

IMPROVING SOIL STIFFNESS BENEATH PAVEMENTS USING POLYURETHANE INJECTION

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Paper prepared for presentation at the

Permeable Pavement Design and Technology Session

of the 2010 Annual Conference of the
Transportation Association of Canada

ABSTRACT

Highway agencies have been experiencing difficulty with roadways settling due to the presence of peat deposits. Traditional remedial methods (such as overlays and cementitious grout) provide short-term solutions by addressing the symptoms, but not the underlying problem. Further, these treatments actually exacerbate the problem by placing additional weight on an already overstressed soil structure. Treatment by full depth removal can be time consuming and extremely costly. An expedient, long-term solution that can reduce the frequency of remedial maintenance is needed. One such solution could include insitu stabilization with a strong, lightweight material.

The broad objective of this study was to evaluate insitu injection of polyurethane foam as a viable method for improving soil stiffness beneath a simulated pavement structure. The specific objective was to assess the URETEK Deep Injection™ (UDI) process for stabilizing buried peat deposits in highway applications.

A simulated rigid pavement system was constructed over a sand subgrade incorporating a 2-ft (610 mm) thick layer of peat. The system was constructed to simulate actual FDOT District 2 site conditions. The pavement system was constructed inside a Florida Department of Transportation (FDOT) Soil Box located at the University of Florida (UF). Site characterization measurements and observations were recorded before, during, and after the stabilization process.

This paper outlines the study methodology, insitu testing protocol followed, and presents the findings and visual observations of the de-constructed soil box.

INTRODUCTION

Highway agencies have been experiencing difficulty with roadways settling due to the presence of peat deposits. Traditional remedial methods (such as overlays and cementitious grout) provide short-term solutions by addressing the symptoms, but not the underlying problem. Further, these treatments actually exacerbate the problem by placing additional weight on an already overstressed soil structure. Treatment by full depth removal can be time consuming and extremely costly. An expedient, long term solution that can reduce the frequency of remedial maintenance is needed.

One such solution could include insitu stabilization with a strong lightweight material. URETEK Worldwide owns the proprietary rights for the URETEK Deep Injection™ (UDI) process to address soil stabilization issues. Specifically, a patented, high-density, expansive, thermoset polyurethane resin is injected into the soil system.

The primary focus of this research study was to apply and evaluate the UDI process in a simulated pavement structure with an underlying peat deposit.

ACKNOWLEDGEMENTS

The completion of this study was the result of a collaborative effort by many parties. A list of the team members include:

- Florida Department of Transportation (FDOT) Headquarters
- Florida Department of Transportation, State Materials Office (FDOT SMO)
- Florida Department of Transportation, District 2 (FDOT D2)
- University of Florida (UF)
- URETEK ICR, LLC (Lakeland, FL)
- URETEK-CRSI (Carrollton, GA)
- URETEK ICR Heartland (Adel, IA)
- URETEK USA
- Applied Research Associates, Inc.

PROJECT DESCRIPTION

The objective of the study was to evaluate insitu injection of polyurethane foam as a viable method for improving soil stiffness. Specifically, the study assessed the UDI process for stabilizing peat deposits found under Florida rigid pavements.

A simulated rigid pavement system was constructed over an AASHTO A-2-4 sand subgrade, incorporating a 2-ft (610 mm) thick peat layer inside the FDOT Soil Box. Using the proprietary UDI process, polyurethane foam was injected into the soil mass to stabilize the peat deposit.

A variety of insitu testing was completed on the pavement system to determine ‘pre’ and ‘post’ injection conditions. The insitu testing included dynamic cone penetration (DCP) testing, static cone penetration (SCP) testing, and soil density and moisture content measurements. In addition to the insitu testing, earth pressure cells were installed to monitor pressure changes within the soil structure during injections.

After the foam injection process, the insitu testing was repeated, followed by the removal of the constructed soil structure to expose the hardened foam formations. The foam flow patterns within the peat layer were observed and documented.

The investigation protocol was completed as follows:

- Construct three instrumented test sections in the FDOT Soil Box, located in the UF Coastal Engineering Laboratory Building.
- Execute pre-injection site characterization of the test sections.
- Perform UDI on the test sections. Variations in test section construction, injection sequence, and injection temperature were minimized. The amount of foam injected into a test section was varied in an effort to establish a relationship between foam usage and stiffness gain.
- Execute post-injection site characterization of the test sections.
- Excavate Soil Box to reveal the injected foam material distribution.
- Complete Compressive Strength testing on recovered foam material.
- Compile documentation and data; prepare report.

Material Specifications

The URETEK Foam Grout is a two-component, high-density expansive thermoset polyurethane resin system formulated for undersealing, void filling, and lifting settled pavements; stabilizing and stiffening weak soils; and encapsulating and sealing buried infrastructure.

The polyurethane foam grout is capable of expanding 25 times its original volume in unconfined conditions. The foam material is formulated in various densities and an expansive coefficient for specific project applications, and when fully cured, is inert and non-toxic. The low viscosity and lubricity of the foam material allows for easy penetration into soils, while compacting surrounding soils and displacing water without detrimental dilution or loss of dimensional stability to the resin system.

The patented chemical composition developed by Bayer MaterialScience allows for direct application into water, or very damp regions, while still maintaining physical properties. The hydro-insensitivity and monolithic nature ensure the polyurethane grout will not be subject to underground water erosion or weakening [1].

The product used for this research study was U486STAR-4, and consists of the properties identified in Table 1.

Table 1. U486STAR-4 Product Specifications

Physical Property	Test Method	U486STAR-4
Grout Density	ASTM D 1622	4 lbs/ft ³ (64 kg/m ³)
Compressive Strength	ASTM D 1621	65 lbs/in ² (448 kPa)
Tensile Strength	ASTM D 1623	110 lbs/in ² (758 kPa)
Shear Strength	ASTM C 273	420 lbs/in ² (2.9 MPa)
Water Absorption	ASTM D 2852	< 2 %
Dimensional Stability	ASTM D 2126	< 2 %

Soil Box Description

A simulated rigid pavement structure was constructed within a Soil Box provided by FDOT. A photograph of the Soil Box and dimensions has been included in Figure 1. All elevation measurements are referenced as heights, from the bottom of the Soil Box.

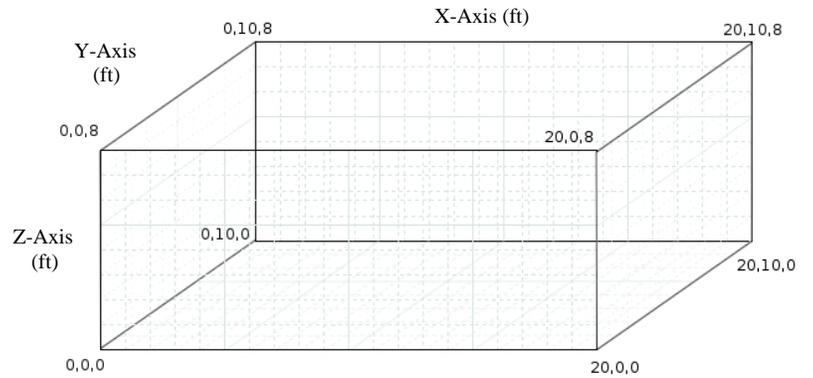


Figure 1. Soil Box provided by FDOT

The Soil Box setup includes three steel rods at the top of the box to provide lateral support within the 20-ft (6.1 m) span. As these rods were at the top of the Soil Box, three individual concrete slabs had to be constructed to fit within each of the three areas. These areas allowed for trials of three different injection patterns. Figure 2 provides a top view of the Soil Box, with the positioning of the steel rods.

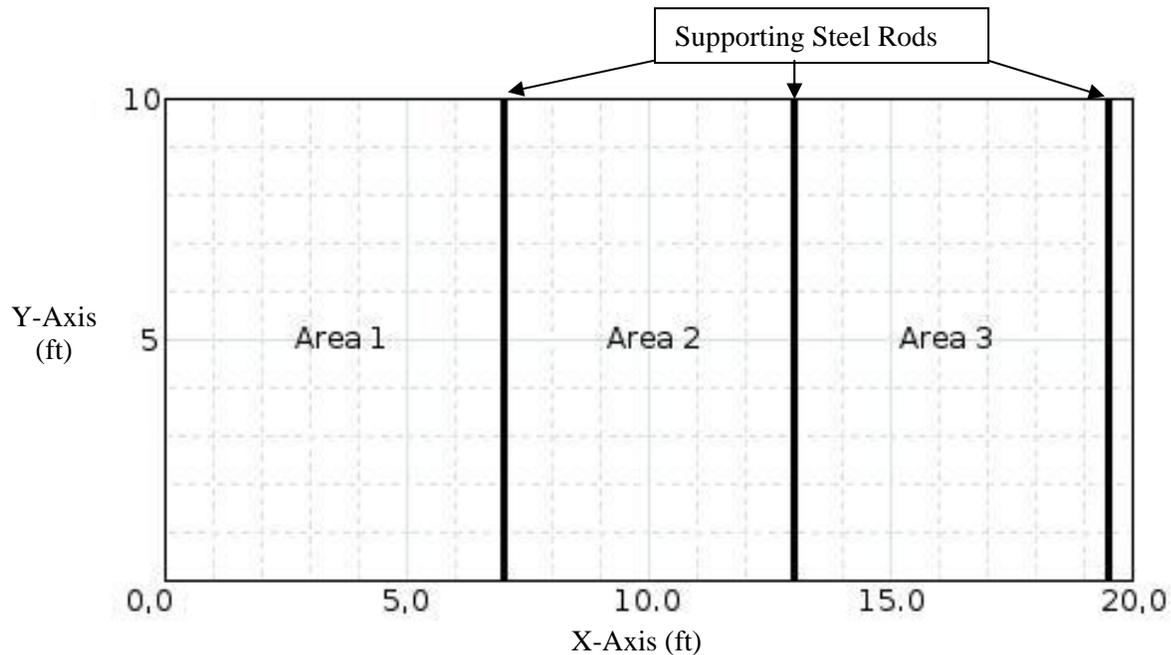


Figure 2. Top View of Test Areas

Construction Materials

The primary materials used in the construction included AASHTO A-2-4 sand and peat. The A-2-4 material was provided by FDOT District 2, while the peat material was purchased for use by URETEK ICR FLORIDA, from a pit in Lake County, Florida. Both materials were delivered to the UF Coastal Engineering Laboratory and temporarily stockpiled until placed within the Soil Box. In addition to the AASHTO A-2-4 sand, a white fine-grained sand (Play Sand) was used as a marker to identify layer boundaries at selected heights.

Samples of all three materials were collected and delivered to the FDOT D2 laboratories for classification testing. Test results have been summarized in Table 2.

Table 2. Laboratory Test Results on Construction Soils

Sample Type	Muck/Peat	Play Sand	AASHTO A-2-4 Sand
Percent Organic (Avg. of 2 tests)	73		
AASHTO Soil Classification	A-8	A-3	A-2-4
% Pass No. 10 Sieve (2 mm)		100.0	100
% Pass No. 40 Sieve (420 µm)		86.2	84.9
% Pass No. 60 Sieve (250 µm)		45.0	45.2
% Pass No. 100 Sieve (150 µm)		7.7	18.2
% Pass No. 200 Sieve (75 µm)		0.6	11.9
% Clay Size Particles (< 0.002 mm)		0.0	5
% Silt Size Particles (< 0.075 mm)		1.0	6
% Sand Size Particles (> 0.075 mm)		99.0	88
Permeability		317.00 cm/day	0.00 cm/day

Three concrete slabs, each 8-inch (203 mm) thick, were constructed for placement on top of the upper A-2-4 sand layer. The concrete slabs were steel reinforced, and were constructed with four chain links to allow for easier transporting.

Soil Box Construction

Construction of the simulated rigid pavement system began with the placement of a 1-ft (305 mm) base layer of A-2-4 sand material, at the bottom of the Soil Box. This layer was placed and compacted in 6 inch (152 mm) thick lifts, with density measurements completed at the 1-ft (305 mm) height. Following placement of this layer, peat material was placed and levelled manually. Due to the compressible nature of the peat, no mechanical compaction effort was attempted on this layer. Furthermore, preliminary evaluation of the peat material indicated that some 0.5-ft (152 mm) of settlement could be expected with the placement of the upper materials. Therefore, to obtain a desired 2-ft (610 mm) thick peat layer, 2.5-ft (762 mm) of uncompacted peat was initially placed into the Soil Box.

Additional A-2-4 sand material was placed on top of the peat material in 6 inch (152 mm) thick lifts. Mechanical compaction was applied to all sand lifts, with the exception of the first 6-inch (152 mm) lift placed directly on top of the peat layer. Compaction of the sand lifts was completed with a 244 lb (110 kg) vibrating plate tamper. The insitu density achieved during compaction of the A-2-4 sand layers was confirmed by a Troxler nuclear density gauge operated by a qualified FDOT SMO technician. The density measurements were completed on the lower A-2-4 sand layer at a height of 1-ft (305 mm), with subsequent measurements in the upper A-2-4 sand layer at 1-ft (305 mm) intervals from heights of 4-ft (1.24 m) to 7-ft (2.13 m). Prior to placement of the concrete slabs, a final 6-inch (152 mm) lift of A-2-4 sand was placed and compacted.

After construction of the simulated pavement system soils, the concrete slabs were positioned, and the entire structure was left to settle overnight. As expected, a total of 0.5-ft (152 mm) of settlement was observed, likely a result of settlement within the peat layer. The resulting pavement structure lift thicknesses (after consolidation) are illustrated in Figure 3. All elevation measurements are referenced as heights, from the bottom of the Soil Box.

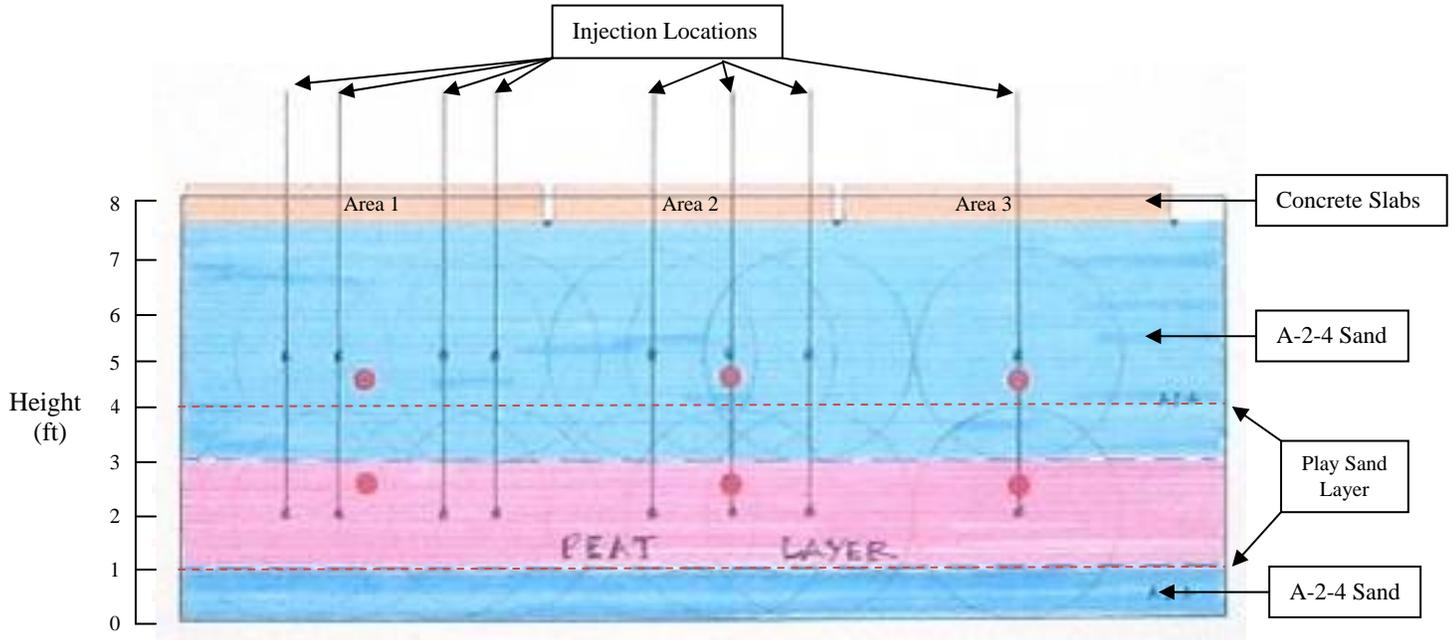


Figure 3. Constructed Pavement Structure (After Consolidation of the Peat Layer)

INSITU TESTING METHODOLOGY

A variety of insitu testing was completed on the pavement sub-structure before the foam injection process to determine the initial soil conditions of the simulated section. The testing protocol included executing nuclear density measurements on the surface of the A-2-4 sand layer prior to placing the concrete slabs. After placement of the concrete slabs, DCP and SCP testing were completed through pilot holes drilled through the concrete slabs.

In addition to the insitu testing, Earth Pressure Cell instrumentation was installed within the Soil Box. In each of the three test sections, Earth Pressure Cells were placed along the sidewalls to observe potential pressure increases as a result of the injection process. One set of pressure cells were located at a height of 2 ft (6.1 m) in the peat layer, with a second pressure cell located at a height of 5 ft (1.52 m) in the A-2-4 sand layer.

Locations of all insitu testing and instrumentation placement are illustrated in Figure 4.

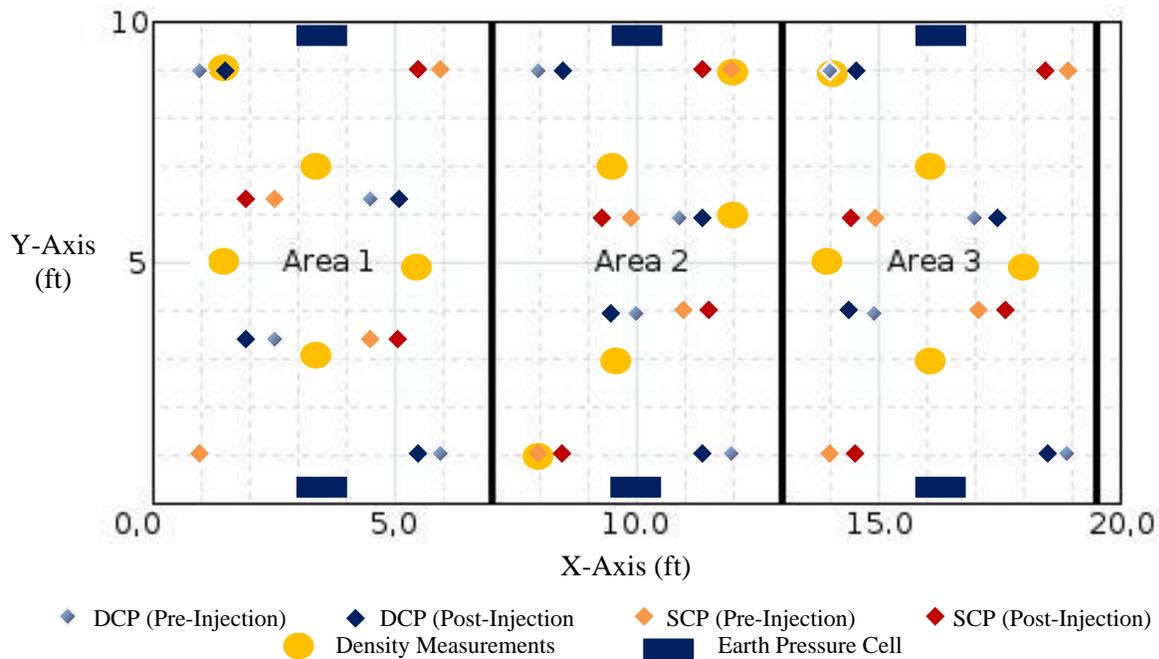


Figure 4. Location of DCP/SCP Testing

Insitu Density and Moisture Contents

Insitu density and moisture content measurements were collected at five selected locations within each area. Density and moisture measurements were taken before and after the foam injection process. The locations for both sets of testing were kept identical, except for Area 2, location 13 (X8 Y1). At this location, the foam was visible on the surface of the sand layer. The post-injection test at this location was offset by 1-ft (305 mm) in the x-direction (X9 Y1).

Dynamic Cone Penetrometer (DCP)

A DCP is a device used to assess soil strength by measuring penetration resistance. A DCP supplies a known amount of kinetic energy to the penetration cone, which causes the cone to advance through the soil. The depth of penetration is dependent on the kinetic energy applied, the geometry of the cone, and the soil penetration resistance.

The DCP equipment used for this investigation was the ‘Pagani’ DCP. This is a mechanical device that uses hydraulic pressure to raise the hammer to a set drop height before releasing the hammer. The cone tip has an included angle of 60°, and a section area of 10 cm² (1.55-in²). Data is recorded as to the number of blows required to drive the cone a depth of 10 cm (4-in). As compared with manual DCP units, the use of the Pagani DCP provided several advantages: more consistent drop heights, reduced operator variability, and larger weights that enable it to penetrate more dense material.

DCP testing was carried out both before the foam injection process, and after the foam injection. After the initial set of DCP testing, the pilot holes through the concrete slabs test were filled with Play Sand material to prevent the foam material from escaping through these holes. All post-injection test locations were offset by 6 inches (152 mm) from the pre-injection locations. All test locations are shown in Figure 4.

Static Cone Penetrometer (SCP)

A Durham Geo Slope Indicator, double-rod, SCP was also used for measuring soil consistency within the Soil Box. The dual rods enable the cone stress to be measured directly, without the soil friction on the outer rods. The cone tip has an included angle of 60° and a section area of 1.5 cm^2 (0.23-in.^2). The cone was pushed into the soil at 150 mm (6-in) intervals, with the maximum total bearing pressure (kg/cm^2) recorded for each interval. Extension rods were used to ensure that the SCP equipment was capable of reaching the bottom of the Soil Box (2.44 m). [2]

Similar to the DCP testing, the SCP tests were completed before and after foam injections, with the post-injection testing offset by 6-inches (152 mm). All of the initial SCP locations were filled with Play Sand material to prevent the foam material from escaping through these holes.

Earth Pressure Cells

Earth Pressure Cells are constructed from two stainless steel plates welded together around their periphery and separated by a narrow gap, filled with hydraulic fluid. External pressures squeeze the two plates together creating an equal pressure in the internal fluid. A length of stainless steel tubing connects the fluid filled cavity to a pressure transducer that converts the fluid pressure into an electrical signal transmitted by cable to a readout location [3]. The Earth Pressure Cells used for this study were Geokon Model 4800 Earth Pressure Cells, provided by UF.

A total of 12 pressure cells were installed along the perimeter of the Soil Box, as illustrated in Figure 6. Six pressure cells were placed within the peat layer at a height of 2-ft (610 mm), with another six pressure cells placed in the A-2-4 sand layer at a height of 5-ft (1.52 m). Coordinates of all pressure cell locations have been provide in Figure 6.

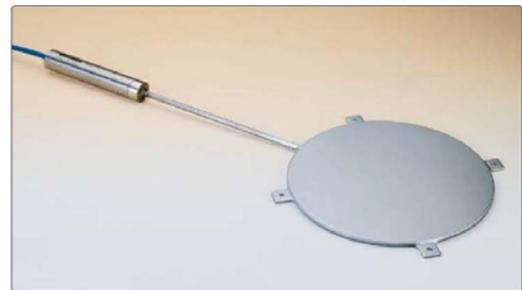
Initial pressure readings were taken prior to the start of the injection process at all pressure cell locations. Throughout the injection process, pressure changes were monitored at cell locations near the injection points. Pressure readings were recorded on 15 second intervals throughout the foam injection process, and continued after injection until pressures stabilized.



a) DCP



b) SCP



c) Earth Pressure Cells

Figure 5. Photographs of Insitu Testing Equipment

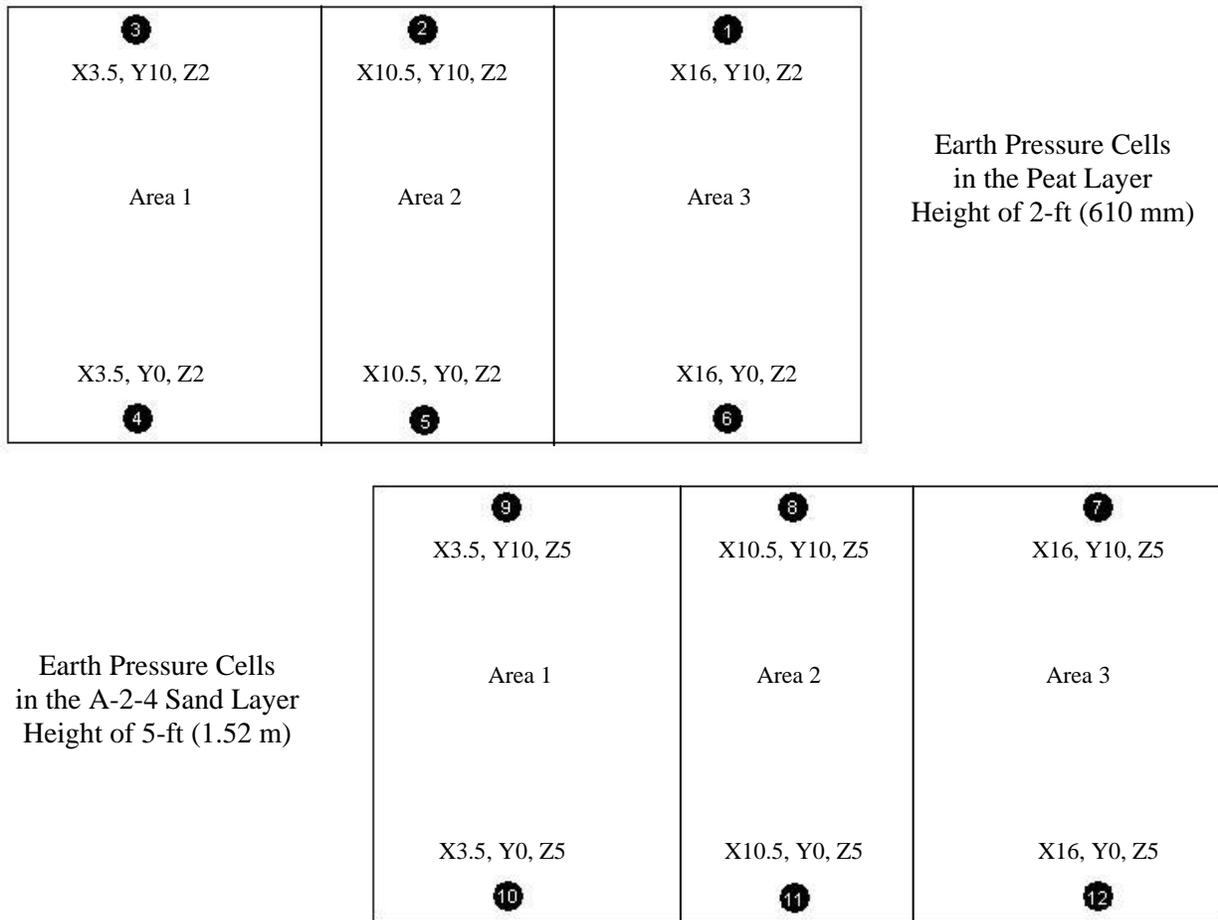


Figure 6. Coordinate Locations of Earth Pressure Cells

URETEK FOAM INJECTION PROCESS

Once the baseline testing was complete, the simulated pavement system was injected with polyurethane foam material. To fill any voiding between the concrete slabs and the A-2-4 sand layer, an initial foam injection (The URETEK Method) was applied to ‘seat’ the slabs and to prevent subsequent injections from escaping beneath the concrete slab. A total of 30 lbs (13.6 kg) of material was used for the Method injection step.

The UDI process was completed at two different heights (shallow and deep). The Soil Box was divided into 3 separate areas on the surface. A variety of injection patterns was attempted, with varying amounts of foam material injected. The various injection patterns in each area are provided in Figure 7.

As part of the shallow injection step, foam material was injected within the A-2-4 sand layer at a height of 5 ft (1.52 m), or roughly 3 ft (915 mm) from the top of slab. These shallow injections were expected to produce a containment cap prior to deep injections into the peat layer. The shallow injection step was followed by the deep injections into the peat layer at a height of 2-ft (610 mm), roughly 6-ft (1.83 m) from the top of slab. The shallow injections were completed in all three areas before proceeding with the deep injections.

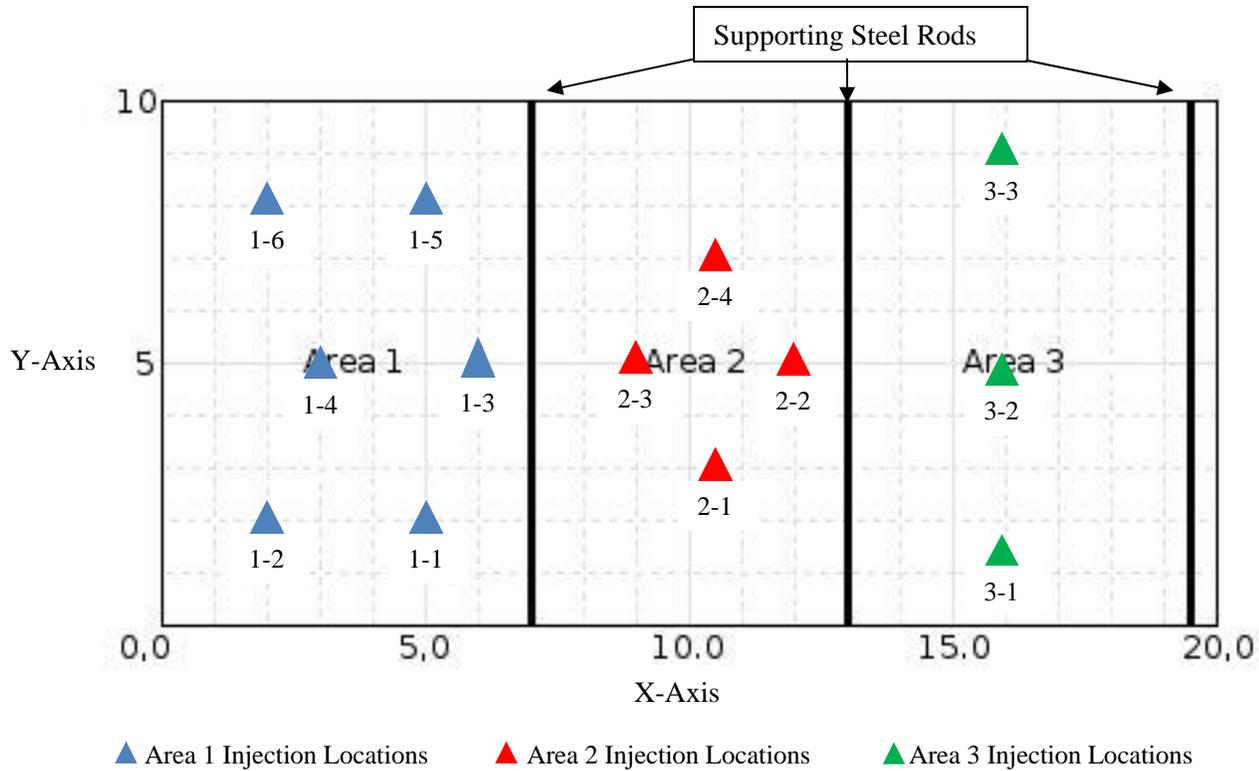


Figure 7. URETEK Injection Locations

Area 1 Injection Process

In Area 1, a six-point injection pattern was utilized in an attempt to provide maximum coverage throughout the injection area. In this area, two locations were injected simultaneously starting with locations 1-3 and 1-4, followed by the injection at locations 1-5 and 1-6, and concluding with the injection at locations 1-1 and 1-2. Each of these locations was injected with as much foam material as required to raise the concrete slab by 1 mm for both the shallow and the deep injection processes. Elevation changes of the concrete slabs were monitored by a laser levelling system.

During the deep injections, pressure readings (pre- and post- injection) were taken at all pressure cells positioned within Area 1, with continuous pressure readings taken at the lower pressure cell positions. During the dual injection process at locations 1-1, 1-2, 1-3 and 1-4, pressure cell position 4 was continuously monitored. Pressure changes were recorded at pressure cell position 3 during the injection of dual locations 1-5 and 1-6.

Area 2 Injection Process

A diamond pattern was used for the injection pattern in Area 2. The dual injection process was initially used at locations 2-2 and 2-4, followed by locations 2-1 and 2-3. As with Area 1, each of these locations was injected with as much material as required to raise the concrete slab 1 mm.

For the deep injection at locations 2-2 and 2-3, pressure readings were recorded on 15-second intervals at pressure cell position 5 (lower position), with pre- and post-injection readings at the upper pressure cell position (Position 11). At the next two injection locations (2-1 and 2-4), pre- and post-injection readings were recorded at all pressure cell positions in Area 2 (2, 8, 5, and 11). However, only the lower pressure cell at position 2 was continuously monitored.

Area 3 Injection Process

The third area was used as a control area with only three injection locations and a fixed amount of material injected at each location. In this area, locations 3-1 and 3-2 were injected simultaneously, while location 3-3 was injected independently. The shallow injections in this area were set at 33 lbs (15 kg) of material at each location, for a total of 99 lbs (45 kg). The deep injections involved 35 lbs (15.9 kg) of material at locations 3-2 and 3-3 and 47 lbs (21.3 kg) of material at location 3-1, for a total of 117 lbs (53 kg). No elevation change was observed for any of the injections completed in this area.

During the deep injection in this area, pre- and post-injection pressures were recorded at all pressure cell positions, with continuous recording of pressure readings completed at the pressure cell position 1 (lower position). As a single injection process was completed at location 3-1, pre- and post-injection pressures were recorded at pressure cell position 12 (upper position), with continuous monitoring of pressure cell 6 (lower position).

FOAM INJECTION OBSERVATIONS

Following the shallow injection operation, which established a containment cap in all three areas, the deep injection was completed to stabilize the peat layer. In this part of UDI process, foam material was injected at a height of 2-ft (610 mm), or 6-ft (1.83 m) below the top of slab, which was in the center of the peat layer. During this injection step, all the foam material remained within the Soil Box, except for a small amount that leaked out of the bottom corner in Area 1 (X = 0, Y = 10).

Deep Injection Observations

The injection in the first area proceeded until a 1 mm grade raise was measured. The total amount of deep injection foam material used at each of these locations is summarized in Table 3.

Table 3. Summary of Material Injected Deep in Area 1

Injection Locations	Foam Material Injected
1-1	34 lbs (15.4 kg)
1-2	38 lbs (17.2 kg)
1-3	45 lbs (20.4 kg)
1-4	58 lbs (26.3 kg)
1-5	15 lbs (6.8 kg)
1-6	20 lbs (9.1 kg)
Total	210 lbs (95.3 kg)

In Area 2, the injection locations were also grouted using a dual injection sequence. The total amount of foam material injected at each of the four locations is summarized in Table 4.

Table 4. Summary of Material Injected Deep in Area 2

Injection Locations	Foam Material Injected
2-1	31 lbs (14.1 kg)
2-2	68 lbs (30.8 kg)
2-3	73 lbs (33.1 kg)
2-4	45 lbs (20.4 kg)
Total	217 lbs (98.4 kg)

Area 3 was injected at three locations, with locations 1-2 and 1-3 injected using a dual injection sequence, and location 1-1 injected independently. A fixed amount of material was injected at each deep location. Injection locations 1-2 and 1-3 were each injected with 35 lbs (15.9 kg) of material, while location 1-1 had 47 lbs (21.3 kg) of material injected into it, for a total of 117 lbs (53.1 kg) injected deep into Area 3.

Earth Pressure Cell Readings

As in the shallow injection operation, pressure readings were recorded before and after deep injection in each of the areas. The results of the Earth Pressure Cell readings are summarized in Table 5.

For the first injection locations in Area 1 (1-3 and 1-4), only pressure cell position 3 observed a significant pressure change. At this position, a pressure increase of 4.75 psi (33 kPa) was recorded. For the remaining injection sequences, earth pressures remained relatively unchanged, except for pressure cell position 4. While injecting foam material at locations 1-1 and 1-2, the pressure at this position increased from 1.6 psi (11 kPa) to a peak of 9.9 psi (68 kPa) at the time the injection of foam material stopped, before stabilizing at a post-injection pressure of 7.6 psi (52 kPa).

During the deep injection at location 2-2 and 2-3, a pressure change was recorded at pressure cell position 5. During this injection sequence the earth pressure increased from 14.1 psi (97 kPa) to a peak pressure of 18.8 psi (130 kPa), before stabilizing at a post-injection pressure of 17.7 psi (122 kPa). Similarly, increased earth pressures were recorded at pressure cell position 2, while foam material was injected at locations 2-1 and 2-4. At this pressure cell position, earth pressures increased from 2.2 psi (15 kPa) and peaked at 8.2 psi (57 kPa), before stabilizing at a post-injection pressure of 7.4 psi (51 kPa).

In Area 3, the trend was similar to those in the other two areas. On the side being injected, pressures cells recorded an increase in earth pressure, which peaked at the time the injection of the foam material stopped. A slight reduction in earth pressures occurred after the injection process stopped.

Table 5. Earth Pressure Cell Results during Deep Injection (Peat Layer)

Area #1				
Pressure Cell Location	3	4	9	10
Injection Locations 1-3 & 1-4				
Pre Injection Pressure, psi (kPa)	2.17 (15)	1.66 (11.4)	2.37 (16.3)	3.96 (27.3)
Post Injection Pressure, psi (kPa)	6.92 (47.7)	1.68 (11.6)	3.47 (23.9)	2.97 (20.5)
Peak Monitoring Pressure, psi (kPa)		1.71 (11.8)		
Injection Locations 1-5 & 1-6				
Pre Injection Pressure, psi (kPa)	5.51 (38)	1.68 (11.6)	3.42 (23.6)	2.97 (20.5)
Post Injection Pressure, psi (kPa)	6.3 (43.4)	1.58 (10.9)	3.19 (22)	2.75 (19)
Peak Monitoring Pressure, psi (kPa)	7.07 (48.7)			
Injection Locations 1-1 & 1-2				
Pre Injection Pressure, psi (kPa)	5.71 (39.4)	1.58 (10.9)	3.08 (21.2)	2.75 (19)
Post Injection Pressure, psi (kPa)	5.12 (35.3)	7.61 (52.5)	2.6 (17.9)	2.65 (18.3)
Peak Monitoring Pressure, psi (kPa)		9.93 (68.5)		

Area #2				
Pressure Cell Location	2	5	8	11
Injection Locations 2-2 & 2-3				
Pre Injection Pressure, psi (kPa)		14.07 (97)		0.82 (5.7)
Post Injection Pressure, psi (kPa)		17.68 (121.9)		1.14 (7.9)
Peak Monitoring Pressure, psi (kPa)		18.82 (129.8)		
Injection Locations 2-1 & 2-4				
Pre Injection Pressure, psi (kPa)	2.22 (15.3)	17.12 (118)	2.69 (18.5)	1.03 (7.1)
Post Injection Pressure, psi (kPa)	7.39 (51)	18.69 (128.9)	3.73 (25.7)	1.24 (8.5)
Peak Monitoring Pressure, psi (kPa)	8.23 (56.7)			

Area #3				
Pressure Cell Location	1	6	7	12
Injection Locations 3-2 & 3-3				
Pre Injection Pressure, psi (kPa)	2.72 (18.8)	0.78 (5.4)	2.07 (14.3)	2.05 (14.1)
Post Injection Pressure, psi (kPa)	5.21 (35.9)	0.8 (5.5)	1.21 (8.3)	2.11 (14.5)
Peak Monitoring Pressure, psi (kPa)	6.81 (47)	-	-	-
Injection Locations 3-1				
Pre Injection Pressure, psi (kPa)		0.78 (5.4)		2.05 (14.1)
Post Injection Pressure, psi (kPa)		3.53 (24.3)		1.03 (7.1)
Peak Monitoring Pressure, psi (kPa)		4.41 (30.4)		-

Note: Shaded Pressure Cell Positions are located in upper sand layer.

Foam Material Flow Pattern within Peat Layer

Excavation revealed the hardened foam material was contained within the peat layer, with only minor propagation into the sand layers above and below. This containment was consistent for all three injection areas. Top view sketch of the foam material formation is presented in Figure 8.

As the excavation of the soil structure continued, the foam material was observed to create a honeycomb pattern within the peat layer. The formation of this honeycomb lattice structure was more of a hydraulic fracture type process (movement through the material), instead of mixing with the organic material. It was further observed that propagation of additional material often followed adjacent to previous flow paths. Furthermore, in Area 3 (where a fixed amount of foam material was injected) the size of the honeycomb pockets was typically larger, with thinner walls surrounding the pockets of peat material.

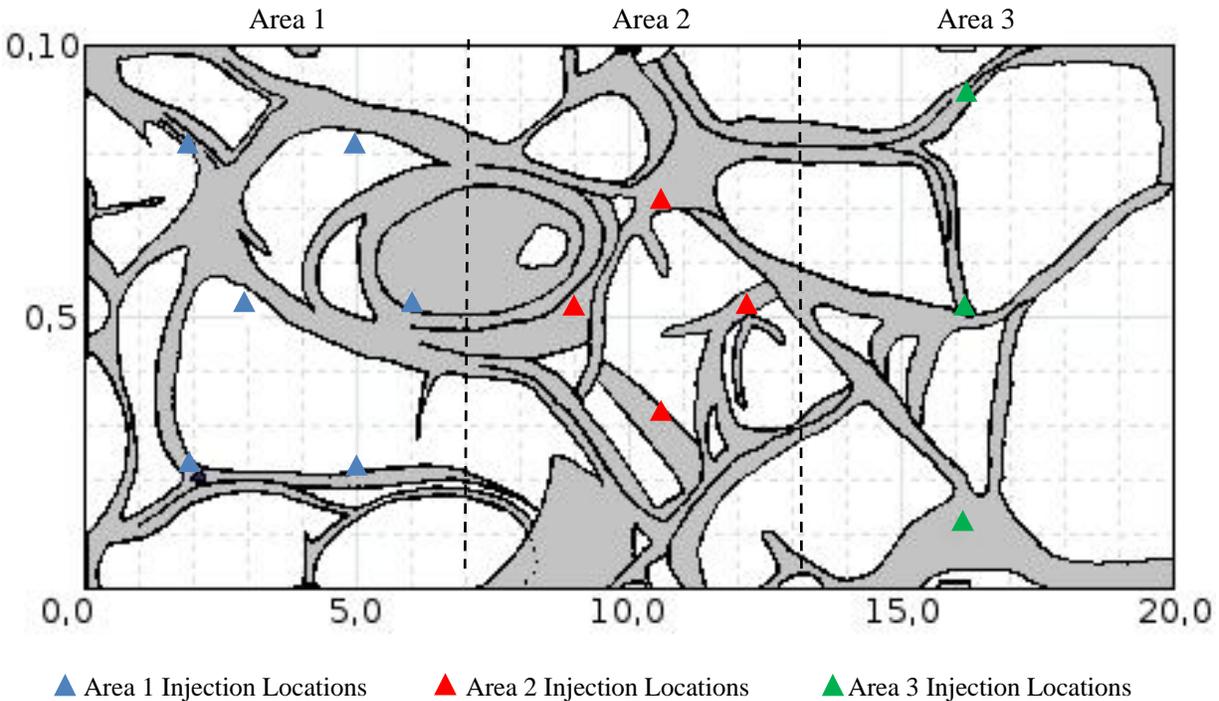


Figure 8. Deep Injection Foam Flow Pattern

COMPARISON OF INSITU TEST RESULTS

Following the injection process, all the insitu testing completed prior to foam injection was repeated. The DCP and SCP testing was repeated at 6-inch (152 mm) offsets from the initial test locations before removing the concrete slabs from the Soil Box.

After the concrete slabs were removed, the density/ moisture content measurements were completed on the surface of the sand layer. These tests were completed at the same locations as prior to injection. No diagrams were provided for these retest locations, as they did not change from the original test locations.

Dynamic Cone Penetrometer (DCP) Comparison

In general, a noticeable difference was observed at the DCP test locations through foam material within the sand layer (capping layer). At these locations the blow counts were found to spike to as high as 30 blows to penetrate a depth of 10 cm. This spike corresponded to as much as 15 additional blows required to penetrate that depth, when compared to the pre-injection testing.

Unlike the sand layer test results, the DCP tests within the depth of the peat layer found little to no difference in the consistency of the peat material. For ease of reference, the DCP test results have been plotted against depth and provided in Figure 9. These plots contain the pre- and post-injection test results.

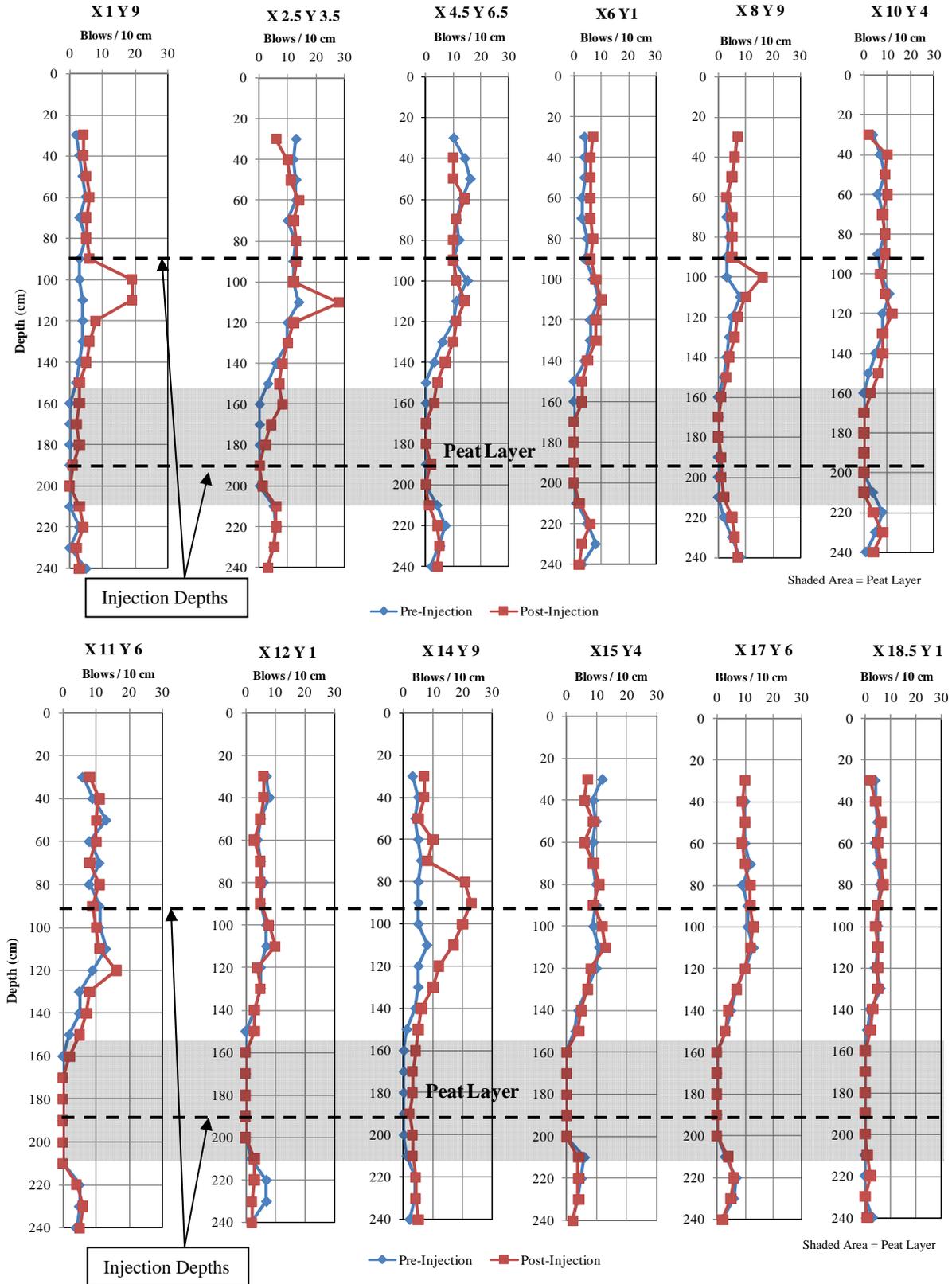


Figure 9. Comparison of DCP Test Results (Pre-Injection and Post-Injection)

Static Cone Penetrometer (SCP) Comparison

Unlike the DCP equipment, the SCP test equipment was unable to penetrate the hardened foam material. No further progress was recorded at eight of the eleven test locations. Three of the eight locations encountered refusal immediately beneath the concrete slabs. The remaining five locations encountered refusal within 30 inches (762 mm) of the concrete surface, near the shallow injection depth.

Of the remaining three SCP test locations that penetrated into the peat layer, only one location found a difference between the pre- and post-injection results. The SCP test completed at location X 6 Y 9, had a slight increase in the Cone Index Reading (CIR) for most of the depths below 36 inches (914 mm). This SCP test is located in close proximity of hardened foam material, which would likely explain the increase in soil consistency at that location.

Insitu Density and Moisture Content Measurement Comparison

After completing the injection process the same density locations were tested again. Only one location (Area 2, Location 13) had to be moved in the post-injection testing due to foam migrating to the surface of the A-2-4 sand layer. A comparison of pre- and post-injection test results comprises Table 6.

Table 6. Insitu Density and Moisture Content Measurement Comparison

Area	Coordinates (ft)			Pre-Injection					Post-Injection				
	X	Y	Z	Wet Density		Dry Density		Moisture	Wet Density		Dry Density		Moisture
				pcf	kg/m ³	pcf	kg/m ³	(%)	pcf	kg/m ³	pcf	kg/m ³	(%)
1	1.5	9.0	7.5	115.5	1850	106.5	1706	8.4	113.1	1812	104.3	1671	8.4
1	3.5	7.0	7.5	122.8	1967	111.8	1791	9.9	123.5	1978	112.0	1794	10.3
1	1.5	5.0	7.5	117.9	1889	107.5	1722	9.7	116.1	1860	105.6	1692	10.0
1	5.5	5.0	7.5	120.2	1925	110.2	1765	9.0	119.2	1909	109.0	1746	9.3
1	3.5	3.0	7.5	120.9	1937	110.6	1772	9.1	118.5	1898	108.2	1733	9.6
2	12.0	9.0	7.5	112.5	1802	102.4	1640	9.9	113.2	1813	104.0	1666	8.8
2	10.0	7.0	7.5	121.3	1943	110.3	1767	9.9	117.1	1876	107.1	1716	9.3
2	12.0	5.0	7.5	114.1	1828	104.3	1671	9.5	114.6	1836	106.0	1698	8.1
2	10.0	3.0	7.5	118.1	1892	108.8	1743	8.5	119.1	1908	108.9	1744	9.3
2	8.0	1.0	7.5	116.9	1873	106.5	1706	9.8	Foam on the Surface				
2	9.0	1.0	7.5	-	-	-	-	-	115.8	1855	105.9	1696	9.3
3	14.0	9.0	7.5	111.3	1783	103.0	1650	8.1	113.1	1812	105.1	1684	7.6
3	16.0	7.0	7.5	119.6	1916	109.2	1749	9.5	113.6	1820	103.6	1660	9.6
3	14.0	5.0	7.5	115.6	1852	105.6	1692	9.4	117.5	1882	108.4	1736	8.4
3	18.0	5.0	7.5	120.3	1927	109.4	1752	10.0	121.8	1951	112.1	1796	8.6
3	16.0	3.0	7.5	118.9	1905	109.0	1746	9.1	118.5	1898	109.1	1748	8.6

Comparisons show little difference in density and moisture content between the pre- and post-injection process, with test results consistently within the accuracy limitations of the testing equipment.

Polyurethane Compression Testing

Samples of the excavated hardened foam material were taken from each area for compressive strength testing. Sample testing was completed at the FDOT SMO Foundation Laboratory, in conjunction with FDOT District 2. Testing was completed in accordance with ASTM D 1621, Standard Method for Compressive Properties of Rigid Cellular Plastics. This test method provides information regarding the behaviour of cellular materials under compressive loads. Test data is obtained, and from a complete load-deflection curve it is possible to compute the compressive stress at any load, as well as the effective modulus of elasticity (apparent modulus) [4].

A total of five cube samples were tested for unconfined compressive strengths. The cube samples were cut to size with all lengths at approximately 2 inches (51 mm). Photographs of representative samples have been provided in Figure 10.



Figure 10. Photographs of Representative Samples for Compressive Testing

Four of the samples were taken from the honeycomb lattice structure within the peat layer, while sample A-2 was from the hardened foam material in the A-2-4 sand layer (capping layer) in Area 2. In all the samples, it was evident that the injected foam had mixed with the insitu materials. Furthermore, the samples from Area 3 appeared to have a thin peat layer sandwiched between adjacent subsequent flow paths. The results of the compressive testing on all cube samples have been summarized in Table 7.

Table 7. Compressive Strength Test Results

Sample	A-1	A-2*	A-2A	A-3	A-3A
Unit Density, lb/ft ³ (kg/m ³)	9.603 (154)	55.093 (882)	13.024 (209)	6.965 (112)	6.080 (97)
Loaded Area, in ² (mm ²)	4.164 (2,686)	3.655 (2,358)	3.991 (2,574)	3.246 (2,094)	3.767 (2,430)
Zero Deformation Offset, inch (mm)	0.009 (0.23)	0.745 (19)	0.013 (0.33)	0.003 (0.08)	-0.121 (-3.1)
10% Corrected Deformation, inch (mm)	0.212 (5.4)	0.935 (24)	0.217 (5.5)	0.189 (4.8)	0.069 (1.8)
Load at 10 % Corrected Deformation, lbs (kg)	270.5 (123)	437.4 (198)	271.7 (123)	107.9 (49)	57.3 (26)
Yield Before 10 % Deformation?	No	Yes	No	No	Yes
If Yes, Maximum Load at Yield, lbs (kg)	N/A	512.1 (232)	N/A	N/A	166.7 (76)
If Yes, Deformation at Yield, inch (mm)	N/A	0.15 (3.8)	N/A	N/A	0.44 (11.2)
Compressive Strength, psi (kPa)	65.0 (448)	119.7 (825)	68.1 (470)	33.2 (229)	15.2 (105)
Apparent Modulus, psi (MPa)	1273.1 (8.8)	2802.2 (19.3)	846.0 (5.8)	563.8 (3.9)	362.8 (2.5)

Note: * - Sample A-2 was taken from the hardened foam material in the A-2-4 sand layer.

The results of the compressive strength test results appeared to have a direct correlation with the unit density of the test sample. The samples from Area 3 (A-3 & A-3A) were found to have the lowest unit density at around 100 kg/m³, and the lowest strength, with compressive strengths as low as 15.3 psi (105 kPa). As Area 3 was injected with a fixed volume of polyurethane foam material, it can be speculated that the reduced volume of material resulted in a low unit density.

In Areas 2 and 3, the foam was injected until a 1 mm bump was observed on the surface. In both of the samples recovered from the peat layer, the density of the foam material varied from 9.6 to 13.0 lb/ft³ (154 to 209 kg/m³), which resulted in compressive strengths varying from 65 to 68 psi (448 to 470 kPa). For the sample (A-2) recovered from the A-2-4 sand layer, the density of the cube sample was found to be significantly higher, with a density of 55.1 lb/ft³ (882 kg/m³). As the A-2 sample was mixed with the insitu sand, the increased density is expected. The increased density also resulted in a higher compressive strength of 119.7 psi (825 kPa).

The compressive strengths of the hardened foam material are dependent on several factors and conditions at the time of injection. Like all fluids, the foam material will take the path of least resistance during injection. Coupled with other factors such as the duration of injection time, volume of material injected, soil and air temperatures, and the soil's resistance to compression, the path of the injected foam becomes unpredictable. Regardless of the path the injected foam material takes, it is important to adjust the controllable factors to maximize the density of the injected foam material, and the resultant the compressive strength. As seen in the compressive strength test results, injecting more material until a bump is observed on the surface is just one of the procedures that can help achieve the increased strength.

COMMENTS, OBSERVATIONS, AND CONCLUSIONS

The objective of this study was to evaluate insitu injection of polyurethane foam as a viable method for improving soil stiffness. Specifically, the study assessed the UDI process for stabilizing peat deposits found under Florida rigid pavements.

The primary purpose of this study was to provide a long-term solution for stabilizing peat deposits encountered in the Florida area. Using an FDOT Soil Box, a simulated rigid pavement structure was constructed over a sand subgrade incorporating a 2-ft (610 mm) thick peat layer. Strength characteristics of the subgrade were collected before and after the stabilization process.

The injection process used a three-step process: undersealing of the concrete slabs, stabilization of the upper sand layer through shallow injection at a depth of 3 ft (915 mm), and stabilization of the peat layer through deep injection at a depth of 6 ft (1.83 m). The intention of the shallow injection was to produce a containment cap prior to deep injection into the peat layer.

The deep injection process tended to form a honeycomb type lattice structure within peat layer. The formation and appearance of the lattice structure would indicate flow through paths of least resistance (hydraulic fracture type process) rather than mixing within the structure/matrix of the peat. It was observed that in areas where the volume of material injected was increased, the lattice walls were thicker, resulting in smaller 'peat cells'. This lattice structure has the potential to add stiffness to the peat layers. Further research should be considered with a focus on refining the injection process to produce an improved lattice structure.

Visual observations of the de-constructed soil box found Areas 1 and 2 did show some rather substantial vertical cell walls within the peat layer. We speculate these cell walls may have the ability to act as supports, or shear type walls, to transfer loads through the peat layer. Evaluation of the potential of ongoing settlement between the vertical walls should be examined in the previously suggested research.

The 'shear wall' type lattice structure has the potential to transfer loads through the peat layer. However, there are a number of factors that should be investigated in the aforementioned research:

- minimum wall thickness to resist crushing under the dead and live loads;
- material density required in the lattice structure; and
- the need for capping layers above, and/or below the peat layer to resist punching failures and settlement between the vertical walls.

Roadways settling due to the presence of underlying compressible peat deposits have been an ongoing problem for many agencies. An expedient, long term solution that can reduce the frequency of remedial maintenance is needed. This study evaluated the potential of insitu stabilization using a proprietary two component high density expanding thermoset polyurethane resin system. While not definitive, the results

of this study indicate the URETEK Deep Injection™ Process has potential for improving weak compressible organics soils through encapsulation. Additional trials will likely be required to confirm field suitability of the process.

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