Effect of dual track wedge welding at 30℃ ambient temperature on post-weld geomembrane oxidative induction time

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ABSTRACT: High density polyethylene geomembranes are used extensively in barrier systems for landfills and mining applications. The geomembrane panels are usually welded together using a duel track hot wedge welder, which can heat the geomembrane at the weld to temperatures in excess of 400℃. It has recently been reported that this can cause depletion of antioxidants and, at least in some cases, a potential reduction in service life of the geomembrane immediately adjacent to the weld. This paper describes experiments that examine the relationship between the ambient temperature and welding parameters (i.e., welding speed and welding temperature) and their effect on standard oxidative induction time (Std-OIT) for an HDPE geomembrane. The welding speed and temperature settings examined represent the range of acceptable values one would reasonably expect an operator to utilize for an ambient temperature of +30℃. Std-OIT test were performed on welded samples following ASTM D3895. Results show that all welds passed ASTM D6392 peel and shear tests and that Std-OIT values varied as much as 18.5 minutes (9%) depending on welding temperatures and speed.

Keywords: Geomembrane seams, Welds, Oxidative Induction Time, Warm Weather, Heat Affected Zone

1 INTRODUCTION

Geomembranes (GMBs) have been used for decades as part of both primary and secondary barrier systems in a variety of liquid and solid waste containment facilities. Although there are many types of GMB in the market today, many applications typically utilize high density polyethylene (HDPE) GMBs because of their high chemical resistance, ease of installation, and relatively low cost (Rowe et al. 2004, Scheirs 2009). Often these HDPE GMBs are required to have a service life, or functional lifespan, from multiple decades to over a century while being exposed to harmful solutions. Such applications require both careful selection and testing of the proposed geosynthetic, but also carful installation and rigorous QA/QC procedures. The degradation, and ultimately service life, of HDPE GMBs in many exposure conditions has been well documented in the literature over the last two decades (Hsuan and Koerner 1998, Rowe and Sangam 2002, Müller and Jacob 2003, Rowe et al. 2004, Rowe et al. 2009, Abdelaal et al. 2011, Ewais et al. 2014). Geomembranes are known to age at varying rates depending on material, time, exposure medium, temperature, and strain, with brittle failure, or stress cracking, being the final failure mechanism. However, one component of the geomembrane barrier, the seams or welds, has had relatively little attention in comparison. In recent years it has be suggested that certain seams may age disproportionally to the geomembrane sheet, resulting in faster degradation and failure (Rowe and Shoaib 2017). This paper will examine the initial post welding properties of 11 seams produced in a +30^{o}C environment utilizing an array of welding parameter combinations.

1.1 *Seams*

Installation of HDPE geomembranes typically involve the fusion welding of two overlapped sections of geomembrane sheet. In the case of dual track wedge welding, a wedge shaped heating element is passed between the overlap subsequently melting the exposed GMB surfaces which are then forced together by nip rollers forming the weld. A welding technician can change the speed, temperature and pressure of welding to suit the environmental conditions, the latter of which being generally set to a value specific to the sheet thickness, such that if a trial or qualification seam passes destructive testing the welding pressure will likely be unchanged for the rest of the installation. If these welding parameters are not property accounted for during qualification, poor seams and localized defects can occur as the result of over or under-heating the weld itself (Müller 2007, Scheirs 2009, Zhang et al. 2017). Seam quality is most often assed in two ways: a destructive test, which measures the seams mechanical strength in a uniaxial tension test, and a non-destructive test, which requires quality control personnel to pressurize an air channel located in the center of the seam. Both of these testing techniques work well to address the short-term mechanical strength of the weld; however, they fail to address any long-term degradation effects the welding procedure may have on the geomembrane during ageing. Rowe and Shoaib (2013, 2017) found that one area in particular (Figure 1), referred to as the heat-affected zone (HAZ), serves as the critical location of the weld with respect to ageing. This area has been reported to experience increased antioxidant depletion (Rowe and Shoaib 2013, 2017), is the point of failure for peel and shear tests (Rowe and Shoaib 2013, 2017), and is known to be a critical failure zone in geomembrane barriers (Giroud 2005, Kavazanjian et al. 2017).

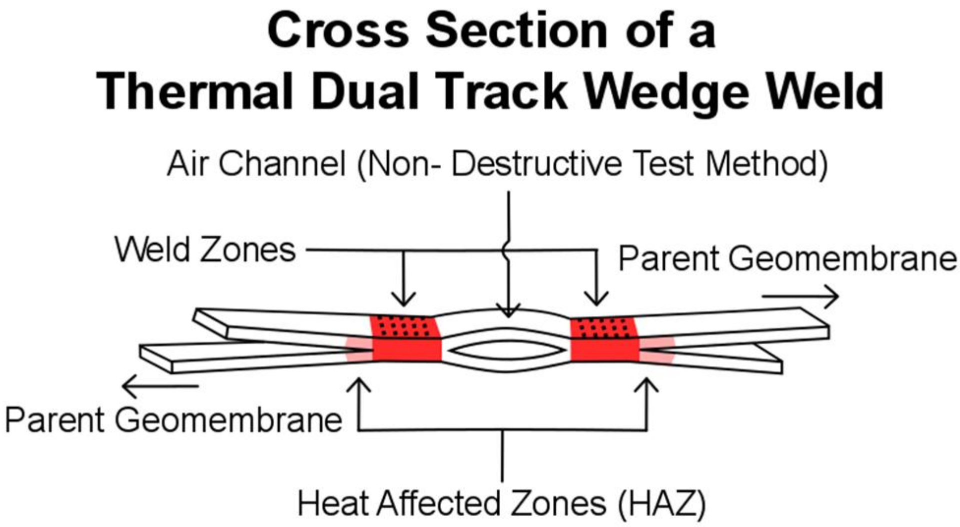

Figure 1. Cross section of typical HDPE dual track fusion weld.

1.2 *Ageing and antioxidant significance*

HDPE may be subject to both physical and chemical aging. Physical ageing refers to changes in the GMB's properties due to a restructuring of the molecular structure as it reaches an equilibrium state post manufacture (Rowe and Sangam 2002). It may be characterized by an increase in yield strength, crystallinity and, sometimes, a reduction in stress crack resistance.

Chemical ageing involves the degradation and breaking of polymer chains. This mechanism is hypothesized to follow a three stage lifecycle ultimately ending in material embrittlement: (a) antioxidant depletion (Stage I), where antioxidants within the GMB are depleted; (b) induction period (Stage II), where additives have been fully depleted but mechanical degradation has not yet occurred; and (c) reduction in mechanical properties (Stage III), where oxidative reactions begin to destroy polymer chains and a reduction in mechanical properties can be observed (Hsuan and Koerner 1998, Rowe and Sangam 2002). The importance of GMB additives, specifically antioxidants, become apparent in this context, where the more effective the antioxidant package added to the GMB during manufacturing the longer Stage 1 can be extended. However, some of the additives do have drawbacks in that they have functional temperature ranges. Once the sheet is exposed to temperature in excess of the effective temperature range, the antioxidant in question may be oxidized. Because of this, the geomembrane welding process has been suggested to cause a long-term degradation effect on the GMB sheet. Welding temperatures can exceed 400℃, which can be higher than the effective temperature range of antioxidants such as thiosynergists and hindered amines (Hsuan and Koerner 1998). Of particular concern are GMB installations at hot (30°C) ambient temperatures, wherein the temperature of black sheet in the sun can reach temperatures as high as 70°C, increasing the overall energy added to a geomembrane during welding for a given set of welding parameters.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

The HDPE GMB examined in this study had the initial (virgin) properties given in Table 1.The sheet was cleaned using tap water and cut into 0.3m by 2.0m strips to prepare for welding. Cut pieces were then transported to the *Queen's University Environmental Liner Test Site* (QUELTS II) located near Godfrey, Ontario, Canada (44.5427° N, 76.6791° W). Welds where conducted by an experienced welding technician using a Demtech Pro Wedge series wedge welder set up to perform dual track wedge welds. All welds were performed between the hours of 12pm and 3pm allowing for maximum sheet sun exposure. Prepared sheets were laid flat on a south facing slope for a minimum of 1 hour before welding. Temperatures of the sheet were monitoring using a spot infrared thermometer and found that sheet temperature reached as high as 65C at ~1-2pm. Once sheet temperature had reached equilibrium, welding procedures commenced incorporating the predetermined temperature and speed combinations (Table 2). For this particular analysis weld pressure was kept constant as it was noted by the installer that the nip roller pressure for a given wedge welder is often set to weld the nominal thickness of the GMB and is seldom changed once the welding for a particular project has commenced. Instead, an operator will adjust the speed and temperature parameters to suit the variability in day-to-day and weekly temperature fluctuations. Once welding had concluded welds were left to cool to ambient temperature for a minimum of 1 hour before being packed and shipped to the laboratory. To help retard any further loss of antioxidants, samples were cut and stored at 1.0℃ before testing in the laboratory.

Table 1. Initial relevant properties of geomembrane examined.

Index Property	Initial Value
Thickness (mm)	1.5
Std-OIT (min)	199±2.2
Melt index	19.6±0.56

Table 2. Welding parameter combinations and resulting HAZ Std-OIT and weld track thickness.

Weld Number	1	2	3	4	5	6	7	8	9	10	11
Welding Speed (m/min)	1.7	3.0	2.1	1.8	2.6	2.6	2.1	2.6	2.1	2.6	3.0
Welding Temperature (℃)	380	415	415	460	350	460	460	380	380	415	460
Average Std-OIT (min)	180.9	186.2	190.0	190.4	190.4	192.6	192.7	193.1	193.8	196.0	196.3
Maximum Std-OIT	182.5	189.9	191.0	192.4	191.5	193.4	196.4	193.4	195.6	197.4	196.9
Minimum Std-OIT	178.9	183.5	188.9	187.1	188.6	192.0	187.8	192.4	192.0	195.1	195.5
Average Weld Thickness* (mm)	1.94 ±0.08	2.75 ±0.03	2.42 ±0.03	2.20 ±0.02	2.70 ±0.06	2.55 ±0.04	2.32 ±0.04	2.65 ±0.05	2.49 ±0.02	2.61 ±0.06	2.66 ±0.04

* ± one standard deviation away from the mean.

2.1 *Differential scanning calorimetry*

Std-OIT tests were performed using a TA instruments Q-2000 series differential scanning calorimeter (DSC). Three small specimens, 1.5 mm-thick and 2.38 mm-diameter were punched from each of the 11 weld's HAZs. Specimens were then placed into standardized aluminum pans and loaded into the DSC for testing in accordance with ASTM D3895. This test is performed by heating a GMB specimen, with a known mass in an inert gas (nitrogen) until a set point temperature is reached, usually 200°C. Once the set point temperature is achieved, the DSC then introduces oxygen into the heating chamber. This allows oxidation reactions to occur and subsequently leads to an exothermic reaction, the onset of this exothermic peak, measured in minutes, serves as a measure of Std-OIT. If a GMB has a more sophisticated antioxidant package this time until an exothermic reaction (Std-OIT) can, in some cases, increase significantly. This Std-OIT value helps measure the amount of antioxidants left in the GMB, such that if one welds HAZ has a lower Std-OIT than another, then its welding process depleted more antioxidants.

2.2 *Peel and shear*

Peel and shear tests were performed following ASTM D6392 on all 11 of the welds to examine their mechanical strength. Interestingly, all produced seams passed peel and shear test despite some qualitative indications of overheating. Figure 2 shows weld 1 being prepared for peel and shear tests. The visible ripples along the weld track indicate overheating during welding – which is why only one weld was performed at a speed of 1.7 m/min – however the overheating was not sufficient enough to cause severe degradation of the welds short-term mechanical strength or elongation and passed the usual QC tests. No separation of the weld was detected for any of the peel tests performed. No welds, other than weld 1, exhibited signs of overheating during this experiment.

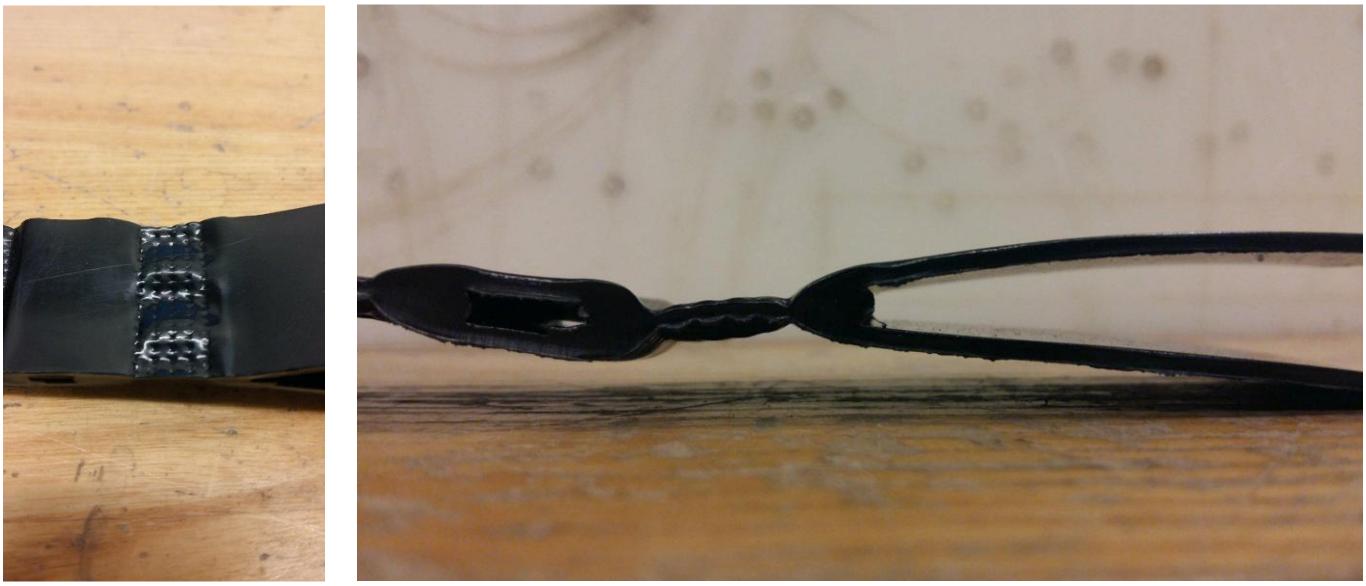

Figure 2. Cross section of a weld 1 shear specimen. Note rippling on weld track as a qualitative indication of overheating.

3 PRELIMINARY RESULTS

During the welding procedures, it became clear that welding at a speed of 1.7 m/min or less would result in an overheated weld. Because of this only one weld was produced using this speed and, as expected, this weld (with an average thickness of 1.94 mm) exhibited the lowest Std-OIT with one reaching as low as 178 minutes (89% of the virgin sheet OIT). Welds 2-11 had weld thicknesses of 2.2mm to 2.75mm (Table 2). Although weld thickness can serve as an indication of an overheated weld, there was no clear trend between weld thickness and Std-OIT. However, it does appear that once a weld thickness reduction threshold (somewhere between 2.0 – 2.1mm for this particular GMB) is reached, then more severe antioxidant depletion in the HAZ can take place.

When Std-OIT is categorized based on welding speed (Figure 3) and welding temperature (Figure 4), this potential threshold becomes apparent. When categorized by temperature the averages for the four temperatures used are quite similar. However, when the same data is categorized by speed, a notable 9% decrease in post weld Std-OIT for the 1.94 mm-thick weld produced at a speed of 1.7 m/min stands out, suggesting an overheating threshold. The 4.3% decrease for next thinnest at 2.2 mm-thick (Weld 4 produced at a speed of 1.8 m/min and wedge temperature of 460°C) was less than half that for weld 1. In fact for welds ≥2.2 mm in thickness there was no clear correlation with between weld thickness and post-weld Std-OIT loss.

The least OIT depletion due to welding was observed for welds 10 and 11 which only experienced a, not statistically significant, 1% decrease in average (Table 2, Figure 5) with (speed, wedge temperature) combinations of (3 m/min, 460°C) and (2.6 m/min, 415°C). The combinations of (2.1-2.6 m/min, 460°C) and (2.1-2.6 m/min, 380°C) all gave very similar 3% post welding decrease in Std-OIT in the HAZ. Welds 3 (2.1 m/min, 415°C) and 4 (1.8 m/min, 460°C) experienced about a 5% decrease in Std-OIT due to welding.

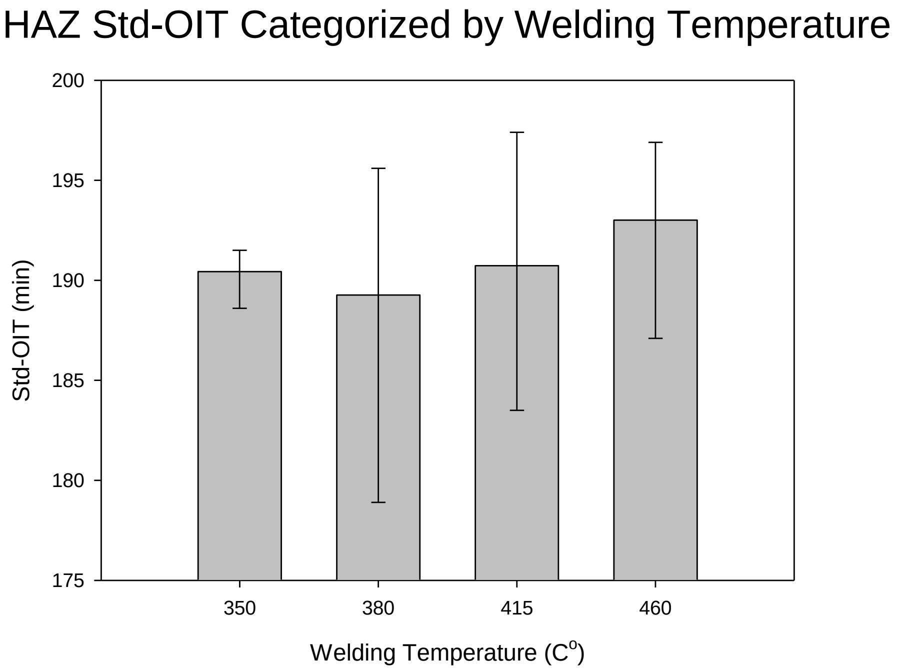

Figure 3. Variation in HAZ Std-OIT categorized by welding temperature. Error bars represent the range of values for a given temperature.

Figure 4. Variation in HAZ Std-OIT categorized by welding speed. Error bars represent the range of values for a given speed.

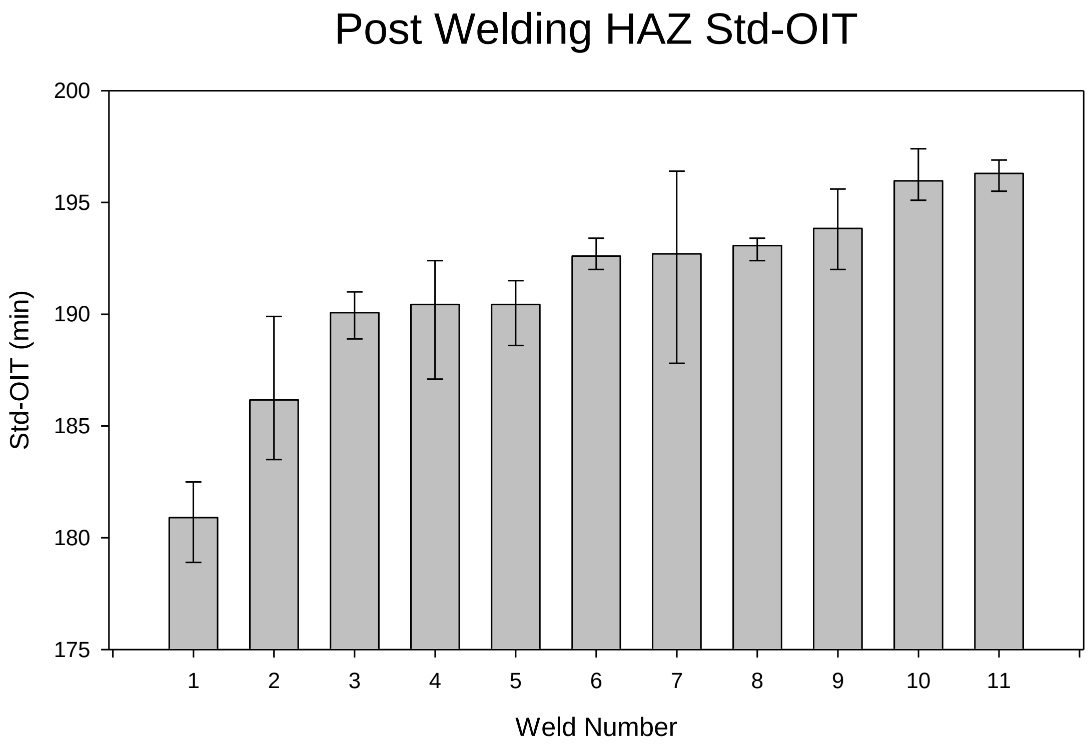

Figure 4. Variation in HAZ Std-OIT categorized by welding speed. Error bars represent the range of values for a given speed.

4 CONCLUSIONS

This paper has reported an examination of the effect of welding speed and wedge temperature on the post-weld Std-OIT in the HAZ adjacent to the weld. The preliminary results suggest the following conclusions for the GMB and weld conditions examined for this GMB with a virgin Std-OIT value of 199± 2.2 min:

- The reduction in HAZ Std-OIT, even for welds which are visually overheated, was not sufficient to decrease the post weld Std-OIT below acceptable GRI guidelines.
- Welding speed appears to have a greater effect on Std-OIT than welding temperature. It was possible to weld at the machines maximum temperature (460℃) and produce a HAZ with relatively little Std-OIT reduction. However, given an ambient and sheet temperature of 30℃ and 65℃, respectively, welding with a speed of 1.7m/min an ambient at temperature of 30℃ gave a visibly overheated weld with greater antioxidant loss even while utilizing a relatively low weld temperature setting.
- Welds that are visibly overheated have the potential to pass QA/QC peel and shear guidelines, meaning that these welds technically pass the guidelines currently used in North America. Germany employs weld thickness reduction guideline which specifies that the weld thickness reduction must be between 0.2 and 0.8mm. Which for a 1.5mm geomembrane means welds must fall between 2.2 – 2.8mm in thickness. Interestingly all welds produced with a speed ≥ 1.8m/min achieved thicknesses within this range and experienced less than half the antioxidant loss during welding than the weld which did not meet this criterion.

These conclusions will be re-examined as more data becomes available.

Despite this near 9% difference in max and min post-welding Std-OIT all values exceeded the current GRI-GM13 guidelines of 100 min. However, these values say nothing about longer-term antioxidant depletion, or general degradation that these welds may experience during their service-life. Further studies must be conducted to assess the impact of this depletion on the functional lifespan of a geomembrane weld.

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