1. Introduction

Factory welded seams have been long presumed to be of higher quality, less variability, and higher predictability than field welded seams due to the controlled and consistent indoor conditions, e.g., little dirt and moisture in the seam, no wind or significant ambient temperature changes in the factory, more rested technicians, and no changes in cloud cover. These constants result in a larger and constant "welding window" (discussed below) than in the field. In terms of thermal seams, higher quality means factory welded seams exhibit higher and more consistent seam strengths than field welded seams and less variability. However, a large database of both factory and field welded seams has not been available for a project to prove this hypothesis because the objective of most projects is to minimize the amount of factory seams. As a result, the number of factory seams that achieved project requirements. Because the geomembrane was primarily factory fabricated, there were about 78% less field seams on this project than if the geomembrane was entirely field fabricated.

This technical paper presents a unique comparison of geomembrane factory and field welded thermal seams for a large off-stream water reservoir project. The results of the comparison show that factory welded seams exhibit higher seam peel and shear strengths at yield, less variability, and more consistency than field welded thermal seams. In particular, the results show that factory seams are about 10% stronger than field seams in shear and about 9% stronger in peel strength at yield. More importantly, this resulted in 100% of the factory welded seams passing the project seam strength requirements even though the factory welding speed was 1.1–1.6 times faster than the field welding speed. Conversely, about 25% of the field welded seams did not pass the initial specified field seam shear strength requirement, which caused significant delays, scheduling, and other construction issues. As a result, the field seam shear strength requirement was reduced from 9.6 kN/m to 8.2 kN/m to increase the number of field seams that achieved project requirements. Because the geomembrane was primarily factory fabricated, there were about 78% less field seams on this project than if the geomembrane was entirely field fabricated.

The individual geomembrane (GM) rolls for projects are usually welded by thermal methods, e.g., hot air or hot wedge, that involves heating the surface of the opposing geomembrane sheets and applying pressure to fuse the sheets together. As a result, the quality of the weld in the short-term (Scheirs, 2009) and long-term (Shoaib and Rowe, 2013; Rowe and Shoaib, 2014) is influenced by welding temperature, speed, applied pressure, damage to the geomembrane, e.g., scoring, reduced thickness, notches, etc., and environmental conditions, such as, ambient temperature, moisture, cleanliness, adhered soil, wind, and personnel fatigue (Zhang et al., 2017). More importantly, Rollin et al. (1999) report that 55% of the damage recorded in GMs installed in basins, ponds, and landfills occurred at seams. Gassner and Fairhead (2014) report a leakage rate survey on sixty-seven (67) liquid holding ponds and report that 32% of the leaks/defects occurred at defective seams with most of them occurring on the floor of the ponds where the hydraulic head is the greatest. They also report that all of the defects

Corresponding author.
E-mail addresses: tstark@illinois.edu (T.D. Stark), m hernandez@langan.com (M.A. Hernandez), danrohe@geomembrane.com (D.S. Rohe).
identified on the slopes occurred at faulty seams (Zhang et al., 2017). In summary, GM seams are a weak point and source of leakage so efforts should be made to create the highest quality welds to reduce one of the largest sources of leakage. As a result, this paper focuses on the higher quality of GM seams that can be achieved by seaming GM rolls together in a controlled factory versus a field site.

2. Upground reservoir

The John R. Doult Upground Reservoir (JRD UGR) is a 27.6 billion liter off-stream water reservoir that covers a plan area of 337 ha. Prior to the JRD UGR, this area was primarily used for farming and is fairly flat. The reservoir was constructed by creating a zoned embankment around the reservoir with a height of about 10.7 m. The zoned embankment consists of low hydraulic conductivity fine-grained soils on the upstream side of the embankment (see Zone 1 Fill in Fig. 1) and the embankment downstream of the centerline consists of both fine and coarse-grained soils, i.e., a higher hydraulic conductivity, (see Zone 2 Fill in Fig. 1). The length of the zoned embankment is about 8.5 km and consists of about 3.5 million cubic meters of fill material.

The reservoir area is underlain by glacial till that consists of fine-grained soil that contains large pockets of high hydraulic conductivity sands and gravels. This permeable layer is about 6 m thick in some areas, which essentially brings the underlying fractured limestone bedrock in close proximity to the bottom of the reservoir. Therefore, reservoir water could seep into the underlying soil and bedrock and increase solutioning of the limestone, increase leakage from the reservoir, and possibly destabilize the reservoir. The fractured and solutioned limestone is also under artesian pressure. As a result, the designers decided to install a geosynthetic liner system on the floor of the reservoir to minimize leakage and connection with the underlying limestone bedrock. The geosynthetic liner system did not extend up to near the embankment crest because the upstream portion of the embankment consists of low hydraulic conductivity soil (see Fig. 1) and could be exposed to ultraviolet light and wave action. In addition, a blanket drain was installed around the perimeter to lower the phreatic surface and control seepage through the embankment.

3. Geosynthetic liner system

The installed geosynthetic liner system on the floor of the reservoir consists of the following components from the top to the bottom (see Fig. 2):

- 0.46 m thick of cover soil to protect the flexible unreinforced polypropylene (fPP) geomembrane.
- Non-woven cushion geotextile over the fPP geomembrane.
- 1.0 mm thick fPP geomembrane, and
- 0.46 m thick low hydraulic conductivity compacted fine-grained soil liner (CSL) constructed using on-site soils.

The project specification for the geomembrane also allowed the use of a 1.0 mm (40 mil) thick flexible unreinforced polyvinyl chloride (PVC) geomembrane but a fPP geomembrane was selected by the fabricator for installation mainly based on weight considerations, which influenced the fabricated panel size. In particular, the weight per area of a 1.0 mm (40 mil) thick fPP and PVC geomembranes are 0.0096 kPa and 0.0134 kPa, respectively. The project initially required a panel size of 2325.6 m² or 76.3 m by 30.5 m. As a result, this panel size would weigh only about 22.24 N using a 1.0 mm (40 mil) thick fPP geomembrane, which facilitated handling and shipping. Conversely, a panel size of 2325.6 m² would weigh about 31.14 N using a 1.0 mm (40 mil) thick PVC geomembrane. The lighter weight panels was one of the primary factors that resulted in fPP geomembrane being selected over the PVC geomembrane. Eventually the project increased the panel size to 76.3 m by 38.1 m or a panel area of 2907.0 m². This larger panel size weighed about 27.80 N using a 1.0 mm (40 mil) thick fPP geomembrane, which is still less than the weight of the smaller 1.0 mm (40 mil) thick PVC GM panel.

The geosynthetics are anchored in an upstream anchor trench near the base of the embankment as shown in Fig. 1. A centerline cutoff trench was included near the embankment centerline to cutoff seepage through the fine-grained soil because pockets of sands and gravels are present under the width of the embankment (see Fig. 1). These seepage cutoff trenches were backfilled and compacted with Zone 1 fill material to reduce under seepage.

Because this is the largest geomembrane lined project in the world, this paper describes the data analysis and resulting comparison of factory and field seam peel and shear strengths at yield. In particular, the tests on 1313 factory fabricated thermal seams are compared with the results on 469 field fabricated seams but a total of 938 seam tests as described below. This means that about 64% of all of the thermal geomembrane seam tested were created in the factory and about 36% in the field. Therefore, this is a unique project where there is almost 470 field seams tested even though the majority of the geomembranes was factory fabricated. In summary, this project provided a unique opportunity to quantify the higher quality and strength of factory welded thermal seams.
4. Geomembrane installation

The factory fabricated panels fPP GM were initially 76 m × 30 m, which corresponds to a weight of about 1850 kg for shipping purposes. As the project progressed the fabricated panel size increased to 76 m × 38 m or a panel weight of about 2820 kg, which still could be shipped/transported on local roads. The main advantages of using a factory fabricated GM for this project include:

- Fabricated panels allowed a compressed construction schedule, in particular, the project schedule required nine (9) factory fabricated panels to be installed per day to cover an area of about 25,992 m² (9 × 76 m × 38 m). In the summer of 2012, twelve (12) GM panels were placed per day, which corresponds to 34,884 m² (12 × 76 m × 38 m), to accelerate construction.
- The project could not be completed within three (3) years using field fabrication so factory fabrication of GM panels was required for this project.
- Fabricating most of the GM seams in the factory significantly reduced project costs because factory labor received non-union wages whereas it was required to pay all field personnel union/prevailing wages. In addition, a faster welding speed was used in the factory further reducing project costs.
- Large panels created a large and open working area for soil cover operations by the contractor,
- All factory fabricated seams could be quickly air-lanced tested before folding the panels for transportation, and
- Destructive seam testing was required for the field seams but not the factory seams, which reduced the number of patches on the “production” geomembrane to only field destructive seam tests.

As usually occurs, several factors intervened during the field seaming operations, such as, adverse weather conditions, portable welding equipment performance, changes in installation personnel, changes in field conditions during a work day, e.g., clouds appearing or disappearing, dust from other construction activities or the subgrade soil entering the seams, and other factors. Specifically, during the project the geomembrane panels were contaminated by fine clay particles from the subgrade and embankment. Due to the small size of the soil particles these could not be cleaned, as these embedded into the raw material itself. Conversely, welding in the factory had fewer variable conditions including no fine clay particles, controlled temperature, no moisture or wind, and a concrete floor to firmly and consistently support the welding equipment.

The fabrication and installation contractor, Environmental Protection, Inc. (EPI), rented a large storage building near the JRD UGR and created a fabrication plant in this building instead of fabricating panels in Michigan where EPI is located. This reduced the geomembrane transportation costs and delays in the completed panels reaching the site.

Construction of the geosynthetic liner system occurred over three construction seasons (2011, 2012, 2013). However, most of liner system was completed in 2012 because 2011 had a late start due to delays in construction sequencing due to earthwork, and it was also a particularly wet year. In addition, the bottom of the reservoir is nearly flat so surface water did not drain to a sump area quickly, which resulted in some ponding. Because of the frequent precipitation, the CSL had to be undercut and/or scarified and recompacted periodically before GM panels could be placed. In addition to minimize freeze-thaw damage to the CSL, a winterization berm was constructed around the completed liner system and the impounded area was flooded with water to reduce the potential for freezing of the CSL. The flooding took place only where the liner system was completed to protect the CSL below the GM. Once flooded, it was left intact. After winter, the installer continued GM installation past the winterization berm. The GM had been installed below the winterization berm, so the berm did not have to be removed because the GM was continuous from the pond and under the berm.

5. Geomembrane seam testing

The fabricated fPP geomembrane was thermally welded and representative samples were obtained for seam shear and peel strength testing in the factory. Duplicate samples of the representative factory seam samples were stored in the quality control archive. In the field, destructive samples were obtained from the welded together geomembrane panels randomly. These samples were used for seam shear and peel strength testing at an independent commercial testing laboratory during construction. The initial project requirements for the field and factory seam shear and peel strengths at yield of the completed geomembrane thermal seams are:

- Seam shear strength at yield: 9.6 kN/m
- Seam peel strength at yield: 4.4 kN/m

The field shear strength requirement of 9.6 kN/m corresponds to about 80% of the peak tensile strength of the fPP geomembrane of 12.6 kN/m. Because many of the field fabricated seams did not achieve the specified field seam shear strength requirement, the field seam shear strength requirement was reduced from 9.6 kN/m to 8.2 kN/m. The field shear strength requirement of 8.2 kN/m corresponds to about 65% of the peak tensile strength instead of the initial 80%. As the specification for field shear strength seams was lowered, fabricated panels were made larger to minimize the required field seams that would be tested for 65% of the peak tensile strength.

During the project it was determined that the main cause of the weaker field seams is fine particles of the underlying compacted fine-grained (clay) soil liner becoming embedded into the fPP GM as reported by the Geosynthetic Institute (GSI) near Philadelphia, Pennsylvania. These clay-size particles were heated during the welding process and incorporated into the weld after application of the applied pressure. This resulted in the soil particles contaminating the resulting weld causing a lower and seam peel and shear strength. This also explains the greater variability in the field seam strengths because the amount of fine-grained particles from the compacted soil liner embedded in the fPP GM varied across the site. Of course, the fine-grained compacted soil liner was not present in the factory so these clay-size particles were not present before or during the factory welding, which resulted in higher and less variable seam peel and shear strengths.

5.1. Factory fabricated seam startup testing

This section describes the factory seam sampling and testing that was performed for the JRD UGR. The installation contractor was required to provide a representative seam sample for testing before production seaming could begin each day. This representative seam had to be fabricated from the same GM material and using the same welding techniques as recommended by the fabricator. The startup seam was to be no less than 3 m in length and be provided at the start of each day or each shift before production seaming could begin. From this startup seam, random specimens were obtained for seam shear and peel strength testing for comparison with the project specification shown above. Before testing, the seams simply had to acclimate to the laboratory temperature.

The factory welded thermal seams were created using a Demtech Pro-wedge with a solid or single fusion welding shoe. All of the factory welded thermal seams were created using a solid fusion welding shoe because air-channel testing was not performed on the factory seams only air lancing testing, which does not require dual track welded. In addition, using a solid fusion welding shoe also results in a wider weld than a dual track welded, which improves its performance and long-term durability.
This brand and type of thermal welder was also used in the field. However, all of the field seams were created using a split fusion welding shoe to create a void in the seam because air-channel tests were performed on all of the field seams using ASTM D5820-18 and ASTM D7177. Before welding, the field crews hand cleaned every field seam in front of the welder. These are two important facts, as the machine specifications are the same so any change in the seam test results is due to factors unrelated to the machinery, and with the hand cleaning of field seams we can determine that conditions for the generation of field welds represent a most favorable comparison between field and factory seams.

Randomly selected thermally welded factory seam samples representative of each GM panel were tested for every shift and a duplicate sample from each test was archived by the project Quality Control (QC) Team. All of the completed factory fabricated seams were air lance tested in accordance with ASTM D4437-18. The completed GM panels were then rolled on hollow cores and stored at the fabricator's facility or shipped directly to the site for installation.

5.2. Field fabricated startup seam

This section describes the field seam sampling, testing, and subsequent patching that was performed during field installation. A minimum of one destructive seam sample was obtained per seaming crew per day. This sample was obtained by cutting a 0.61 m long section of the field fabricated seam from the installed GM. The frequency of the destructive samples was determined by the size of the GM installation that had occurred. Depending on the amount of GM installed, one or two destructive samples may occur during a day, which is significantly less than every 152.4 m required for high density polyethylene (HDPE) geomembranes (Kolbasuk, 1990). In 2011, sampling was conducted for each 152.4 linear meters of seams. In 2012 after the specification for shear strength in the field was lowered, the sampling was required only once for the seams worked per day per crew because of the high passing rate of the tested factory and field seam samples.

After the GM panel was installed, welding of the adjacent panels commenced immediately using a split fusion welding shoe to create an air channel for field testing. GPS surveying was used to locate the four corners of each panel after installation. After welding was complete, air channel testing of the field seam(s) was performed. During or after the air channel testing, destructive field seam samples were removed for independent laboratory destructive testing. A GPS survey of the location of the destructive field seam sample was performed for quality control purposes. After the destructive sample was obtained in the field, the resulting hole in the geomembrane was patched with an oval-shaped piece of new geomembrane that extended at least 0.15 m past the hole. The patching material was seamed in accordance with the control purposes. After the destructive sample was obtained in the field testing, ten (10) specimens were used per seam sample with (5) 25.4 mm (1 inch) wide and 150 mm (6 inches) long specimens with the field seam at the center of the field specimen and perpendicular to the centerline were used for seam testing. A gage length of 25.4 mm (1 inch) with grips positioned 13.0 mm (0.5 inch) on either side of the start of the seam bond were used with a constant machine crosshead speed of 500 mm/min (20 inch/min) for the seam peel testing. The specimen was fully supported within the tensiometer grips across the specimen.

The seam peel strength tests were performed in accordance with ASTM Test Method D6392. For the unreinforced fPP geomembrane specimens, a minimum of five (5) 25.4 mm (1 inch) wide and 150 mm (6 inches) long specimens with the field seam at the center of the field specimen and perpendicular to the centerline were used for seam testing. A gage length of 25.4 mm (1 inch) with grips positioned 13.0 mm (0.5 inch) on either side of the start of the seam bond were used with a constant machine crosshead speed of 500 mm/min (20 inch/min) for the seam peel testing. The peel strength specimen was fully supported within the tensiometer grips across the specimen. All of the field seams were dual track welded so air-channel testing could be performed on the field seams, which was not done for the factory seams. After cutting the field seam to perform the air-channel testing, seam test specimens were obtained from both sides of the weld for field seam shear and peel strength tests. For all of the field peel strength testing, ten (10) specimens were used per seam sample with five (5) specimens sampled symmetrically along each side of the welded seam. The average peel strength value for each set of five (5) strips was reported and used in the plots presented below.

5.3. Welding parameters

This section describes the welding parameters, e.g., temperature, speed, and pressure, used for the factory and field seams. In the consistent controlled environment of the factory, the Demtech Pro-solid wedge welders were typically set at 330 degrees C and 899 on the speed setting. The welders were setup using a solid wedge with seam guides and rollers made for a smooth floor. Trial welds were made and tested to verify settings prior to production.

In the variable field environment, there were many factors that had to be accounted for when setting the welder temperature and speed including, weather, wind, ambient temperature, humidity, soil particles on and in the GM, and precipitation. As a result, the field Demtech Pro-split wedge welders utilized a setup with larger wheels and no seam edge guides. The field welder settings ranged from a temperature of 288–355 degrees C and speed settings from 550 to 810. Comparing these welding parameters with the factory settings above the following observations can be made:

- Factory and field welders used similar welding temperatures with the factory being at the higher end of the field temperature range because of the difference in welder speed.
- Factory welders used a much faster welder speed setting (899) than field welders (550–810), which meant that factory welding was faster and also of higher quality as shown below than field welding. This is a significant finding of this research, which confirmed the likely higher quality but also lower cost because of the faster welder speed that could be used in the factory. The factory welding was conducted at a speed 1.1 to 1.6 times, or 10–60%, faster than the field welding.
- The difference between the factory and field welding parameters does not explain the observed variation between the field and factory seam shear strengths presented below because the factory used a much faster welder speed. In other words, using a faster welder speed means there is less time to heat the opposing GMs, apply pressure, and fuse them together so there is a greater potential for lower seam quality and seam strengths. However, the data below shows that the factory seams are always stronger and more consistent than the field seams, which means environmental factors, e.g., clay-size particles being present in the completed weld and changes in climatic conditions, play a greater role in seam quality than the welder settings.

5.4. Seam testing
For the field seam peel strength tests, two different peel tests were performed for each seam sample. One peel test utilized the exposed flaps on one side of the dual-track seam and the other peel test utilized the exposed flaps on the other side of the dual-track seam. This resulted in two (2) field peel strengths for each sample. As a result, two (2) datasets of field seam peel strengths were created, and they are denoted as Field Peel A and Field Peel B in the plots and data analysis below. Both of these field peel strength datasets report the average peel strength of five (5) tests from opposing tracks, out of the ten (10) seam peel specimens obtained and tested from each field sample.

The factory seam shear and peel tests were performed in the factory on test welds using equipment in the factory. The field destructive seam tests were conducted onsite in a custom-built mobile laboratory prior to sending to sample of the field destructive sample to an independent laboratory for confirmation testing.

6. Test results

6.1. Seam peel strength test results

Field and factory seam peel strength tests all yielded strength values that exceeded the initial project specification of 4.4 N/mm. However, the field peel strength test results are more variable and consistently lower than the factory values. In fact, there is variability even in the peel strength for the two (2) field datasets, i.e., Field Peel A and Field Peel B, for a given seam. Figs. 3 and 4 show the two (2) field datasets, i.e., Field Peel A and Field Peel B, respectively. For comparison purposes, Fig. 5 presents the results of the seam peel strength tests measured using the created factory seam samples. Each of the seam peel strength diagrams in Figs. 3 through 5 show the number of specimens tested and plotted for each graph, e.g., 469 and 1313. The implication of field seam samples having lower peel and shear (see below) strength than factory seam samples is these locations can develop leakage over time as the GM is subjected to tensile stresses during its service life.

The data in Figs. 3–5 are used to identify the upper and lower bounds of each dataset, and how the field datasets compare with each other and the factory dataset. The first important assumption for this analysis is that the Central Limit Theorem can be used to approximate the test results as a normal distribution. For this assumption each trial of a field or factory seam test, i.e., either peel or shear strength, is assumed to be independent of each other. For independent variables, the Central Limit Theorem is generally valid for datasets with more than thirty (30) components or data points. Using a normal distribution to characterize the three (3) datasets allowed the prediction of which percentage of the data would fall within the average value plus or minus a number of standard deviations. For this analysis, it was observed that the peel strength data fell within the average value of each dataset plus or minus two (2) standard deviations. Therefore, the approximate percentage of each dataset that should fall within this range, i.e., average plus or minus two standard deviations, is 95%. This is illustrated with the shaded area in Fig. 3 through 5.

Fig. 3 shows the average peel strength value for the Field Peel A dataset is 7.40 N/mm (see dark horizontal line through the data) with a standard deviation of 0.59 N/mm. The Upper Bound of this dataset is 8.59 N/mm (see upper horizontal line) and the Lower Bound is 6.23 N/mm (see lower horizontal line).

Using the minimum allowable peel strength for this project, i.e., 4.4 N/mm, a ratio between the measured peel strength and minimum allowable peel strength was calculated and is referred to as the Peel Ratio. If the value of Peel Ratio is at or below unity (1.0), the seam did not meet project specifications and if the value is greater than unity (1.0) it did meet project requirements. Fig. 3 shows the Peel Ratio is greater than unity because none of the values plot below the required 4.4 N/mm, which is the horizontal dashed line. In fact, the Peel Ratio for the dataset Field Peel A, dataset is 1.69, which can be analogized to a factor of safety of 1.69 against failure of the seam peel strength specification.

From the statistical analysis, 97% of the Field Peel A dataset falls within two (2) standard deviations of the average, which is only 2% different from the predicted value of 95% of the dataset falling within two (2) standard deviations of a normal distribution. Therefore, the
Field Peel A dataset can be assumed to be normally distributed.

Fig. 3 also shows the average and upper and lower bounds of seam peel strength for the Field Peel B and Factory Seam Peel datasets using a dotted line to the right of the graph. The dotted line shows the range between the upper and lower bound, and the symbol in the middle of this range corresponds to the average of each dataset. These data symbols show that the Field Peel A average, upper bound, and lower bound are slightly lower than those for the Field Peel B dataset. Therefore, there is variability in the field peel tests even for a given field seam sample. More importantly, the Field Peel A strength values are clearly lower than the Factory Seam Peel dataset (see Fig. 3).

Fig. 4 shows the average peel strength value for the Field Peel B dataset is 7.59 N/mm with a standard deviation of 0.58 N/mm. The upper and lower bounds for Field Peel B are 8.75 N/mm and 6.43 N/mm, respectively. From the statistical analysis, 95.7% of the Field Peel B dataset are within two (2) standard deviations of the average, which is only 0.7% away from the predicted 95% of the dataset being within two (2) standard deviations. Therefore, the Field Peel B dataset also can be assumed to be normally distributed.

The average and upper and lower bounds of seam peel strength for the Field Peel A and Factory Seam Peel are also shown as the symbols on each dotted line plotted to the right of the graph. The comparison of the two (2) dotted lines to the right of the graph with the Field Peel B data clearly shows the different variability between the three seam peel strength datasets.

The Peel Ratio for the Field Peel B dataset is 1.73, which is slightly higher than the ratio of 1.69 obtained for the Field Peel A dataset. In summary, the field seams exhibited seam peel strengths that exceeded project specifications but with some variability. More importantly, both field datasets yielded seam peel strengths that are significantly lower than the factory fabricated seam peel strengths.

Fig. 5 shows the average peel strength value for the Factory Seam Peel dataset is 8.06 N/mm with a standard deviation of 0.49 N/mm. The upper and lower bounds are 9.03 N/mm and 7.09 N/mm, respectively. From the statistical analysis, 96.1% of the Factory Seam Peel dataset are within two (2) standard deviations of the average, which is only 1.1% away from the predicted 95% of the dataset being within two (2) standard deviations. Therefore, the Factory Seam Peel dataset also can be assumed to be normally distributed.

The Peel Ratio for the Factory Seam Peel dataset is 1.84, which is higher than the values of 1.69 and 1.73 obtained for the two (2) field datasets, i.e., Field Peel A and B. In summary, the factory welded seams clearly exhibited more consistent and higher seam peel strengths than the field samples. In addition, the Factory Seam Peel dataset in Fig. 5 shows the higher values of the upper and lower bounds of the factory dataset in comparison with the two (2) field datasets as shown by the data symbols along the vertical axis to the right of the graph. The range between the upper and lower bounds for the Field Peel A and B datasets is 2.36 N/mm and 2.32 N/mm, respectively. For comparison purposes, the Factory Seam Peel dataset range is only 1.94 N/mm or 18% lower than the highest field dataset, which shows the factory seams are much less variable than the field seams. The average Factory Seam Peel strength is also significantly greater than both field peel strength datasets.

Fig. 5 also shows the factory seam peel strength decreases around Sample Number 400 and remains low until about Sample Number 700. This decrease occurred while the fabricator was changing its welding parameters to increase the seam strength as discussed below (see Fig. 7). This is a general trend in which an increase in seam shear strength results in a decrease in seam peel strength due to changing in the welding parameters, such as, temperature, speed, and pressure. Fig. 5 also shows a general increase in factory seam peel strength after about Sample Number 700. This is attributed to the welding crews being more familiar with the FPP GM and the welding process and not changing of the welding parameters. The factory welding parameters for the solid wedge welders remained at 330 degrees C and 899 on the speed setting after a sample number of about 700.

6.2. Seam shear strength test results

Seam shear strength test results from factory seams yielded strength values that all exceeded the initial project specification of 9.63 N/mm. Due to a number of failing field seam tests, the required field seam shear strength was lowered from 9.62 N/mm to 8.23 N/mm, which is also used in the comparisons below. In addition, the Geosynthetic Research Institute, 2015 in Geomembrane Material Specification GM-19 Table 3(a) for Thermally Bonded Nonreinforced and Scrim Reinforced Flexible Polypropylene (FPP) for a 1.0 mm material requires a seam shear strength of only 5.25 N/mm (130 N/25 mm), which is also used herein for comparison purposes because it is significantly lower than the other requirements used for this project. The GRI GM-19 specification is used in the comparisons herein as the minimum specification and also for calculating the Shear Ratio for each dataset. The Shear Ratio is the ratio between seam shear strength and the GRI GM-19 allowable shear strength and was calculated using the data in Figs. 6 and 7. If the value of the Shear Ratio is at or below unity (1.0), the seam did not meet project specifications and if the value is greater than unity (1.0) it did meet project or GRI GM-19 requirements.

PVC geomembranes have long required that factory and field seam shear strengths meet or exceed 80% of the peak tensile strength of the
PVC geomembrane (PGI, 1997). Because the project specifications allowed either a PVC or fPP geomembrane to be used, the initial fPP geomembrane seam shear strength requirement also corresponded to 80% of the peak tensile strength of the fPP geomembrane to create a similar or equal seaming standard for these two GMs for bidding purposes. Conversely, the GRI GM-19 specification requires that factory or field seam shear strength only correspond to about 44% of the peak tensile strength of the fPP geomembrane. Therefore, the GRI GM-19 specification only requires that factory or field seam shear strength exceed only 5.25 N/mm even though higher seam shear strengths can be obtained as illustrated by this project. If the project had required a seam shear strength of only 5.25 N/mm, all of the field and factory seams would have passed but would have been more likely to develop a leak over the service life of the project than the specified seams (Rollin et al., 1999).

GM-19 also uses seam ductility, or shear elongation, of the adjacent geomembrane to assess the seam shear strength to ensure that the mechanical preparation required before seaming, i.e., grinding, and thermal input during welding does not embrittle the high-density polyethylene (HDPE) geomembrane (Peggs, 2004). Grinding is not required to remove waxes and other materials before welding fPP and PVC geomembranes (Stark et al., 2004) so ductility was not included in the project seam specifications. In addition, GM-19 does not require ductility or shear elongation for field seams.

The data in Figs. 6 and 7 are used to identify the upper and lower bounds from the raw dataset and how the field dataset compares with the factory dataset. The Central Limit Theorem is also applied to these results, so the data can also be assumed to be normally distributed as shown below. Therefore, each field and factory seam shear strength is assumed to be independent of each other. Each of the seam shear strength diagrams in Figs. 6 and 7 show the number of specimens tested and plotted for each graph, e.g., 938 and 1313.

Fig. 6 shows the average field seam shear strength is 10.2 N/mm (see dark horizontal line through the data) with a standard deviation of 0.84 N/mm for the field seam shear strength test results. The upper bound of this dataset is 11.9 N/mm (see upper horizontal line) and the lower bound is 8.5 N/mm (see lower horizontal line) as shown in Fig. 6. Fig. 6 also shows the Field Shear Ratio is only slightly greater than unity (1.06). This resulted in nearly 25% of the field seams failing to meet the initial project requirements. The Shear Ratio increased from 1.06 to 1.21 after the project allowable seam shear strength was decreased from 9.63 N/mm to 8.23 N/mm.

The data in Fig. 6 shows that during the first year of the project, a significant number of tests failed the 9.63 N/mm seam shear strength requirement. This resulted in a number of repairs, which slowed installation of the bottom liner system. However, after the first year the field seams achieved a more consistent seam shear strength. This continued until near the end of the project, i.e., end of the 2013, when a couple of values fell below the lowered seam shear strength requirement of 8.23 N/mm.

The statistical analysis of the field seam strength dataset in Fig. 6 also shows that 95.7% of the data fall within two (2) standard deviations from the average. The margin of error from the initial assumption is 0.7%. The percentage of field samples that did not meet the initial project requirements of 9.63 N/mm is 24.5% and about 0.6% did not satisfy the lowered seam shear strength specification of 8.23 N/mm.

Fig. 7 shows that all of the factory seam samples easily exceeded the initial project requirements of 9.63 N/mm. This leads to the most important point of this study, which is nearly 25% of all field seams were failing to meet the initial project requirements while none of the factory seams were failing. This is more important than the factory seams being 10% stronger in shear than the field seams because a failure rate of almost 25% resulted in significant delays and scheduling problems for the project. In addition, the failed seams had to be retested and patched in the field resulting in patches in the final geomembrane. Failure of almost one-quarter (1/4) of the field seams also impacted the geosynthetic liner system installation process and the rate of other construction activities, e.g., cover soil placement, which resulted in additional project costs.

Fig. 7 shows the average factory seam shear strength is 11.15 N/mm with a standard deviation of 0.50 N/mm. The upper and lower bounds are 12.13 N/mm and 10.15 N/mm, respectively. The Shear Ratio for the factory seams is 1.16 for the original project specification and 1.33 using the modified or lowered project specification. The Shear Ratio for the factory seams is 2.12 when the GRI GM-19 specification is used, so the factory seams significantly exceeded the project requirements under all available specifications.

From the statistical analysis, 96% of the Factory Seam shear dataset are within two (2) standard deviations of the average, which is only 0.8% away from to the predicted 95% of the dataset being within two (2) standard deviations. By comparison, the range of factory seam shear strength is smaller or more compact with the lower and upper bounds greater and lower, respectively, than those from the field shear strengths. For example, the range between the higher and lower bound values for the factory seams is only 1.99 N/mm while the range for the field seam shear strength dataset is 3.35 N/mm. Therefore, the range of the factory seam dataset is 41% smaller than the field shear strengths, which is illustrated by the thinner shaded area in Fig. 7 compared to Fig. 6. Fig. 7 also shows the upper and lower bounds for the factory dataset to the right of graph. This comparison shows that the lower bound of the field dataset is considerably lower than the lower bound for the factory seams by a 1.63 N/mm. The average factory seam shear strength is 0.95 N/mm greater than the average field shear strength.

Fig. 7 also shows the factory seam shear strength decreases around Sample Number 550 and remains low until about Sample Number 800. This decrease occurred while the fabricator was changing its welding parameters to increase the seam strength (see Fig. 5). As mentioned above, increases in seam shear strength usually results in a decrease in seam peel strength due to changes in the welding parameters, such as, temperature, speed, and pressure. Fig. 7 also shows there is a general increase in factory shear strength after sample number of about 800. This is attributed to the welding being more familiar with the fPP GM and the welding process and not changing of the welding parameters. The factory welding parameters for the solid wedge welders remained at 330 degrees C and 899 on the speed setting after about Sample Number 800. As mentioned above, the main cause of the lower field shear strengths is fine particles of the underlying compacted fine-grained (clay) soil liner getting embedded into the fPP GM and contaminating the field thermal welds. Of course, the fine-grained soil liner was not present in the factory so these clay-size particles were not present before or during the factory welding.

7. Statistical analysis

Further analysis of the field and factory seam test results were conducted because the data appears applicable to a normal distribution. For example, Fig. 8 compares the original Field Peel A seam test data with that of a normal distribution relationship constructed using the average (7.41 N/mm) and the standard deviation (0.59 N/mm) of the original Field Peel A strength dataset. Fig. 8 also shows the project requirement of (4.38 N/mm) for the shear peel strength tests. The average and standard deviation for each dataset used to the compute the normal distributions between plus and minus six (6) standard deviations from each average value are summarized in Table 1 and used in subsequent graphs.

To further illustrate that the raw data from each seam test dataset follows a normal distribution, a histogram of each dataset is plotted together with the normal distribution generated using the average and standard deviations values shown in Table 1. Because the number of samples differ between the factory seam dataset (1,313) and field seam dataset (469), a different histogram interval is used for the peel and
shear strength graphs for each dataset. In other words, the thickness or width of each histogram bar in a given graph will be the same but that width will vary from graph to graph. To compare the field and factory seam datasets that have a different number of samples, the histogram intervals for the factory seam tests are calculated by multiplying the seam strength intervals of the field samples by a factor of 469/1313. In other words, the number of field samples (469) is divided by the number of factory samples (1,313) to determine the strength interval.

For the Field Peel A and Field Peel B datasets, a peel strength interval of 0.26 N/mm (1.48 lbs./in) is used for these histograms. The factory peel strength dataset uses a peel strength interval of 0.09 N/mm. The project required seam peel strength is shown in each figure with a dashed line for comparison purposes.

For the Field Peel A and Field Peel B datasets, a peel strength interval of 0.26 N/mm (1.48 lbs./in) is used for these histograms. The factory peel strength dataset uses a peel strength interval of 0.09 N/mm. The project required seam peel strength is shown in each figure with a dashed line for comparison purposes.

**7.1. Statistical analysis seam peel strength results**

Field Peel B dataset follows the normal distribution better or more closely than the Field Peel A dataset. The most frequent results for the Field Peel B strength histogram match the normal distribution curve maximum values near the average. Fig. 10 shows the histogram for the Factory seam peel strength dataset also follows a normal distribution. The average and standard deviation of the normal distribution curve is the same as for the factory seam peel strength dataset shown in Table 1. The histogram shows that the factory seam peel strength data also follows the normal distribution curve but there is an increase in variance near the middle of the distribution.

In summary, the histograms for all of the peel strength datasets closely follow their corresponding normal distribution curve. This is important because future projects can assume a normal distribution for thermal seam peel strength test results and use it to predict the number of seams that have a 5% chance to fail outside of the normal distribution and possibly fail the project requirement. This can be used to better predict the amount of time that it will take to install, test, patch, and certify the geomembrane before cover soil can be placed by predicting the number of seams that might fail a given seam peel strength requirement.

**Table 1**

Summary of average and standard deviations for the field and factory seam datasets.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>Peel A</td>
<td>7.41 N/mm</td>
</tr>
<tr>
<td></td>
<td>Peel B</td>
<td>7.59 N/mm</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
<td>10.20 N/mm</td>
</tr>
<tr>
<td>Factory</td>
<td>Peel</td>
<td>8.06 N/mm</td>
</tr>
<tr>
<td></td>
<td>Shear</td>
<td>11.15 N/mm</td>
</tr>
</tbody>
</table>

**Fig. 8.** Histogram of Field Peel A dataset and the corresponding normal distribution using the average and standard deviation of this dataset from Table 1.

**Fig. 9.** Histogram of Field Peel B strength dataset and the corresponding normal distribution curve using the average and standard deviation of this dataset in Table 1.

**Fig. 10.** Histogram of Factory Seam Peel strength data and the corresponding normal distribution using the average and standard deviation of the dataset from Table 1.
Fig. 11 compares the normal distribution curves from seam peel strength datasets shown in Figs. 8–10. This comparison shows that the normal distribution of tests performed at the factory have greater peel strengths and less variance than the peel strength from both field datasets, i.e., Field Peel A and Field Peel B. The difference between the average peel strength values from the factory and the field peel dataset Peel A is 0.65 N/mm or about 8.8% increase for the factory seams. In addition, the difference between the average peel strength values from the factory and the field peel dataset Peel B is smaller with 0.47 N/mm or about 6.2%.

7.2. Statistical analysis seam shear strength results

For the field seam shear strength dataset, a shear strength interval of 0.32 N/mm was selected for the histograms. Conversely, the factory seam shear strength dataset uses a shear strength interval of only 0.11 N/mm because of the larger sample size. The project required seam shear strengths are also shown in each figure for comparison purposes. Figs. 12 and 13 show the normal distribution and histogram for the field and factory seam shear strength data, respectively.

Fig. 12. Normal distribution generated using Field Shear strength dataset average and standard deviation shown in Table 1 and compared with Field Shear strength data histogram.

Fig. 13. Normal distribution generated using Factory Shear strength dataset average and standard deviation shown in Table 1 and compared with Factory Shear strength data histogram.

The field seam shear strength histogram in Fig. 12 shows that the Field Seam Shear Strength data somewhat follows the normal distribution curve but the data concentration, i.e., histogram bars, is towards the left section of the peak of the normal distribution curve meaning more of the values correspond to lower values than the average of the normal distribution. Fig. 12 also shows most of the field seam shear strength dataset plots at the initial project requirement of 9.63 N/mm. Therefore, almost 25% of the field shear strength dataset plots below the project requirement. This resulted in the shear strength requirement being lowered to 8.23 N/mm as shown in Fig. 12. Plotting the data as shown in Fig. 12 is helpful to set the required seam strength requirement using the data from prior projects.

Conversely, Fig. 13 shows the factory seam shear strength dataset nicely follows the normal distribution curve with the data concentration, i.e., histogram bars, near the peak of the normal distribution. Fig. 13 also shows all of the factory seam shear strength dataset plots above the initial project requirement of 9.63 N/mm. Therefore, 100% of the factory shear strength dataset achieved the initial project requirement. In comparison, when the seam shear strength requirement for field samples was lowered to 8.23 N/mm, the factory seam shear strength data significantly exceed the new field seam requirement as shown in Fig. 12.

Fig. 14 compares the normal distribution curves from both the Field and Factory seam shear strength datasets and the two (2) project specifications that were used during the construction of the JRD UGR. The difference between the Factory and Field shear strength averages is 0.95 N/mm or a 9.3% difference between factor and field shear strengths. Similar to the previously analyzed seam peel strength tests, the distribution of the field shear strength dataset has a higher standard deviation and a lower average than the factory shear strengths. As a result, the maximum probability of the average value for the field dataset is notably lower than that of the factory dataset. The normal distribution shows that the values near the average will have the highest probability of occurrence for a given average and standard deviation. In this case, the field shear strength values near the field average are less likely to occur than the factory shear strength values near the factory average.

As shown above for both seam shear strength datasets, the normal distribution follows closely the histograms. Fig. 15 shows the percentage of samples that failed under the normal curve model. Fig. 15(a) shows that 25.2% of the field seam samples failed to comply with the original specification. After the shear strength specification was lowered to 8.23 N/mm only 0.96% of the field seam samples failed to pass (see Fig. 15(b)). Conversely, 100% of the factory seam samples
complied with the original specification of 9.63 N/mm. The factory shear tests projected normal distribution curve satisfies the original and modified specification while the field dataset projected normal distribution curve still resulted in some failures even after the specification was lowered. This may be beneficial in some respects because Fig. 15(b) indicates the revised specification was still somewhat challenging for the field conditions.

Further comparison between the actual field seam datasets and the statistical approximation using a normal distribution shows that the predicted percentage of field samples that failed under the original and modified specifications of shear strength, according to the normal distribution curve approximation, i.e., 25.2% and 0.96%, respectively; are near the percentages of the real field samples that failed to reach the original and modified specification required shear strengths with 24.5% and 0.63% respectively. This further illustrates that the assumption of a normal distribution is valid for this field seam dataset and may be applicable to future field seam datasets to better predict field seaming, repair operations, and construction sequencing.

7.3. Comparison of seam peel and shear strength

To further illustrate the reliability and higher strength of factory seams compared to field seams, the factory seam shear and peel strength test results are plotted against each other in one graph (see Fig. 16). The factory seam dataset shows that all of the shear and peel strength datasets for the same seam plot above the project requirements with the peel strength significantly exceeding the project requirement of 4.38 N/m. Fig. 16 also shows there is a similar range for the measured factory seam peel strengths (about 6.4–9.7 N/mm) as the seam shear strength (9.7 to about 13.0 N/mm). In general, the data indicates that increasing the seam peel strength results in an increase in seam shear strength. Further Fig. 16 shows there is less scatter about the blue trend line for the factory seam data than for the field seam datasets shown in Figs. 17 and 18. This means there is higher strength and decreased variability in the factory seam shear and peel strengths for a given factory seam than in the field seams.

The pink shaded area in Fig. 16 represents the average factory seam shear strength plus and minus two (2) standard deviations, or it encompasses 95% of the data. Similarly, the blue shaded area in Fig. 16 represents the average factory seam peel strength average plus and minus two (2) standard deviations, or 95% of the data. The rectangle formed by the intersection of these two shaded areas corresponds to

![Fig. 14. Comparison of normal distributions for Field and Factory seam shear strength datasets with the normal distribution being generated using the dataset average and standard deviation shown in Table 1.](image)

![Fig. 15. Comparison between normal distributions for Field and Factory shear strength datasets. Red fill indicates the percentage of Field seam samples that failed under the Original Specification (left) and under the Modified Specification (Right).](image)

![Fig. 16. Plot of all factory seam peel and shear strength test results with the initial and revised project specifications.](image)
welding personnel because the same equipment and personnel were consistency and measured strengths than the type of welder and the suggests that the welding conditions are more important for seam cause of the variability in

The dark brown linear trend line for the Field Peel A data in Fig. 17 indicates a more rapid increase in seam shear strength with increasing in seam peel strength but this is due to the large scatter in the data and the more logical increase is reflected by the factory data represented by the blue trend line. Using the dark brown linear trend line in Fig. 17, the following linear expression was developed to relate the Field Peel A strength with the corresponding seam shear strength:

Field Shear Strength A (N/mm) = 0.6467 * Peel Strength (N/mm) + 5.41 N/mm

(2)

The residual sum of squares of the data is 260.3 N²/mm² with a coefficient of determination (R-squared coefficient) of 0.207 for 469 data points.

Similarly Fig. 18 shows the correlation between Field Peel B and the corresponding field seam shear strength for that particular seam. The blue linear trend line for the factory seam peel and shear strengths shown in Fig. 16 is superimposed on the data in Fig. 18. A comparison of the data in Fig. 18 with the trend line from Fig. 16 shows that the Field Peel B data is also much lower and considerably more variable or spread out than the factory data. For example, the lowest field Peel B seam shear strength is 3.68 N/m versus 9.76 N/m for the factory seams.

Using the orange linear trend line for the Field Peel B data in Fig. 18, the following linear expression was developed to relate the Field Peel B strength with the corresponding seam shear strength:

Field Shear Strength B (N/mm) = 0.756 * Peel Strength (N/mm) + 5.41 N/mm

(3)

The residual sum of squares of the data is 238.35 N²/mm² with a coefficient of determination (R-squared coefficient) of 0.274 for 469 data points.

Figs. 17 and 18 show that the minimum shear strength represented by the lowest shear strength of 5.41 N/m is significantly lower for the field seams than the factory samples, with a greater variability or spread of the data from the trend line. The variability and lower base shear strengths in the field seams can be attributed to one or more of the variable conditions in the field such as: fine soil particles in the soil and GM, variable temperature, personnel and machinery, moisture in the soil before welding, changes in cloud cover, among other conditions. All of these conditions result in a decrease in the “welding window” in the field or alternatively, the factory has a greater “welding window” than the field. The welding window is the range of welder temperature, speed, and pressure that yields thermal welds that meet project specifications. For example, a decrease in temperature due to a change in cloud cover, will require a change in welder speed and possible pressure to achieve acceptable welds. These inter-related conditions are constantly changing in the field making field welding more difficult and variable than factory welding. The constant conditions make factory welding more efficient, faster, and of higher quality because welder temperature, speed, and pressure can be set at the beginning of the day and they do not have to be changed due to the constant conditions can be in a factory setting.

The light blue trend line in Figs. 17 and 18 represents the linear fit of the factory seam dataset. From the coefficients of determination of each linear correlation, a linear relationship between peel strength and shear strength is currently not viable for field and factory conditions. The spread and variance of both of the field seam datasets is greater for the shear strength and similar for the peel strength in comparison with the factory datasets (see Fig. 16). This shows that at factory conditions shear strength for that particular seam. The blue linear trend line for the factory seam peel and shear strengths shown in Fig. 16 is superimposed on the data in Fig. 17. A comparison of the data in Fig. 17 with the blue trend line from Fig. 16 shows that the Field Peel A data is much lower and considerably more variable, or spread out, than the factory data. For example, the lowest field Peel A seam shear strength is 5.32 N/m versus 9.76 N/m for the factory seams.

95% of the factory seam peel and shear strengths. Therefore, it should be expected that the field seam test results should plot within this rectangle if the field seam samples are yielding similar results as the factory seam samples, which is not the case as shown in Figs. 17 and 18.

Using the blue trend line in Fig. 16, a linear relationship between factory seam peel and shear strength was developed and the resulting equation is:

Factory Seam Shear Strength (N/mm) = 0.17 * Peel Strength (N/mm) + 9.76 N/m

(1)

The residual sum of squares for the data is 315.04 N²/mm² with a related coefficient of determination (R-squared coefficient) of 0.0279 for the 1313 datapoints in Fig. 16. This relationship suggests that factory seams yield consistent results in shear tests by maintaining a high minimum seam shear strength represented by the lowest factory seam shear strength being 9.76 N/m as shown in Eq. (1). Unfortunately, the field data plotted in Figs. 17 and 18 below show that a similar high minimum seam shear strength is not likely for field welded seams because of the variability in field conditions and field welding. This suggests that the welding conditions are more important for seam consistency and measured strengths than the type of welder and the welding personnel because the same equipment and personnel were used for the factory and field seaming on this project.

Given there are two different datasets for field seam peel strength, they are compared separately for that seam. For example, Fig. 17 shows the correlation between Field Peel A and the corresponding field seam

Fig. 17. Plot of Field Peel A seam peel and shear strength test results with the initial and revised project specifications and the linear trend line for the factory seam peel and shear strengths shown in Fig. 16.

Fig. 18. Plot of Field Peel B seam peel and shear strength test results with the initial and revised project specifications and the linear trend line for the factory seam peel and shear strengths shown in Fig. 16.
the data boundaries are decreased within a smaller “box”, that will represent decreased variance in peel strength and shear strength. For Fig. 16 the size of the box is: 1.94 N/mm for Peel Strength and by 1.98 N/mm for Shear Strength. For Fig. 17 the size of the box is: 2.36 N/mm in Peel Strength by 3.4 N/mm in Shear Strength. For Fig. 18 the size of the box is: 2.32 N/mm in Peel Strength by 3.4 N/mm in Shear Strength.

Comparing the range where 95% of the data of peel strength and shear strength from the factory samples using this “box”, the observations of the factory dataset can be made: (1) the size of the “box” is 41.8% smaller in shear strength and 17.8% smaller from the Field A dataset and (2) the size of the “box” is 41.8% smaller in shear strength and 16.9% smaller from the Field B dataset. From Figs. 16 and 17 and 18, it may be concluded that fabrication of a seam in a factory setting benefits the sample by greatly reducing the spread of expected shear strength and a smaller reduction of the spread of expected peel strength.

7.4. Other test results

The shear strength test performed on the field welded seams is specified in ASTM Test Method D6392 for the unreinforced fPP geomembrane specimens. This test method requires a minimum of five (5) 25.4 mm wide and 150 mm long specimens be obtained and tested from a sample with the field seam at the center of the field sample. Test specimens are obtained perpendicular to the centerline of the seam and used for seam testing. In accordance with ASTM D 6392, 1999, the results of the five (5) specimens are averaged and the average value is used as the shear strength value for a given seam and the average is used in the figures above.

In this section, the measured value for each of the five (5) field specimens tested to obtain the average used above are considered. By doing so a more rigorous evaluation of success rate can be performed by considering the individual test results instead of just the average as allowed by ASTM D 6392, 1999. By comparing the number of samples in which all of the specimens passed the specification with the samples in which one or more of the five (5) field specimens failed to pass the specification, a more thorough evaluation of success rate can be developed by considering the strength of each test specimen (see Table 2).

This analysis considers that the individual failure of one of the five (5) field specimens can be critical for the integrity of the entire seam sample. The results from this criterion show that 51.6% of the field seam samples possess at least one (1) individual specimen that failed to reach the original seam shear strength specification of 9.63 N/mm and 34.8% of the field seam samples possess at least two (2) individual specimens that failed to meet the original specification of 9.63 N/mm. The lowered seam shear strength of 8.23 N/mm was used for quality control, replacing the original specification of 9.63 N/mm. Under the new circumstances and considering all of the test specimens from the beginning of construction, the individual specimen success rates increased greatly. Due to the lowering of the seam shear strength to 8.23 N/mm, now only 3.8% of the field seam tests had at least one (1) individual specimen that failed instead of 51.6%.

| Table 2 | Individual specimen success rates for each field seam shear strength tests. |
| --- | --- | --- | --- | --- | --- |
| | Initial Seam Shear | Revised Seam Shear |
| | Strength9.63 N/mm | Strength8.23 N/mm |
| # of Field Specimens | One Failure | Two Failures | One Failure | Two Failures |
| 227 | 306 | 451 | 461 |
| % Success | 48.4 | 65.2 | 96.2 | 98.3 |
| % Fail | 51.6 | 34.8 | 3.8 | 1.7 |

7.5. Implications of field test results

The results of this comparison show that field welded seams exhibit lower seam peel and shear strengths at yield, more variability, and less consistency than factory welded thermal seams. The implications of this data include that the field seams may develop leakage before the factory. Therefore, if leakage is detected during the service life of the reservoir, the initial investigation into the leakage could focus on the location of the field seams, which are located using a GPS survey during installation. A leak location survey was conducted on the installed and covered fPP geomembrane so any leakage that occurs would have developed after initial filling of the reservoir. As a result, the location of the field seams may be helpful in identifying the course of leakage because the field seams exhibit lower seam peel and shear strengths at yield, more variability, and less consistency than the factory welded thermal seams.

8. Welded seam length comparison

The original rolls of manufactured 1.0 mm thick fPP GM that were used for the Columbus Upground Reservoir have the following dimensions: 7.6 m wide by 228.8 m long with an area of 1739 m². These geomembrane rolls were fabricated into two different panel sizes during the project. Due to the reduction of the field seam shear strength specification, the panel size was increased during the project to reduce the length of field seams, i.e., increase the length of factory seams. Initially, the fabricated panels measured 30.5 m wide and 76.3 m long and with an area of 2325.6 m², which is referred to herein as Panel A. Later the manufactured geomembrane rolls were fabricated into panels measuring 38.1 m wide by 76.3 m long with an area of 2907 m², which is referred to herein as Panel B. To complete construction, the project required a total of 1226 fabricated panels of 1.0 mm thick fPP geomembrane, i.e., Panels A and B, to be fabricated and installed to cover the reservoir area using the reservoir dimensions shown in Fig. 19.

![Fig. 19. Approximate dimensions of Columbus Upground Reservoir.](image-url)
the project used solely Panel A fabricated geomembranes, approximately 1398 panels would have been needed to cover the reservoir area. If the project used solely Panel B fabricated geomembranes, approximately 1119 panels would have been needed because Panel B dimensions are larger than the Panel A dimensions.

Using the original manufactured geomembrane rolls, more than 1864 original geomembrane rolls would have been needed. The following calculations use two (2) installation scenarios: (a) the project used the original roll with dimensions (7.6 m wide by 228.8 m long); and (b) the project used the fabricated geomembrane Panel B with dimensions of 38.1 m wide by 76.3 m long. For each of these scenarios the amount of field and factory seam lengths were estimated. The field seam length was determined using a CAD drawing to determine the length of field seaming needed for the construction of the reservoir with the dimensions shown in Fig. 19 and with the final positioning of the geomembrane in the reservoir for both scenarios shown in Fig. 20. The field seam model counts the length of all the line lengths in a grid that would correspond to the field seams needed to join integrally the total amount of geomembrane rolls used in the reservoir. The perimeter length of the reservoir is ignored for both scenarios because the perimeter length of the panels on the reservoir perimeter would not need to be seamed with another panel.

For the original roll scenario, the length of field seams needed would have been more than 563,600 linear meters. For the fabricated geomembrane Panel B scenario, the 1864 manufactured original geomembrane rolls would need to be seamed in the factory to produce 1119 panels of fabricated geomembrane. The calculated length of factory seams needed to create these panels is 340,888 linear meters. Therefore, factory fabrication reduced the amount of field seams needed to complete the field installation to about 126,709 linear meters or 77.5% less field seams than field fabricating rolls of the manufactured geomembrane. Table 3 compares the seam lengths that had to be welded in the factory and the field for the manufactured rolls and fabricated Panel B geomembrane, with the percentage that each factory and field seam length would represent from the total seam length required.

This section shows that by fabricating a geomembrane panel with a greater area than the original roll, the number of panels to be transported is reduced. More importantly, the length of seams needed for the project will be reduced in the field substantially, because this activity is transferred to a factory setting with generally lower associated costs, shorter completion time, better quality, and higher predictability.

9. Summary

The data analysis performed on test results from factory and field welded seams from the Columbus Upground Reservoir yielded the following observations:

- The use of fabricated panels allowed the lengthy project schedule to be compressed and completed in the required three (3) years.
- The use of large fabricated panels created a good and open working area for soil cover applications and allowed rapid cover operations.
- The use of large fabricated panels also resulted in about 77.5% less field seams being created, which accelerated construction during good weather conditions and improved seam quality.
- The average peel strength of factory thermally welded seams is about 8.8% and 6.2% greater than the peel strength of the two field seam datasets, i.e., Field Peel A and Field Peel B, respectively. The average factory seam shear strength is 9.3% greater than the shear strength of the field seams.
- More importantly, 24.5% of the field seams failed the initial seam shear strength requirement, which caused additional testing, repairs, costs, and construction time. In contrast, zero (0) percent of the factory seams failed the initial seam shear strength requirement. As a result, the initial seam shear strength requirement of 9.63 N/mm was reduced to 8.23 N/mm.
- The factory seam test datasets when compared to a normal distribution predicted the shear strength failure rates for the field seam tests. As a result, a normal distribution may provide a means for predicting the success of factory seams in future projects with similar conditions.
- With 24.5% of the field samples failing the original specification of 9.63 N/mm and 25.2% failing the specification based on the normal distribution curve derived from the data, a normal distribution also may provide a means for predicting the failure of field seams in future projects with similar conditions.
- Analysis of the factory welded seam shear and peel strength data shows that for a given seam sample these strengths are more consistent and higher due to a lower standard deviation than the field seam data. Conversely, the field seam shear and peel test data show higher standard deviations, which is attributed to the variable field conditions, e.g., soil particles in the seam and geomembrane, temperature, cloud cover, wind, direct, moisture, etc., compared to the clean and consistent conditions in a factory.
- Analysis of each individual shear strength test used to obtain the average of five (5) specimens under ASTM D6392, shows that the
failure percentage for field seams is 51.6% in which at least one (1) of the five (5) specimens did not meet the seam shear strength specification of 9.63 N/mm. The failure percentage in which at least two (2) out of the five (5) individual specimens failed the specification is 34.8%. With the subsequent change of the field seam shear strength specification to 8.23 N/mm, the failure percentage for at least one (1) out of the five individual specimens from each seam sample was reduced to 3.8% from 51.6% and for at least two (2) out of the five individual specimens it was reduced to 1.7% from 34.8%.

Acknowledgments

The contents and views in this paper are those of the individual authors and do not necessarily reflect those of any of the represented corporations, contractors, agencies, consultants, organizations, and/or contributors including the City of Columbus, Ohio and the Ohio Department of Natural Resources.

References