion welds are mainly used to undertake geomembrane repairs. For instance, project specifications often require that double-wedge welded seams be destructively tested at regular intervals. The region of the seam where destructive test samples are removed must then be repaired using a extrusion fillet welder. In this process, typically, 1 m of a double wedge weld is replaced with about 3.5 m of a manual extrusion weld. It is well known in the geosynthetics industry that manual extrusion welds have a significantly higher failure rate than double wedge welds (Darilek and Laine, 2001).

Figure 17.26 Photograph of an example of a well-made extrusion weld

It is important that the extrusion welder is purged prior to beginning a weld until the heat-degraded extrudate is removed.

Extrusion Welding Procedure

The molten extrudate should be deposited directly on top of the overlapped seam with the centre of the extrudate weld positioned directly along the edge of the upper liner. The width of the extrudate should be such that it completely covers the edge of the upper liner and the majority of the underlying grind marks. The extrudate bead should be approximately twice the specified sheet thickness as measured from the 'crown' of the extrudate to the top surface of the bottom sheet.

17.3.3 EXTRUSION WELDING TIPS

The following are tips and hints to be mindful of during extrusion welding of geomembranes.

Degraded Polymer

Since polyethylene will degrade when kept molten for extended periods of time care should be taken to ensure that the liners are not welded with degraded material which has much lower strength than virgin PE. Thus the barrel of the extrusion welder should be purged of all heat-degraded extrudate for about 30 s before starting a new weld. This should be done every time the extruder welder is restarted after being idle for more than 2 min. It is also important that the extrudate purgings are not allowed to be deposited on the surface of the liner since it may damage the liner.

Poor Weldability of HDPE

HDPE contains very low molecular weight components (known as oligomers) that can bloom (migrate to the surface) of the HDPE and produce a waxy layer that makes welding and adhesion very difficult. Before thermally welding HDPE geomembranes these surface waxes need to be removed by surface grinding in the case of extrusion welding and scrapping off by the hot wedge during thermal fusion welding. Other migratory compounds that can make welding difficult are fatty acid amide lubricants that may be present in the geomembrane formulation, such as erucamide.

Welding Rod Compatibility

Weld rods used for extrusion welding are often not manufactured from the same parent material as the geomembrane. This can lead to incompatibility issues and possible stress cracking. The two principal factors to consider when determining polymer compatibility are MFI (which indicates molecular weight) and density (which indicates the degree of chain branching). Polymers with widely different molecular weights and/or chain branching are not miscible or compatible. For instance while HDPE and PP are both polyolefins they are immiscible and cannot be melt blended since they phase separate and delaminate on cooling. This leads to ‘a plane of weakness’ at the interface of the two phases. It is known that different PE resins such as HDPE and MDPE or HDPEs of different density or melt flow index or carbon black concentration can lead to ‘in-plane separation’ of the final GM.

Case Study

A fabricator was wishing to weld Solmax HDPE geomembrane with a Huikwang WR040 welding rod made from Marlex K306. It was first necessary to determine whether the two HDPEs are compatible when welded and if they form a continuous miscible integral weld.

The two polymers to consider in this case are:

- K306 (melt index of 0.11 g/10 min and density of 0.937 g/cm^3 when unfilled with carbon black).
- Petromont S7000 (melt index of 0.12 g/10 min and density of 0.937 g/cm^3 when unfilled with carbon black).

On the basis of melt index and density results these two polymers appear substantially identical and therefore should be compatible and able to form a continuous miscible integral weld when correctly welded.

It needs to be mentioned however that MFI and density are not sufficient indicators to form the basis of a comprehensive comparison. The other two important properties are S-OIT and SCR (stress crack resistance). For instance it is known that Solmax use Petromat S7000 from Canada which has an OIT of 145 min at 200 °C. The S-OIT of K307 is known to be greater than 100 min.

In regard to SCR, the datasheets list the SP-NCTL results as >400 h and >900 h for the Petromat S7000 and K306 resins, respectively. Given that the minimum acceptable value to pass the SP-NCTL test is 400 h, both these resins pass.

The above conclusion on weld compatibility is predicated on the assumption that correct welding practices are followed, including adequate surface preparation, adequate polymer fusion and adequate melt pressure/residence time.

17.3.4 SEAM GRINDING

As mentioned above polyethylene and polyproplyene geomembranes contain low molecular weight waxes (polyoils) that can migrate and diffuse to the surface of the geomembrane and make welding difficult. These waxes and oils produce a weak boundary layer. In addition to this thin layer of wax, the outermost surface of polyolefin geomembranes become oxidized and the oxidation products which are polar compounds such as ketones and acids, can also make welding difficult.

Before extrusion fillet welding, these low molecular weight waxes and oxidation by-products need to be removed from the surface of the geomembrane by grinding/buffing and the leading edge of the upper membrane needs to be beveled or tapered to a 45 degree angle. The grinding can be done with a surface grinder but care needs to be exercised that no deep grooves or notches are introduced into the sheet as a result of the grinding process since these can act as stress concentrations which are the precursors to environmental stress cracking. Poor surface preparation can therefore leave waxy residues that can contaminate the weld and lower the integrity of the seam or track.

It is important however that grind marks are not deeper than 10% of the sheet thickness. Ideally, the grind marks should be about 5% of the liner thickness. The purpose of grinding is to remove the oxidized surface layers, additive blooms and dirt from the liner surfaces.

It should be noted that the grinding marks should not extend much beyond either side of the extrudate bead. For instance, if the final extrudate bead width is 38 mm, the width of the grinding trail should not exceed 40 mm. Furthermore the orientation of the grinding marks should be perpendicular to the seam direction rather than parallel to it (see Figure 17.27).

The welding should be performed shortly after grinding so that additive blooming and surface oxide formation does not reform. Seam grinding should be completed less than 1 h before seam welding.

Sheets of sandpaper are available with different grits (#40, #60, #80, #150, #240, #600). Sandpaper 'grit' is a reference to the number of abrasive particles per inch of sandpaper. The lower the grit number, the rougher the sandpaper and conversely, the higher the grit number, the smoother the sandpaper. The rotary grinder should use #80 grit sandpaper. Sandpaper that is coarser than #80, such as #60, is not acceptable for smooth HDPE liners as it may gouge the surface and introduce detrimental stress concentrating notches.

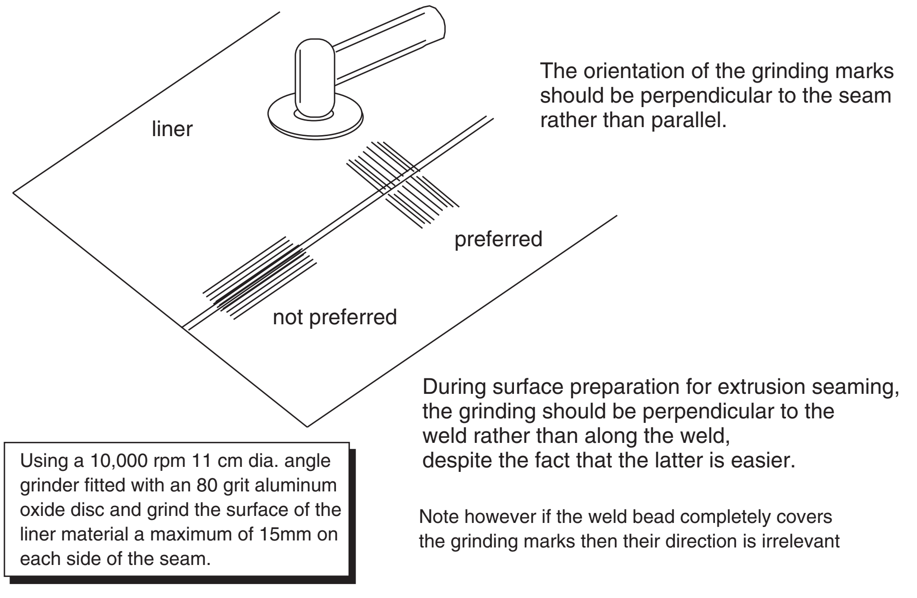

Figure 17.27 Schematic showing that grinding marks perpendicular to the extrusion weld are preferred to avoid potentially damaged score lines at right angles to tensile stresses

If the liner is 1.5 mm or thicker, the upper leading edge needs to be ground to a 45 degree bevel angle. During this procedure it is very important that the top sheet be lifted up and away from the lower sheet during the bevelling process so that no deep gouges are introduced onto the lower sheet. For this reason the bevelling procedure should be done before tack welding.

The polymer dust produced during grinding the liner must be removed from the weld area before welding.

The ends of existing welds (i.e. welds that are more than 5 min old) are ground to expose new material before restarting a weld (applies to extrusion welding only).

17.3.5 EXTRUSION FILLET WELDING CHECKLIST

Surface preparation for extrusion fillet welding requires diligent care and attention in order to obtain a satisfactory weld. This makes extrusion fillet welding labour-intensive and time consuming compared with hot wedge welding. Hot wedge welding is therefore clearly the preferred welding technique in welding situations where it is permissible. However wedge welding is not always possible in configurations such as difficult-to-access areas, around penetrations and connections in the liner, as well as for liner repair work. The quality of an extrusion fillet weld is highly dependant on the welder's skills and experience.

The following table provides a checklist of the key aspects of extrusion fillet welding.

Thin layer of surface wax and oxidation has been ground off	✔
Surface preparation has not caused deep scores, nicks or grooves	✔
Upper geomembrane has been tapered to a 45 degree bevel (if liner is 1.5 mm or thicker)	✔
All grinding marks run mainly perpendicular to the seam direction	✔
All ground material has been blown or cleaned away from weld area	✔
The extrusion welder is purged prior to beginning a weld	✔
The weld rod/extrudate is compatible with the geomembrane to be welded[a]	✔
Width of the extrusion fillet weld is sufficient to cover entire weld zone	✔
The weld is smooth and has a streak-free texture	✔
The seam has acceptable external appearance	✔
The seam has acceptable dimensions	✔
The seam has acceptable strength (both in shear and peel) (that is the seam should be ductile in shear and have no peel separation).	✔
The seam has been vacuum box[b] tested for water tightness	✔

[a]Note the weld rod should have the same or comparable melt flow rate (i.e. melt flow properties), stress crack resistance, UV stability (if used in exposed applications) and oxidative stability (i.e. oxidative induction time) as the parent geomembrane sheet. The German Guide, DVS 2207-1 'Welding of Thermoplastics – Heated Tool Welding of Pipes, Pipeline Components and Sheets made of PE-HD' (08/2007) (DVS-Verlag, 2007) specifies that HDPE resins with a melt flow rate (or melt flow index at 190 °C and 5 kg) in the range 0.3–1.7 g/10 min can be welded together.

[b]Vacuum box testing is performed in accordance with ASTM D5641 'Practice for Geomembrane Seam Evaluation by Vacuum Chamber'.

17.4 GENERAL OVERVIEW OF THERMAL WELDING METHODS

Temperature and pressure during welding should be set so that the heat and mechanical stresses on the geomembrane are minimized and long-term weld integrity is maximized.

17.4.1 RECORDING OF WELDING CONDITIONS

Welding machines need to be well maintained, regularly monitored for output consistency and all the welding parameters should be recorded. For instance in the case of hot wedge welding, variables such as welding temperature, welding speed, wedge temperature, ambient temperature, temperature of the geomembrane surface and nip roll pressure during the welding process need to be monitored to ensure that welding conditions were kept constant and also for the purpose of quality control and quality assurance. Other information to be recorded includes date, time, machine number, operator initials and installation contractor. Similar records need to be kept for fillet welding.

17.4.2 TESTING THE WELDING EQUIPMENT

Prior to embarking upon geomembrane welding, all welding equipment (both wedge and extrusion welders) must be tested in accordance with the specifications to ensure if the equipment is functioning properly. At a minimum this should be conducted at daily start-up and prior to resuming work after any break, and/or any time the machine is turned off for more than 30 min.

17.5 POTENTIAL THERMAL WELDING PROBLEMS

The quality of geomembrane welds (or seams) is significantly affected by welding temperature, welding speed, welding pressure and on-site conditions (particularly the ambient temperature). These parameters have a major influence on the long-term behaviour of the geomembrane welds. Therefore, controlling and optimizing weld process parameters are critical to achieving consistent wedge welds over a wide range of field conditions.

Theoretically, proper welding of geomembrane liners should not cause a reduction in the tensile strength across the weld as the welded sheets are expected to perform as a single geomembrane sheet. In reality, however, welding can cause a marginal reduction in tensile strength and tensile elongation relative to the adjacent parent geomembrane sheet because of the stress concentrations that arise from the weld geometry and the change in thickness across the weld. However, the converse is also observed, where the strength across the weld is higher than in the adjacent parent geomembrane (i.e. the weld performs as a local reinforcement to the liner).

Potential welding-related problems that can affect the integrity of geomembrane welds include:

- wrinkling/distortion in seam area;
- non-uniform weld;
- excess crystallinity;
- contamination in the weld such as moisture, dust, dirt, debris, wax and other foreign material within the seam;
- insufficient overlap;
- ‘score’ lines in the vicinity of the weld.

17.5.1 LOW AMBIENT TEMPERATURE DURING WELDING

The set point of the controller for the welding machine needs to be increased to compensate for the heat transfer effects of wind and temperature. Both welding processes are affected by heat transfer phenomena (i.e. the rate of heat transfer away from the welding process to the environment). The heat loss rates increase both with increasing temperature difference and increasing wind velocity. Increasing the temperature set point maintains the necessary temperature on the surface of the liner being welded.

Thus welding of geomembrane liners requires ongoing calibration during variable weather conditions. Failing to conduct adequate trial samples can cause incorrect calibration of the welding equipment. This can influence the welds adversely such that the sheets are inadequately welded together.

17.5.2 WELDING DURING HOT WEATHER

Black geomembranes (especially HDPE) in full sun on a hot day will expand and form wrinkles. This will make welding difficult and leads to abnormal strains when the geomembrane cools down. In extremely hot weather, geomembrane liner installation is recommended early in the morning or late in the afternoon or under special tents.

Wide variations in ambient temperature and resulting wider variations in sheet temperature coupled with the high coefficient of linear thermal expansion of HDPE can thus make maintaining good control of the welding parameters (e.g. uniform width of the joints) extremely difficult to achieve.

17.5.3 EFFECT OF MOISTURE ON WELDING

Rainfall or moisture on the geomembrane surface can interfere with the thermal fusion process by cooling down the geomembrane. Consequently the geomembrane does not reach the optimum and constant welding temperature required for a consistent quality weld. Hence it is necessary to ensure there is no free moisture in the weld area.

Surface water present on the geomembrane can vaporize during welding resulting in encapsulated bubbles and voids within the weld region that reduce weld strength and may ultimately result in leakage (see Figure 17.28).

When welding in wet or muddy conditions, it is recommended that HDPE off-cuts be used as 'drop sheets' under each join to keep mud and water from fouling the welding zone.

Moisture is a major concern in all geomembrane welding operations. Precipitation in any form, whether rain, snow, dew or fog can bring geomembrane installation to a halt and affect the integrity of welds.

Figure 17.28 Porosity in an HDPE weld due to entrapped moisture

17.5.4 HUMIDITY DURING WELDING

High humidity can cause condensation on the welding surface which can adversely affect seam strength. At humidity levels exceeding 80%, special care needs to be taken to ensure that the difference between the air temperature and the dewpoint is a minimum of 3 °C. This will prevent any substantial condensation of free water on the geomembrane being welded.

17.5.5 POROSITY IN WELDS

Porosity observed in moisture effected welds is often in the form of galleries and channels. This is consistent with water volatization in the weld interface during thermal fusion. The moisture-induced steam pressure causes elongated pathways. If elongated porosity is observed in the exposed surface of a weld that has undergone adhesive failure, then the likely cause of porosity is moisture in the weld zone during welding.

17.5.6 WINDY CONDITIONS

During windy conditions, the correct welding temperature may not be reached. To remedy this the welding temperature is typically increased by 20–30 °C. If the wind is too strong, the welding area should be shielded from the wind.

17.5.7 DIRT CONTAMINATION DURING WELDING

The presence of dust/debris on the weld faces is another practical problem that needs to be controlled during the welding process. Dirt and dust in the weld region can lead to poor quality welds especially in the case of textured or structured geomembranes. Crack initiation in welds can occur at defects like grit, dust and sand trapped in thermal welds. This problem can be reduced by specifying geomembranes with smooth edges that are easily wiped clean.

Some manufacturers offer geomembranes with a removable, protective plastic edge strip to keep the edges of the geomembrane contamination-free for welding (see Figure 17.29). German guidelines call for GML to have a 15 cm protective tape strip in the smooth land area to protect against surface contamination (BAM, 1999). The plastic protective strip is applied in production. The adhesion of the strip must be sufficient to prevent separation during transport and site handling but must not leave residues on the surface of the geomembrane when removed.

17.5.8 PRESENCE OF WAXY LAYERS

HDPE and fPP geomembranes contain very low molecular weight components that migrate to the surface to form a waxy layer that can make adhesion and welding difficult. When such geomembranes are thermally welded these surface waxes need to be removed

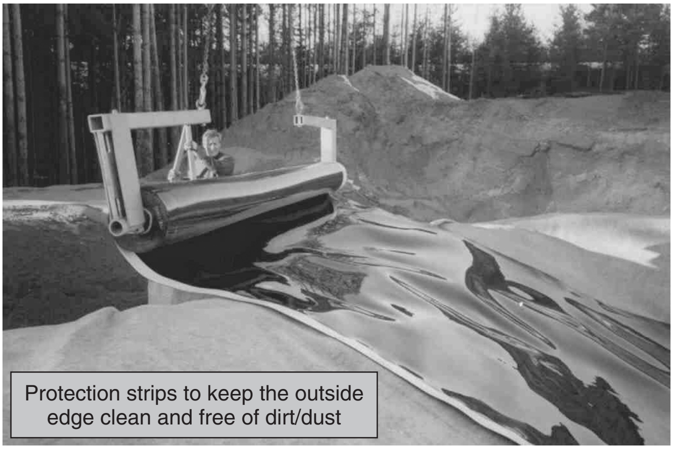

Figure 17.29 Photograph of a specialty HDPE geomembrane showing the white protection strips on the edge of the geomembrane to keep the edge clean and free of dirt/dust for welding. Reproduced by permission of NAUE

by scraping off by the hot wedge during thermal fusion welding or grinding prior to extrusion welding.

17.5.9 PRESENCE OF ADDITIVE BLOOM LAYERS

Additive 'blooms' can form on the liner surface due to exudation of the additives by migration/diffusion processes to the liner–air interface. These additives can interfere with the weldability of the geomembrane since they act as weak boundary layers. Before wedge welding, this bloom needs to be removed with a polar solvent such as acetone or limonene. Once a good fusion weld is formed then migration of additives over time will not interfere with the weld integrity.

The main factors affecting welding of polymeric geomembranes are summarized in Table 17.11

17.5.10 CONTRAINDICATIONS FOR WELDING

In summary, welding should *not* be performed when:

- the ambient temperature is below 5 °C unless special precautions are taken;
- the relative humidity is greater than 80%;
- the wind is causing significant dirt contamination in the weld zone;
- the wind is causing misalignment of the edges to be welded;
- the wind is causing localized cooling during the welding process;
- the temperature is below the dewpoint;
- there is significant water or/in the substrate beneath the geomembrane
- there is significant condensation/precipitation.

Table 17.11 Main factors (i.e. other than direct welding parameters) known to affect field welding and the quality/integrity of the resultant welds

Factor	Examples
Temperature	• the ambient temperature during welding • the surface temperature of the geomembrane panels being welded • the effect of clouds on the geomembrane temperature
Wind	• the effect of wind on localized cooling during the welding process • the effect of panel 'up-lift' during welding • misalignment of the edges to be welded due to wind forces
Water	• the relative humidity • moisture on/at the weld interface • condensation/precipitation • the water content of the substrate beneath the geomembrane
Contamination	• cleanliness of the weld interface with respect to windblown dust and debris • the presence of waxy or additive layers on the geomembrane • the extent/care to which surface preparation of the geomembrane to be joined is carried out
Support surface	• the nature of the subsurface on which the geomembrane is being seamed

17.6 DEFECTS THAT CAN AFFECT WELD INTEGRITY

There are a number of factors that can lead to weld defects and affect long-term weld integrity such as overheating of welds, scoring along welds, thickness reductions on or near welds, included dirt or particulate contamination, notch effects and stress concentrations in or near welds, stress cracking, welding of dissimilar geomembranes, etc. (Figure 17.30).

17.6.1 OVERHEATING OF THERMAL WELDS

During thermal welding the applied heat must be controlled carefully to avoid under- or overheating of the geomembrane sheets. Overheating of the polymer during welding leads to structural changes such as a reorganization of the polymer chains leading to an increase in the crystallinity of the polymer (in the case of HDPE). In addition, overheating causes accelerated consumption of the antioxidant reserves in the polymer. Both these factors increase the susceptibility of the geomembrane to stress cracking (see Figure 17.31).

An extruded bead (or extrusion weld) should not be applied to an already existing weld as this can lead to overheating of the adjacent geomembrane and render that region more susceptible to stress cracking. It is now well known that cracking failure is more likely to be initiated at such locations (see Figure 17.32).

The quality and integrity of thermal welds depends mainly on the experience/expertise of the operator and importantly the reliability of the welding machine's calibration and the accuracy of the temperature/pressure indicators. For instance, if the temperature calibration is inaccurate, then excess heat would have been applied to the geomembrane liner

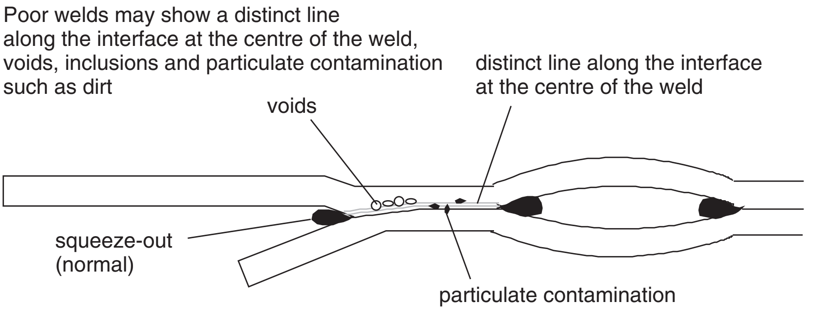

Figure 17.30 Schematic of various types of defects that can occur in wedge welds such as voids/porosity, inclusions and particulate contamination (e.g. dirt/sand)

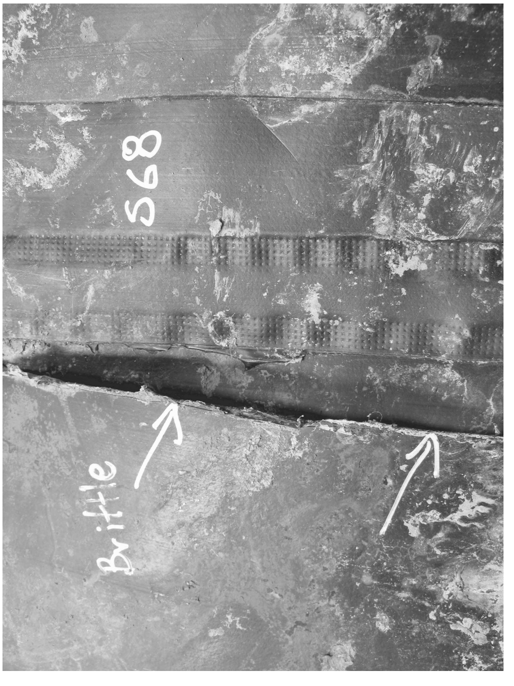

Figure 17.31 Photograph of brittle failure along the edge of a wedge weld track in an HDPE geomembrane (see crack area indicated by white arrows)

without the operator's knowledge. Overheating of the liner can also lead to considerable distortion/buckling of the geomembrane (see Figure 17.33). Figure 17.34 shows the cross-sectional view of two welds in 1 mm HDPE and the obvious distortion has been termed a 'hot day weld' due to the failure of the operator to reduce the wedge temperature (or increase the welding speed) during hot weather conditions.

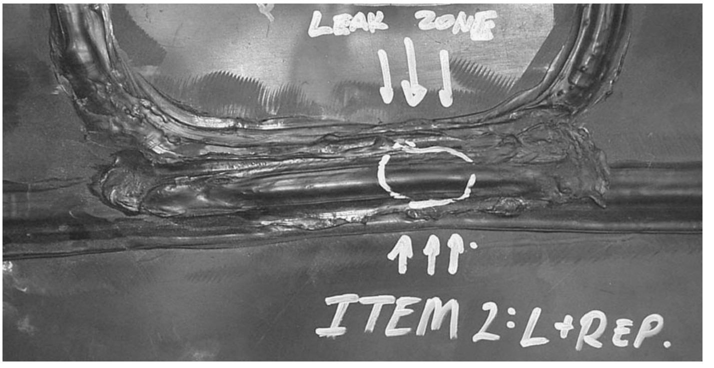

Figure 17.32 Photograph of an example of a poorly made extrusion weld which resulted in a leak zone

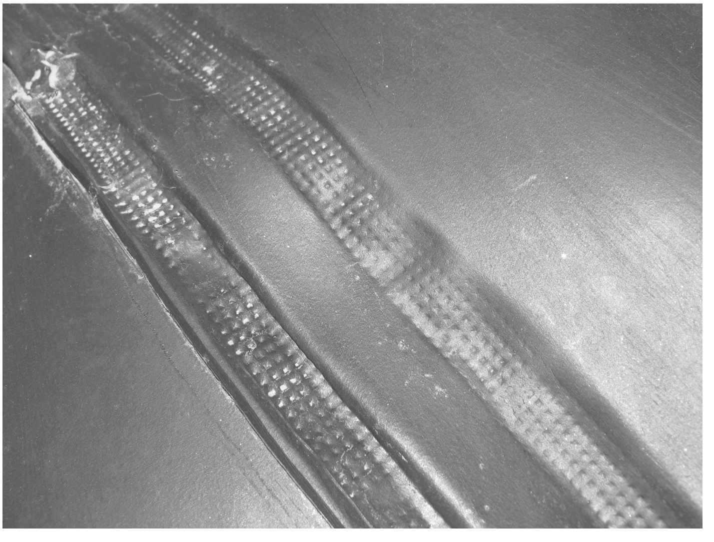

Figure 17.33 Photograph of a heat affected weld in a 1 mm HDPE liner

Points to Check:

- *check the welder's temperature calibration is correct using an external calibrated thermocouple;*
- *check the welding machine's temperature read-out is displaying the correct temperature.*

Thermal welding PVC geomembranes may lead to localized loss of plasticizer. The localized loss of plasticizer may lead to a zone of embrittlement.

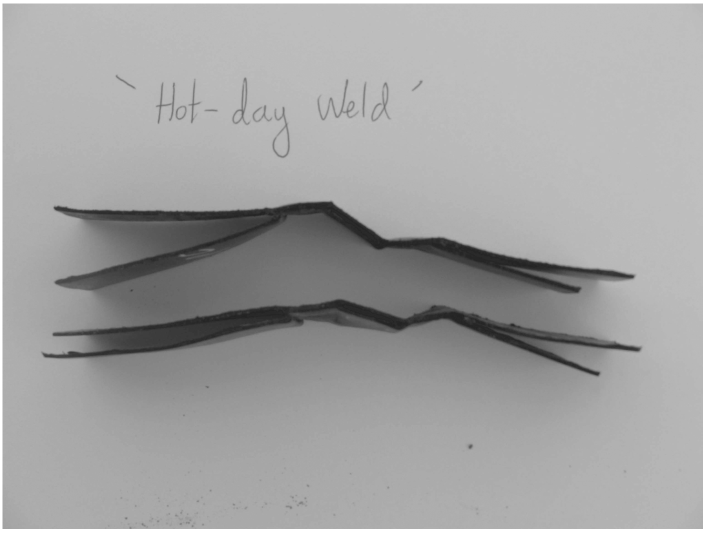

Figure 17.34 Photograph of DT weld coupons (side view) showing the distortion termed a 'hot-day weld' due to heat-affected welds

17.6.2 HEAT AFFECTED ZONE

Peggs and Carlson (1990) first identified that thermal welding of an HDPE geomembrane affects the microstructure, stress cracking resistance and durability of the adjacent geomembrane. Using constant tensile load tests for single-edge-notched specimens it was demonstrated that thermal welding of HDPE caused a reduction in the stress cracking resistance of adjacent geomembranes. This reduction in SCR was attributed to a combination of microstructural reorientation effects at the edge of the resolidified weld material and secondary crystallization of the geomembrane in the heat affected zone (HAZ) of the adjacent geomembrane (Peggs and Carlson, 1990).

17.6.3 SCORING ALONG WELDS

Welding machines can sometimes score the geomembrane in the process of welding, thereby creating a flawed region that can initiate cracking under an applied tensile force. This scoring may be detected by destructive shear testing since it will manifest itself as a sample having low elongation.

17.6.4 THICKNESS REDUCTION ON AND NEAR WELDS

Thickness reduction in geomembranes can have important implications with respect to durability of the geomembrane. Firstly a thickness reduction implies less material per cross-sectional area to resist loads, but more importantly it is the stress concentration effect that results from an abrupt change in thickness that is of concern.

Thickness reduction in geomembranes can arise from the following causes:

- Grinding down of geomembrane in preparation for extrusion fillet welding can lead to a thickness reduction immediately adjacent to the weld.
- Scoring and scratches due to improper handling and a lack of care during geomembrane installation.
- Imprinting (deformation) of a hard geonet into a softer geomembrane under the pressure of overburden loads (Giroud, 2005).

Such geomembrane thickness reductions can have a marked effect on weld behavior if they occur in the vicinity of a weld. Stress concentration can occur when there is a localized thickness reduction occurring adjacent to a weld.

In wedge welding the fact that the centre of the track has more molten material, which is subsequently squeezed out by nip pressure, is demonstrated by measuring the thickness of the weld across its width. Invariably the centre of the weld is thinnest and the thickness gradually increases towards each edge of the weld-track (see Figure 17.35).

An important parameter for determining weld quality is the 'thickness reduction' due to welding. The thickness reduction (T_r) is defined as follows:

$$T_r = (T_t + T_b) - T_w$$

where:

T_r = thickness reduction

T_t = thickness of the top geomembrane

T_b = thickness of the bottom geomembrane

T_w = thickness of the weld

The seam thickness reduction is defined as the difference between the thickness of the two original geomembranes and the welded seam thickness (as measured by an ultrasonic thickness gauge or by Vernier calipers). The reduction of thickness in the weld area (i.e.

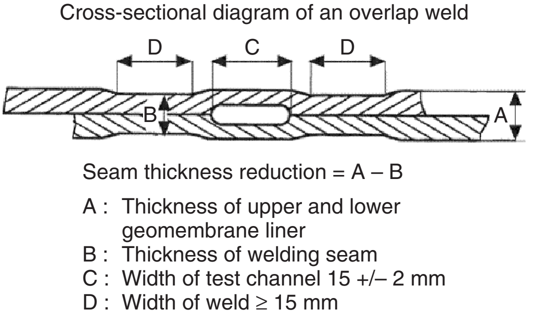

Figure 17.35 Schematic of a cross-section of a double wedge weld. Reproduced by permission of Barry Smith, Plastic Welding Division, Plastral Pty Ltd

seam thickness reduction) can influence the long-term behaviour of a weld, particularly its strength and water tightness. The seam thickness reduction reflects an interaction of welding parameters under changing field conditions (geomembrane temperature, humidity, moisture, wind, etc.) during the welding process. The weld thickness uniformity is an indicator of how constant the welding process was maintained and the uniformity of the seam itself.

It is necessary to limit the extent of the thickness reduction to within a predetermined acceptable range (Lueders, 1998).

The allowable seam thickness reduction range must be within 0.2–0.8 mm for 2.5 mm thick HDPE geomembrane according to the German guide DVS 2225, while the allowable seam thickness reduction for 1.5–2.0 mm HDPE should be within 0.2–0.7 mm.

17.6.5 STRESS CRACKING OF WELDS

A study on comparative testing of HDPE geomembrane sheets and welds according to ASTM D-2552 (stress rupture under constant tensile load) found that the sheets could resist stress cracking better than the welds, with about 40% of the welds exhibiting cracking compared to only 1% of the sheet samples which cracked (Halse *et al.*, 1989). The stress cracks that formed were examined and it was evident that the cracks which appeared in the welded specimens were almost always initiated near the overlapping junction of the two geomembrane sheets where the stress concentration was likely to be highest. It was also observed that the cracks were preceded by crazing which formed in a direction perpendicular to the applied stress.

17.6.6 'SQUEEZE-OUT' STRESS CONCENTRATION IN WEDGE WELDS

The weld 'squeeze-out' at the edge of the extruded bead is generally not completely (i.e. 100%) bonded to the sheet leading to the propensity for notch-like stress concentrations to develop there (see Figures 17.36 and 17.37). This can cause issues in cold climates since water ingress into the notch will freeze at sub-zero temperatures causing peel forces (i.e. weld opening forces) to be exerted at the 'squeeze-out' notches.

17.6.7 NOTCH EFFECTS IN EXTRUSION WELDS

A characteristic common of extrusion welds is that the weld bead edges are not completely and intimately bonded to the geomembrane. The hottest part of the weld bead deposited on the liner is at the centre and a temperature gradient develops towards the edges due to faster cooling. As a consequence the edges of the weld bead are not as well bonded to the geomembrane as the central portion. The same is true for the start and the end of an extrusion weld track. Edges and extremities of welds have a tendency for less than 100% bonding to the parent, hence peel-back forces can develop and concentrate at these notch shaped features (see Figure 17.38).

It is important that cuts or tears in a geomembrane are cut out in a round hole and then patched using an extrusion weld as this will prevent the rip propagating (see Figure 17.39).

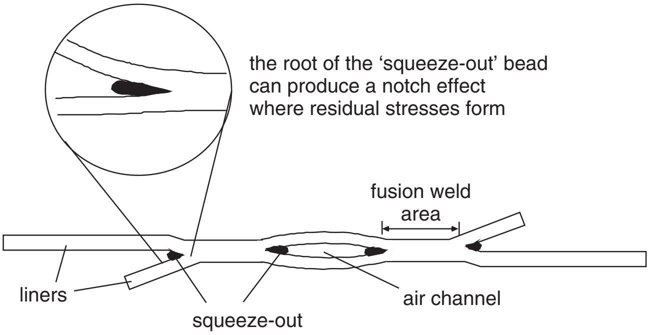

Figure 17.36 Cross-section of a dual wedge weld showing that a notch effect can occur at the root of the 'squeeze-out' bead

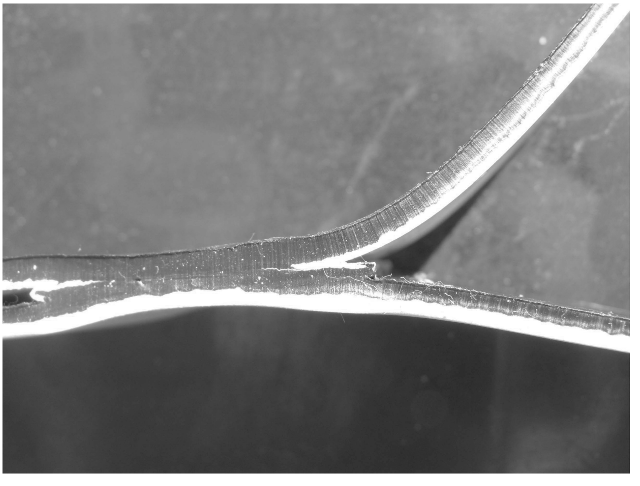

Figure 17.37 Photograph of the notch effect in a welded HDPE geomembrane

17.6.8 WELDING OF DISSIMILAR GEOMEMBRANES

Welding problems can occur when welding different geomembrane types together such as:

- LLDPE to HDPE;
- fPP to HDPE (very problematic);
- FHDPE to HDPE (note FHDPE is fluorinated HDPE);
- white HDPE to black HDPE (though not normally problematic);
- old to new GML (since old liners can have a surface layer of oxidation).

Old geomembranes can have an oxidized surface and if not removed these oxidized compounds can reside in the weld as a plane of weakness. Therefore before welding begins the oxidized surface should be removed by light grinding.

Figure 17.38 Cross-section of a fusion weld in an HDPE geomembrane showing crack formation

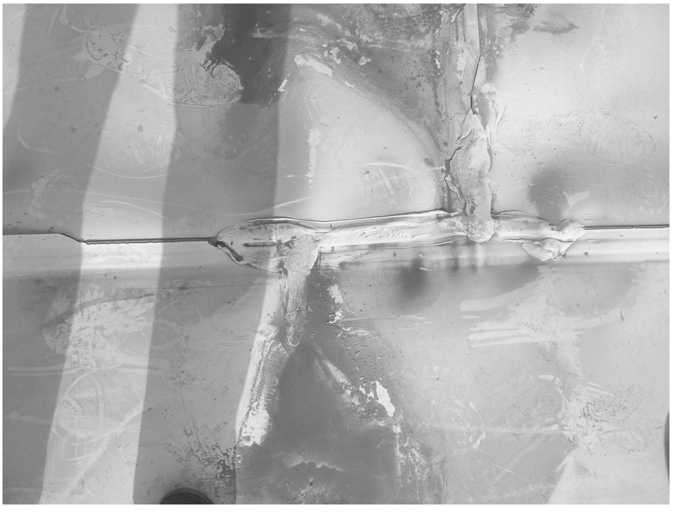

Figure 17.39 Photograph of extrusion welding used to repair a rip in a white HDPE geomembrane. Unfortunately the rip continued to propagate (see left of image). In order to prevent this it is necessary to cut a round hole at the end of the rip and seal it with a patch. Reproduced by permission of NAUE

The general rule is that only geomembranes made from the same resin may be welded together. If the welding of geomembranes made from two different resins is unavoidable, then the two resins must either be in the same melt flow rate (MFR) group as defined in DIN 16776-1 or in the MFR groups 006 and 012 (BAM, 1999).

17.7 TRIAL WELDS AND FIELD WELDS

17.7.1 PANEL PREPARATION

Prior to welding, the adjoining geomembrane sheets need to be overlapped a minimum of 100 mm (and in no case less than 75 mm at any location). The overlap should not exceed 150 mm for double-wedge fusion welds. Weld overlaps on the bottom area of an impoundment or canal should be made such that the direction of flow over the lined surface is from the top sheet toward the bottom sheet to yield a 'shingle effect'.

The edges to be welded require thorough wiping and cleaning to eliminate any dirt, dust, moisture or other foreign materials. All field welds must be uniform in appearance, width and properties, with no observed warping due to overheating from welding. The peel and shear strengths of the welded welds must comply with the strength criteria shown in Table 17.12.

17.7.2 TRIAL WELDS

Trial welds (also referred to as 'qualifying' welds) are test welds on the same geomembrane as that to be installed. They are performed for the purpose of qualifying that the

Table 17.12 Recommended test method details for geomembranes and geomembrane seams in shear and in peel

Test details	HDPE	LLDPE, fPP	PVC	fPP-R, EIA-R, EPDM-R, CSPE-R
Tensile Test on Sheet				
ASTM test method	D-6693	D-6693	D-882	D-751
Specimen shape	Dumb-bell	Dumb-bell	Strip	Grab
Specimen width (mm)	6.3	6.3	25	100 (25 grab)
Specimen length (mm)	115	115	150	150
Shear Test on Seams				
ASTM test method	D-6392	D-6392	D-882	D-751
Specimen shape	Strip	Strip	Strip	Grab
Specimen width (mm)	25	25	25	100 (25 grab)
Specimen length (mm)	150 + seam	150 + seam	150 + seam	225 + seam
Peel Test on Seams				
ASTM test method	D-6392	D-6392	D-882	D-413
Specimen shape	Strip	Strip	Strip	Strip
Specimen width (mm)	25	25	25	25
Specimen length (mm)	100	100	100	100

welding contractors are using the optimum welding conditions and to identify whether the welding equipment and procedures are performing adequately. Trial seams can also be used for pre-qualifying various contractors by ranking the strength of the test welds they produce.

Trial welds seek to simulate all aspects of the on-site field welding activities intended to be performed on location using identical geomembrane material under the same climatic conditions as the actual field production welds (and on a horizontal or vertical concrete or soil substrate accordingly) in order to determine equipment and welding operator proficiency.

Trial welds are generally conducted by welding technicians prior to each seaming period as specified or as directed by the project engineer if welding problems are suspected. Unless authorized by the project engineer, once qualified by a passing trial weld, welding technicians should not change parameters (temperature, speed, wheel adjustment) without performing another trial weld.

The trial seams should be performed on strips of geomembrane from approved rolls to verify that welding conditions are adequate. Such trial welds should be made at the beginning of each welding period (start of day, midday and anytime equipment is turned off and allowed to cool down) for every welding apparatus used. A trial seam sample shall be approximately 1.0 m long by 0.3 m wide (after welding) with the seam centred lengthwise. Seam overlap is nominally 100 mm with a minimum acceptable overlap of 75 mm.

The trial welds are tested under both shear and peel conditions using a field tensiometer, and they should not fail in the seam (also needing to meet minimum specified strength criteria). Five peel and five shear specimens shall be cut from the centre of the trial seam and tested alternately in peel and shear respectively (note that the precise number of specimens to be tested in shear and peel varies and is set by the project engineer). In the event of nonconformance, an additional trial seam shall be made and tested. If this still fails to meet specifications the welding machine shall be examined and adjusted and not used for production seaming until two passing trial welds have been made.

Trial welds shall be produced each day, at the start of each workday, and thereafter at least once every 5 h of continuous operation, after each break in seaming of 30 min or longer, following a break that results in equipment replacement or shutdown. New trial welds will also be required whenever the geomembrane temperature changes by more than 25 °C.

Recommended test method details for geomembranes and geomembrane seams in shear and in peel are shown in Table 17.12.

17.7.3 FIELD WELD STRENGTH

Typical requirements for field welds include:

1. When the weld is tested in **shear** in accordance with ASTM Standard D-6392 (or ASTM D-4437), the specimen shall exhibit a film tear bond (FTB)[2] failure, and the

[2] FTB refers to failure only in the parent material of the geomembrane and not in the weld area. It is deemed to be an acceptable form of failure. Due to different interpretation by different people its use is discouraged today although it still appears widely in many project specifications.

Table 17.13 Typical weld strength criteria for HDPE geomembranes (kN/m)

Thickness	1.00 mm	1.5 mm	2.0 mm	2.5 mm
Peel	10.5	15.9	21.2	26.4
Shear	14.0	21.0	28.0	35.0

strength shall be equal to or greater than the values specified in Table 17.13. The tests shall be performed at a rate of displacement of 51 mm/min (2 in/min). Some specifications allow a faster rate (i.e. 510 mm/min) of travel after the maximum load is reached.

2. When the weld is tested in **peel** in accordance with ASTM Standard D-6392 (or ASTM D-4437), the specimen shall exhibit an FTB failure and/or the liner must fail before the weld, and the strength shall be equal to or greater than the values specified in Table 17.13. The peel strength criteria shall apply to both the primary and secondary welds of double-wedge fusion welds.

The following pass/fail criteria are commonly used to determine compliance of field welds with the strength criteria shown in Table 17.13:

1. All five weld specimens from a given sample or coupon tested in peel (both weld tracks in the case of double-wedge fusion welds) and all five specimens tested in shear shall exhibit the required strengths, and display film tear bond (FTB) failures (i.e. no allowance for failures based on strength and no non-FTB failures).
2. All five weld specimens from a given sample or coupon tested in peel and all five specimens tested in shear shall exhibit the required strengths and at least four out of five test specimens, for each type of test, shall exhibit a film tear bond (FTB) failure (i.e., 0% strength failures and up to 20% non-FTB failures are permitted.
3. One weld specimen from a given sample or coupon tested in peel or shear may exhibit a non-FTB failure and a strength no less than 80% of the specified strength provided that all five field weld specimens tested from the duplicate (or archive) sample coupon exhibit the required strength and no more than one test specimen out of the five additional specimens exhibits a non-FTB failure.

Despite the above pass/fail criteria it should be recommended that all welds pass. Good welders can easily achieve that these days.

If a field weld fails the criteria specified, then additional coupons may be obtained (as agreed by the various site staff), at progressively increasing distances from both sides of the failed sample, until two consecutive samples on each side of the original sample pass the field weld criteria. At that point, the extent of the original defect in both directions along the field weld will be considered isolated and the Liner Contractor may then: (i) either cap, re-weld and re-test the weld up to and including the closest of the two passing samples, and patch and weld the hole of the furthest passing sample, or (ii) cap, re-weld and re-test the entire length of sampling.

If approved by the Site Engineer, double-wedge fusion welds may be repaired by extrusion welding the flap of the top sheet to the bottom sheet if the weld non-compliance is due only to a non-FTB failure of the destructive test sample.

The pass criteria in destructive weld testing are summarized in Table 17.14.

Table 17.14 Pass/fail criteria in destructive weld testing

Pass criteria	Comments
The weld specimen must fail outside of the weld region and the entire weld must remain intact	This is denoted as a 'film tear bond' (FTB) failure. Note use of the FTB term is being phased out.
The failure force reached should be greater than the specified values for shear and peel, respectively	For the ***shear*** test, generally the specified value is 85 to 95% of the parent sheet value. For the ***peel*** test a value between 50–80% of the parent geomembrane sheet is usually specified for thermal fusion welds since the peel test is a more severe test than the shear test
The elongation at failure for the shear test should achieve the minimum threshold value	There must be clear elongation outside of the weld (e.g. at least 50% and preferably greater than 100% break elongation)
The peel test specimen should not delaminate or separate more than a specified amount at failure (e.g. not more than 10% across the weld front)	No delamination is highly preferred

17.8 CHEMICAL WELDING OF GEOMEMBRANES

Chemical welding of geomembranes uses some form of solvent or solvent cement to seam the liner. Chemical welding is very versatile allowing many complex and detailed seam configurations to be achieved. Note that chemical welds are not made with a glue but with solvents that dissolve and soften the surface of the liners.

Chemical fusion joining applies mainly for PVC, EIA-R, TPU and CSPE-R geomembranes since these polymers can be readily dissolved by appropriate solvents. A solvent (e.g. methyl ethyl ketone (MEK)) is applied between the two geomembrane sheets to be joined. The solvent causes the surfaces of the liner to soften and then roller pressure is applied to intimately bond the sheets together. The softening and solvation of the two adjacent materials allows increased mobility, interpenetration and entanglement of the polymer molecules at the surface. Note HDPE, LLDPE and fPP cannot be chemically welded as these polymers have no solvents at ambient temperature.

It is important that the amount of solvent applied is carefully controlled as too much solvent will lead to over softening, solvent entrapment and will weaken the sheet material. Sometimes the solvent is converted to a solvent cement by dissolving some of the parent polymer in the solvent to increase its viscosity and retard the evaporation rate. The solvent or solvent cement is brushed onto the geomembrane surfaces to be bonded. A list of typical solvents for chemical welding of polymeric geomembranes and liners is shown in Table 17.15.

In the case of chemical fusion welds and adhesive seams, strength testing is best done after full curing which takes several days. Alternatively a field oven may be used to accelerate the curing of the weld.

Table 17.15 List of typical solvents for chemical welding (Layfield, 2008)

Liner material	Solvent[a]
Flexible PVC	THF
Supported PVC	THF
CSPE	Xylene
CSPE-R	Xylene
Urethane (certain grades)	Xylene or THF

[a]THF, tetrahydrofuran; xylene is not permitted in potable water applications as it is a suspected carcinogen.

Thermoset geomembranes, like EPDM and nitrile rubber, generally require bonding by chemical adhesives or vulcanization tapes, although Trelleborg modify the surface of their EDPM liners so they can be thermally welded.

PVC produces excellent solvent welds and has the versatility of being easily field solvent welded enabling excavation contractors to install a PVC liner without specialty crews. Solvent welding of seams, patches and pipe boots can all be done by the excavation contractor, thereby making PVC liners the lowest installation cost alternative.

Note there is an important distinction between a glue bond and a chemical weld. Glues or adhesives have only been found to last 7–8 years in service. A glue is actually a different polymer than the liner material and forms a distinct layer between the two liner sheets. Such glues are commonly based on epoxy or acrylic polymers. The extreme conditions that a geomembrane liner is subject to in service often limits the expected glue service life. In contrast, chemical welding is a permanent process capable of producing bonds that will last as long as the liner material.

A chemical weld is formed when the opposing faces of each liner surface are joined in a controlled fashion with a welding solvent. The welding chemical is a volatile solvent that is blended with other solvents or dissolved parent polymer to control the speed at which it dissolves the surface of the liner material and to control its rate of evaporation. The welding chemical can be brushed, poured or squirted onto the liner surface before they are pressed together. By carefully pressing the semi-dissolved liner surfaces together a bond is formed in a similar manner to a thermal bond made by thermal fusion welding. The solvent 'flashes off' or evaporates, and after about 24 h a homogeneous weld with no foreign material between the two liner surfaces is established (Layfield, 2008).

Chemical welding is also one of the most versatile welding processes. In liner installations it is easier to perform detail work with a chemical weld than with most heat welding processes. Chemical welding is suitable for small as well as large projects and has a low initial skill level; workers can be trained to make effective welds quickly and reliably.

Rather than using straight solvents, chemical welding is usually performed using a 'bodied solvent'. A bodied solvent is a chemical welding solvent that has between 5–25% of the parent liner material dissolved in solution. This additional 'body' allows the solvent to be placed on vertical surfaces, helps to fill in uneven surfaces and slows down the cure time in very hot welding conditions.

Table 17.15 shows the liner materials that can be chemically welded and the corresponding solvent. Tetrahydrofuran (THF) is a volatile solvent with an 'ether-like' odour that works very well on most PVC products but is usually limited to temperatures above +10 °C. Below this temperature heat must be applied to facilitate the evaporation of the solvent. THF evaporates completely after the weld has set and the residue is undetectable. THF is the most common solvent in use on PVC liner materials.

Xylene is an aromatic solvent that is used primarily for chemical welding of CSPE liners, but has been used for some PVC work. CSPE liners crosslink (i.e. cure) over time and they become progressively more difficult to weld with age. A wipe with xylene can reactivate the surface of aged CSPE liners in most cases so that thermal welding can be accomplished. Chemical welding of 'aged' CSPE liners is dependant on the material condition (Layfield, 2008).

The two most critical aspects of chemical welding of liners such as PVC is (i) to ensure that only clean dry surfaces are bonded and (ii) that the temperature is adequate to drive the welding (i.e. to evaporate the solvent).

The bonding surfaces of the liner should be pre-cleaned using soapy water. If there is an oily residue on the liner then a commercial cleaning agent should be used. The ambient temperature must be at least 10 °C to perform a solvent weld using THF. If the temperature is above 4 °C but below 10 °C, then a ''bodied' THF/MEK blend is recommended in place of THF. Below 4 °C, solvent welding will not be possible without supplying heat to the process. With older, weathered (i.e. aged) geomembrane liners it is advisable to roughen the surface with a medium grit sandpaper to remove the oxidized surface layer, followed by a wipe clean with THF.

When patching using chemical welds, align the patch on the damaged area, ensuring that it conforms to the bonding surface. Then work a brush dipped in solvent between the old material and the patch material. Apply the solvent liberally to thoroughly wet both surfaces to be bonded. The solvent should flow out of the seam and onto the adjacent areas on the liner. Using a small roller, roll out the patch from the centre to the edges or press the patch down and smooth using a rag. A small bead of solvent should press out of the patch seam when pressure is applied. Excess solvent from the liner surface should be wiped off with a clean rag. It is necessary to allow 24 h curing time (at 20 °C) before testing the seam. The integrity of the seam can be tested by directing 0.24 MPa (35 psi) air at the edge of the seam. Any areas which 'lift' need to be resealed by applying more solvent and pressure to the area.

17.9 GENERAL WELDING INSTRUCTIONS FOR HDPE/LLDPE/fPP GEOMEMBRANES

The general instructions provided below are some recommendations on surface preparation for polyolefin geomembrane welding. It is the responsibility of the fabricator to determine the optimum method of surface preparation for consistent welding performance.

17.9.1 SURFACE INSPECTION

The welding surface of an HDPE geomembrane is the critical interface in any fabricated installation. It is estimated that nearly 24% of all geomembrane leaks occur at the field seam (weld) area. To ensure the highest possible weld integrity the welding surface of a polyolefin geomembrane needs to be carefully inspected for signs of dirt, contamination, waxy deposits (bloomed additives), moisture and so on.

A convenient method of relatively assessing the surface condition of multiple rolls is to check the surface of each roll prior to installation with a 'dyne pen' which indicates surface energy of 'wettability'. The result is an indication of any significant variation between the rolls. If variability in the 'dyne number' is detected the welder could then test weld a small portion of the differing rolls to determine the optimum weld settings prior to fabrication.

17.9.2 SURFACE CLEANING

The extent of cleaning depends on the degree of contamination at the welding surface. Commonly it is sufficient to remove adherent dirt by wiping with a dry or moist rag, also with the aid of air blowers. In these cases, water or soapy solutions, sometimes alcohol (i.e. spirit) or acetone can be employed. It is important to ensure that the weld surface is completely dry and that no residue remains after the cleaning.

In other instances, more extensive cleaning methods are required. For instance, it has been reported that outdoor exposed thermoplastic sheets could have welding problems due to factors such as industrial pollution after acid rain, surface oxidation, bloomed-out additives and oligomers (low molecular weight polymer chains).

For highly contaminated surfaces, the following procedure could be used to clean the weld surfaces:

1. Remove rough dirt using a commercial dishwashing detergent and dry surface with a rag.
2. Wipe with ethyl acetate.
3. Apply d-limonene (e.g. Citroclear, Carlisle Syntec Systems, Brussels, Belgium).
4. Rub several times using a rubbing and wiping action.
5. Immediately wipe with ethyl acetate (only), to remove the greasy residues.
6. Dry thoroughly using clean rags.

In extreme cases, light buffing with a sanding disc may be necessary: however, this should be carried out with caution since the material could be damaged. It is important that the mechanical abrasion process must not damage the liner with excessive heat, should not remove too much polymer nor damage the membrane during handling. Abrasion must be conducted only when it is called for and should be conducted just prior to the welding process.

It should be noted that sometimes it will be sufficient to clean only with ethyl acetate (e.g. in the case of blooming additives or oxidized surfaces).

The d-limonene also has excellent cleaning properties. It acts by diffusing deep into the polymer surface and extracting short molecular chain segments and blooming additives. However, it can produce a greasy film on the surface. Thus additional wiping with ethyl acetate is therefore required. The use of d-limonene requires protection against open fire, inhalation as well as eye- and skin-contact. Instructions on the safety data sheet must be followed. d-limonene is used as a substitute to xylene and is considered much less hazardous than xylene.

The extent of cleaning undertaken should be adjusted to the actual on-site situation and needs to be tested on liner fragments prior to the welding process.

17.9.3 ON-SITE CONDITIONS

On-site weather conditions can influence the seaming process and weld quality, thus requiring a high level of welding skills. The following are important considerations.

Wet surfaces compromise the formation of a secure weld. Welding or installation should not be conducted at areas of still water, or during/immediately following precipitation, unless suitable protection (e.g. a tent) is utilized.

Welding should not be performed during or after periods of high humidity since water will condense on the surface and water molecules can diffuse into the outer layers of the polymer. Heating by the welding tool can cause small water bubbles to be generated at the interface of the seam leading to unsealed spots and subsequent weld failure. Tests have revealed that an amount of 1000 ppm (0.1 wt.%) surface moisture is sufficient to hinder the formation of a good weld. The water will diffuse out of the liner over an appropriate drying time.

Welding should ideally not be conducted during strong winds since the membrane can be lifted, the welding temperature can be lowered and dust can be blown onto the weld region, unless suitable wind barriers and appropriate ballasts (e.g. sand bags) are employed.

Welding should not be attempted during prolonged and intensive sunshine which heats up the membrane and causes thermal expansion of the liner. This could result in the formation of waves, which complicate and hinder the welding operation. It also increases internal tensions around the seam region after welding. A high degree of thermal expansion will manifest itself in higher levels of residual stress at the seam area. This has contributed to the stress cracking phenomena (i.e. ESCR) exhibited by HDPE geomembranes.

Any equipment used must not damage the geomembrane due to handing, producing excessive heat, leakage of chemicals or other means. The on-site crew should not smoke in the vicinity of the installation, wear shoes that might damage the liner, or engage in activities that could otherwise damage or harm the liner.

Whenever welding is interrupted, the seam region must be protected from water, sun and blown contamination.

It is good practice for trial welds to be made on spare sections of geomembrane liners prior to the actual work on-site being started or resumed following an interruption. They should be made for each apparatus used, under the same conditions as the actual seaming operation in order to verify that the seaming equipment and conditions are adequate.

Hot air and extrusion welding technologies needs to contend with surface oxidation and radical chain scission initiated by the presence of oxygen. Using nitrogen instead of air reduces surface oxidation and degradation.

It has been noted that wedge welding requires less cleaning than hot air welding, as the direct contact of the wedge creates a melt flow which removes surface contamination (e.g. blooming products, oxide layer, fine dirt) out of the seam area into the bulge, or, mingles ‘dirty’ with ‘clean’ material. The heat transition between the wedge and the membrane is more defined and the seam is more homogeneous compared to hot air welds. However, hot air welding anneals the edge of the weld reducing residual stresses at the transition from the molten region to the unmelted region.

The above recommendations have been gathered from various industry sources and represent 'best practice' guidelines in the area of welding of HDPE geomembranes.

17.10 GENERAL WELDING INSTRUCTIONS FOR PVC GEOMEMBRANES

17.10.1 THERMAL WELDING OF PVC

The principle of thermally welding PVC geomembranes is similar to that for welding polyolefin geomembranes. Fusion is brought about by compressing the two melted surfaces together, causing an intermingling of the polymers from both sheets. The heat source itself melts the surface of the viscous polymer sheets, followed closely by the nip rollers which squeeze the two geomembranes intimately together.

Temperature controllers on the thermal welding device should be set according to PVC liner thickness, ambient temperature, rate of seaming and location of the thermocouple within the device. Ambient factors such as clouds, wind and sun require temperature and rate of travel settings to vary. Records for destructive test samples should include the temperature and travel rate settings of the thermal welder used to construct the seam.

It is necessary that the operator keep constant visual contact with the temperature controls, as well as the completed seam coming out of the machine. Occasional adjustments of temperature or speed as the result of changing the ambient conditions will be necessary to maintain a consistent seam. Constant visual and 'hands-on' inspection is also required.

A 2 m long test strip is normally fabricated and test specimens manually tested prior to constructing each seam, or at any time the seaming procedure (e.g. speed, machine temperature) has changed. A minimum of one test strip should be made each morning and afternoon prior to commencement of welding.

17.10.2 PVC ULTRASONIC WELDING

Ultrasonic welding is a thermal technique which melts the two opposing geomembrane surfaces to be welded by passing an ultrasonically vibrated metal wedge or knife between them. Pressure is simultaneously applied to the top and/or bottom geomembrane, to form a continuous bond. Some welds of this type are made with dual bond tracks separated by a non-bonded gap or channel which is used for air pressure testing (i.e. similar to double-wedge hot fusion welding). These welds are referred to as dual-track welds or double-track welds.

17.10.3 PVC SEAMING BY SOLVENTS (CHEMICAL WELDING)

A 150 mm wide overlap must be cleaned of all dust, dirt or foreign debris no more than 30 min prior to applying the chemical fusion agent. If mud has adhered to the sheet surface overlap area, it needs to be removed with clean water and allowed to dry prior to seaming. Seaming cannot be conducted in the presence of standing water. Wet surfaces must be allowed to dry. A slip sheet or seaming board may be used to lift the geomembrane above damp surfaces. If wind conditions contaminate the seaming area or displace the geomembrane sheets, temporary ballast and additional cleaning procedures will be required.

All field seams will be a minimum of 50 mm wide and a sufficient amount of chemical fusion agent should be applied such that, upon compressing the seam surfaces together, a thin excess of chemical fusion agent will be forced out. Then a high durometer rubber, nylon or steel roller can used to compress the seam surfaces together until a bond is formed. Roller action will be at a parallel direction to the seam's edge so that excessive amounts of chemical fusion agent will be purged from between the sheets. Trapped solvent or adhesive should be rolled out of the seaming area.

A continuous wet layer of chemical fusion agent is necessary to prevent a leak at the 'tie-in point' between the last chemical fusion agent application and the next. If the chemical fusion agent, which is initially shiny when applied, takes on a dull filmy appearance, this indicates that the interfaces may require a faster closing together or, the ambient temperature is too high to continue seaming.

With decreasing temperature and with increasing thickness, PVC becomes increasingly more convenient to thermally weld. For this reason, chemical seaming is not generally recommended below 10 °C.

17.10.4 REPAIRS AND PATCHES IN PVC

'Fishmouths' or wrinkles at the seam overlaps should be cut back and overlapped, then patched with an oval or round patch of the same material and thickness as the primary geomembrane. Patches are also necessary where destructive samples are removed or if material is damaged. Patches should extend 150 mm beyond the area to be repaired, be oval or rectangular with round corners and can be chemically welded a minimum of 50 mm around the perimeter.

17.10.5 PVC FIELD SEAM TESTING

Field Quality Control seam testing involves both non-destructive and destructive testing. Each seam must be checked visually for uniformity of width and surface continuity. Proper fusion chemical application visually changes the surface appearance. Usually the installer will use an air lance or blunt-end pick to check for voids or gaps under the overlapping geomembrane. For dual-track welds air channel testing is performed according to ASTM D-7177-05 'Standard Specification for Air Channel Evaluation of Polyvinyl Chloride (PVC) Dual Track Seamed Geomembranes'.

When un-bonded areas are located, they can sometimes be repaired by inserting more chemical fusion agent into the opening and applying pressure. If that is not satisfactory, a round or oval patch must be placed over them with at least 150 mm of geomembrane extending on all sides.

17.10.6 FACTORY SEAMS

Factory seams in liners such as PVC, fPP and CSPE-R are generally of a high standard since they are made in a clean and controlled environment. The large prefabricated panels are then shipped to the installation site on pallets and additional seaming is conducted in the field to produce their final configuration. In contrast field welds can be problematic and lack integrity leading to leaks due to the uncontrolled nature of the outside environment with respect to temperature/wind etc. and to the potential for contamination by dust/dirt.

REFERENCES

ASTM D-7176 'Standard Specification for Polyvinyl Chloride (PVC) Geomembranes for Buried Applications'.

ASTM D-7177, 'Standard Specification for Air Channel Evaluation of Polyvinyl Chloride (PVC) Dual Track Seamed Geomembranes'.

BAM, 'Certification Guidelines for Plastic Geomembranes Used to Line Landfills and Contaminated Sites', Federal Institute for Materials Research and Testing (BAM) (September, 1999).

Comer, A. I., Repairing Geomembranes in the Field, *Water Operation and Maintenance Bulletin*, 29 (1997).

Darilek, G. T. and Laine, D. L., Costs and Benefits of Geomembrane Liner Installation CQA, in *Proceedings of the Geosynthetics 2001 Conference*, Portland, OR, USA (February, 2001).

DVS-Verlag, The German Guide DVS 2207-1 'Welding of Thermoplastics – Heated Tool Welding of Pipes, Pipeline Components and Sheets made of PE-HD (08/2007)'; available from DVS-Verlag GmbH, Düsseldorf, Germany [www.dvs-verlag.de] (2007).

Giroud, J. P., Quantification of Geosynthetic Behavior, *Geosynthetics International*, **12**(1), 2 (2005).

Halse, Y. H., Koerner, R. M. and Lord Jr, A. E., Laboratory evaluation of stress cracking in HDPE geomembrane seams, in R. M. Koerner (Ed.), *Durability and Ageing of Geosynthetics*, Elsevier, New York, NY, USA, pp. 177–194 (1989).

Layfield, 'Chemical Welding Guidelines' (2008).

Lueders, G., 'Assessment of Seam Quality and Optimization of the Welding Process of HDPE Geomembranes', article by Bundesanstalt fuer Materialforschung und pruefung, Berlin, Germany. Published in the *Proceedings of the Sixth International Conference on Geosynthetics*, Atlanta, GA, USA (March, 1998).

Novaweld [http://www.novaweld.com/html/geomembranes.html] (2008).

Peggs, I. D. and Carlson, D. S., The effects of seaming on the durability of adjacent polyethylene geomembranes', ASTM Special Technical Report, 1081, in R. M. Koerner (Ed.), *Geosynthetics Test Waste Containment Application*, pp. 132–142 (1990).

SKZ, Testing and other polymer data from DVS Guidelines (225, Part 1); available from DVS-Verlag GmbH, Düsseldorf, Germany [www.dvs-verlag.de].