FINAL REPORT

IMPROVING RIGID PAVEMENT SMOOTHNESS USING POLYLEVEL®

Project #: RES2016-18

UTC Report Submitted to TDOT

By:

Dr. Mbakisya Onyango (PI)

Dr. Aldo McLean (Co-PI)

Dr. Joseph Owino (Co-PI)

Dr. Ignatius Fomunung (Co-PI)

Dr. Louie Elliot (Co-PI)

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16. Abstract

Concrete pavement slab differential settlement (drop-off) is one of the major problems encountered in jointed rigid pavements after years of service. The conventional method to rectify this problem is to lift the slabs using injected asphalt or concrete mud, slab grinding, partial/full depth repair or asphalt overlay. The Tennessee Department of Transportation (TDOT) investigated the use of PolyLevel® material to level settled slab in Chattanooga, Tennessee (TN). The study sections were monitored for two and half years to evaluate pavement surface roughness using a high-speed inertia profiler to obtain raw longitudinal profiles; and a smartphone-based application called Roadroid app to obtain the estimated IRI (eIRI). The raw longitudinal profiles were analyzed by the profile viewing and analyzing (ProVAL) software to compute the international roughness index (IRI) and the mean roughness index (MRI).

The application of PolyLevel® was within the scheduled time. A ride quality survey was conducted before application of the material, and at about every eight months after application using the high-speed inertial profiler. The smartphone-based app was used to monitor the treated sections monthly. Generally, the pavement ride quality improved (numerical decrease in index values) immediately after application. It increased approximately one year after application on some section and continued to decrease on others. However, the decrease or increase in MRI did not change the state of section (in terms of ride quality condition) in which it was before application of the material. The questionnaire sent to state DOT's indicated that out of the respondents that have used polyurethane materials, about 90% recommend a continual use of polyurethane materials. Laboratory tests were performed to obtain mechanical properties of PolyLevel® needed for finite element (FE) analysis. FE analysis indicated that strains on PolyLevel® material will increase with increase on cyclic loading but the number of cycles it takes for materials to fail was not determined in this study.

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EXECUTIVE SUMMARY

This study was conducted by the University of Tennessee at Chattanooga (UTC) in collaboration with the Tennessee Department of Transportation (TDOT) to analyze the smoothness improvement on rigid pavements lifted using PolyLevel® material. PolyLevel® is a high density expanding polyurethane foam formed after an exothermic reaction when two main components are mixed together with water and catalysts.

In recent years, concrete slab lifting technique using polyurethane material has been used to improve concrete pavement smoothness. They have primarily been used in residential and commercial applications to lift sidewalks, driveways, and office floors, but found effective in leveling settled concrete pavement slabs. Several state DOT's and the US Air Force have used PolyLevel®/URETEK 486® or similar materials to lift pavement and airport slabs with success. Polyurethane material has less weight therefore, it exerts less stress while densifying the soil underneath the slab as it cures, due to its cementitious and flowability properties. Compared to the traditional slab jacking material such as concrete mud and asphalt; polyurethane materials are cost effective, can be installed with fewer lane closure, and they take short time to react and cure hence the section can be opened to traffic within an hour after injection.

This study evaluates the effectiveness of the injected PolyLevel® material as a rigid pavement maintenance material to improve pavements smoothness in Tennessee. The assessment was performed by monitoring surface roughness of five sections treated with PolyLevel® materials on two interstates I-24 and I-75, in Chattanooga, Tennessee. The application of PolyLevel® on the five sections happened between February 2015 and June 2016. The research team evaluated both immediate and long-term pavement performance by collecting longitudinal profiles data on the treated sections using a high-speed inertial profiler before and after application of the material, and estimated IRI (eIRI) using Roadroid App after PolyLevel® application for the contract period time of two and a half years. The raw profile data was analyzed using the profile viewing and analyzing (ProVAL) software to obtain the international roughness index (IRI) and mean roughness index (MRI).

MRI was used to evaluate the improvement before and after PolyLevel® application. There was an average MRI reduction of 0.07 m/km (4.56 in./mi.), which is 3.32 percent (3.32 %) improvement. Four out of the five sections experienced reduction in MRI readings while one section had increased MRI reading immediately after application. Long term data analysis, after two years, indicated fluctuations on both MRI and eIRI readings. The trends of MRI data are limited by the length of intervals of data collection (about 8 months). The eIRI data was collected on monthly interval and its readings are fluctuating. The overall trend using linear regression gave a negative slope indicating continual improvement with time. Only one section had MRI readings slightly above the initial reading, twenty-nine months after PolyLevel® application. The other four are still below the initial reading and within the acceptable MRI range, about two years from its application.

It was also determined that eIRI underestimated roughness measurements as compared to MRI. The section that is on “failed” category using MRI is in “good” category using eIRI ranking. All the data points collected using eIRI fall within the “good” category at least two years after PolyLevel® application.

Laboratory testing provided PolyLevel® properties useful for finite element modeling. Tests performed yielded density, yield stress, elastic modulus, dynamic modulus and Poisson’s ratio. Results also indicated that Poisson’s ratio of polyurethane material increased with increase in vertical strain. The finite element modeling revealed that the cycling loading increases permanent strains on PolyLevel® material. This indicates that PolyLevel® could render a quickly lift of pavement slabs, but it may experience permanent deformation with time under repeated traffic loading. The finite element model did not capture the time it takes to deteriorate PolyLevel® material below acceptable limits due to limited number of cyclic loads applied.

1. INTRODUCTION

1.0 Rigid Pavements

Pavements are designed to provide to road users a smooth ride, resulting to comfort, safety, and lower vehicle operating cost. Distresses on pavements, such as slab faulting (drop-offs), pose safety hazard to motorists, especially motor bikes. Therefore, it is imperative for transportation agencies to maintain pavement smoothness by correcting the developed pavement defects. There are two types of pavements flexible pavements and rigid pavements.

Rigid pavements consist of Portland Cement Concrete (PCC) slab(s) resting on a granular base course or directly on a subgrade. Concrete slabs develop transverse cracks when thermally induced tensile stresses exceed the concrete tensile strength; hence, concrete slabs require either transverse joints or tensile reinforcements [1].

There are mainly three types of concrete pavements: (1) Continuously reinforced concrete pavements (CRCP), constructed with reinforcement bars to take care of the tensile stresses, this type does not have joints but allows transvers cracks to develop randomly along the slab as the reinforcements support tensile stresses. (2) Jointed reinforced concrete pavements (JRCP) have reinforcement bars and joints spaced between 9 to 30 m. (30 to 100 ft.). Joints are provided to control transverse cracks, and load transfer mechanism (dowel bars) are provided at the joints. (3) Jointed plain concrete pavement (JPCP) have no reinforcement bars but jointed slabs between 4.57 to 9.14 m (15 to 30 ft.) long. For JPCP, vertical load transfer mechanism between adjacent slabs is provided by either aggregate interlock or dowel bars (Figure 1). When vertical load transfer efficiency is reduced due to subgrade erosion (pumping) or other reasons, slab faulting or drop-off is experienced that may pose unsafe driving conditions [1].

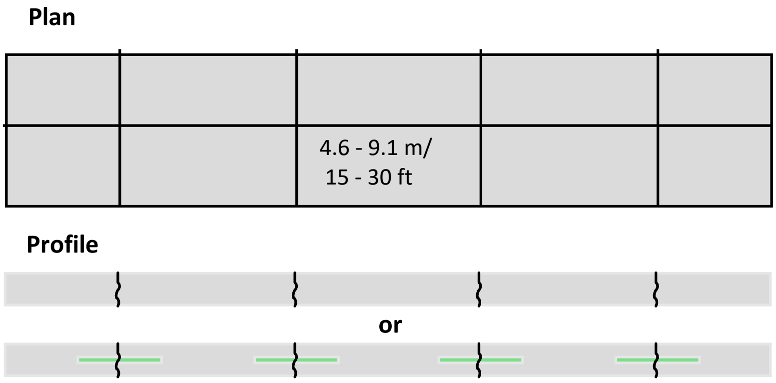


Figure 1.1 Jointed Plain Concrete Pavement (JPCP) plan and profile

This study evaluates the performance of polyurethane materials (injected under rigid pavement - JPCP) immediately after installation and their long-term performance. To assess the long-term performance of the material, the treated sections are monitored by measuring their surface roughness using a high-speed inertial profiler, a smartphone-based app (Roadroid app) and visual inspection.

1.1. Problem Statement

After several years of performance, rigid pavements deteriorate due to traffic loading, environmental effect, and failure due to displacement of undelaying materials caused by pumping. This creates voids underneath the pavement slabs at the joints, causing slab drop off and/or faulting of joints, sometimes the failures may extend to mid-slab cracks. Pavement failures increase pavement roughness, resulting to poor ride quality and increased road users vehicle operating/maintenance costs. The conventional method to rectify concrete slab drop-off is to lift the slabs using injected asphalt, concrete mud or slab grinding. When the concrete slab distresses are extensive, full/partial depth slab repair (slab replacement) or asphalt overlay is recommended.

In recent years, a different concrete slab lifting technique using polyurethane materials was introduced to level concrete structures. PolyLevel® and a similar product called URETEK 486® are high-density expanding foam that are formed by combining diisyconate and polyol to form a urethane linkage. These high-density polyurethane (HDP) foams stabilize/lift PCC slab with poor foundation support (voids). HDP foams have primarily been used in residential and commercial applications to lift sidewalks, driveways, and office floors, but it has been found effective in leveling of concrete pavement slabs. Several DOTs and the US Air Force have used PolyLevel®/URETEK 486® to lift pavement and airport slabs with success [2]. The advantage of these materials is that the repair requires shorter time and fewer lane closures compared to the conventional materials.

TDOT Region 2 has been experiencing severe slab settlement (drop-offs) on some of the sections of its concrete pavements (I-24 and I-75), that carry high traffic volumes. Generally, the settlements varied from 25 mm. (1 in.) to almost 75 mm (3 in.) on some locations. Figure 1.2 shows faulting experienced on sections of I-24 West. Evaluating possible maintenance techniques, such as mud jacking, slab replacement, and diamond grinding, TDOT Region 2 elected to treat few sections of distressed areas with polyurethane materials. Reasons being that this method requires fewer lane closures and shorter lane closure times, the work can be performed at night (9:00 pm to 4:00 am or 5:00 am) when the interstates are less congested, and the sections can reopen to traffic in about half an hour after application. A TDOT Region 2 engineer also deemed this method to be more cost effective.

Figure 1.2 Mid slab cracks and longitudinal joint faulting of over 1 in. on I-24 West

This project was conducted to evaluate the performance of five (5) pavement sections on U.S interstates I-24 and I-75 in Chattanooga, Tennessee that were treated with polyurethane material (PolyLevel®) to preserve and improve the performance of the pavements section. Table 1.1 shows the sections treated with PolyLevel® materials and considered for monitoring program.

Table 1.1 Sections treated with PolyLevel® Materials

Highway Section ID	Start Mile	End Mile	Length (mi.)	Treated Lane #	PolyLevel® Application Date
I-24 West	179.50	178.2	1.30	2	9/27 - 10/1/15
I-24 East_182	182.35	183.00	0.65	3	11/2 - 11/5/15
I-24 East	Moore Brg	McBrien Brg	0.30	2	2/9 - 2/11/15
I-75 North	7.00	9.00	2.00	3	6/5 - 6/9/16
I-75 South	9.00	7.00	2.00	3	5/8 -5/9/16

[1.00 mi. is equivalent to 1.61 km]

Treated lanes are counted from the left in the direction of travel

1.1.1. Objectives

The objective of this project was to evaluate the effectiveness of the injected PolyLevel® material as rigid pavement maintenance technique to improve pavement smoothness in Tennessee. The tasks of this research project included:

1. Monitoring the condition of the selected pavement sections with PolyLevel® to evaluate the performance of PolyLevel® materials.
2. Collect pavement roughness regularly with help from TDOT Region 2 using high-speed inertial profiler.
3. Use Roadroid App to collect estimated international roughness index (eIRI) monthly for two years.
4. Perform visual inspection for cracks and similar distresses that may have resulted from the PolyLevel® installation on the slabs.
5. Distribute a questionnaire to DOT's to gather information about and experiences with polyurethane materials.
6. Use linear and/or nonlinear predictive models to estimate pavement condition deterioration in comparison to measured condition.
7. Obtain mechanical properties of PolyLevel® materials needed for computational modeling of the material.

1.1.2. Scope

The scope of this project included:

1. Literature review on PolyLevel® materials
2. Development and distribution of a questionnaire to evaluate the usage of PolyLevel® or similar material among DOTs in USA.
3. Conducting a pavement condition survey to obtain roughness measurements of the treated section by using a high-speed inertial profiler.
4. Collection of pavement condition data after every specified period of time (one month in this case) using Roadroid app.
5. Use linear predictive models to estimate pavement condition deterioration.

1.1.3. Deliverables

Upon acceptance of this report, the University of Tennessee at Chattanooga (UTC) research team will provide TDOT with:

- Results of pavement roughness measurements using the high-speed inertial profiler and Roadroid Application.
- Results of DOTs survey on the use of polyurethane materials in USA.
- Correlation of pavement roughness over time
- A final report documenting literature review, results, analysis and findings.

2. LITERATURE REVIEW

This literature review presents published information related to the use of polyurethane materials on lifting and/or leveling concrete pavement slabs to improve ride quality or pavement smoothness. The literature review also reports the methods used to evaluate pavement performance in comparison to method used at UTC and the expected/anticipated performance period after polyurethane application. The review includes polyurethane materials as construction material.

2.1. Polyurethane materials for rigid pavement smoothness improvement

Vennapusa and White (2014) reported the results using high-density polyurethane (HDP) foam by Penn DOT on 9.70 km (6.03 mi.) of US Highway 422, near Indiana and Pennsylvania. According to this report, the objective of the project was to stabilize the subbase aggregate layer, mitigate faulting, and improve joint load transfer efficiency (LTE). In situ test methods selected for this project included a robotic total station to monitor elevation changes; a high speed inertial profiler to measure the ride quality of the section (in IRI); lightweight deflectometer (LWD) to determine elastic modulus of the subbase layer; dynamic cone penetrometer (DCP) which was correlated with the California Bearing Ratio (CBR) to determine the strength of the foundation layers; air permeameter test device to determine saturated hydraulic conductivity of the subbase layer. After one year of testing, results showed that spatial extensions of the HDP foam propagation in the subbase layer ranged between 0.30 to 1.00 m (0.98 to 3.28 ft.) from injection points. Consequently, the process resulted in concentrated areas of foam in the subbase, which when compared to untreated areas, exhibited low permeability, low stiffness, and high shear strength. Unfortunately, the average IRI measured in this section increased from an average of 1.70 m/km (107.71 in./mi.) before treatment to 1.90 m/km (120.38 in./mi.) after treatment. This suggested poor ability of the foam lifting process to control variations in the pavement surface elevation. LTE at cracks increased from 15% to 45% shortly after treatment and LTE at joints did not show significant improvements [3].

Opland and Barnhart (1995) evaluated the performance of pavement sections lifted using URETEK 486® injected by the Michigan DOT. Tests were conducted on three sections of I-75 in Monroe County: a trunk road with 255 to 280 mm (10 to 11 in.) reinforced concrete slabs, resting on an open-graded base course After monitoring, these three sites showed hairline or minor cracks, severe transverse cracking, faulting, and severe cracked slabs with settlement. They collected and analyzed data from before and after ride quality tests, as well as falling weight deflectometer (FWD) measurements, and before/after pavement elevations. Measurements showed that after the placement of URETEK 486®, there was some initial improvement on ride quality, but it returned to the pre-treatment levels after one year. Base support and joint transfer were initially improved as well, but improvements decreased during the one-year trial period. Their final recommendation was not to use URETEK 486® as a substitute for mud-jacking for pavement with open-grade base. Additional testing to gain experience on the limitations and capabilities of URETEK 486® was recommended [4].

Soltesz (2002) assessed Oregon DOT's test sections, which used injected URETEK 486® to raise slabs at 12 sites around the Glenn Jackson Bridge on southbound side of I-205. The test site was monitored for elevation changes for over two years. Laboratory tests measured hole infiltration, compressive strength, and expected water permeability of the polyurethane material. Observations taken a few days after injection showed exposed polyurethane, indicating that either the grout seal had not been applied or had popped out. Soltesz observed that slabs may have settled after being raised with polyurethane, producing elevations changes during settling. The maximum decrease in elevation observed was 10.50 mm (0.41 in.), with most of the decrease occurring in the first three months after injection. Settling continued during the two years of observations. The concern was that settling might open-up new or existing cracks. On the other hand, the compressive strength of the material did not appear to decrease in the 23 months following application [4]. Regarding the drilled polyurethane infiltration holes, the team concluded that the injected material can penetrate openings as small as 6.35 mm (0.25 in.) due to the high pressure and temperature at which the material is injected. Polyurethane expands before settling, which tends to seal the holes. Therefore, the injected polyurethane will help to reduce water infiltration and flow to the subgrade [5].

Gaspard and Movak (2004) assessed the effectiveness of the URETEK® process in leveling faulting on continuously reinforced concrete pavement, jointed concrete pavement, and bridge approaches for the Louisiana Transportation Research Center. They determined that URETEK® could be used for undersealing or leveling operations. They recommended the polyurethane injection process to be included as an alternative rehabilitation method and that other Departments of Transportation to set up methods for accurate cost estimation of material and labor for this practice. The team also developed guidelines for selecting appropriate pavement projects for polyurethane application. This includes specifications and application methods that consider the benefit of soil improvement and identify applications as they relate to various base course and pavement types. They concluded that suppliers and/or contractors should be responsible for developing a detailed lab testing protocol for addressing issues with the polyurethane foam and developing a detailed field testing program to evaluate various pavement conditions. It was also recommended to carefully monitor the long-term performance of the treated sections while establishing the life expectancy of the polyurethane injection repairs [6].

Abu and LaBarca (2007) conducted a five-year project for the Wisconsin Department of Transportation to monitor the effectiveness of using URETEK 486® to reestablish Portland cement concrete (PCC) pavement elevations and increase the stability of the slab after pavement lifting. The project focused exclusively on evaluations of concrete pavement leading to bridge approach slabs. Pavement evaluations used visual inspections and ride quality inspections to measure improvements. Two sites were tested. The first test site included treatment to four concrete slabs in the bridge approach for both the passing and driving lanes on I-39 and USH 78, in Columbia County. The second site included lifting four slabs, left and center lanes, in the bridge approach of the three-lane highway on USH 12 near the city of Middleton in Dane County. Results showed that the slab lifting process was successful and that the pavement ride quality and safety improved at both test sites. However, on site 1, the lifting method took longer than anticipated and required a total of 1,450 kg (3,200 lbs.) of material on both lanes, 862 kg (1,900 lbs.) for the passing lane and 590 kg (1,300 lbs.) on the driving lane. This by far exceed the initial contractor estimate of 272 kg (600 lbs.) for both passing and driving lanes. Likewise, site 2 required 474 kg (1,043 lbs.) of material, compared to an initial estimate of 250 kg (550 lbs.) Abu and LaBarca concluded that the method is successful on lifting concrete slabs but might not be cost effective when filling large voids is required. They also recommend using ground penetrating radar (GPR) technology for an accurate estimate of the type and size of voids underneath the pavement as well as material required to fill the void. An acceptable material estimation should be within 10 - 25% of what is required. A six-month inspection of site 1 showed four fine transverse cracks developed in the approach slab, likely due to the drilling of injection holes. Site 2 did not develop new cracks after the lifting process [7].

Priddy, Tingle, McCaffrey and Rollings (2007) reported the results of a test designed to determine whether foam injection could increase the bearing capacity of compacted soil and fill the voids under distressed pavements. They also compared foam backfill to a traditional backfill materials, capped with similar materials having same thicknesses. Results validated polyurethane foam as viable options for backfilling repairs, but the quality of the repairs were not as strong as clay-gravel as they did not sustain as many simulated vehicles passes before failure [8].

Priddy, Jersey and Reese (2010) evaluated the use of injected polyurethane material for the repair of deteriorating concrete slabs on rigid pavements and airfields. The main objective was to quantify the benefits of foam injection technology for conducting rapid repairs of PCC pavement. For this purpose, they prepared four test slabs: (1) slab with 32 holes, (2) slab with nine holes, (3) slab with five holes, and (4) slabs with no holes (control slab). The test also included simulation of traffic load, and full-depth PCC repairs with traditional backfill materials, such as compacted aggregates and poured foam. The concrete slabs were tested after 28 days of curing (considered as “young concrete”), a first for the polyurethane injection method, which has been used almost exclusively on fully cured (old) PCC pavements. Initial observations confirmed significant cracking occurrences after injection on the first test slab due to high number of injection holes and high volume of injected material. Results showed that 5 to 9 holes were adequate as injection holes and had fewer cracks compared to 32 holes [9].

Gaspard and Zhang (2012) presented their findings on the assessment of the effectiveness of reducing faulting on jointed concrete pavement (JCP) using polyurethane foam (PF). The analysis took place on sections of the Louisiana LA 1 Bypass. Pre-test and post-test were performed on the three test sections of the Bypass, each with eleven slabs. Performance evaluation continued for a period of five years using falling weight deflectometer (FWD), walking profilers, and manual fault measurements tests. In addition, cores were taken from various locations for polyurethane foam (PF) lab testing and statistical analysis, including experimental design techniques to identify the differences between the test samples. Significant improvements to reducing faults at joints were found, as well as service live extensions of 3.10 to 5.70 years based on IRI and 6.00 to 8.00 years based on fault height tests. However, it was noticed that the slab correction process reduced load transfer efficiency (LTE) at the transverse joints. These finding lead the team to not recommend the use of polyurethane foam lifting processes as a pavement preservation treatment for fault correction or ride quality improvements [9].

From the literature review, different experiences on the usefulness and life expectancy of polyurethane materials are reported. Some researchers experienced cracking after the applications polyurethane materials, while others did not. The sections monitored by UTC did not crack after application of polyurethane. There are reports on IRI measurements and load transfer efficient that did not improve with polyurethane applications, although other reports recommend the use of polyurethane materials since there was improvements in IRI measurements. Similarly, UTC experienced a general improvement on IRI readings from most sections although some of the sections improvements were not statistically significant as reported in Chapter 6 of this report. Louisiana DOT recommended the use of polyurethane materials as one of concreter preservation techniques and developed guidelines to select candidate pavements for polyurethane treatment.

This study utilized PolyLevel® materials unlike most of the studies above that used URETEK 486®. Much as they are from different manufacturers, similar performance is expected. This study used both a high speed inertial profiler and a smartphone-based app to monitor the performance of pavement sections with PolyLevel® application. The findings from this study are similar to the findings presented in the literature review as detailed in the conclusion of this study. A DOT survey conducted during this study, on the use of polyurethane materials, gives conflicting views according the DOT’s experience with the materials. Some recommend the use of the materials others do not. Generally, 89 percent of respondents that have used polyurethane materials recommend its use for maintaining rigid pavements.

2.2. Pavement Performance Prediction Models

Pavement performance is usually defined by a means of performance curve that depicts the trend between the pavement distress condition and service time or accumulated load applications [10]. Performance indicators include pavement condition index (PCI), present serviceability index (PSI), and IRI. The outcomes of the pavement performance assessment are used in estimating the state probabilities and transition probabilities deployed by the Markov model [11]. An effective pavement performance prediction model is considered an essential component of any modern pavement management system. Several advanced pavement management systems have incorporated a stochastic-based model to develop an optimum long-term pavement maintenance and rehabilitation (M&R) plan at the network level [12-14].

Markovian-based pavement performance prediction models

The goal for most models, including the Markovian-based modeling, is to assess pavement cracking and deformation. This method includes visual inspection of roadway distress and measurement of roadway riding quality where data is obtained after every year or two. The probabilistic models are typically represented by Markov transition or knowledge-based-expert-decision models for the prediction of pavement performance or deterioration modeling [15]. Markovian models also describe a probable before and after condition of the pavement. The before condition is described by probabilities that the pavement will be found in each of the assumed finite number of states and the after condition is described is a similar manner [16]. The types of Markovian prediction models include: the primary pavement response to traffic loading and climatic conditions *"Primary Response model"*. Pavement distress of all sorts *"Structural Performance Model"*. Pavement functional performance (PSI) *"Functional Performance Model"*. Pavement damage models *"Damage Models"*. In addition, *survivor models* described by survivor curves used for planning maintenance and rehabilitation alternatives on pavement networks [16].

Initially UTC planned to use performance prediction models to evaluate the performance of the sections treated with polyurethane, but the pavement condition data available on sections with polyurethane materials was less than two year, while the models requires longer data collection time, about ten years' worth of data to establish the prediction models. Furthermore, the team did not have enough time to work on the available pavement condition data before PolyLevel® due to limited time from data availability to end of the project. Therefore, this task was not performed instead linear regression of collected data was used to estimate the longevity of the pavement sections treated with polyurethane material. The data collection period was also an issue on the linear models. Longer data collection period is recommended in order to develop reasonable prediction models.

2.3. Polyurethane (PolyLevel®) Materials

According to the manufacturer's website [2], PolyLevel® is a high-density polyurethane compound that offers concrete leveling solutions for both commercial and residential concrete faulting. PolyLevel® material comprises of two liquid parts that combine in the nozzle at high pressure and temperature while being applied:

1. A petroleum-based isocyanate that is a modified geotechnical version of spray polyurethane foam (SPF), a commonly building insulator.
2. A mixture of polyol resin, a surfactant, a blowing agent, and a catalyst.

When the mixture reacts with the isocyanate, the result is an expanding foam, which is injected directly beneath the slab through strategically drilled, 15.88 cm (0.63 in.) diameter holes, a much smaller injection point than in mud jacking techniques, which often require holes that are 50.00 mm (2.00 in.) in diameter or larger. The foam weighs 2.37 kg/m^3 (4.00 lb./yd^3), a fraction of the weight of materials used in mud jacking (typically 71.2 kg/m^3 (120.00 lb./yd^3)). PolyLevel® achieves 90 percent of its full rigidity and strength in 15 minutes, compared to the hours or days required for materials applied through mud jacking techniques to cure. Cured PolyLevel® is inert. It does not leech chemicals into the soil, wash away, or absorb water [2]. Polyurethane (PU) is used in most concrete slab collapse repairs because of its flexibility and strength. It can also seal out cracks, so that wet and leaking spots do not pose any structural risks.

2.3.1. Performance Specifications

Testing of polyurethane product used in a TDOT project must follow the procedure stated in ASTM D1621-D1623. Table 2.1 below, shows the minimum requirements for TDOT and the actual product specifications for PolyLevel® material.

Table 2.1 TDOT minimum requirements and PolyLevel® product specification

Category	TDOT Requirements	PolyLevel® Product Specs
Free-Rise Density (lb./ft^3)	3.00	4.00
Density in Place (lb./ft^3)	-	6.50
Compressive Strength at Free-Rise Density (psi)	-	75
Compressive Strength in Place (psi)	80	100
Tensile/Shear Strength (psi)	100	140
Strength Gain	90% Comp. Strength in 15 Minutes	90% Comp. Strength in 15 Minutes
Longevity	-	Less than 10% degradation in 100 years
Water Resistance	-	Water Proof

3. METHODOLOGY

The main objective of this project was to evaluate the effectiveness of PolyLevel® as material used to improve rigid pavement smoothness. Pavement surface roughness index was used to assess the performance of the treated sections. TDOT hired a contractor to collect roughness measurements by using a high-speed inertial profiler before and after application of the material. This raw roughness data collected by the standard inertial profiler was analyzed using the profile viewing and analyzing (ProVAL) software to obtain IRI and MRI. The UTC team used the Roadroid app to collect estimated IRI (eIRI) monthly. ProVAL was used to analyze longitudinal profile data into IRI and MRI because the app gives its reading in estimated IRI only.

3.1. Pavement Roughness (Smoothness) Measurements

Pavement roughness is a phenomenon that results from the interaction of the road profile and the vehicle moving along the road. Road roughness is affected by parameters such as a vehicle's suspension (including how the tires are connected to the vehicle body with springs and a shock absorber), tire pressure, and human sensibility to vibration as the vehicle travels at a certain speed. Road comfort and safety to its users are mostly related to smoothness (roughness) of the particular road. Road smoothness also affects vehicle-operating costs, including the cost of tires, fuel, maintenance, and repairs. If all other factors are constant, the smoother the road the less it costs to operate and maintain the vehicle [18]. Two pavement surface roughness (or smoothness) indices used in this research (i.e. IRI/MRI and eIRI) are explained here below.

3.1.1. International Roughness Index (IRI) Measurements

IRI was agreed to serve as an index for measuring road roughness after the International Road Roughness Experiment, which was conducted in Brasilia, Brazil in 1982 [17]. The IRI is based on a simulation of the roughness response of a quarter car travelling at 80 km/h and represented by the scale shown in Figure 3.1 [17]. The scale can be used for calibration and for comparative purposes and to calculate the average rectified slope (ARS), or the ratio of the accumulated suspension motion of a vehicle during the test. The IRI summarizes the roughness qualities affecting vehicle response. IRI is appropriate when a roughness measure relates to the overall vehicle operating cost, overall ride quality, dynamic wheel loads (e.g., damage to the road from heavy trucks and braking and cornering safety limits available to passenger cars), and overall surface condition is desired [17].

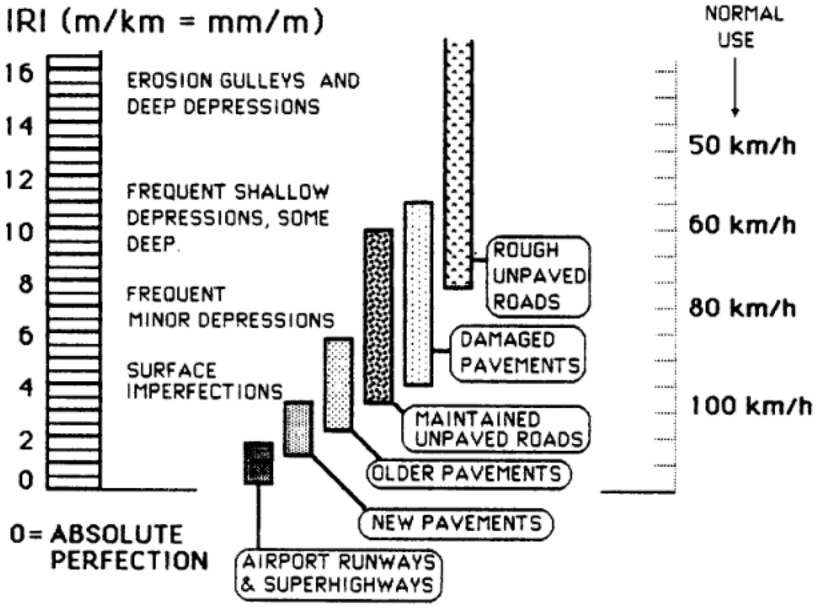


Figure 3.1 The IRI Roughness Scale

3.1.2. Longitudinal Pavement Profile – Profile Index (PI)

A longitudinal pavement profile is the measure of road roughness/smoothness and road texture resulting from the difference in elevation as the vehicle transverses along the pavement. It varies from gravel roads to asphalt/concrete paved roads. According to Sayers and Karamihas, (1996) instruments and tests are used to produce a sequence of numbers related to a “true profile” from an imaginary line in the road. Sometimes the measurements do not obtain the true profile; instead, its components are used for analysis [18].

Static methods (Rod and Level, Dipstick) and automatic instruments (profilers such as California Profilograph, ICC Laser Profiler etc.) are available for measuring the longitudinal pavement profile. The static methods are slower, time consuming, and liable to human errors. The mentioned drawbacks of static method make them less preferred over dynamic methods (automatic instruments) which compute profiles with high accuracy. Important factors such as humidity, temperature, and operating speed affect the accuracy of the data collected. The manufacturer should specify the range (for instance operating speed) in which the profiler will yield accurate profile readings [19].

After collecting pavement profiles, digital profilers send the data to a computer where a software developed or specified by the manufacturer is used for analysis. Sample intervals (the longitudinal distance between points) are digitized and fed into the computational algorithm. The sample interval ranges from 25 mm to 360 mm (1 in. to 14 in.) [19].

Relationship between International Roughness Index and Profile Index

Road roughness is a function of the profile index (PI). Some profile measuring devices and software packages (e.g., Rodruf and ProVal) have a built-in capability to process profile data and yield the IRI. Various research studies conducted in the US have published correlation equations between IRI and PI using different roughness measuring devices. This study did not develop any correlation between PI and IRI.

3.1.3. Road Roughness measurements using estimated IRI - Roadroid

To monitor project performance, the team used a low-cost app to collect pavement roughness data each month. The research team considered three apps for this purpose. The team assessed the app “rRuf,” and “rInspector,” which are based in Canada. Logistics and app data availability involved with these apps made the UTC team to opt the “Roadroid” app.

Roadroid App

Roadroid is a free pavement condition-monitoring app developed by a Swedish company. This app is compatible with android phones, specifically the Samsung Galaxy 5 or higher. The advantage of this app is that it works over a Wi-Fi connection, so it does not require a phone line or data plan. During data collection, the app saves the data file until it is connected to Wi-Fi, when it sends the data to Roadroid servers. Data is accessed from the server into the computer.

The download link for the classic app is at: www.Roadroid.com/app/Roadroid.apk. The latest Roadroid app version is Pro2 v2.3.5. Roadroid also has a beta-testing version 2, which has GPS-video and a brake friction test option. Roadroid manager requires the phone IMEI number for account registration. This app is free for university researchers. Data acquisition is also free for higher learning institutions. Roadroid maintains a Facebook group of app users at: https://www.facebook.com/Roadroid.

Roadroid, an android application, evaluates pavement smoothness based on an in-built accelerometer, and its results are affected by vehicle vibrations as it (the vehicle) travels. Roadroid is low cost, portable, and easy to use compared to other profilers [21, 22]. After data collection, the operator imports the data from a smart phone. The measured data are aggregated in sections of 5 m, 10 m, 20 m, 50 m, 100 m (default), 160 m and 200 m depending on the length of the section, accuracy required and importance and purpose of the project. Roadroid also has the capability to capture GPS photographs during the survey, which can be processed at the locations they were taken or used for in-office visual inspection of the road surface in case there are other pavement distresses [22].

Roadroid collects roughness data at a Class 3 level (IRI computed based on correlation equations). Essentially, Roadroid is a response-type road roughness measuring system. It is easy and cost effective to use, especially for roads where expensive and complex instruments cannot be used (e.g., bicycle paths, low volume roads and roads in developing countries). Compared to Class 4 (subjective rating), Roadroid is objective, highly portable and gives powerful and effective data collection and visualization through an online map. Furthermore, Roadroid can be used in winter to determine the performance of snow-removal and ice grinding. Moreover, in frost and heave actions it tells when and where is happening while comparing the situation to the previous event IRI [19].

The IRI will vary depending on the vehicle type, vehicle operating speed, and road surface condition. A study conducted in 2013 by the University of Pretoria evaluating the variations of estimated IRI obtained from Roadroid application with factors such as speed, pavement surface, tire pressure, etc. concluded that Roadroid yields consistent results if the above-mentioned key indicators are standardized [20]. Roadroid gives two options for obtaining the road section IRI [20, 22]:

1. Estimated IRI (eIRI) which is based on the peak and root mean square vibration analysis and correlates to Swedish laser measurements on paved roads. The eIRI values are collected in a speed between 20 - 100 km/hr. (12 – 62 mi./hr.). eIRI is the base for Roadroid Index (RI) classification of single points and road stretches.
2. Calculated IRI (cIRI) is based on the quarter car simulation. Data are collected at a speed of 60 – 90 km/hr. (37 – 56 mi./hr.). The operator can set a known reference when measuring cIRI.

For this study pavement profile data collected by TDOT Region 2 contractor using high-speed inertial profiler (ICC Profiler) at an interval of about 8 months and eIRI collected monthly using Roadroid app by UTC team are used to evaluate the smoothness of the pavement test sections on I-24 and I-75.

3.2. Methodology

This study was conducted to evaluate the effectiveness of PolyLevel® material as rigid pavement maintenance technique for pavement smoothness improvement in Tennessee. The study included five pavement sections treated with PolyLevel® materials on US Interstates I-24 and I-75 as listed on Table 3.1. As per 2017 TDOT traffic data log the Average Annual Daily Traffic (AADT) of sections treated with PolyLevel® material on I-24 East and I-24 West was 134,740 vehicles per day and 119,930 vehicles per day respectively, with trucks being 18.50 percent. The AADT on I-75 sections was 77,150 vehicles per day; of which 14.50 percent were trucks. TDOT Region 2 engineers determined the treatment sections depending on the severity of observed distresses (roughness). Figure 3.2 maps the location of tested sections.

Table 3.1 Test site information and PolyLevel® application dates

Highway Section ID	Start Mile	End Mile	Length (mi.)	Treated Lane #	PolyLevel® Application Date
I-24 West	179.5	178.2	1.30	2	9/27 - 10/01/15
I-24 East_182	182.35	183	0.65	3	11/20 - 11/5/15
I-24 East	Moore Brg	McBrien Brg	0.30	2	2/09 - 2/11/15
I-75 North	7	9	2.00	3	6/05 - 6/09/16
I-75 South	9	7	2.00	3	5/08 -5/09/16

Note: [1.00 mi. is equivalent to 1.61 km]
Treated lanes are counted from the left in the direction of travel

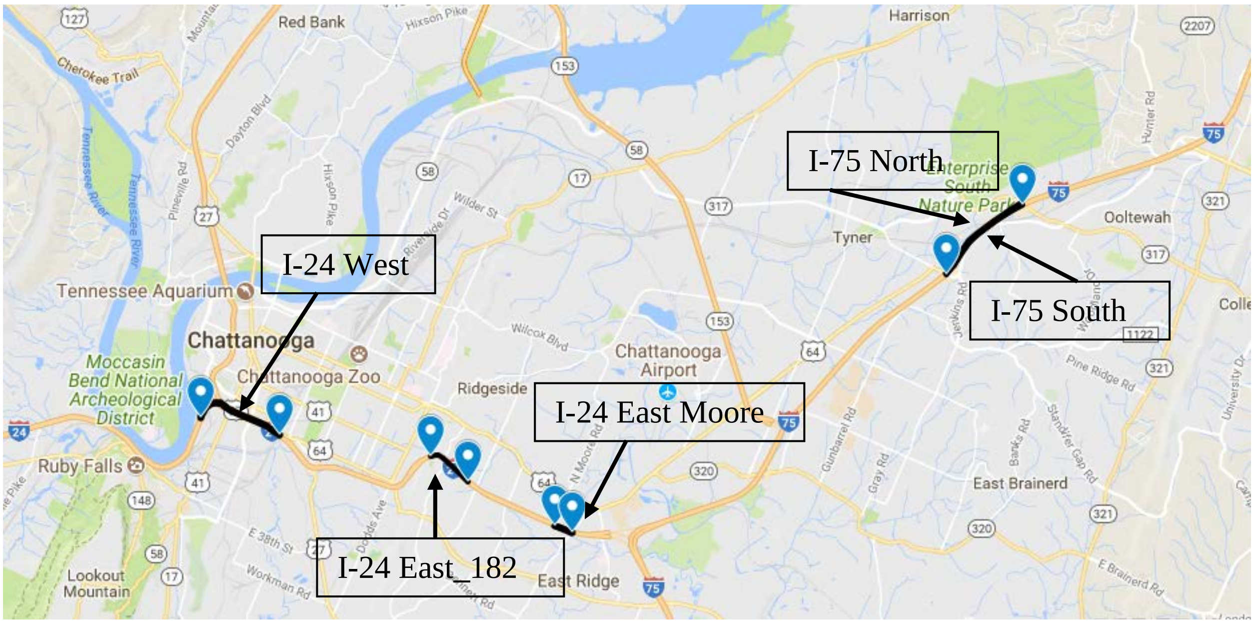


Figure 3.2 Google map showing the tested sections on I-24 and I-75

The test sections have lane width of 3.65 m (12.00 ft.) slab thickness of 255 mm (10 in.) and joint spacing of 4.57 m (15.00 ft.) Figure 3.2 shows slab faulting on I-24 West section with a faulting of 25 mm (1 in.) before and about 3.80 mm (0.15 in.) after treatment.

Figure 3.3 Before and after leveling slabs using PolyLevel® material on I-24 West

The application of PolyLevel® materials involve drilling holes that are about 1.58 cm (5/8 in.) diameter. The main two components of polyurethane materials are mixed in the nozzle and injected at high pressure and temperature under the slab through the holes. As the materials mix they expand and lift the 254-mm (10-in.) rigid pavement slab. Care must be taken to avoid slab overcorrection. Figure 3.4 shows AFS crew drilling the holes with a three-rig drilling machine and applying the PolyLevel® material through the holes.

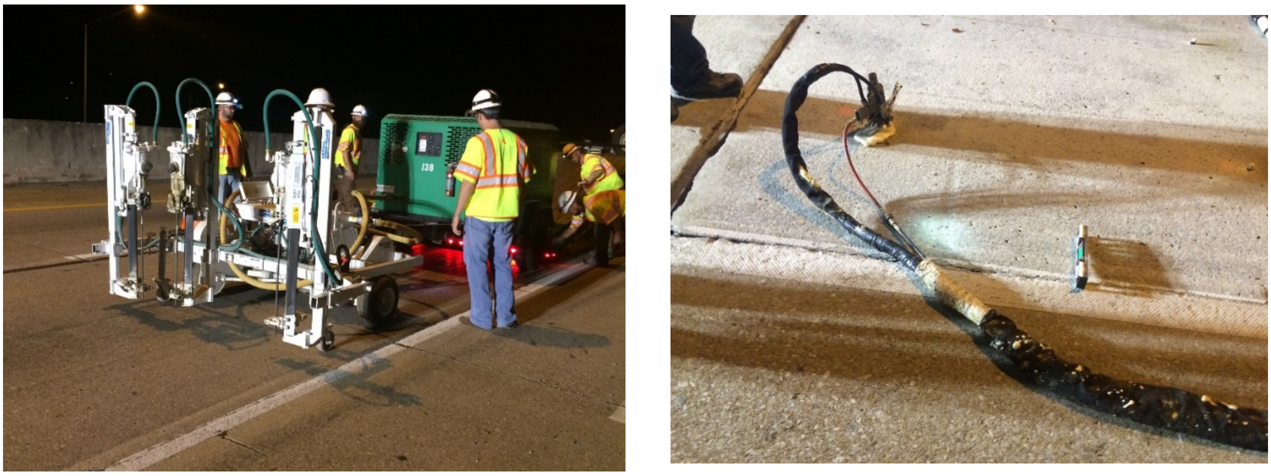


Figure 3.4 Drilling holes and installation of PolyLevel® materials on I-24 West

Figure 3.5 below shows a view of I-75 North before installation. Figure 3.6 shows the preparation of drilled holes before the application of polyurethane materials. The application of the two-part polyurethane materials via injection nozzle is shown in Figures 3.4 and 3.6. Holes are patched after injection of the material as shown in Figure 3.7. As polyurethane is pumped, it fills the air or water pockets underneath the concrete slab and water or mud is expelled out. A more stable underlying layer results from the process.

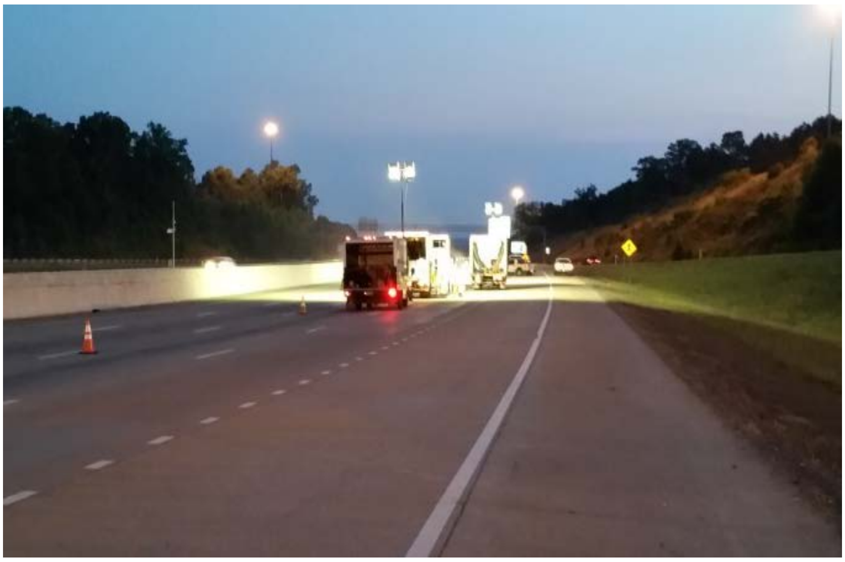


Figure 3.5 View of I-75 South

Figure 3.6 Injection holes on concrete slabs

Figure 3.7 PolyLevel® injection on I-75 South

Figure 3.8 Injected PolyLevel® material sipping out mud/water under the slab.

The pavement roughness was measured before and after application of polyurethane materials to evaluate the immediate effectiveness of the material for pavement maintenance and performance. UTC used the Roadroid app to conduct monthly pavement roughness measurements for the project duration (two and a half years). The average pavement roughness index (MRI) before and after was compared using statistical analysis methods to evaluate the improvement at 95% significance level.

3.2.1. Tasks

The tasks performed during the course of this project include:

Task 1: Literature Review

A comprehensive literature search was conducted to obtain published and unpublished information on the use and performance of polyurethane materials as applied for improvement of pavement smoothness. Resources such as library holdings, databases, and gateway services and external database services, such as TRB, ASCE, ITE, NCHRP, TRIS, Elsevier Science, Google Scholar and others were accessed as reported in Chapter 2.

Task 2: Pavement Condition Monitoring

Longitudinal profile data (MRI) and eIRI data were collected periodically to monitor the condition of the selected pavement sections treated with PolyLevel® to evaluate the performance of the materials. Visual inspection was also performed regularly.

Task 3: Evaluation of Pavement Performance

Pavement performance was evaluated by gaging measured pavement condition to the FHWA acceptable thresholds. Tables 6.1 show an example of the IRI rating thresholds in m/km.

Task 4 DOT Survey

A questionnaire was sent to state DOT’s to collect information regarding the usage of polyurethane materials as pavement levelling or pavement preservation technique. This is reported in Chapter 4.

Task 5: Laboratory testing of Polyurethane materials and Finite element Analysis

This task included testing PolyLevel® material to obtain its physical characteristics like density, Poisson’s ratio, yield stress, yield strain elastic and dynamic moduli and its response to pavement loading. Chapter 5 presents findings from lab testing and finite element analysis.

Task 6: Result Analysis

The analysis of data collected was performed to provide information pertaining the performance of PolyLevel® material for improving pavement smoothness and the possible adoption of it as rigid pavement preservation technique.

Task 7: Quarterly reports and Final report writing

Quarterly reports were submitted documenting activities performed in that quarter as well as the final report with all results, analysis, conclusions and recommendations.

4. DOT QUESTIONNAIRE ON POLYURETHANE MATERIALS

In April 2016, a 19-question questionnaire was sent through Survey Monkey to pavement and maintenance engineers at all 50 state DOTs as well as Canadian Ministries of Transportation to collect information on the use of polyurethane materials. The engineers' contact information was obtained from the American Association of State Highway and Transportation Officials (AASHTO) website. The questionnaire submission window was left open for six months to give the DOT engineers time to respond. The questionnaire is appended to this report in Appendix 1.

Twenty-five state DOTs and British Columbia Province Ministry of Transportation and Infrastructure in Canada responded to the questionnaire. Figure 4.1 shows the states that responded. Of the 26 respondents, 20 states (76 %) currently use or have used polyurethane material for slab lifting and six state DOTs (24 %) have not. Three states had conflicting responses ("yes" and "no") on the use of polyurethane materials. The questionnaires with a "no" response was discarded, as the answers to the remaining questions were not applicable.

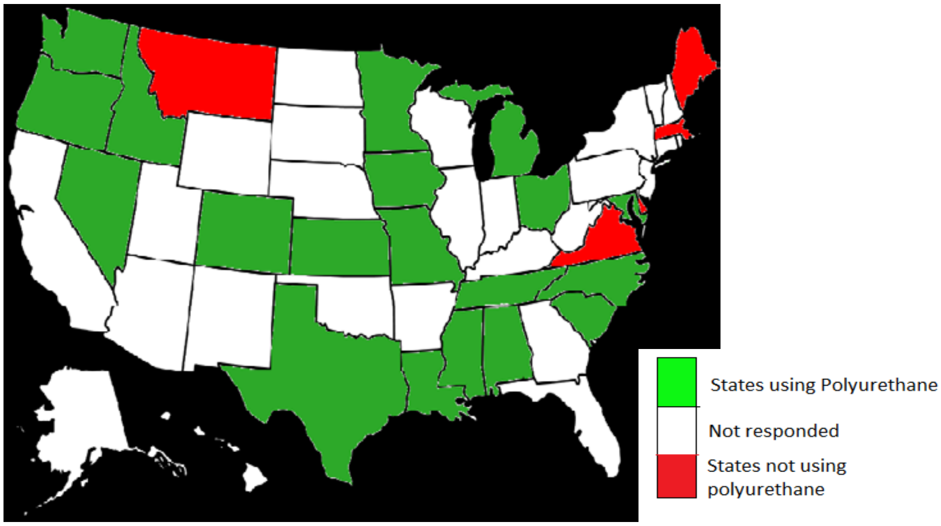


Figure 4.1 Map of USA showing states that responded to the questionnaire

Nearly 90% of the respondents that have used polyurethane materials recommend its use. However, they noted that severely cracked slabs and subsurface condition may limit the ability to apply the material. Therefore, polyurethane materials should only be used to level slabs that are structurally sound. Further analysis of survey results yielded the following:

i. Of the five types of materials/methods commonly used to level concrete slabs, slab replacement was reported to be used by 73 % of respondents, followed by polyurethane material at 69 %, HMA overlay at 54 %, and mud jacking at 42 %. Asphalt injection was the least used at 4 %. Nearly one quarter of respondents (23 %) reported the use of other methods, such as diamond grinding or compaction grout. Figure 4.2 summarizes the percentage of techniques used, as reported on the survey.

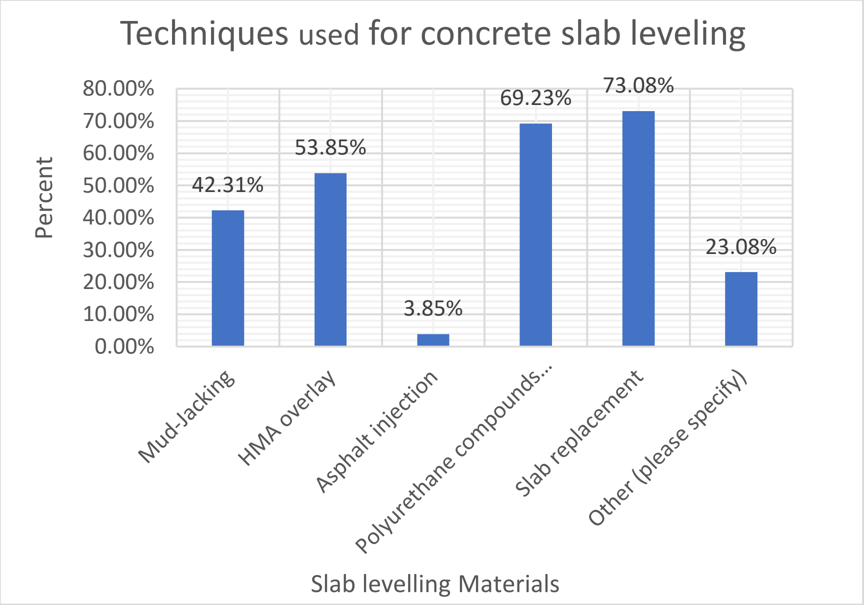


Figure 4.2 Methods commonly used for levelling concrete pavement slabs

ii. Regarding the use of Polyurethane material, 20 of the 26 respondents reported to have used it. As shown in Figure 4.3 below, URETEK 486® is the most commonly used brand, followed by PolyLevel®.

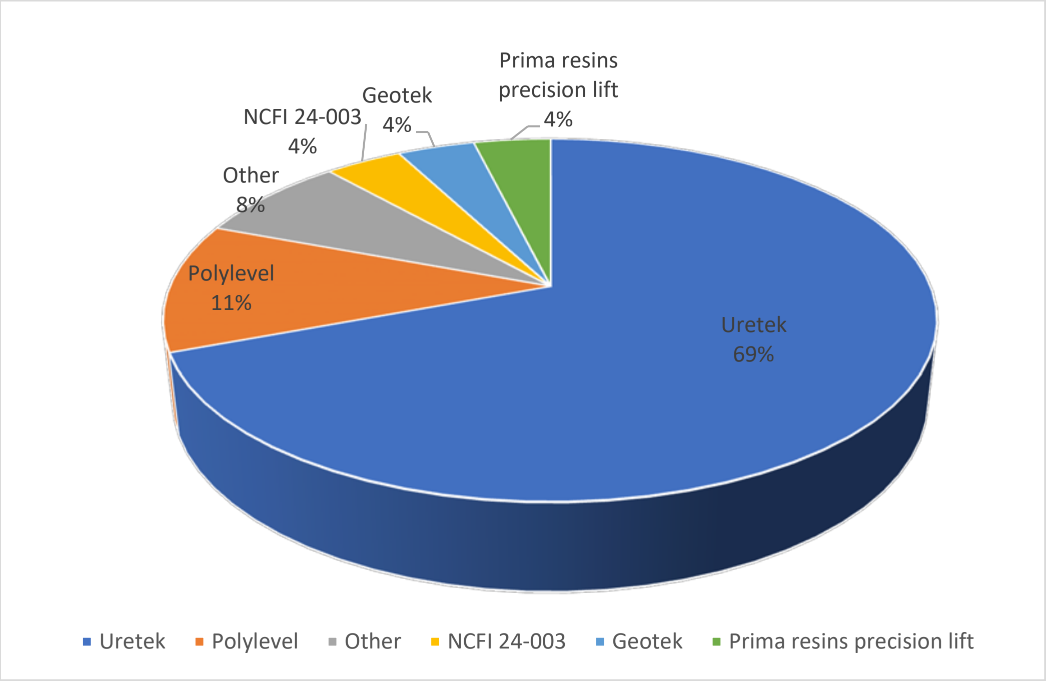


Figure 4.3 Polyurethane brand names used in US DOTs

iii. Respondents were asked to rate the cost-effectiveness of the methods used by their DOT to repair concrete pavements. A scale of 1 to 5 was used to define the cost effectiveness of the methods, with 1 being the least cost effective (too expensive and time consuming) and 5 being very cost effective (performance is comparable to capital invested). Respondents found the use of polyurethane to be the most cost effective, followed by HMA overlay, slab replacement, and mud jacking, which all received the same average score. However, slab replacement was reported the most cost-effective method when slabs are severely damaged. Asphalt injection, which is not commonly used, was reported the least cost effective. Table 4.1 summarizes the cost effectiveness score of the methods, as reported by respondents.

The cost of the material/methods varies by state and are dependent of factors like slab thickness, subsurface conditions, and amount of work. Slab replacement costs range from US$100 - US$1,000 per square yard. Polyurethane injection costs vary from US$40 - US$300 per square yard, and HMA overlay costs range from US$3.75 - US$15 per square yard. Diamond grinding and mud jacking had an average cost of US$5.50 and US$10 per square yard, respectively, based on the survey responses.

Table 4.1 Cost effectiveness of methods

Material/Technique	Average Score
Mud-Jacking	3
HMA overlay	3
Asphalt injection	2
Polyurethane injection	4
Slab replacement	3

iv. As shown in Figure 4.4, most of the respondents (94 %) reported that their slab repair budget was consistently on or below the allotted amount. Out of seventeen respondent, only one respondent (6 %) experienced projects that were over budget.

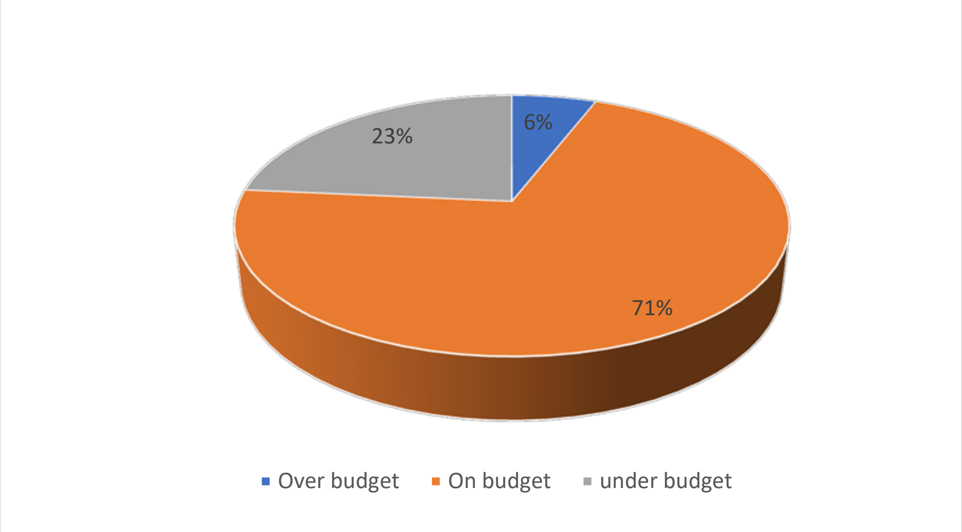


Figure 4.4 DOT slab repair project budgets

v. All 20 respondents who have used polyurethane for slab levelling drilled holes for material injection, and 89% did not experience any effects due to drilled holes. Of those who reported experiencing effects stated that they were minimal since the holes are small (approximately 15.88 mm or 0.63 in.). Only four (4) respondents out of 20 used GPR to determine voids underneath the slab prior to injection.

vi. While some sections treated with polyurethane took as long as 10 years to show signs of failure (e.g., cracking or settlement), other respondents reported that signs of failure appeared after only 1 to 1.5 years. Respondents noted that cracking is caused by overcorrection of slabs, which induces tensile stresses that crack the slabs, and not due to the holes drilled during the injection of the material underneath the slab. Small lifts of the slabs are recommended to minimize overcorrection and cracking. Settling of the slabs appeared 2 to 3 years after application was also reported.

vii. Respondents used the following methods to monitor the treated pavement sections:

- Ride Quality (PRI or IRI)
- GPS surface elevation
- Continuous laser level and dial indicator method
- Site evaluations
- Falling Weight Deflectometer (FWD) before and after application

Some respondents did not monitor the sections post treatment, specifically, but they did include the sections in the usual pavement condition data collection process.

The conclusions drawn from the survey is that polyurethane injection is good for preventive maintenance of rigid pavements on open graded granular base as it is cheaper than slab replacement, but it is very important to evaluate the extent of slab failure before application. If the slab is severely damaged, slab replacement is more cost-effective method. More than three-quarters (78%) of respondents who use polyurethane stated that the method is cost effective. Seventeen out of twenty respondents (89%) recommended the use of polyurethane. Those who did not recommend gave the following reasons:

- Increased in deflections on joints that were stable before application of the material
- Thin injection of polyurethane material created more voids underneath the slab so deep injections were recommended.
- Polyurethane application worked better to correct slab settlement but not level pavement.

5. LABORATORY TESTING AND FINITE ELEMENT ANALYSIS

Mechanical properties of materials are essential in finite element modeling of materials. Several tests were performed at UTC laboratory and Texas A & M Transportation Institute to obtain physical and mechanical properties of PolyLevel®. Tests performed include compressive strength and dynamic modulus. Finite element analysis was performed as reported in section 5.2

5.1. Compressive Strength Test

Laboratory tests on PolyLevel® materials were performed to obtain the mechanical properties of the PolyLevel® material for the finite element analysis. PolyLevel® samples were obtained from AFS Foundation and Waterproofing Specialists. The sample were casted in plastic cups, which allowed the research team to shape the samples in the cubic shape required by test procedures. These yielded either cylindrical samples with 55 mm. (2 in.) diameter or cubical samples with sides approximately 55 mm (2 in.). Larger samples were then casted by AFS Foundation in cylinders that were 101 mm (4 in.) diameter by 202 mm (8 in.) height. Tests were performed on both the smaller and the larger samples. Material properties required for FEA model in Abaqus were density, Young's modulus, Poisson's ratio, yield stress and yield strain. Three tests were conducted: (1) compressive stress-strain test to obtain elastic modulus, yield stress, and strain measurements; (2) compressive stress test to obtain Poisson's ratio and Elastic modulus; and (3) dynamic modulus test to obtain the dynamic modulus of the material. The UTC lab conducted compressive strength tests that followed the procedures described in ASTM D1621-00 and density determination tests based on ASTM D1622-03. Test numbers 1, 2 and 3 also were performed at Texas A & M Transportation Institute (TTI).

5.1.1. Compressive Strength tests at UTC

The unconfined compressive strength test was conducted in accordance to ASTM D695 to obtain the elastic modulus and yield stress and strain measurements. The test was performed on an Instron 5655 Machine available at the UTC Mechanics of Materials Laboratory on the 55 mm (2 in.) cubes specimens. The results indicate that the materials contained voids due to the slippage observed on the curve before the materials attain a linear relationship. This is expected for foam materials. Results also indicate the material becomes a perfect plastic after it yields (Figure 5.1).

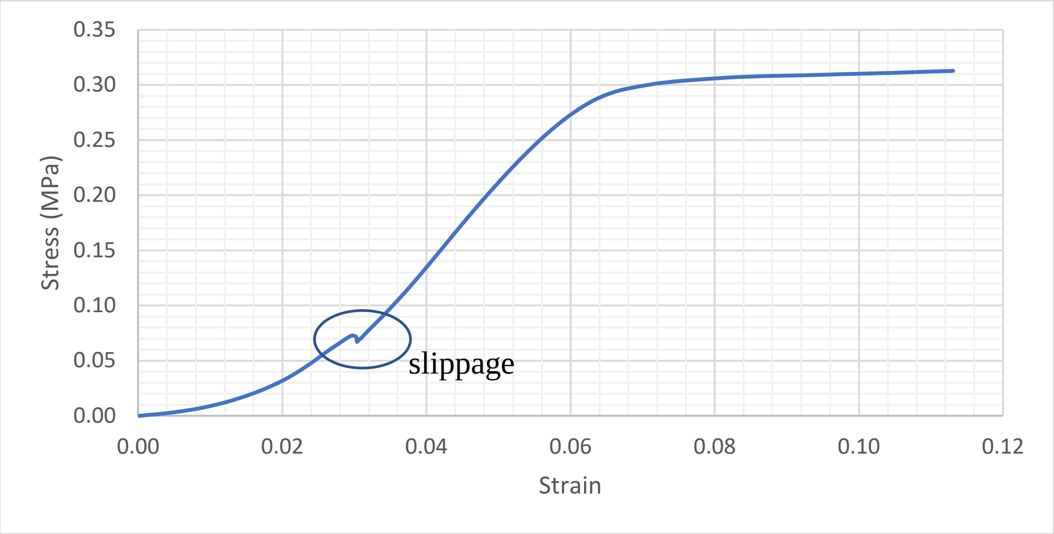


Figure 5.1 Stress-strain relationship for PolyLevel® material

Eight cubic shaped samples were tested and yielded significant variations in density and Young's modulus values (Table 5.1). Since the production of PolyLevel® materials follow standardized procedures, the team expected the values to be repeatable or have minor variations. The variation in this density results may be due to the manual process involved in measuring the specimen's dimensions and the fact that specimens were not in a perfect square.

Table 5.1 Specimens' Bulk densities and Young's modulus

Specimen	1	2	3	4	5	6	7	8	Mean	STD
Bulk density (kg/m^3)	52.41	52.52	51.73	54.33	50.66	50.03	51.69	48.06	51.43	1.88
Young's modulus (MPa)	6.59	5.57	4.93	8.00	9.66	4.47	7.30	6.16	6.58	1.71

STD stands for standard deviation

Furthermore, PolyLevel® is injected under confined conditions, whereas the tests were conducted on specimens that were fabricated without or with partial confinement. The values obtained in Table 5.1 are very low compared to in service values. For instance, the test density is half of the in-service density of PolyLevel®, which is 104.12 kg/m^3 (6.50 lb./ft^3) [2]. The team, therefore, used high-density polyurethane material properties obtained from literature for modelling PolyLevel® material in Abaqus. Further testing was performed at Texas A & M transportation Institute (TTI).

5.1.2. Compressive Strength tests at TTI on small samples

Additional PolyLevel® samples were sent to TTI to cross-check the UTC lab results. The samples at TTI laboratory were shaped in cylindrical form as shown in Figure 5.2 and tested using the procedures described in ASTM D-1621. The specimens were compressed up to one-third of their original height.

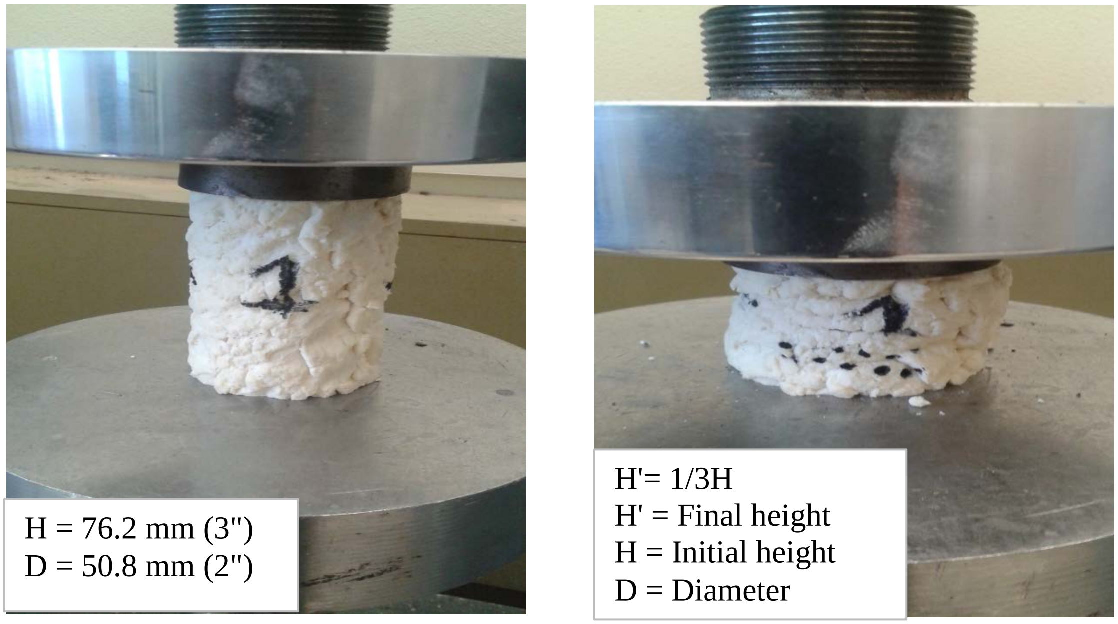


Figure 5.2 Compression test of PolyLevel® specimen

Figure 5.3 shows the stress-strain relationship of the material. The stress-strain curve shows that the material behaves in elastic, secondary, and tertiary stress-strain behavior (i.e., an elastic-plastic, nonlinear elastic). Poisson’s ratio ranges from 0.20 to 0.30 at the linear elastic zones. Figure 5.3 shows the variation of Poisson’s ratio measured at different vertical strains. As expected for foam material, the Poisson’s ratio increases with increase in vertical strain (reduction in height).

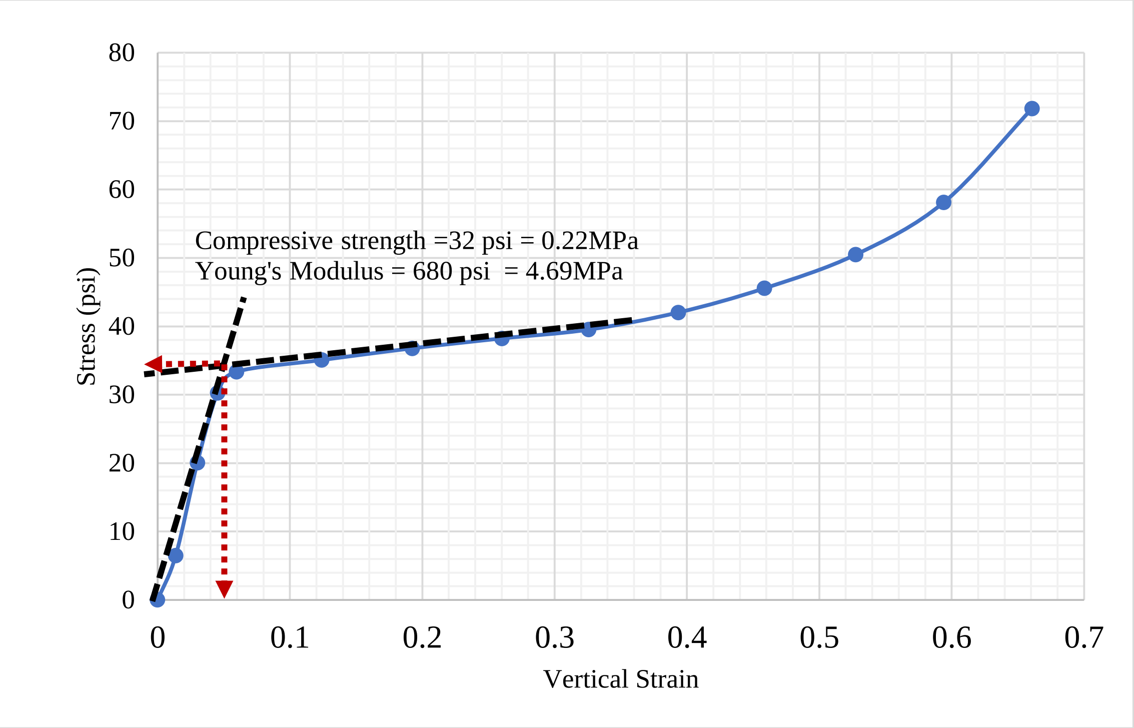


Figure 5.3 Stress-strain curve

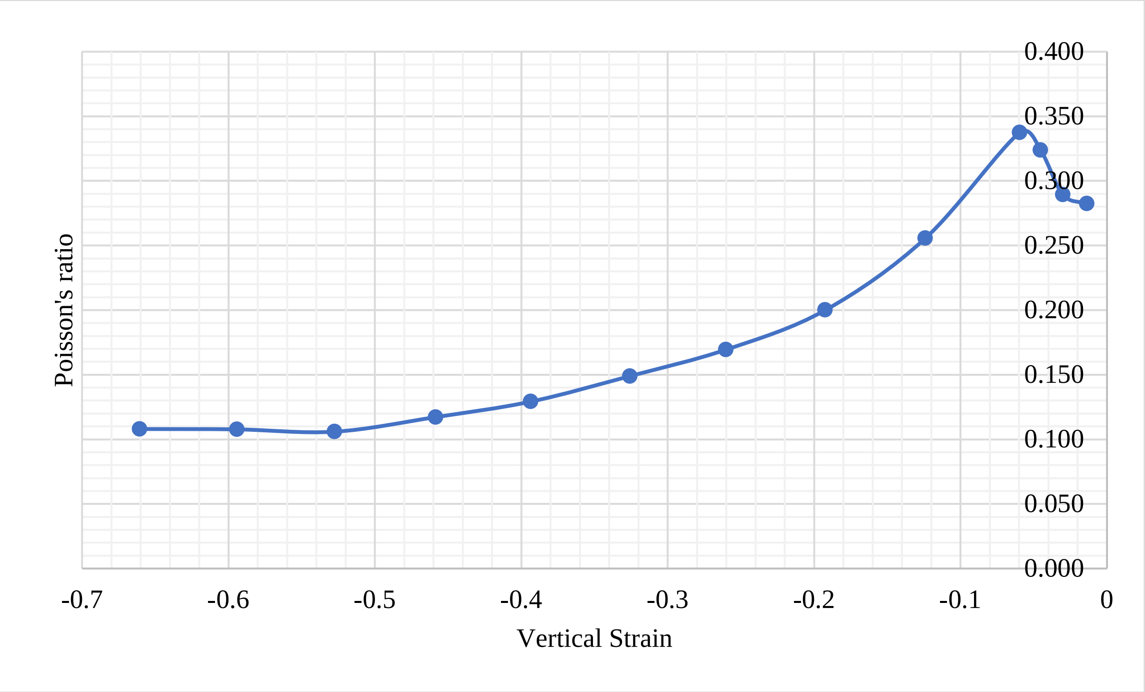


Figure 5.4 Poisson’s ratio-strain relationship

Table 5.2 shows compressive strength and modulus of elasticity of the material. Variations of the results (i.e. specimen 3 and others) is due to differences in the height of the specimens. Stress-strain curves of all specimens were compared. The curves of specimen 1 and 2 are close because their dimensions are the same (Figure 5.5). It has to be pointed out that the lab tests were not laterally confined, which is different from the field application. The expansion pressure or compressive strength and modulus of elasticity of the material are expected to be high even without experiencing a large vertical strain as seen in Figure 5.5. To limit the vertical deformation, higher density PolyLevel® is desired.

Table 5.2 Compressive strength and Young's modulus [Units: MPa (psi)]

Specimen	1	2	3	Mean	STD
Compressive strength	0.22 (32)	0.22 (32)	0.32 (47)	0.26 (37)	0.06 (9)
Young's modulus	5.17 (750)	4.69 (680)	8.10 (1175)	5.98 (868)	1.85 (268)

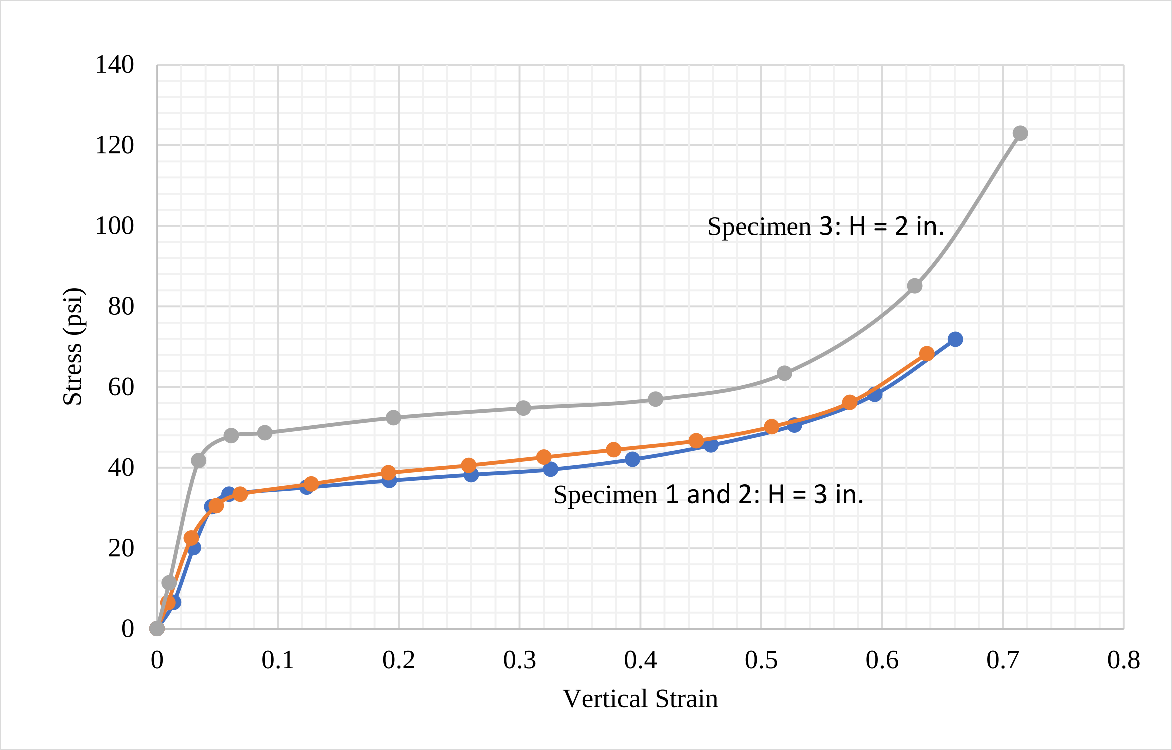


Figure 5.5 Stress-strain curves comparison

5.1.3. Compressive Strength tests at TTI on large samples

AFS Foundation availed to UTC larger test samples, 101 mm (4 in.) diameter by 202 mm (8 in.) height (Figure 5.6), that were trimmed to 101 mm (4 in.) diameter by150 mm (6 in.) height for testing. These were subjected to compressive strength to obtain the elastic modulus and Poisson's ratio (Table 5.3). The Elastic modulus of 40 MPa (4985 psi) and Poisson's ratio ranging between 1.125 to 2.40 were measured. Much higher values of bulk density were obtained from these samples (Table 5.3). with average density of 91.22 kg/m^3 (5.69 lb./ft^3) which is much closer to the publish values of 104 kg/m^3 (6.50 lb./ft^3), and much better than density measured from the smaller samples (unconfined). Larger sample (semi-confined) yielded density values closer to the published values because the confinement in making larger samples increased the density compared to the smaller unconfined samples. So smaller sample have more air voids and hence lower density.

Figure 5.6 Larger samples

Table 5.3 Large sample test results for density and elastic modulus

Specimen ID	Diameter (mm)	Height (mm)	Volume (mm^3)	Weight (gram)	Density (g/cm3)	Density (kg/m3)	Compressive Strength (psi)	MPa
PU-C/D1	101.80	63.41	516.14	45.6	0.0883	88.35		
PU-C/D2	101.50	77.84	629.81	58.77	0.0933	93.32	5800	40
PU-C/D3	101.30	74.97	604.19	55.95	0.0926	92.60		
PU-C/D4	101.70	75.72	615.12	54.45	0.0885	88.52	4214	29
PU-C/D5	100.80	77.42	617.82	57.36	0.0928	92.83	4940	34
PU-C/D6	101.10	75.27	604.27	55.42	0.0917	91.71		

Mean	91.22	4984.67	34.33
STD	2.22	793.94	5.51
CV	2.437	16	16

CV stands for coefficient of variation

Poisson's ratio (PR) results indicates that the Poisson's ratio values increased with increase in vertical strain (VS), which is expected for foam materials like PolyLevel®. Figure 5.7 shows the variation of Poisson's ratio against vertical strain for combine data, yielding a linear relationship PR = 0.2047 VS + 0.2442 with a correlation value R^2 of 0.7789. The average peak stresses and strains on larger samples were 0.84 MPa (121.54 psi) and 7.62 mm/mm (0.30 in./in.) respectively.

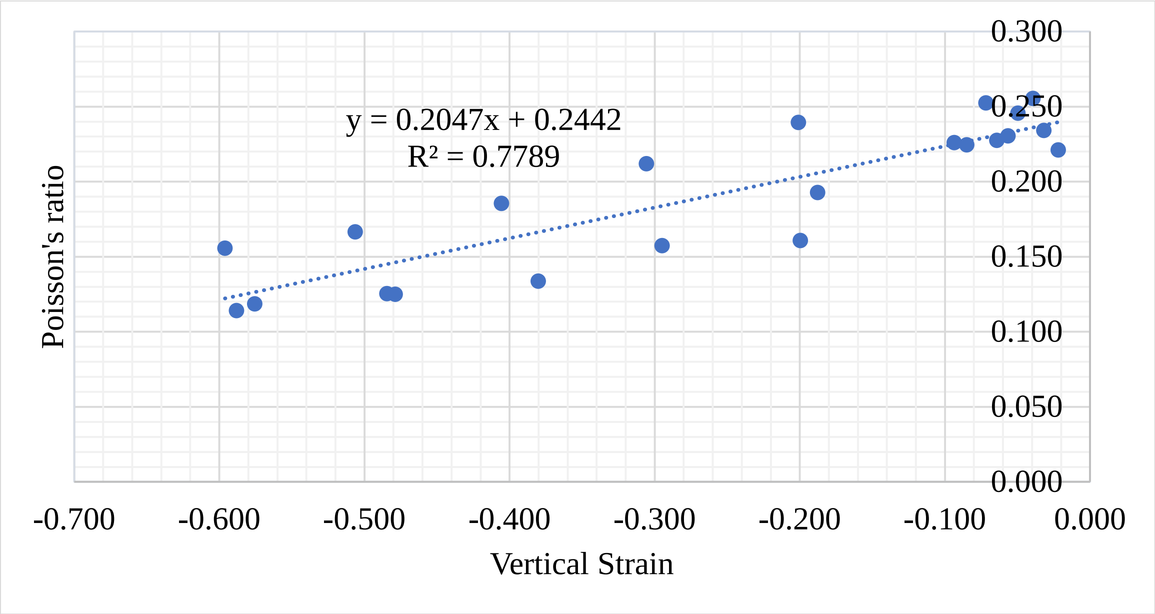


Figure 5.7 Poisson's ratio versus vertical strain for PolyLevel® combined data

5.1.4. Dynamic Modulus of PolyLevel® Material

The dynamic modulus of the PolyLevel® large specimens was performed using the Asphalt Mixture Performance Tester (AMPT). The test was conducted on cylindrical specimen with a diameter of 101 mm (4 in.) and 153 mm (6 in.) in height. Standardized procedure described in AASHTO PP 60 and AASHTO TP 79 were followed during specimen preparation and dynamic modulus testing, respectively. Figure 5.8 shows the PolyLevel® specimen in the AMPT testing chamber.

Figure 5.8 Dynamic modulus test setup

During dynamic modulus testing, specimens were subjected to continuous sinusoidal, stress-controlled loading at a specified frequency and temperature. The dynamic modulus varied from 78 MPa to 55 MPa (11312.90 psi to 7977.08 psi) at temperatures ranging from 4ºC to 40ºC (39ºF to 104ºF) (Figure 5.9). According to [23], the dynamic modulus is defined as the peak stress divided by the peak strain and is a measure of the overall stiffness of the mixture at a particular test temperature and loading frequency.

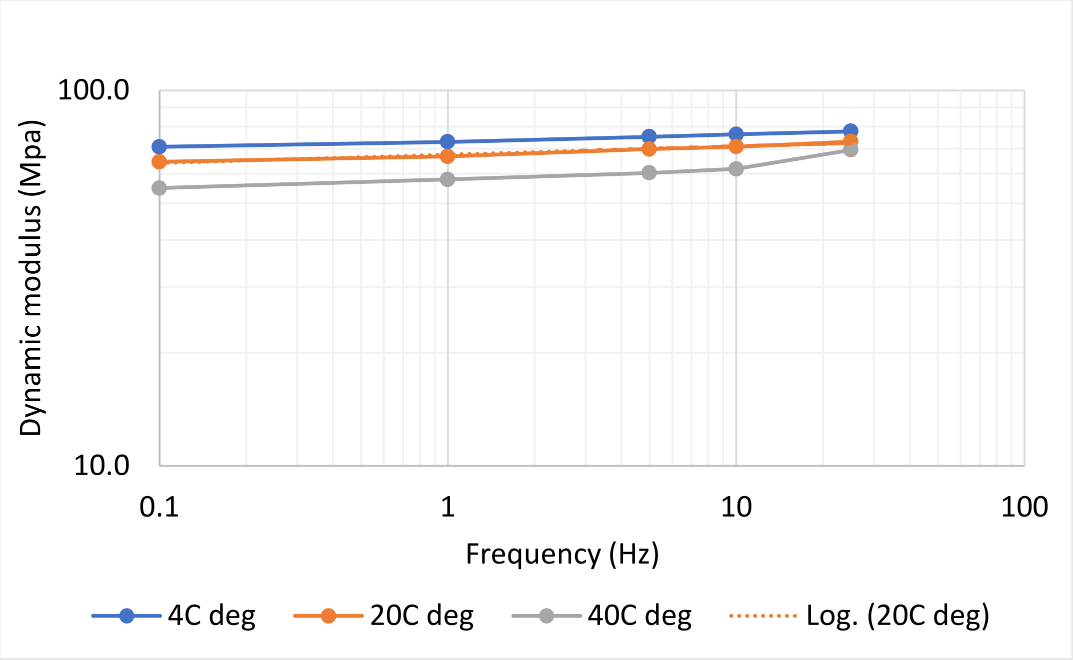


Figure 5.9 Dynamic modulus against frequency at different temperature

Dynamic modulus curves obtained at different temperatures and frequencies are aligned to form a smooth continuous curve called the master curve (Figure 5.10). The master curve represents the material response at various temperature and loading rates. Conditions relating to cold temperature and fast traffic speeds are the high reduced frequencies on one end (left hand side) of the master curve and conditions relating to high temperature and slow traffic speeds are the low reduced frequencies at the other end (right hand side) of the master curve [23]. This method was used because currently, there is no protocol to measure the dynamic modulus of polyurethane materials.

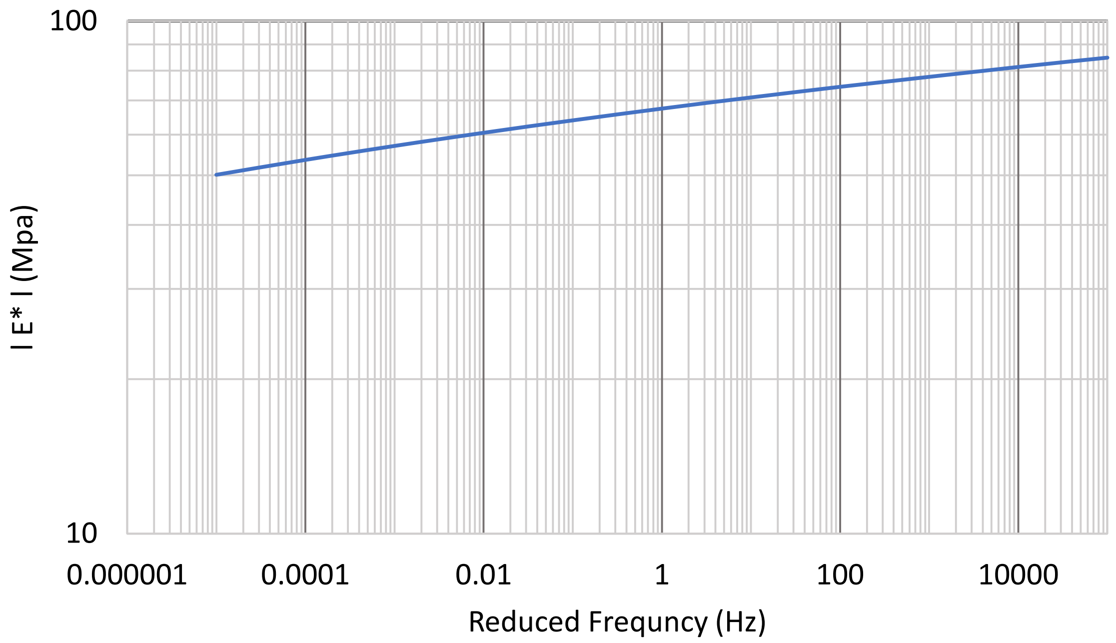


Figure 5.10 PolyLevel® master curve

5.2. Modelling of PolyLevel® material under Traffic Loading by using Finite Element Analysis

PolyLevel® is polyurethane foam of high-density polymers with capabilities of being expandable. Some state DOT’s (TDOT, IDOT, NDDOT etc.) are using this material for quick repair of settled concrete pavements. However, literature review revealed that there has been very limited research conducted in regard to the properties of this material, and its long-term performance under cyclic traffic loading.

This study utilized finite element method (FEM) to evaluate long-term performance of PolyLevel® since it is a mature numerical tool being widely adopted to study many aspects of pavements. A commercially available FEM package, Abaqus, is used because it features user defined materials and loadings, as well as strong adaptability in geotechnical engineering. An Abaqus subroutine DLOAD written in FORTRAN is developed to model cyclic loadings. The highway traffic loads are applied on a twelve meters-long Accelerated Loading Facility (ALF) field test pavement. Two PolyLevel® foams with different densities are placed underneath a concrete slab joint. Deformations of the PolyLevel® foams are monitored to evaluate its performance.

Studies that are mostly related to this research include: Hadi and Bodhinayake [24] modelled pavement deflection by considering the non-linear material properties with cyclic loading. Zaghloul and White [25] conducted a sensitive 3D Finite Element analysis to investigate the effect of various factors (cross-section and load attributes) on pavement performance. Properly chosen material behavior for the pavement foundation is critical in FE modeling, Kim, Tutumluer and Kwon [26] thus developed an Abaqus user material subroutine to model the nonlinear stress-dependent behavior of the geomaterials.

5.2.1. Finite Element Model

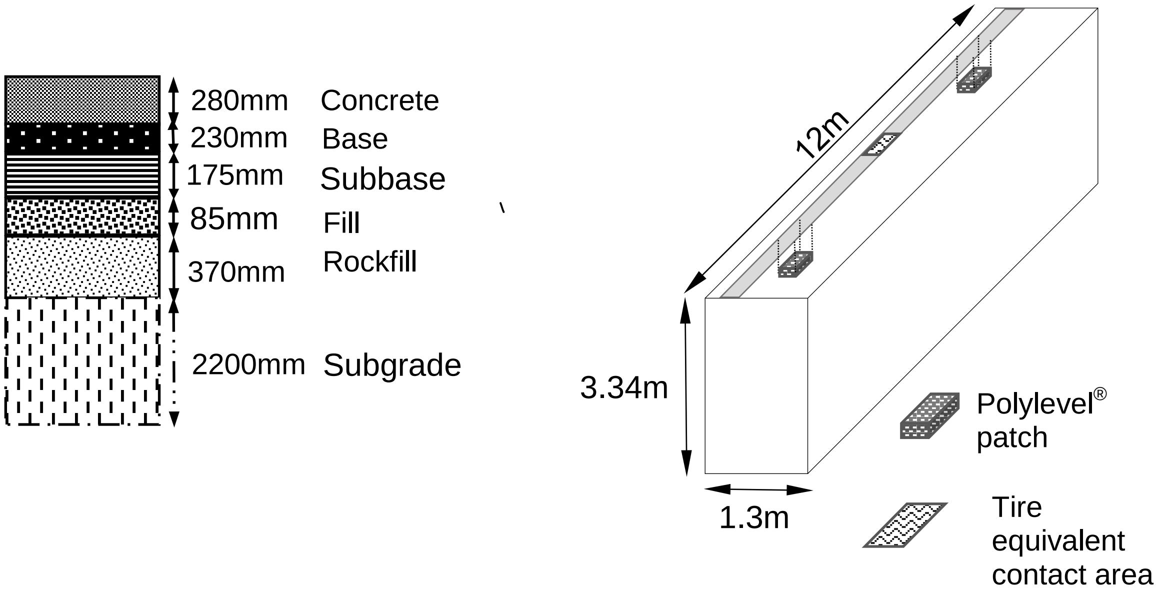
The pavement structure used in this study (Figure 5.11(a)) is modified from a pavement section where ALF test was carried out, at Callington, South Australia [23, 27]. A rigid concrete slab replaces the top asphalt layer with an average thickness of 280 mm. The length of the ALF field test pavement is 12 m. (Figure 5.11(b)) more about ALF is outlined in [28]. Two injected polylevel foam patches $0.6\,m \times 0.2m \times 0.05m$ (L× W× H), one with a density of 72.10 kg/m^3 (4.50 lb./ft^3) and the other of 152 kg/m^3 (9.50 lb./ft^3) are placed right underneath the bottom of the rigid concrete slab. A cyclic load of up to 80.00 KN (17984.7 lbf.), on dual Michelin X type tires, is applied along a 0.2 m (0.66 ft.) wide strip (darker area in Figure 5.11 (b)) on the surface of the pavement at a constant speed of 20 km/hr. (12 mi./hr.) Approximately 380 load cycles are applied each hour, which is equivalent to about 9 seconds per cycle. The load is applied in one direction only, the tires are lifted off the pavement at the end of each cycle [28].

The cyclic moving traffic load created by a Fortran subroutine DLOAD is used to apply two different loads; 40 KN and 80 KN (8992.36 lbf. and 17984.72 lbf.) on an equivalent tire contact area of 0.29 m by 0.20 m (0.95 ft. by 0.66 ft.) (the zig zag pattern filled area pavement surface in Figure 6.1(b)), which originally was suggested by Huang [29]. In the Abaqus subroutine, by properly defining the positions of two ends of the equivalent contact area (i.e. the contact area between tire and pavement surface) as a function of current value of step time, the traffic load can be modeled as moving the equivalent contact area back and forth. Similar work has been seen in reference number [30].

The bottom of the pavement structure is fixed, and symmetry boundaries are applied on all four sides. A general-purpose linear brick element, with reduced integration C3D8R is used with sufficient mesh density.

5.2.2. Material Properties

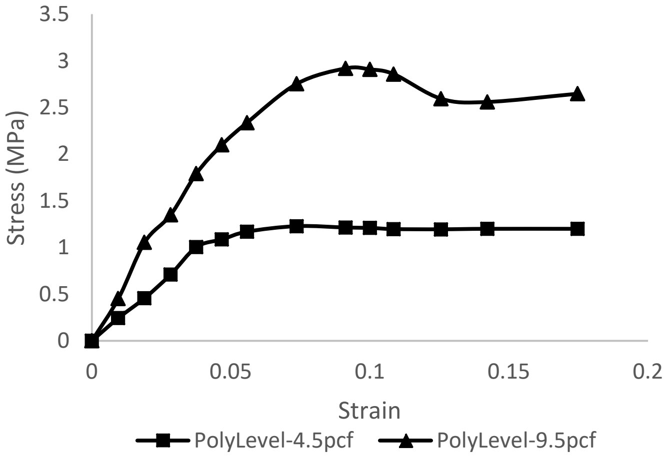
The expansion pressure laboratory tests carried out by Larsen [31] reveal that PL250 type (with a free-rise density of 40 kg/m^3 (2.50 lb./ft^3) PolyLevel® can achieve expansion pressure of 575 kPa (83.40 psi) vs. 239 kPa (34.66 psi) of PL400 under confined conditions. Nevertheless, PL400 is preferred, the material in-site expands or spreads from the injection point under free-rise condition, which requires PL400 to achieve a higher density and pressure locally. The mechanical properties of PolyLevel® depends on its densities, the denser the material, the higher the strength. The exact constitutive behavior of PolyLevel® is very complex. Without much knowledge of the true stress-strain constitutive relation, it is hypothesized that the behaviors of high density PolyLevel® with confined boundaries are closely related to high-density rigid polyurethane foams. The stress-strain behavior of PolyLevel® applied in the current study follows [32] and is shown in Figure 5.12.



(a) Pavement structure

(b) ALF field test pavement

Figure 5.11 Finite Element Pavement model



PolyLevel- 4.5pcf PolyLevel® material with a density of 72.10 kg/m^3 (4.50 pcf.)

Figure 5.12 Stress-strain behavior of PolyLevel® used in FEM modeling

The mechanical properties of pavement layers used in this study are given in Table 5.4. Researches show proper definition of nonlinear material behaviors for subgrade materials is essential to accurately predict the total deflection of pavement [23, 25]. In this study, the focus was on comparison of vertical deflections on the top of two types of injected polylevel foams with a certain cycles of traffic loading. Linear elastic material properties are used for all the layer materials except for the subgrade. Mohr Coulomb plasticity model is used to define subgrade whose properties follow the ones given in [33].

Figure 5.5 shows that the stress-strain constitutive relation of PolyLevel® is size dependent and the PolyLevel® experiences very large deformation without lateral confinement. However, the lateral deflection of PolyLevel® used in pavement leveling is constrained, which means the stress-strain relation seen in Figure 5.5 may not actually represent the true response of the material under the pavement. It is also known that the expansion pressure (thus compressive strength) of PolyLevel® is positively correlated to its density [31]. The bulk density of PolyLevel® material used by TDOT was found to be 90.53 kg/m^3 (5.7 pcf) (Table 5.7), which is in between 72 kg/m^3 (4.5 pcf) and 152 kg/m^3 (9.5 pcf). Without knowledge of true stress-strain relation, it could be a good representation to use well-established stress-strain constitutive relation of high density polyurethane foam with densities of 72 kg/m^3 and 152 kg/m^3 to capture or estimate the response of PolyLevel® under critical traffic cyclic loadings.

Table 5.4 Pavement layer material properties

Pavement Layer	Modulus of Elasticity (MPa)	Poisson’s Ratio
Concrete	30337.00	0.25
Base	138.00	0.35
Sub-base	96.60	0.35
Fill	72.45	0.35
Rock fill	62.10	0.35
Subgrade*	55.20	0.35

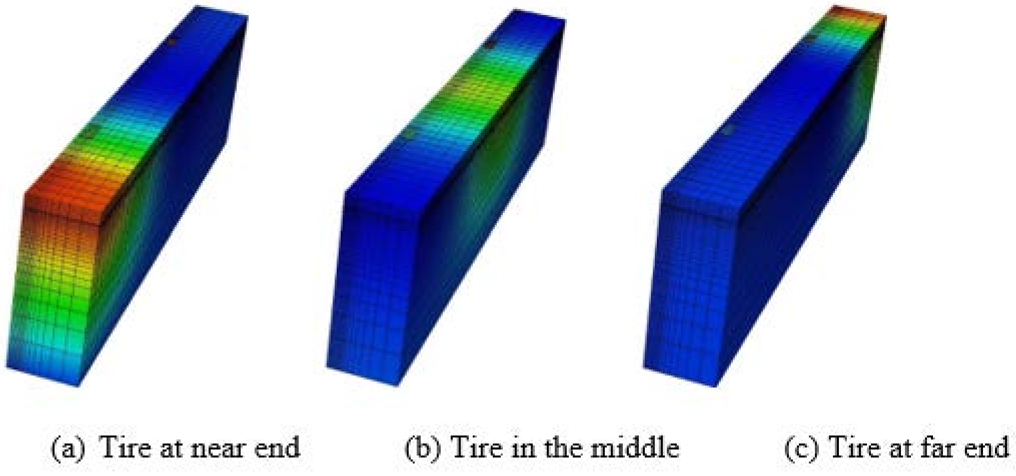
***** Mohr Coulomb Plasticity model is used for this material.

5.2.3. Analysis Results

A geostatic stress field procedure allows verification of equilibrium of the initial geostatic stress field with applied loads (i.e. gravity force in this study) and boundary conditions [34]. Elevation-dependent initial stresses were specified in each layer of the pavement structure in order to reach equilibrium that can be verified by negligible soil displacement in the vertical direction at the end of geostatic step.

In 1974, Brown established a relationship between the permanent strain and the number of stress cycles for a granular material through a repeated load tri-axial test under drained condition [35]. His study demonstrated that permanent strains would reach equilibrium value after about 104 stress cycles. It would be computationally expensive to apply such cyclic loadings in order to determine the equilibrium permanent strains. Currently this study limits the number of cycles to 28 to test the workability of the user subroutine. Traffic loadings with many more cycles will be considered in future studies.

The 0.2 m (0.66 ft.) wide strip is defined in Abaqus CAE, the loads (40 K and 80 K) are specified in FORTRAN subroutine DLOAD that is called by Abaqus to execute the job. Figure 5.13 shows the vertical deflection contour plots when the equivalent contact area (tire) moves from one end of ALF test pavement to the other. The deflections on the top of PolyLevel® leveling foams when using different levels of traffic loads (40K and 80K) and different PolyLevel® materials (72 kg/m^3 and 152 kg/m^3) are presented in Figure 5.14.



(a) Tire at near end (b) Tire in the middle (c) Tire at far end

Figure 5.13 Vertical deflection contours when tire moves from one end of ALF test pavement to the other

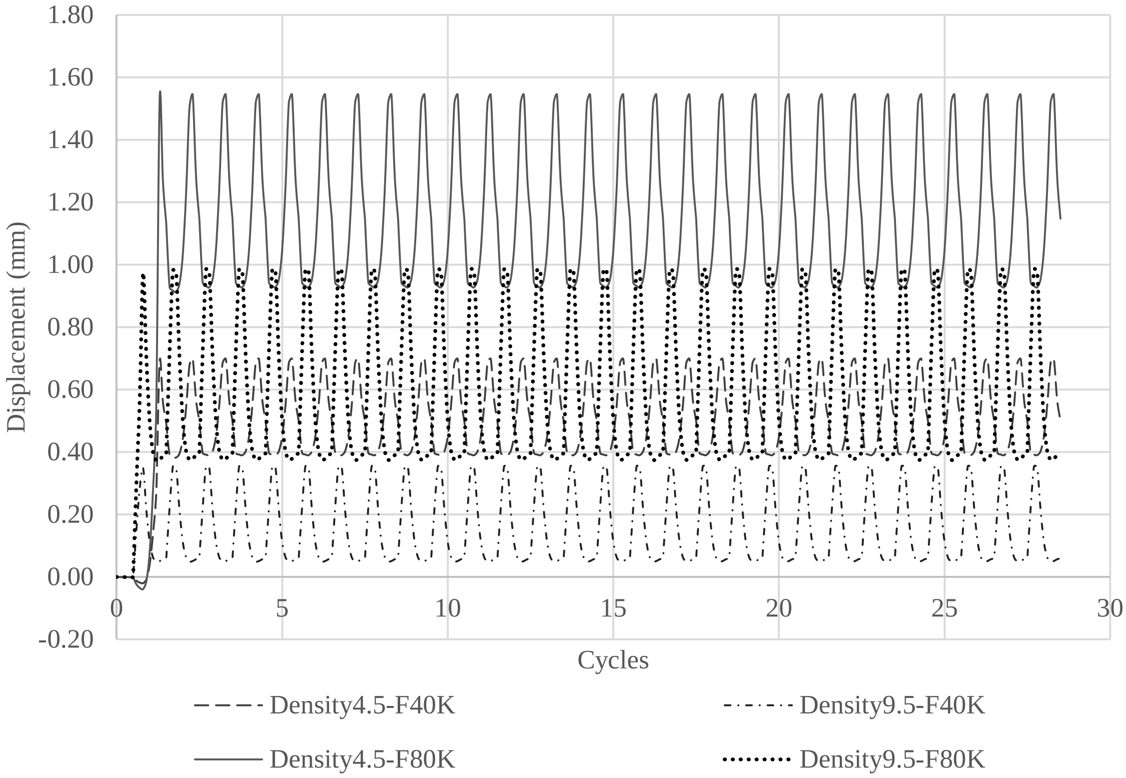


Figure 5.14 Deflections at the top of PolyLevel® leveling patch with cyclic traffic loading

5.2.4. Finite Element Analysis Conclusions and Discussions

It was determined that:

- The deflections fluctuate when cyclic traffic loads move back and forth on the rigid pavement surface along the strip. Relatively small permanent deformations are observed. The maximum peak deflection of all four cases is nearly 1.55 mm (0.6 in.). The increasing trend of permanent deflection is not observed.
- It is found that the permanent deflection tends to be most significant when the largest traffic load (i.e. 80 KN of 18,000 lbf) and the lowest density (72.10 kg/m^3 or 4.50 pcf) rigid polyurethane foams is used.
- One notices that the permanent deflections are almost identical if the load is 40 KN (9,000 lbf) with a density of 72.10 kg/m^3 (4.50 pcf) PolyLevel® and a load of 80 KN (18,000 lbf)

but with a density of 152 kg/m^3 (9.50 pcf) PolyLevel®. Nevertheless, the amplitude of the fluctuation is almost doubled with high-density PolyLevel® and very large traffic load.

- When a high-density PolyLevel® foam is used for leveling the pavement, small traffic load will result in the smallest permanent deflection and peak displacement. Relatively small permanent deflection of polyurethane foam type PolyLevel® is observed with cyclic traffic loadings applied. PolyLevel® may be used to quickly repair and restore slab drop-offs on rigid pavement if proper density of PolyLevel® material is injected. Higher density PolyLevel® is necessary to reduce the deflection and resist heavier highway traffic loads. With increasing cycles, the permanent deflection is expected to become even larger, which is not obvious through this study. Further and careful characterization of PolyLevel® material is needed.
- The PolyLevel® may be used to level settled rigid pavement quickly but it may experience permanent deformation under long-term cyclic traffic loadings.
- Cyclic loading effect (increasing permanent deformation) is not significant with limited cycles applied in this study. Well-established constitutive material models have to be created through extensive experimental testing in order to better and further capture the performance of PolyLevel®.
- Long-term permanent deformation may not be captured by cyclic traffic loading only without properly considering material behaviors of subgrade layers and PolyLevel®.
- The creep property of PolyLevel® may also need to be considered, which is believed to contribute significantly to the ultimate deformation of PolyLevel®.

6. DATA ANALYSIS, RESULTS AND FINDINGS

Mean Roughness Index (MRI) and estimated International Roughness Index (eIRI) data was collected periodically to monitor a key variable that correspond to pavement performance (smoothness) of the PolyLevel® treated sections. Data was collected on five test locations on I-24 and I-75 in Chattanooga, Tennessee using the Roadroid app (eIRI), and high-speed inertia profiler (for MRI). The MRI data was collected by a TDOT contractor at about eight months intervals, while eIRI data was collected by UTC team every month after the application. The eIRI before treatment is not available because the research team did not have the app ready when PolyLevel® was applied on the selected sections. This section details the data collection and results.

6.1. Pavement Roughness Data Collection using Roadroid App

UTC adopted the use of Roadroid application for data collection. A Samsung Galaxy 5 was purchased for this purpose. The trial eIRI data was collected on May 1st and May 15th of 2016 for segments on I-24 West and I-24 East_182 (mile marker 179.5 to 178.2, and 182.35 to 183 respectively) using the Roadroid app. Roadroid classifies the IRI profile index with the categories/thresholds shown on Table 6.1 [1].

Table 6.1 Estimated IRI ranking in Roadroid

IRI Threshold (m/km)	Speed (km/hr.)	Rating
< 2.2	> 70	Good
2.2 – 3.8	50 - 70	Ok
3.8 – 5.4	30 - 50	Fair
> 5.4	< 30	Poor

[1.00 m /km is equivalent to 63.36 in./mi.]

The data was collected on five sections listed on Table 1.1. Figures 6.1 and 6.2 provide a satellite view of the trial section taken by the Roadroid app at the I-24 West near neat US-27 split. The dotted lines are somehow off mark due to GPS errors, but they serve an illustrative purpose. Figure 6.1 is a zoomed photo near the split.

Figure 6.1 Satellite view of Roadroid data points on I-24 in Chattanooga, TN

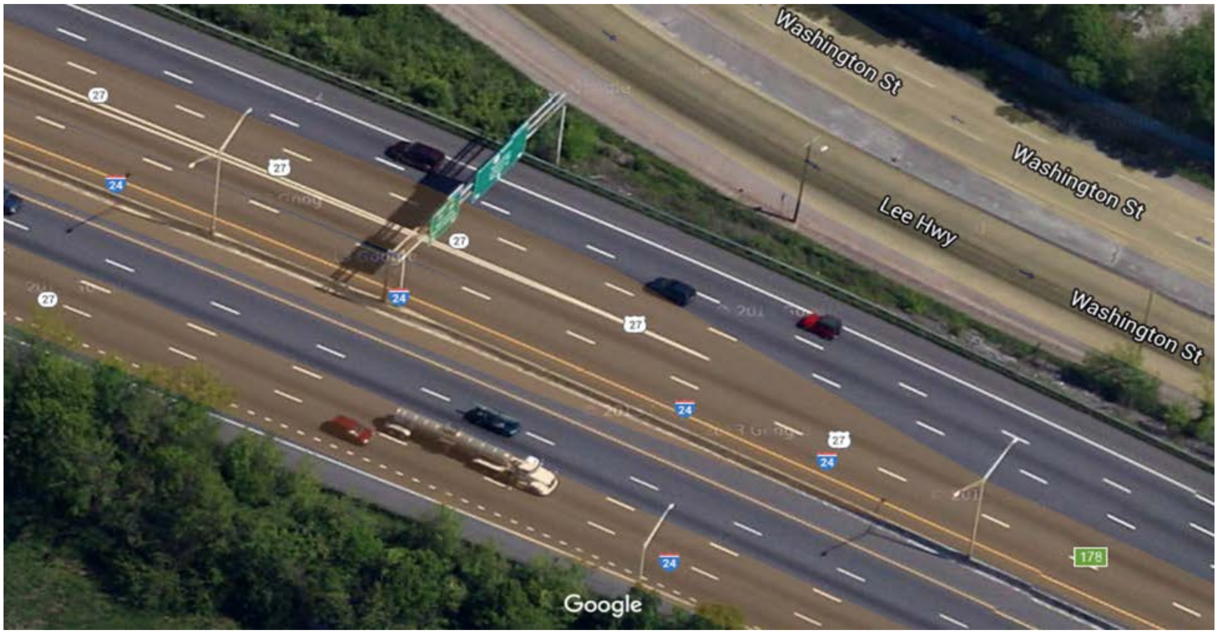


Figure 6.2 Zoomed view near I-24 and Hwy 27 split in Chattanooga, TN

6.1.1. Testing Variability of Roadroid Data Due to Vehicle Change

In anticipation of possible variations of the IRI measurements caused by the condition or type of vehicle used, an experimental test was conducted in June 2016. This experiment used three (3) passenger cars with different vehicle conditions to collect two full runs of IRI measurements at 80 km/hr. (50 mph) for each vehicle. The testing utilized the UTC vehicle test track, a 1.61 km

(1.00 mi.) track managed by the Center for Energy, Transportation, and the Environment (CETE). The results are shown in Figure 6.3 below, with two runs each for vehicle i, j, and a, respectively.

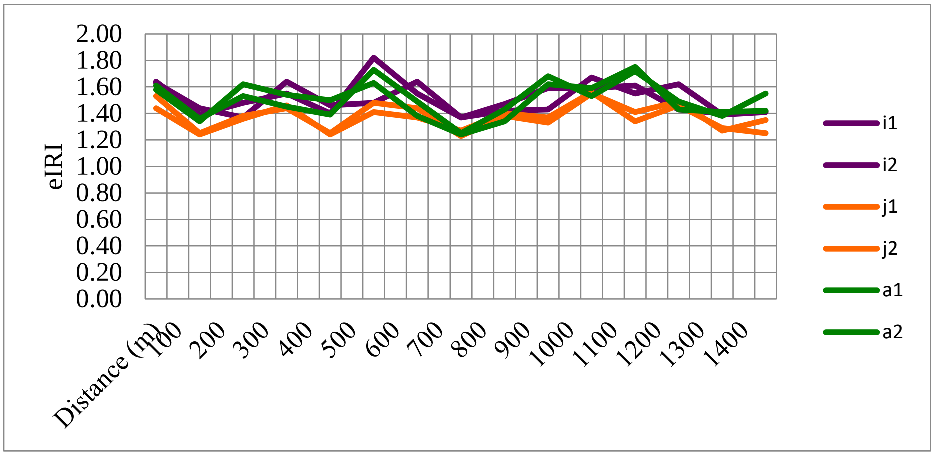


Figure 6.3 Repeatability of eIRI with vehicle type

The eIRI data obtained from the six runs on the test truck were analyzed using the Analysis of variance (ANOVA) test, to evaluate the difference of the mean eIRI of the six runs. The results showed that there is a mean difference at 95% significance level, since the p value 0.000655 was smaller than 0.05 indicating rejection of the null hypothesis that eIRI means are equal for the six runs. This analysis did not provide what test sets have different means. Therefore, a further analysis using Turkey Honest Significant Differences (HSD) test, which performs pairwise comparison of data sets, indicated existence of mean eIRI difference on four or five pairs out of fifteen pairs tested (Table 6.2).

Tukey HSD test results show that there is a difference between the following means (the rest in Table 6.2 are regarded have no difference)

j1 and i1: p-value adjusted = 0.009

j2 and i1: p-value adjusted = 0.037

j1 and i2: p-value adjusted = 0.028

a1 and j1: p-value adjusted = 0.021

a2 and j1: p-value adjusted = 0.048 (can also be interpreted as no difference ~ 0.05)

The difference was mainly between other cars (a and i) against car j which is older than the other two cars used for the test. We can conclude that there could be some difference in measurements depending on the car age and maintenance status. However, since two out of the three vehicles showed no difference in mean eIRI values, we assumed no mean difference. The eIRI data collection utilized only two cars, one car in the first year and the second car in the second year.

Table 6.2 Analysis of variance of means using Turkey (HSD) test

Data Groups	Mean Differences	Confidence Interval		P-value adjusted
		Lower End	Upper End	
i2 - i1	-0.020	-0.150	0.111	1.000
j1 - i1	-0.157	-0.287	-0.027	0.009
j2 - i1	-0.135	-0.266	-0.005	0.037
a1 - i1	-0.015	-0.145	0.115	0.999
a2 - i1	-0.028	-0.158	0.102	0.989
j1 - i2	-0.137	-0.265	-0.009	0.028
j2 - i2	-0.116	-0.244	0.012	0.098
a1 - i2	0.005	-0.123	0.133	1.000
a2 - i2	-0.009	-0.137	0.119	1.000
j2 - j1	0.021	-0.107	0.149	0.997
a1 - j1	0.142	0.014	0.270	0.027
a2 - j1	0.129	0.001	0.257	0.048
a1 - j2	0.121	-0.007	0.249	0.076
a2 - j2	0.107	-0.021	0.235	0.152
a2 - a1	-0.013	-0.141	0.115	1.000

6.1.2. Roadroid Data Analysis

From September 2016 to March 2018, the research team at UTC conducted nineteen (19) Roadroid runs, using a smartphone mounted on the front windshield of a passenger car travelling at speeds ranging from 82 km/hr. (51 mi./hr.) to 102 km/hr. (63 mi/hr.). Data collected using Roadroid smartphone app at these speeds was stored on Roadroid servers, downloaded into a computer over Wi-Fi, and analyzed.

As Figures 6.4 – 6.8 show, all sections are performing well, with estimated IRI varying in a band of 1.0 to 1.5 m/km (63.36 in./mi. to 95.04 in./mi.) except I-24 West and I-24 East_182, which had values higher than 1.5 m/km (95.04 in./mi.) runs conducted from September 2016 to January 2017 and October 2017 to March 2018 respectively. All sections however, are performing within the desirable IRI (below 2.2 m/km) for measurements conducted at a speed greater than 70 km/hr. (43 mph).

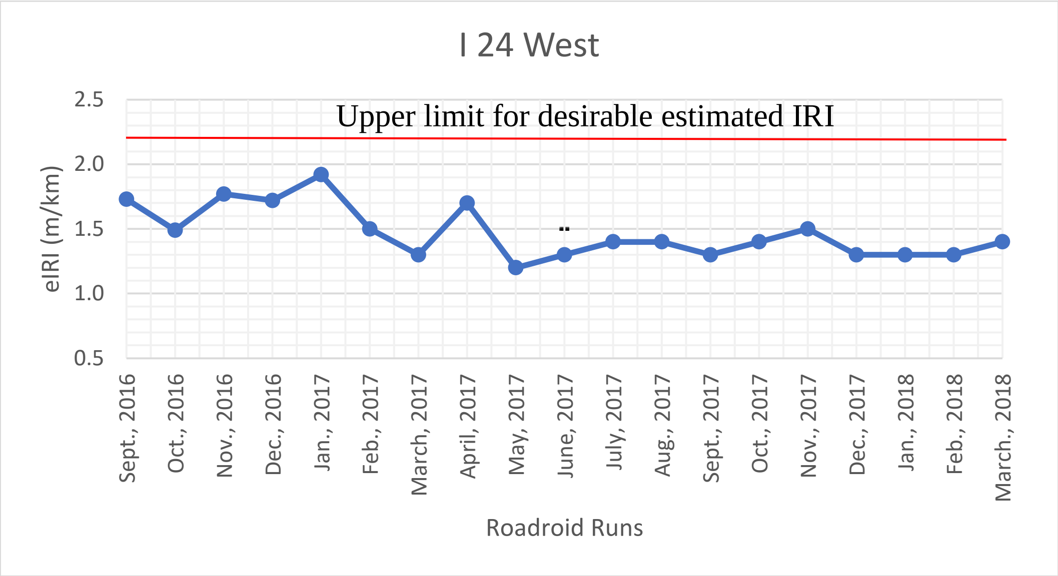


Figure 6.4 Average IRI variations on I-24 West from Sept. 2019 to March 2018

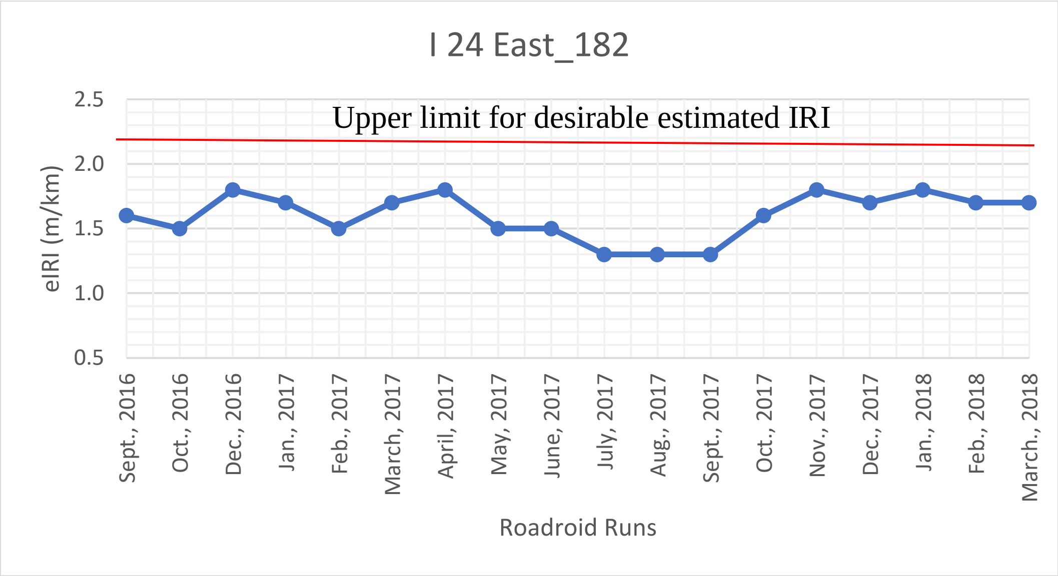


Figure 6.5 Average IRI variations on I-24 East_182 from Sept. 2019 to March 2018

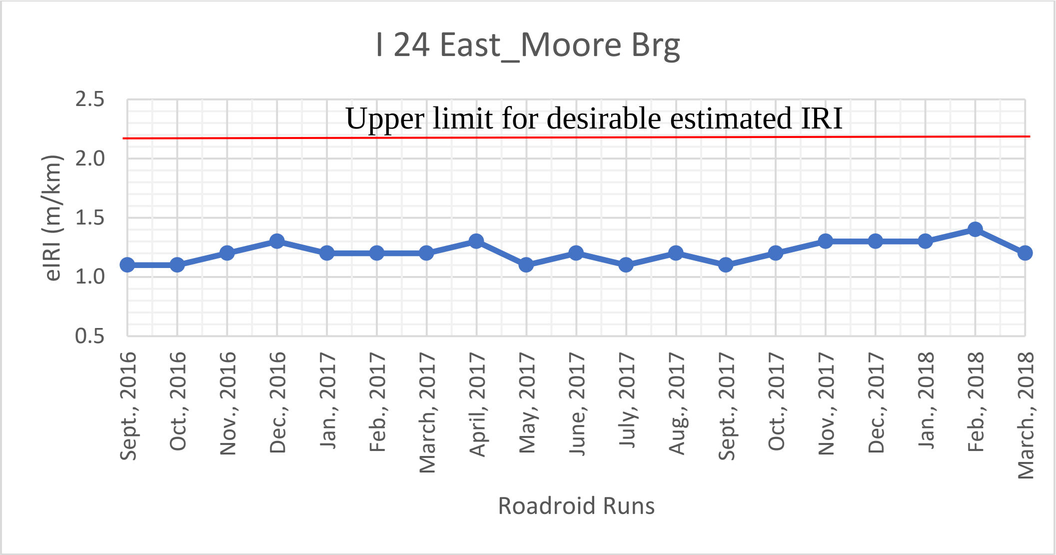


Figure 6.6 Average IRI variations on I-24 East at Moore Bridge from Sept. 2019 to March 2018

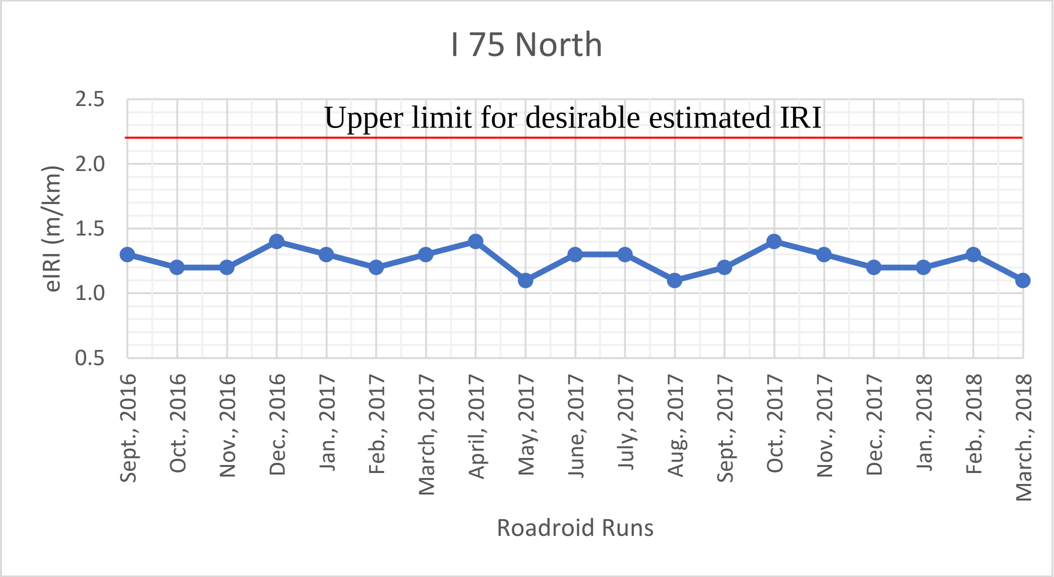


Figure 6.7 Average IRI variations on I-75 North from Sept. 2019 to March 2018

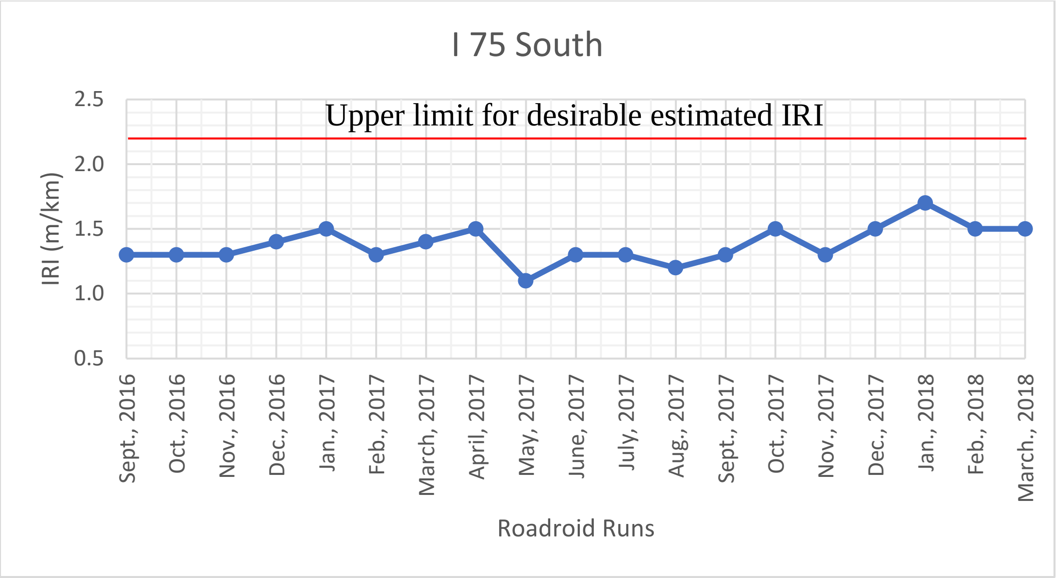


Figure 6.8 Average IRI variation on I-75 South from Sept. 2019 to March 2018

It can be concluded that, eIRI data may, to a small extent, be affected by a vehicle used for data collection depending on the vehicle condition. The eIRI data collected was below the upper limit (2.2 m/km), which indicated that the sections performed well. The correlation between eIRI and MRI was not performed on this study.

6.2. Ride Quality Assessment Using the ICC Profiler

An ICC profiler was used to obtain a true ride quality that had no influence of vehicle vibrations as it travels. TDOT hired a contractor to collect the longitudinal profiles using the standard ICC inertial profiler before and after injection of the PolyLevel® material underneath the test sections slabs. The data was analyzed using ProVAL. Raw profile data were collected at a sampling interval of 26.27 mm (1.03 in.).

The FHWA categorizes the pavement condition of the National Highway System (NHS) based on ride quality as follows: Good for IRIs below 1.50 m/km (95 in./mi.); Fair for IRI between 1.5 and 2.70 m/km (95 and 170 in./mi.); and Failed for IRIs above 2.7 m/km (170 in./mi.). The ride quality of the pavement is considered acceptable if the IRI falls in either the good or fair category [37].

Table 6.3 NHS ride quality scale

IRI (m/km)	Rating
< 1.50	Good
1.50 - 2.70	Fair
> 2.70	Failed

[1.00 m/km is equivalent to 63.36 in./mi]

The ride quality of the test sections was within the acceptable level before application of the PolyLevel® and remained the same nineteen months or more after the injection. The only exception was the section at I-24 East_182, which consistently measured in the failed category (IRI > 2.7 m/km (170 in./mi.)) before and after application, with an irregularity at the eighth month post injection measurement that fell within the acceptable level (see Figure 6.12). This may be attributed to wheel wander, in which wheel paths differ per vehicle passes, among other things. The Roadroid results also indicated fluctuations on IRI measurements (Figures 6.4 – 6.8). The material was injected on different dates while the ICC profiler runs were conducted on the same dates each time. This means that data were collected on different pre- and post- application lengths/intervals.

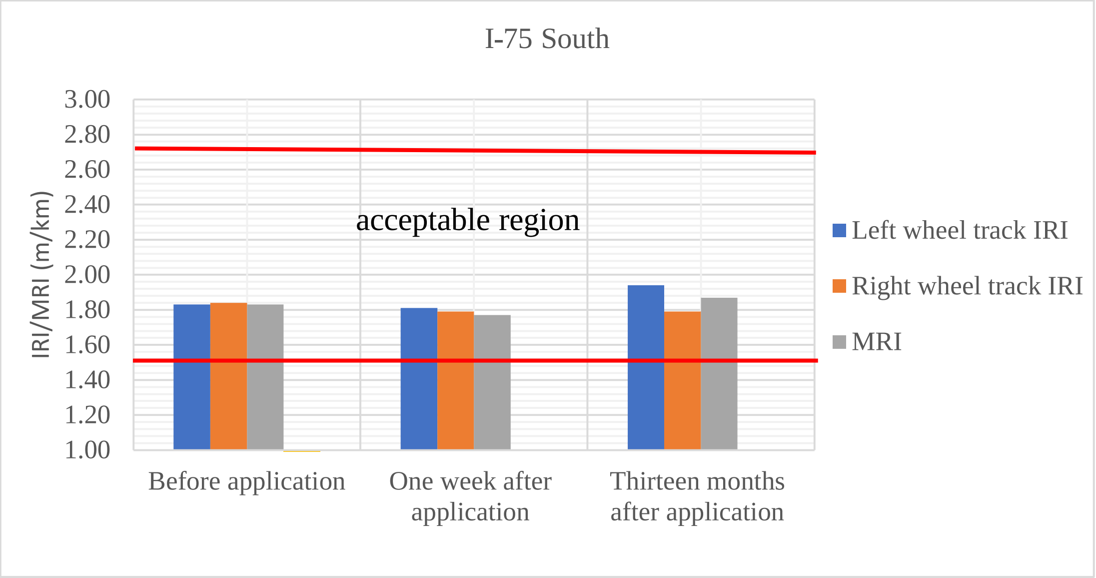


Figure 6.9 IRI and MRI measurements for I-75 South MM 9 to MM 7

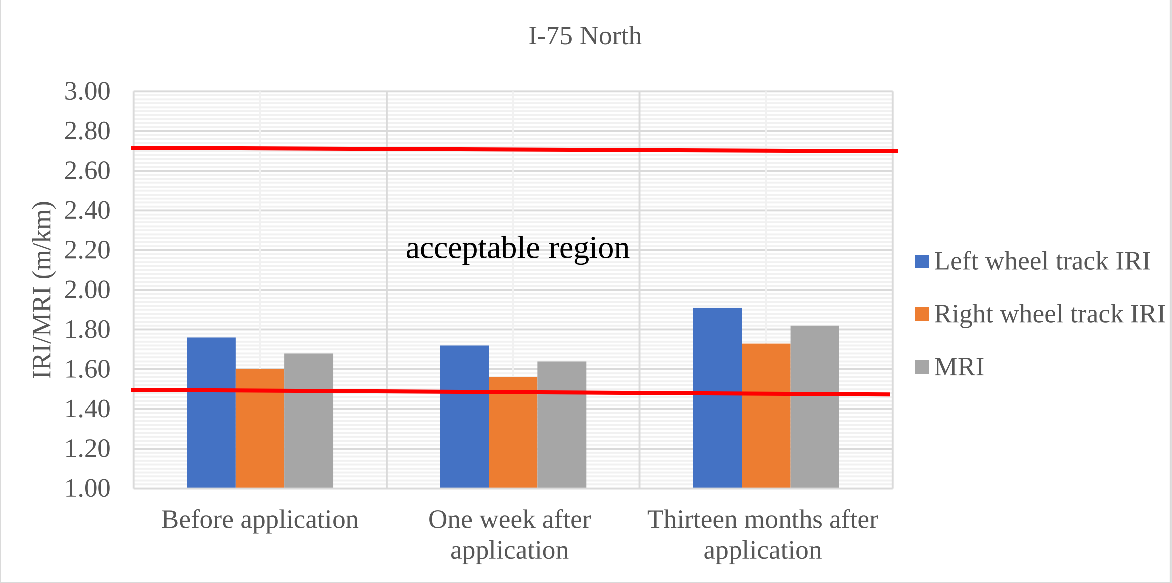


Figure 6.10 IRI and MRI measurements for I-75 North MM 7 to MM 9

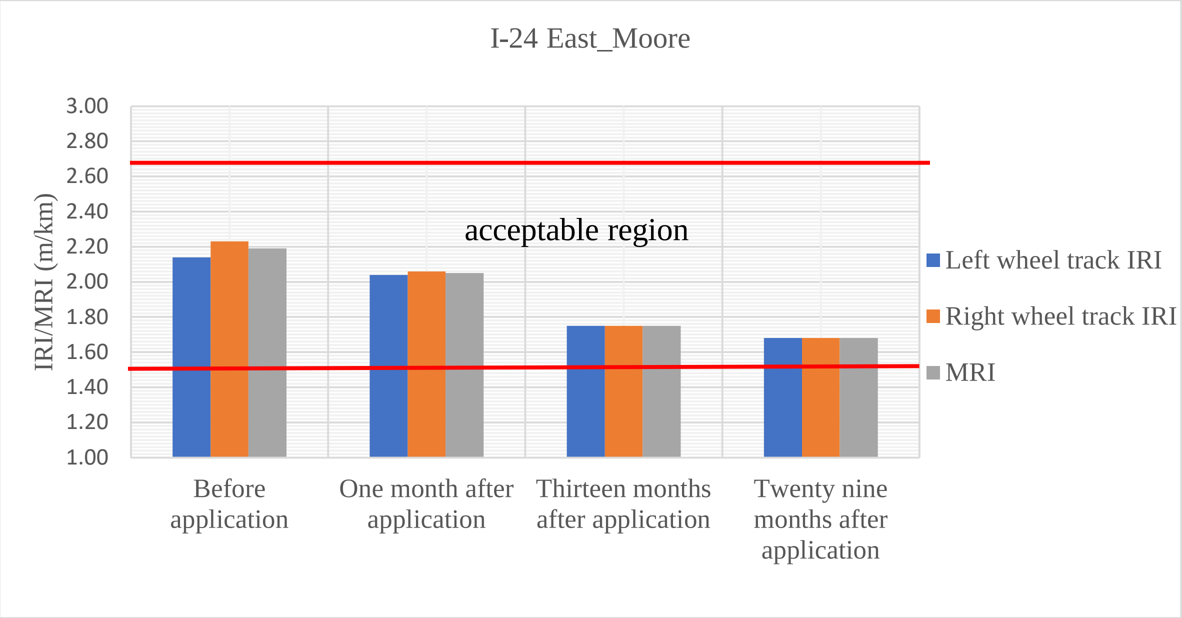


Figure 6.11 IRI and MRI measurements for I-24 between Moore Rd. and Mc Brien Rd

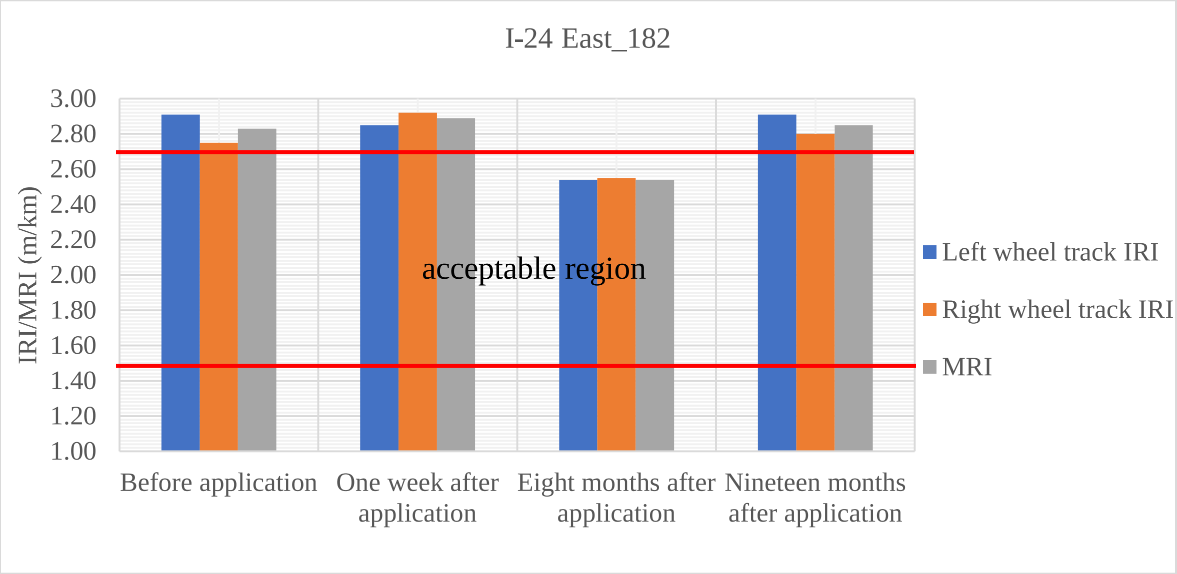


Figure 6.12 IRI and MRI measurements for I-24 East, between MM182.3 and MM183

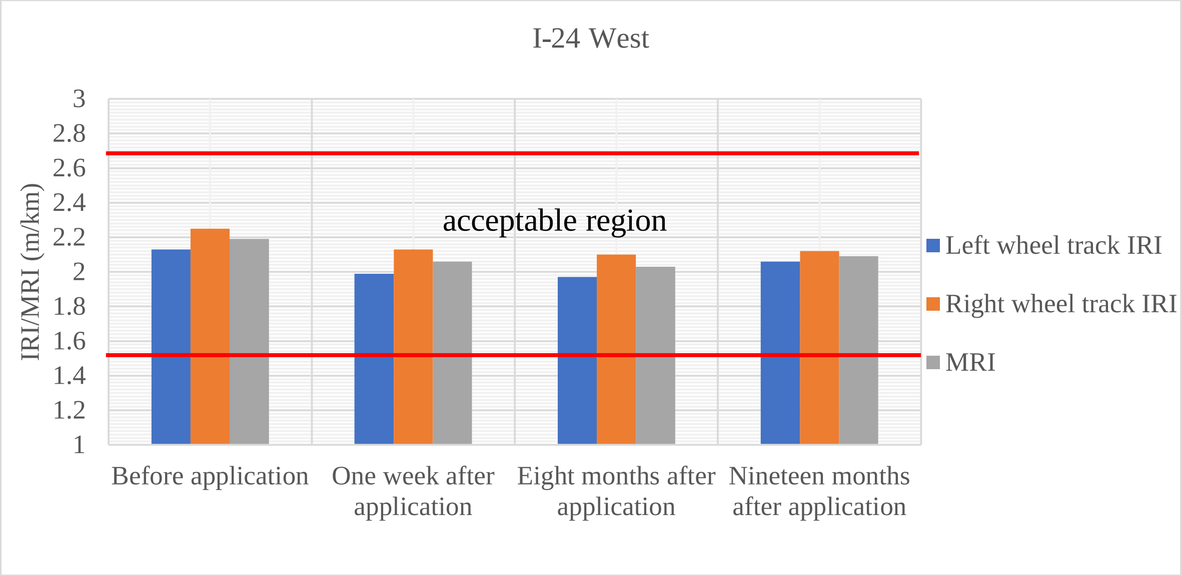


Figure 6.13 IRI and MRI measurements for I-24 West, between MM 179.5 and MM 178.2

6.3. Analysis of Results and Findings

Roughness data collected using ICC Profiler was subjected to statistical analysis to determine the if a statistical difference in MRI before and after PolyLevel® applications exists.

6.3.1. Effectiveness of PolyLevel® to Improve Pavement Ride Quality

The UTC research team conducted a statistical analysis of MRI data collected before and after PolyLevel® application to assess the improvement on ride quality of the sections treated with PolyLevel®. The raw roughness measurements obtained using an ICC profiler were initially analyzed using the ProVAL software to obtain the mean roughness index MRI. Table 6.4 below shows the overall roughness measurements of the treated sections.

Table 6.4 Overall MRI measurements of before and after PolyLevel® application

Highway Section ID	Start Mile	End Mile	Lane #	Before Application		After Application		After Application		After Application	
				Date	MRI	Date	MRI	Date	MRI	Date	MRI
I-24 West	179.5	178.2	2	9/24/2015	2.19	10/08/2015	2.06	6/16/2016	2.03	7/12/2017	2.09
I-24 East_182	182.35	183.0	3	9/24/2015	2.83	10/08/2015	2.89	6/16/2016	2.54	7/12/2017	2.85
I-24 East	Moore Brg	McBrien	2	2/9/2015	2.19	3/2/2015	2.05	3/21/2016	1.75	7/12/2017	1.68
I-75 North	7.0	9.0	3	3/21/2016	1.68			6/16/2016	1.64	7/12/2017	1.82
I-75 South	9.0	7.0	3	3/21/2016	1.83			6/16/2016	1.77	7/12/2017	1.87

*MRI is in m/km [1m/km is equivalent to 63.36 in./mi.]

The following is observed from Table 6.4:

i. In general, the MRI of four test sections decreased after application of PolyLevel® except for I-24E_182, which slightly increased. This section had MRI before application on the failed region with (MRI > 2.7 m/km) while the rest of the test sections were in the fair region (1.5 < MRI <2 .7 m/km) (Table 6.3).

ii. A continual decrease in MRI readings after application was observed on section I-24 East_Moore Bridge, while I-24 West MRI readings remained almost the same as after applications. There is no specific pattern observed, almost all sections had fluctuations on MRI readings except for I-24 East Moore Brg., which its MRI values continued to decrease (improved smoothness). Fluctuations were also experienced with eIRI readings.

iii. Approximately two years after the PolyLevel® injection on I-24 East_182, the ride quality is almost the same as before application. Two and a half years after application on I-24 East_Moore Bridge, the ride quality is continuing to show improvement (MRI values decreasing).

Further statistical analysis to assess changes in ride quality of the sections was conducted on every interval of 100 m using a paired t test to compare MRI measurements (before and after application of PolyLevel®). The assumption was the underlying MRI population data is normally distributed and the null hypothesis was accepted if the MRI means are equal; otherwise, it was rejected with confidence level of 95% or a level of significance of 0.05. Results of the paired t tests summarized in Table 6.5.

The results in Table 6.4 show a reduction on MRI readings after PolyLevel® application, although Table 6.5 show that no statistical significant changes were achieved in all sections immediately after application. I-75 North and I-24 East_182 had statistical significant changes on MRI readings thirteen and eight months after PolyLevel® application respectively. The MRI of I-24 East_Moore decreased from 2.19 m/km to 2.05 m/km (138.76 in./mi. to 129.89 in./mi.) one month after application, this change was not statically significant, but it continued to decrease thirteen month and twenty-nine months after application, which was a statistical significant decrease in MRI (Figure 6.11). Sections on I-75 South and I-24 West did not show any statistical significant changes on MRI readings at any time on the data collection periods although there was a reduction on MRI readings immediately after application and it went back to almost original readings thirteen months after application for I-75 South. I-24 West had a reduction on MRI immediately after application and twenty-nine months after application it was still below the original readings although not statistically significantly different.

Highway section ID	I-75 South	I-75 North	I-24 East_Moore	I-24 East_182	I-24 West
	Any Statistical Significant changes?				
One week after application	No	No			
Thirteen months after application	No	Yes			
One month after application			No		
Thirteen months after application			Yes*		
Twenty-nine months after application			Yes*		
One week after application				No	No
Eight months after application				Yes*	No*
Nineteen months after application				No	No

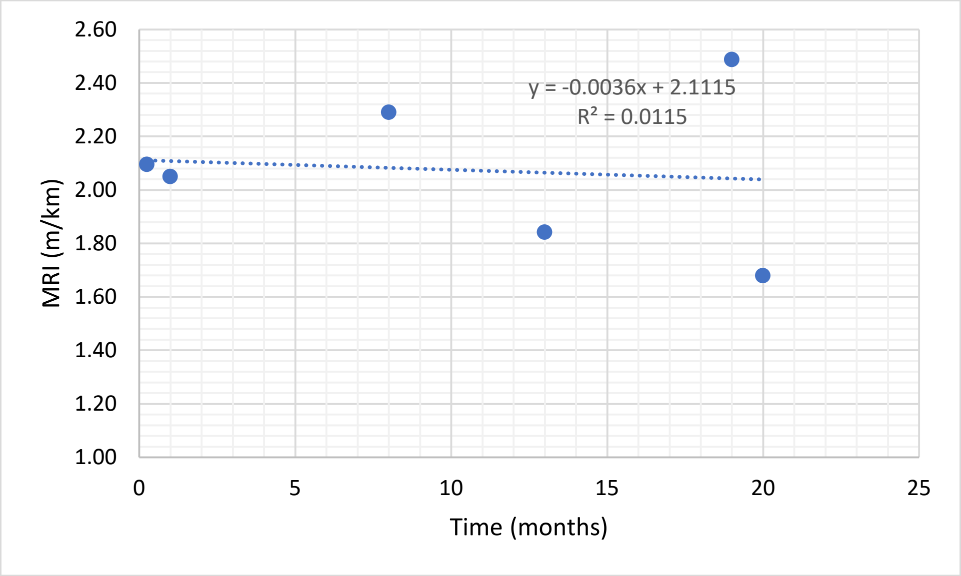
Table 6.5 Paired t tests to assess improvements of the test sections

Note: *Data sets were reduced to be comparable to the paired original data set

The results indicate that there are no statistically significant changes on ride quality immediately after application although on three sections out of five a statistically significant improvement was observed thirteen or eight months after PolyLevel® application. Although overall MRI dropped for I-75 South and North one week after application and for I-24 East_182 eight months after application, the MRI for the same sections rose again fifteen and nineteen months after injection (Refer appendix 3).

The MRI data was further plotted to establish a linear correlation between roughness readings and time. The average of all roughness data collected in one day was calculated and plotted against time. Figures 6.14 and 6.15 show the linear regressions for both MRI and eIRI data to be decreasing with time, respectively. Both the slopes and R-squared values are very small, which implies a poor fit of the data and the linear relationship between the two variables (time vs. MRI and eIRI) is not significant. This indicates that, a longer data collection period is needed to a point where most of the sections fail to determine a better deterioration model and a true performance period of the PolyLevel® material on highways. The linear regression models are currently not a good representation of long term performance of pavements with PolyLevel application.

Fluctuations on MRI and eIRI readings could be attributed to test vehicle wheel wonder or change in properties of PolyLevel® materials with change in temperature or environment (humidity and rainfall), which is not part of this study.



6.14

Figure 6.14 Regression model of averaged MRI versus time

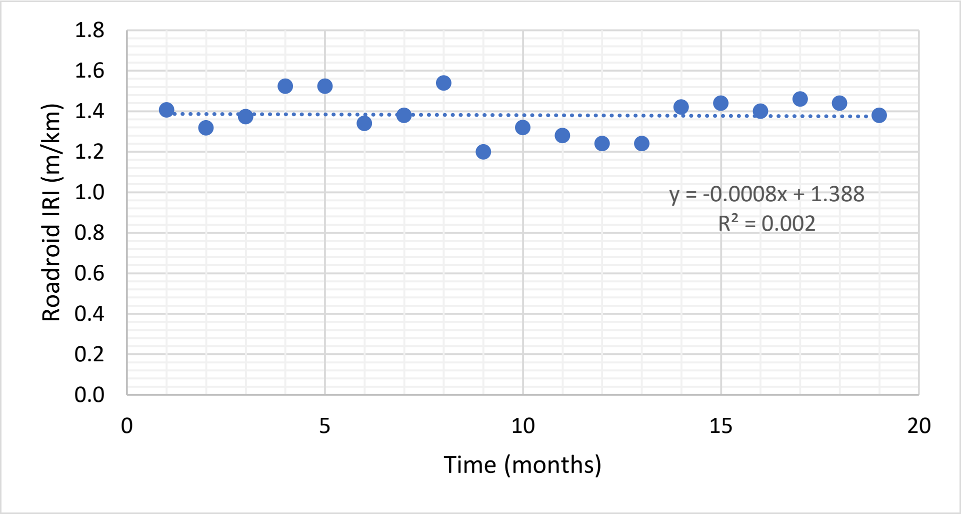


Figure 6.15 Regression model of averaged eIRI versus time

7. CONCLUSION AND RECOMMENDATIONS

This study was conducted to evaluate the effectiveness of the injected PolyLevel® material in rigid pavement slabs to improve surface smoothness on interstates I-24 and I-75 in Chattanooga, Tennessee. To evaluate the short and long-term performance of the material, three main methodologies were applied:

i. A detailed questionnaire to state DOTs maintenance engineers to obtain their experience on using polyurethane material
ii. Monitoring the treated sections and assessing surface roughness changes before and after application of the material.
iii. Finite element modeling of a pavement section with PolyLevel® application.

PolyLevel® material were applied on five sections of U.S interstate I-24 and I-75 in Chattanooga Tennessee between February 2015 and June 2016 (Table 1.1). These sections had length ranging from 1.050 km (0.65 mi.) to 3.220k m (2.0 mi.). The sections rest on a 255 mm (10 in.) granular base; they are made of PCC slabs with thickness of 255 mm (10 in.), and joint spacing of 4.57 m (15 ft.). By 2017, the AADT of the treated sections on I-24 East and I-24 West was 134,740 vehicles per day and 119,930 vehicles per day respectively, with trucks being 18.50 percent. The AADT of treated sections on I-75 was 77,150 vehicles per day, of which 14.5 percent were trucks.

7.1. DOT Questionnaire

The questionnaire was dispersed to 50 state DOTs in the U.S and one Canadian province ministry of infrastructure and Transportation. Fifty percent (50 %) of the questionnaire recipients responded, of which approximately 90 percent of those who used or are using polyurethane for leveling settled pavement slabs, recommend a continual use of polyurethane materials. It was reported that the most common or preferred technique for slab levelling is slab replacement followed by polyurethane application and the least is asphalt injection. On cost effectiveness, respondents indicated that polyurethane injection was the most cost-effective technique (low cost and shorter time) whereas asphalt injection is reported as the least cost-effective technique. Ninety four percent (94 %) of respondents who have used polyurethane material reported that their projects were below or on the budget, only six percent (6 %) had over the budget experience with polyurethane materials. The life span of polyurethane treated sections varied from one year to ten years, and slab cracking and settlement are the common indicator for failure of the section.

7.2. Finite Element (FE) Analysis

Laboratory tests were performed to obtain mechanical properties of PolyLevel® materials needed for FE analysis. However, challenges of obtaining samples and testing the on time made it difficult to use the parameters on the model. Laboratory results indicated that the materials contain voids therefore the confinement of the material changes its properties. The bulk density of PolyLevel® material sampled under non-confined condition (small samples) was 51 kg/m^3 which corresponds to the free rise density specified by TDOT of 48.00 kg/m^3 (3.00 pcf) but twenty percent (20 %) below the PolyLevel® free rise density specifications (Table 2.1). The compressive strength and Young's modulus were 0.26 MPa (37.71 psi) and 5.98 MPa (867.33 psi) respectively; with Poisson's ratio ranging from 2.00 to 3.00. Specimen sampled under a partially confined condition (larger samples) have a bulk density of 91.22 kg/m^3 (5.69 pcf) with compressive strength of 34 MPa (4931.28 psi).

The finite element analysis (FEA) model showed that treated sections will undergo permanent deformation under long term cyclic loading; this analysis also recommend use of high density foam to resist the effect of heavy traffic loading.

7.3. Pavement Surface Roughness Measurements

Ride quality survey for pavement surface roughness was conducted to assess both short- and long-term pavement performance. Longitudinal profiles data on the treated sections was collected using a high-speed inertial profiler before and after application of the material, and a smartphone-based app after PolyLevel® application for a period of two and a half years. Since the PolyLevel® application dates differed significantly the data collection intervals between the sections also differed (Table 6.4). The following conclusion can be drawn:

i. Generally, the pavement roughness measured (MRI) after the application showed reduction of MRI readings, meaning improved smoothness, but the improvement was not statistically significant at 95% confidence level (Table 6.5).

ii. The MRI of four test sections (I-75South, I-75North, I-24East_Moore, and I-24West) decreased just after application of PolyLevel® except for I-24East_182, which increased by 2.12 percent. Approximately one year after application of the material, the MRI of I-75 South and I-75 North increased, while that of I-24 East_Moore and I-24 West decreased approximately two years and one year and a half after injection of the material respectively.

iii. MRI of section I-24 East_182 before application of the material was in the failed region (MRI > 2.70 m/km) and it has remained in the same region after application of PolyLevel®. The MRI of other four sections were in fair region (1.50 <MRI<2.70) and they remained in this region after application of PolyLevel®. For the sections monitored there was no improvement that went beyond the performance region after PolyLevel® application.

iv. The fluctuations observed in roughness reading for both MRI and eIRI resulted into a negative slope when a linear regression was performed on the data, indicating that the smoothness is increasing with time. A longer data collection period is recommended to capture the time when most of the sections will have readings below the acceptable range.

v. Approximately two years after the PolyLevel® injection on I-24 East_182, the ride quality is almost the same as before application. Two and a half years after application on I-24 East_Moore, the ride quality is continuing to show improvement (MRI values decreasing). For the data collection period it can be concluded that the PolyLevel® lasted from thirteen (13) months to over twenty-nine (29) months from the application date. These results are similar to what was reported from the questionnaire that most sections lasted from one year to 10 years.

vi. On average eIRI indicated that all sections performed within the acceptable region, while MRI readings showed that section I-24 E_182 was in a poor condition. This shows that eIRI may under estimate roughness readings compared to MRI.

In conclusion, application of PolyLevel® underneath the pavement slabs neither did statistically significantly improve nor retrogress the condition of the sections but maintained it in their state before application of the material. Therefore, for a pavement section in a poor condition (IRI/MRI >2.70 m/km) polyurethane foams injection is not the best option, as the section will remain in the same state even after application of the material. However, state DOTs can apply polyurethane foams on section with good or those transiting to a fair condition to extend the life of the pavement.

7.4. Recommendations

This research study recommends the following:

i. Prior injection of the material, a detailed ground investigation of the damaged pavement section must be carried out to establish the causes, and whether polyurethane foam injection will be the appropriate remedial measure.

ii. Polyurethane foams should be injected under structural sound slabs resting on granular base; and sophisticated leveling equipment should be used to avoid overcorrection of the treated slabs.

iii. For structural damaged slabs, slab replacement (full/partial depth repair) is more cost effective and a very appropriate option.

iv. If polyurethane injection is conducted on interstates where heavy trucks are expected; the density of the material is recommended to be very high. A further study on PolyLevel® is necessary to establish material properties required on high traffic roadway.

v. Development of a standardized protocol for selecting pavement sections suitable for treatment with PolyLevel® and application procedure to avoid overcorrection of slabs.

vi. Progressive monitoring of the sections to capture a full long-term performance of the material, and possible appropriate treatments after their service life time.

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APPENDIX 1 State DOTs Questionnaire

Application of PolyLevel® Materials on Pavements

PolyLevel®/URETEK is a high-density polyurethane compound that offers concrete leveling solutions for both commercial and residential projects. This method of leveling foundations and highways has been in practice since 1975. This questionnaire is prepared by the University of Tennessee at Chattanooga (UTC) for Tennessee Department of Transportation (TDOT), with the aim to find ways to evaluate and improve the cost effectiveness of concrete pavement leveling by using PolyLevel® materials in the state of Tennessee. Your response to this questionnaire will be very beneficial to this study and is highly appreciated. At the end of this study, results will be shared with you. Thank you in advance for your participation.

1. Please provide your state DOT? ___________________________
2. Your contacts:
   Name: __________________________
   Phone number ______________________
   Email Address_________________________
   Position ____________________________

3. What method do you use for leveling concrete pavement slabs (Check all that apply)?
   a. Mud-jacking
   b. HMA overlay
   c. Polyurethane compounds
   d. Slab replacement
   e. Other: Please specify: _______________________

4. Out of the methods listed on Q 3, what is the approximate cost per sq. yd. of each method?
   a. Mud-jacking ____________
   b. HMA overlay ______________
   c. Polyurethane compounds ___________________
   d. Slab replacement _________________
   e. Other: Please specify: _______________________

5. According to your experience, what is the cost effectiveness of the materials, 1 being not cost effective (too expensive and time consuming) and 5 being very cost effective (good performance for the money paid)?

		Cost effectiveness				
		1	2	3	4	5
a	Mud-jacking					
b	HMA overlay					
c	Poly compounds					
d	Slab replacement					
e	Other: ___________					

6. Have you used PolyLevel®/URETEK (polyurethane compound) materials in your state?
   a. Yes b. No

If the answer to questions 6 is no, you may stop here. If the answer to question 6 is yes please proceed to question 7.

7. What type or trade name of Polyurethane materials (PolyLevel®®, URETEK etc.) have you used?
    a. ________________________________
    b. _______________________________
    c. ________________________________
    d. ________________________________

8. Was the project completed on predicted time?
    a. Yes　　　　b. No

9. Was the project cost as estimated correctly?
    a. Yes　　　　b. No

10. Did the contractor use ground penetrating radar (GPR) prior to project implementation?
    a. Yes　　　　b. No

11. Did the contractor bore holes to inject the material?
    a. Yes　　　　b. No

12. What effects does the hole drilling have on the slabs? Did they provide weakness (Such as cracking) to the pavement structure?
    ____
    ____

13. How did you monitor the performance of pavement sections with Polyurethane material?
    ____
    ____

14. How long did the section last before first sign of distress?
    Cracking ____
    Settling _________________________
    Other: Specify ____

15. Would you consider Poly materials to be cost effective?
    a. Yes　　　　b. No

16. What was the saving in cost per yd^2 compared to other methods?
    a. Mud-jacking ____________
    b. HMA overlay ______________
    c. Polyurethane compounds ____________________
    d. Slab replacement __________________
    e. Other: Please specify: ________________________

APPENDIX 2 States that Responded to questionnaire

SN	States Responded	Usage of Polyurethane		No. Responded	Not responded
		Yes	No		
1	ALABAMA	Y		1	ALASKA
2	BRITISH COLUMBIA[×]		N	1	ARIZONA
3	COLORADO	Y		1	ARKANSAS
4	DELAWARE		N		CALIFORNIA
5	IDAHO[+]	Y	N	2	CONNECTICUT
6	IOWA[+]	Y	N	2	D.OF COLUMBIA*
7	KANSAS	Y		1	FLORIDA
8	LOUISIANA	Y		1	GEORGIA
9	MAINE		N	1	HAWAII
10	MARYLAND	Y		1	ILLINOIS
11	MASSACHUSSETS		N	1	INDIANA
12	MICHIGAN	Y		1	KENTUCKY
13	MINNESOTA[+]	Y	N	2	NEBRASKA
14	MISSISSIPI	Y		1	NEW HAMPSHIRE
15	MISSOURI	Y		1	NEW JERSEY
16	MONTANA		N	1	NEW MEXICO
17	NEVADA	Y		1	NORTH DAKOTA
18	NEW YORK	Y			OKLAHOMA
19	NORTH CAROLINA	Y		1	PENNSYLVANIA
20	OHIO	Y		1	PUERTO RICO*
21	OREGON	Y		1	RHODE ISLAND
22	SOUTH CAROLINA	Y		1	SOUTH DAKOTA
23	TENNESSEE	Y		1	UTAH
24	TEXAS	Y		2	VERMONT
25	VIRGINIA		N	1	WEST VIRGINIA
26	WASHINGTON	Y		2	WYOMING
27					WISCONSIN
28					
29					
	Totals	20	6	26	

[+] Two conflicting response were received, during the analysis one was discarded based on question #6 on the questionnaire, Yes survey was used because it could be the other engineer was not aware of the usage of polyurethane materials.

[×] Canadian Province

* Puerto Rico and District of Columbia were contacted.

Highway section ID	I 75 South	I 75 North	I 24 East_Moore	I 24 East_182	I 24 West
IRI (m/km)					

APPENDIX 3 Treated sections IRI readings prior and post injection of PolyLevel

Wheel track profile	Left	Mean	Right	Left	Mean	Right	Left	Mean	Right	Left	Mean	Right	Left	Mean	Right
Before application	1.83	1.84	1.84	1.76	1.68	1.6	2.14	2.19	2.23	2.91	2.83	2.75	2.13	2.19	2.25
One week after application	1.81	1.80	1.79	1.72	1.64	1.56									
Thirteen months after application	1.94	1.87	1.79	1.91	1.82	1.73									
One month after application							2.04	2.05	2.06						
Thirteen months after application							1.75	1.75	1.75						
Twenty-nine months after application							1.68	1.68	1.68						
One week after application										2.85	2.89	2.92	1.99	2.06	2.13
Eight months after application										2.54	2.55	2.55	1.97	2.04	2.10
Nineteen months after application										2.91	2.86	2.8	2.06	2.09	2.12

[1.00 m/km is equivalent to 63.36 in./mi.]