GEORGIA DOT RESEARCH PROJECT 15-10

FINAL REPORT

LONG-TERM PERFORMANCE OF GRANULAR BASES INCLUDING THE EFFECT OF WET-DRY CYCLES ON INVERTED BASE PAVEMENT PERFORMANCE

Georgia Department of Transportation

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Final Report

Long-Term Performance of Granular Bases Including the Effect of Wet-Dry Cycles on Inverted Base Pavement Performance

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16. Abstract:
The main objective of this study was to advance the understanding of alternative pavement designs. In particular, potential techniques such as inverted base pavements (IBP) have increased the importance of granular aggregate bases (GAB) in pavement structures. While extensive research has been conducted on the resilient behavior of GAB's, their long-term behavior has not been give much attention, particularly under near-surface stress-moisture conditions prevalent in inverted base pavements. This project involved a series of preliminary tasks aimed at establishing a working framework for future studies on IBP and included: (i) investigations of alternative laboratory approaches to study the effect of wet-dry cycles on permanent deformation; (ii) field studies of the performance of existing IBP test sections using imaging techniques to establish a baseline for future performance measurements; (iii) development and initial testing of an apparatus for laboratory investigation of the "slushing" compaction technique; and (iv) promotion of IBP as a construction alternative.

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EXECUTIVE SUMMARY

In recent years, the Georgia Department of Transportation (GDOT) has sought to advance the understanding of alternative pavement designs. In particular, evaluation of potential techniques such as inverted base pavements (IBP) have increased the importance of granular aggregate bases (GAB) in pavement structures. While extensive research has been conducted on the resilient behavior of GAB's, their long-term behavior has not been give as much attention, particularly under near-surface stress-moisture conditions prevalent in inverted base pavements. This project involved a series of preliminary tasks aimed at establishing a working framework for future studies on IBP and included: (i) investigations of alternative laboratory approaches to study the effect of wet-dry cycles on permanent deformation; (ii) field studies of the performance of existing IBP test sections using imaging techniques to establish a baseline for future performance measurements; (iii) development and initial testing of an apparatus for laboratory investigation of the "slushing" compaction technique; and (iv) promotion of IBP as a construction alternative.

Based on this study, a number of important insights have been observed and form the basis for a framework for future studies:

a) The Precision Unbound Material Analyzer (PUMA) tests reiterated the huge significance of the molding water content on the performance of the aggregate layer system. Specimens molded wet of the optimum water content showed lower stiffness moduli (up to 50%) and larger plastic deformations (up to 3 times larger) compared to specimen molded closer (and dryer) to the optimum water content. The increased permanent deformation in wetter conditions is potentially reflective

of fines-migration within the specimen in an attempt to achieve an optimized load-bearing particle matrix and also results in a higher matrix stiffness. Repeated cycles of wetting drying gradually deteriorates the particle matrix as was evident from the CBR test results.

b) Preliminary laboratory simulations of the slushing technique clearly showed the ejection of fine particles at the surface of the aggregate layer along with excess water. This establishes the effectiveness of the laboratory system towards simulating the slushing construction process as followed in the field, while enabling close control over testing conditions and electronic measurements of various metrics to quantify the improvements potentially achievable using this novel technique.

c) Combining the insights from the PUMA apparatus and the "slushing" compaction apparatus, a base layer that is compacted, within a reasonable range, close to the maximum modified-proctor dry density and optimum water content, followed by implementation of the slushing process to further enhance the stiffness of the system would potentially achieve a significant improvement in resiliency of the system. Moreover, this improvement would be achieved by minimizing void space in the unbound aggregate layer while minimizing crushing of aggregate particles, which is otherwise expected to occur with conventional high-energy low-lubrication compaction techniques.

d) The field studies undertaken as part of this project to quantitatively evaluate pavement distress and rutting at the two existing locations of inverted base pavement test sections have provided both valuable information on the relative performance of the conventional and alternative pavement sections as well as critical quantitative baseline data so that future pavement distress surveys can be quantitatively compared to the baseline data. The field measurements provided clear evidence of the significantly better performance achievable with alternative pavement structures such as inverted base pavements.

e) The interest shown through both attendance as well as active engagement in discussion at both the Special Session at the TRB 2016 Annual Meeting on “Inverted Pavement Performance” and the subsequent webinar on “Inverted Pavements”, both of which were organized by the AFP70 Mineral Aggregates sub-committee, and in which the PI participated as a speaker, provided strong evidence in the significant interest that exists nationwide amongst state DOT’s for alternative pavement structures. GDOT has been playing an important lead technical role in these efforts.

ACKNOWLEDGEMENTS

A number of individuals made important contributions in the course of this study and to the findings presented herein.

Dr. Mark Wayne and Mr. Andres Peralta of Tensar International and Dr. Jayhyun Kwon of Kennesaw State University (formerly of Tensar International) provided valuable insights and assistance in the use of the PUMA device which is located in the laboratory of Tensar International.

Dr. James Tsai, Ms. Yiching Wu and Mr. Geoffrey Price of Georgia Tech conducted the pavement distress data collection and analysis using the Georgia Tech sensing vehicle. The assistance of Mr. Jim Maxwell (Martin Marietta) in coordinating access to the Morgan County Quarry Road and providing safety support there as well as Mr. Dwane Lewis (GDOT) in coordinating access and safety at the LaGrange Bypass site is gratefully acknowledged.

The efforts of Mr. Rick Boudreau (Boudreau Engineering) in coordinating both the TRB AFP70 Mineral Aggregates Sub-committee Special session and in organizing the TRB webinar on Inverted Base Pavements was most valuable. In addition, the roles of Messrs. Boudreau and Kevin Vaughn (Vulcan Materials) as co-presenters, along with the project PI, of the TRB webinar are acknowledged.

Finally, the support and assistance of Mr. David Jared and Ms. Gretel Sims of GDOT at various stages of the project are sincerely acknowledged and appreciated.

1. INTRODUCTION

1.1. Objectives

GDOT has been actively engaged in the study of alternative pavement structures, and more specifically inverted base pavement structures, for more than 15 years. This has involved: (i) participation in the design, construction and monitoring of full scale test sections where the performance of conventional as well as alternative pavement structures could be directly compared (Morgan County Quarry Access Road and LaGrange By-pass Road (Pegasus Parkway); and (ii) support of research studies at Georgia Tech that led to two Ph.D. theses (Cortes, 2010 and Papadopoulos, 2014) and associated publications on the topic. To continue to promote the national conversation on this important subject, GDOT funded an additional one-year study to advance insights through a series of preliminary tasks aimed at establishing a working framework for future studies on IBP that included: (i) investigations of alternative laboratory approaches to study the effect of wet-dry cycles on permanent deformation; (ii) field studies of the performance of existing IBP test sections using imaging techniques to establish a baseline for future performance measurements; (iii) development and initial testing of an apparatus for laboratory investigation of the "slushing" compaction technique; and (iv) promotion of IBP as a construction alternative. This report summarizes the findings of this one-year project.

1.2. Report Organization

The report is organized as a series of summary sections with additional detailed supporting materials included in appendices, as appropriate.

Section 2.1 summarizes a laboratory study conducted to assess the modulus and deformation behavior of pavement materials under multiple cycles of loading using a new apparatus called the "Precision Unbound Material Analyzer (PUMA) device. A parallel series of CBR tests were also conducted and are presented in Section 2.1. The significance of the work presented in this section is that it illustrates the potential for this new apparatus and test method to provide important insight into the performance of pavement structures under controlled conditions including wet-dry cycles.

Section 2.2 summarizes the results of two field studies conducted to quantify the pavement distress and rutting at two test sections that had both conventional as well as inverted base pavement sections. The field work and subsequent analysis was conducted using a vehicle developed at Georgia Tech with support from GDOT and others over the past decade. The importance of the work presented in this section is that its provides the first quantitative summary of pavement cracking and rutting conditions at both the Morgan County Quarry Access Road and the La Grange By-pass Road (Pegasus Parkway) and can serve as a critical baseline for future similar measurements at these test sections.

Section 2.3 summarizes the design, fabrication and initial testing of a new apparatus to simulate the "slushing" compaction technique in the laboratory under controlled conditions. The importance of the developments described in this section are that they provide the opportunity to study, under controlled conditions, the evolution of the microstructure of GAB during application of the "slushing" compaction technique. The technique is known to provide for superior performance of pavement structures but the specific mechanisms why are not understood yet.

Section 2.4 summarizes several important educational efforts which are based on the previous studies that GDOT participated in and/or supported and provide a significant portion of the basis by which inverted base pavement structures are recognized for their technical merit. The importance of the efforts summarized in this section are that they clearly identify GDOT as a leader in the search for alternative pavement structures.

Aside from the specific summaries presented in Sections 2.1 to 2.4 of the report, several appendices to the report provide detailed complementary information as follows. Appendix A includes the full report for the Morgan County Access Road pavement measurement study. Appendix B includes the full report for the LaGrange By-pass Road pavement measurement study. Appendix C includes copies of the presentation materials used at the 2016 TRB AFP70 Special Session on "Inverted Base Pavement Performance" and the 2016 TRB webinar of "Inverted Pavements".

2. WORK PLAN

2.1. Laboratory Investigation of Effect of Wet-Dry Cycles on Permanent Deformation

2.1.1. Material Characterization

Granular aggregate base (GAB) material used for the study was collected from Norcross, Georgia and the following geotechnical laboratory tests were run to characterize the material.

Grain Size Distribution

Grain size distribution for the GAB material was obtained by conducting sieve analysis tests (as per ASTM D422) over two trials; the results are shown in Figure 1. The GAB was checked to satisfy GDOT gradation requirements (represented by dashed lines) for aggregate materials to be used as base material in pavements, as conveyed by the particle distribution curves in Figure 1.

The GAB material was visually classified as a well-graded mixture of predominantly gravel and sand, containing angular gray-colored coarse particles and non-plastic finer particles. Table 1 presents the parameters pertaining to the gradation curve, indicating the well-graded nature of the GAB material.

Table 1: Sieve analysis results on GAB

USCS Classification	GW (well-graded gravel)
Percentage Fines (%)	7 - 7.5
Coefficient of Uniformity, C_U	70 – 90
Coefficient of Curvature, C_C	0.51 – 0.76

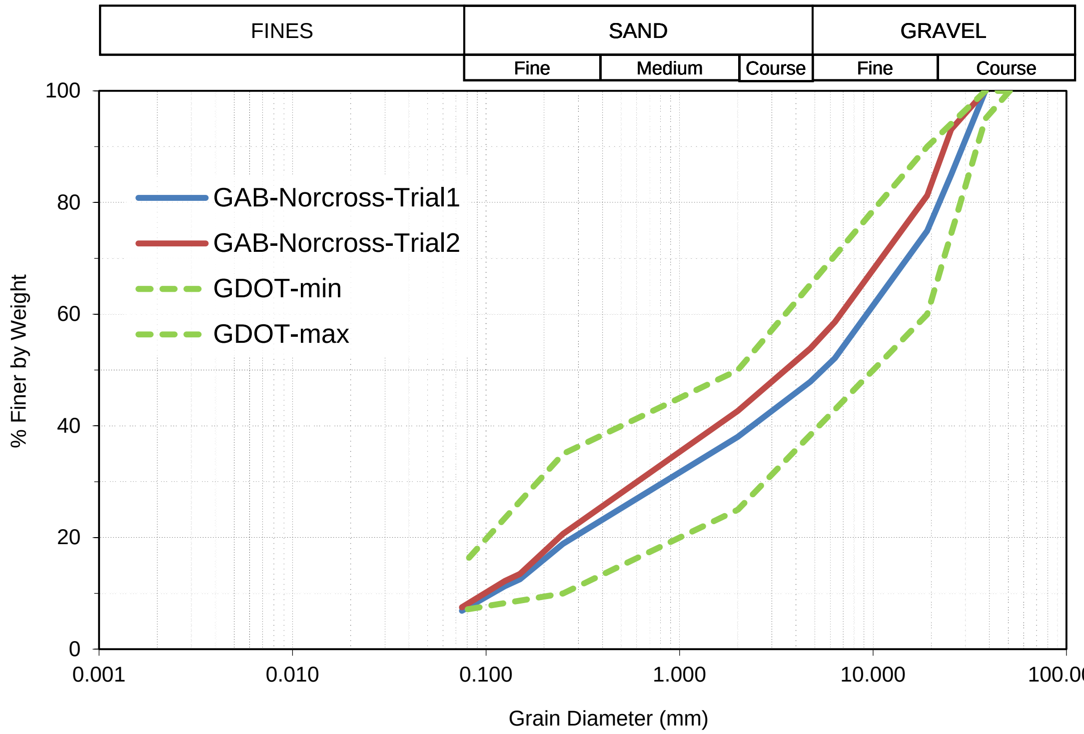


Figure 1: Grain size analysis for GAB material used for study.

<u>Modified Proctor Compaction Curve</u>

The specific gravity (G_S) of the GAB material was first computed as per ASTM D854, and estimated to be 2.737. A modified proctor test (ASTM D1557-12) was conducted at four sample water-contents to assess the moisture-density relationship of the material. The sample was sieved through a ASTM ¾" sieve prior to compaction in the proctor mold to minimize particle-boundary interactions and edge-effects. This sample adjustment was then accounted for by using the correction method stated in ASTM 4718-87. Figure-2 present the compaction curve for the GAB material, where the dashes lines represents the modified sample (excluding ¾" and bigger particles) and the solid line represents the correction for coarse-fraction adjustment. The red-dashed line is the zero-air void line which denotes a state of complete water saturation in the material.

Maximum dry density and optimum water content values were estimated to be 148 pcf and 4.5% respectively, which are typical for GAB material.

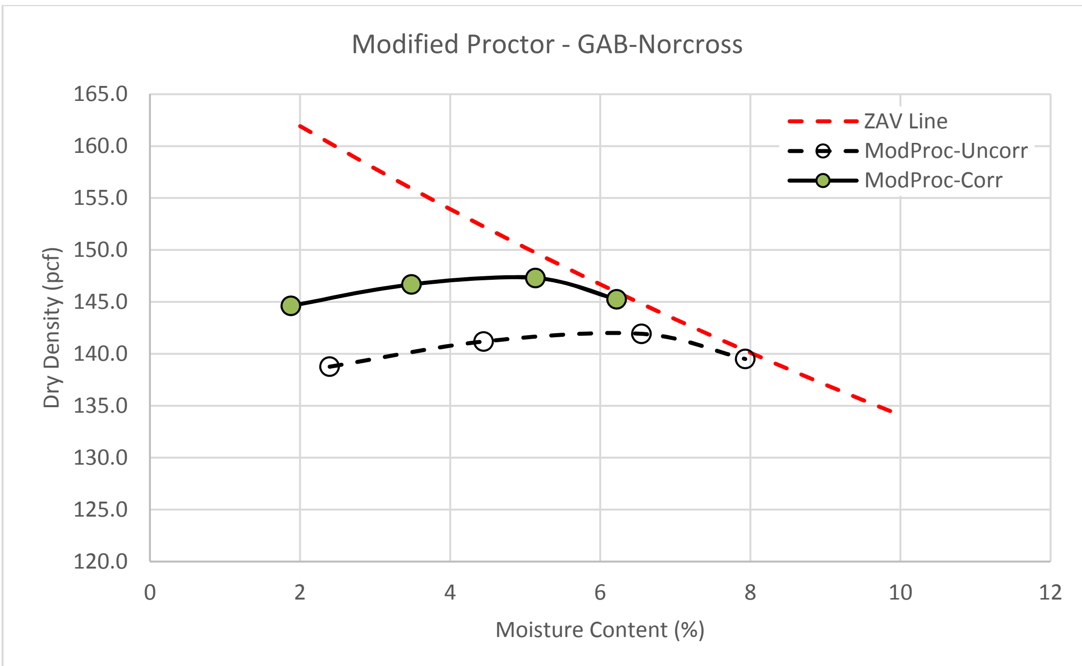


Figure 2: Proctor compaction curve obtained using the Modified method.

2.1.2. Effect of Moisture-Stress Cycles on GAB

In order to quantify the effect of moisture-content and wet-dry cycles on the resiliency of the compacted granular-base-matrix, a series of tests were conducted using the Precision Unbound Material Analyzer and the California Bearing Ratio methods.

This section details the experiments conducted to characterize the performance of the compacted GAB specimens to moisture-stress changes, with focus on stiffness modulus and permanent deformation. These objectives were achieved using the following two testing programs:

- Precision Unbound Material Analyzer (PUMA) tests to study evolution of stiffness modulus and permanent deformation over multiple loading cycles and at varying compaction water contents.

- California Bearing Ratio tests to quantify the effect of wetting and drying cycles on samples molded at the same water content

Precision Unbound Material Analyzer (PUMA) Tests

Method: The PUMA is a new laboratory testing technique designed specifically for testing modulus and deformation behavior of pavement materials under multiple loading cycles. This method efficiently captures the unbound nature of the insitu road-base layer by using a flexible mold for the specimen [Brown, 2013]. The flexible wall is composed of eight curved wall segments, which are circularly arranged to form the mold, and a rubber-lined steel band is inserted around the mold to measure the horizontal strain experienced within the specimen. The horizontal strain in the specimen increases with increasing axial loads thus simulating the responsive nature of unbound pavements. The GAB test specimen was prepared in the 6”-tall by 6”-diameter using the modified method (5 layers with 56 blows/layer), and tested in a UTM loading frame as indicated in Figure 3. High frequency cyclic load was applied over thousands of cycles and the vertical-deformation at the surface is continuously monitored using two displacement transducers.

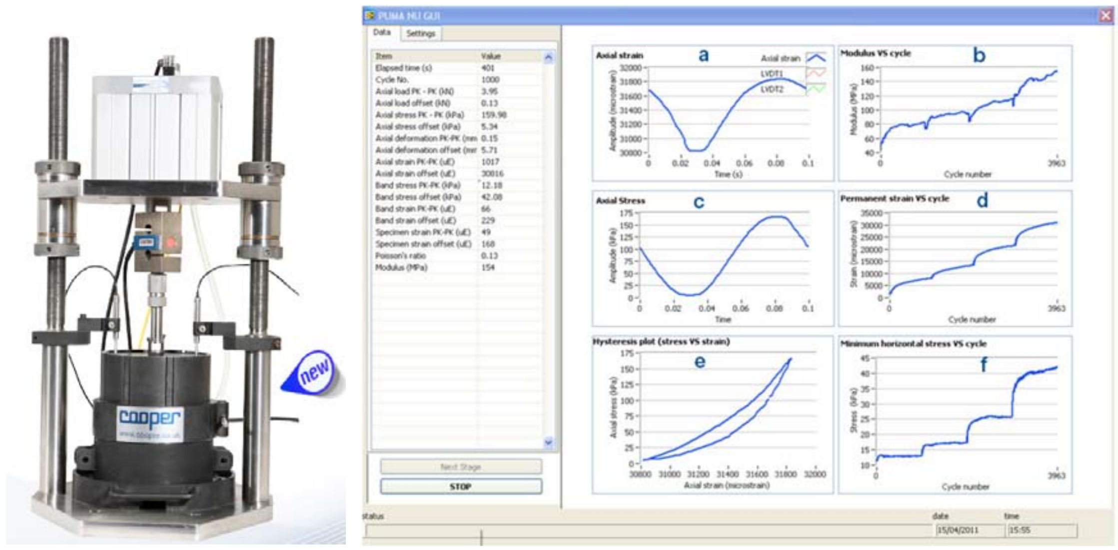


Figure 3: (a) Typical test apparatus showing the loading frame and specimen-mold, (b) screen capture of data monitoring software

PUMA tests were conducted on specimens molded at three water contents, i.e. 3, 6 and 9% to assess the effect of water content on multiple loading cycles. Each sample was subjected to loading stages as per Table 2. Photographs from various stages of a typical test are presented in Figure 4.

Table 2: PUMA Tests loading stages

Stage No.	Stress (psf)	Frequency (Hz)	No of Cycles
Stage I	418 (20 kPa)	10	1000
Stage II	835 (40 kPa)	10	1000
Stage III	1671 (80 kPa)	10	1000
Stage IV	3342 (160 kPa)	10	1000

Figure 4: Stages of PUMA test (a) Sample preparation, (b) testing in loading frame and (c) specimen after test showing dismantled mold

Results:

Results from the PUMA tests conducted on compacted GAB specimens are shown below. In general, higher permanent deformation and smaller stiffness modulus was observed for samples molded at water contents wet of optimum (w_{opt}= 4.5%). Both parameters increased at higher axial stresses, with most of the increase occurring over the first few hundred cycles followed by a more steady rate of increase as seen in Figure 5.

Table 3: PUMA test results

Test No.	Measured WC (%)	Stiffness Mod (MPa)	Stiffness Mod (tsf)	Perm Def (mm)	Perm Def (in)
1	3	248.0	2589.3	2.89	0.114
2	6	137.4	1434.7	7.68	0.302
3	9	133.3	1392.0	7.43	0.293

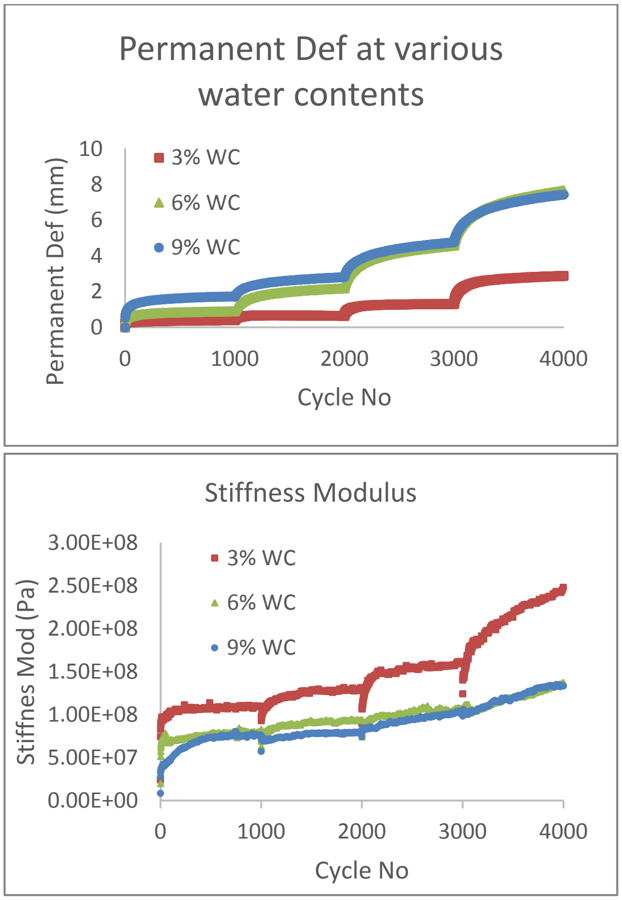


Figure 5: Plots showing evolution of permanent deformation and stiffness modulus with loading cycles

These observations can be categorized and analyzed in three parts as follows.

- Effect of Axial Stress:
  - The GAB specimen almost instantly responds to a higher applied vertical stresses by accommodating deformation as well as mobilizing the additional stiffness required to resist the extra applied stress. Figure 6 shows a linear trend in the mobilized stiffness versus applied axial stress.

- Since the PUMA tests is a drained loading scenario with discrete wall elements, the additional deformation can be a combination of expulsion of void pockets through the mold walls (resulting in a tighter and stiffer particle matrix) as well as the radial expansion experienced by the specimen.

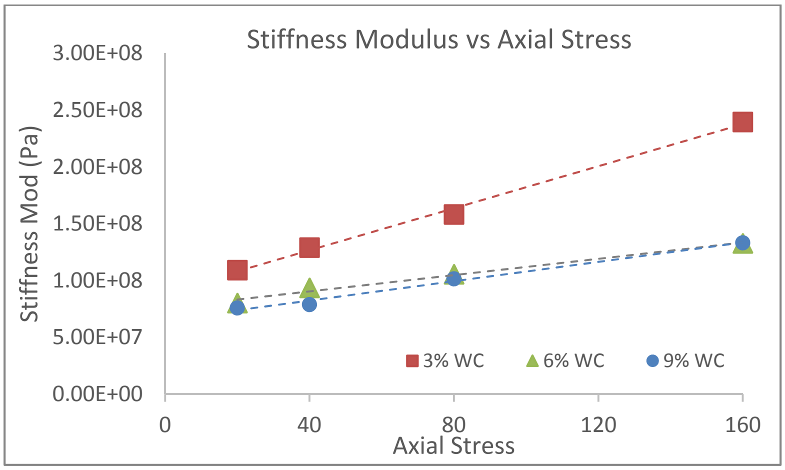


Figure 6: Stiffness modulus versus axial stress for all three tested specimens

- Effect of Loading Cycles:

  - Deformation curve in Figure 5(a) shows a plateau towards the second half of each loading stage, indicating the resiliency of the particle-system in supporting the applied load (from a soil mechanics perspective, the GAB reaches an over-consolidated state in the latter cycles). In other words, most of the plastic strain occurs in the first few hundred cycles until additional stiffness is mobilized by the specimen.

- Effect of Water Content:
  - Specimens compacted on the dry side of optimum generally tend to show greater stiffness moduli than specimens compacted wet of optimum, as is seen in these scenarios.
  - There isn't much variation in the behavior of the 6 and 9% compacted specimens as both of these are wet of optimum, and considering the GAB material is a free-draining material, the excess water in the 9% specimen just flows out. It should be noted that water was indeed observed to being expelled while the test was in progress confirming the open drainage along the walls.

California Bearing Ratio

Method: The California Bearing Ratio (CBR) is one of the oldest and most common engineering parameters used to characterize the stiffness of pavement base and subgrade material. CBR tests are conducted as per ASTM D1883-14, on compacted GAB specimens subjected to varying cycles of wetting and drying. This would allow the assessment of the effects of moisture-cycles on the resiliency of the compacted pavement base layer.

Four samples, with maximum-particle-size once again reduced to ¾-inch to mitigate edge-effects, were prepared in a 6-inch mold by compacting using the Modified-proctor method. These samples were subjected to 0, 1, 2 and 4 cycles of wetting-drying (shown in Table 4), with each cycle corresponding to 2 days of complete soaking in a water tub followed by 2 days of oven-drying. All CBR tests were conducted on soaked specimens. Swell measurements on initial tests indicated no swell upon soaking (as expected), and hence are not presented in this report.

Table 4: CBR testing program

	Soaking Stage									
Specimen 1	Wet	Cycle-0								
Specimen 2	Wet	Dry	Wet	Cycle-1						
Specimen 3	Wet	Dry	Wet	Dry	Wet	Cycle-2				
Specimen 4	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Cycle-4

Results: The observed behavior of resistance to penetration for all four tested specimens is presented in Figure 7. The degradation in stiffness caused by wet-dry cycles is apparent, which is also exacerbated at larger strains. Although traditionally CBR stress-penetration curves are concave-upwards in shape, the initial convex shape observed herein can be attributed to a softer upper crust, loosened by water seepage/expulsion during the wet/dry cycles. Figure 8 shows the expected gradual reduction in 0.2”-CBR values (i.e. the CBR estimated at 0.2" penetration) for the four specimens. The 0.2”-CBR was selected for comparison over the 0.1”-CBR to get a more representative value of resistance after overcoming the surface irregularities caused by wet/dry cycles.

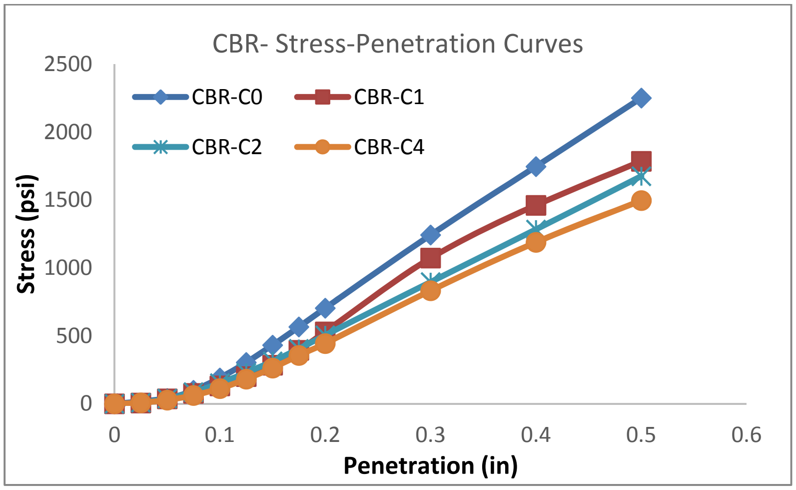


Figure 7: CBR stress versus penetration for four tested specimens

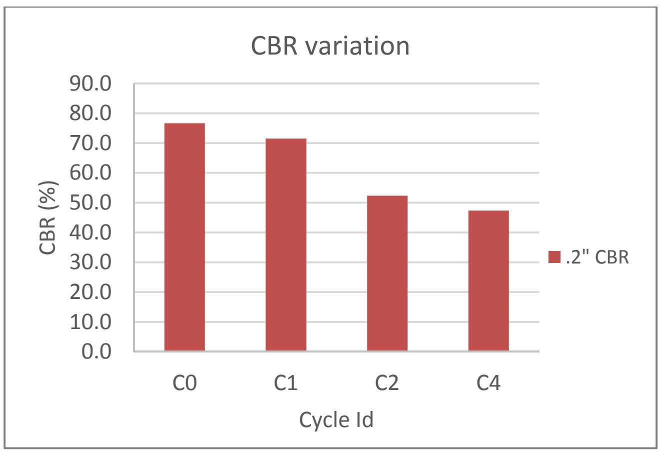


Figure 8: CBR estimated at 0.2” of penetration for four tested specimens

The loss in stiffness observed with wet-dry cycles can be attributed to sample disturbance caused by water forming flow channels through the specimen, which disturbs any previously-formed load-bearing contacts/chains among particles. Also, the CBR test involves penetration at the surface, which is also probably the zone that is most affected by moisture cycles being an open boundary. This is depicted in the pictures in Figure 9, showing some of the specimens that were tested. A stark contrast can be identified in the visibility of coarse aggregates at the surface in the C4 specimen relative to C1 and C0 specimens, which is probably, in part a result of dislodgement of surrounding finer particles over the course of the wet-dry cycles.


(a) Sample being soaked (b) C0 specimen


(c) C1 specimen (d) C4 specimen

Figure 9: Selected pictures of CBR tested specimens

2.2. Pavement Evaluations for Establishing a Pavement Condition Baseline

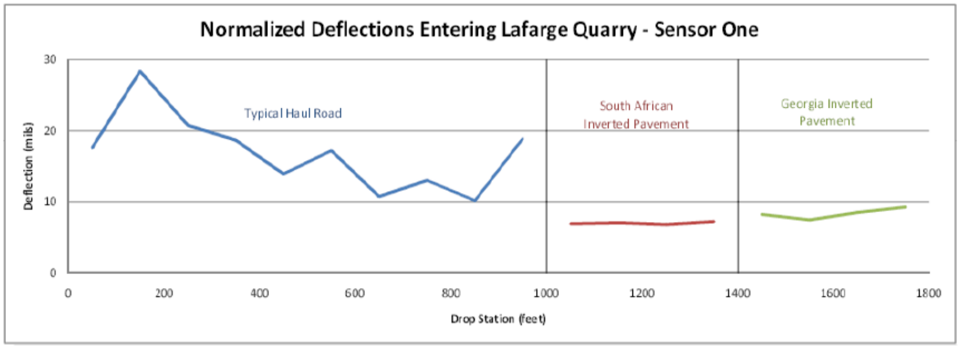
Full-scale test sections provide for comprehensive evaluation of the relative performance of alternative pavement systems.

2.2.1. Morgan County Quarry Access Road

Three test sections with different pavement designs were constructed on an entrance road to the Martin-Marietta Morgan Quarry in Morgan County, Georgia in 2001. The three test sections were 1) conventional pavement), 2) South African inverted pavement, and 3) Georgia inverted pavement. Although a visual inspection was conducted in 2006, there has been no pavement surface distress condition evaluation conducted on these three test sections. The objectives of this study are to 1) critically evaluate the pavement condition of these three test sections using quantitative measures defined in the Pavement Condition Evaluation System (PACES) by the Georgia Department of Transportation (GDOT) (GDOT, 1993) and 2) establish a quantitative baseline for future deterioration analysis. Full details of the site, the data collection method, data processing steps and data analysis are presented in Appendix A.

For the Morgan County quarry access road, the measurements from the 2016 study were compared with falling weight deflectometer (FWD) test results conducted in 2007, along with previous rutting measurements obtained in 2003 and 2006 (Lewis et al.,2012) to identify any potential performance trends.

Figure 10 shows that FWD test deflection readings along the test section. Higher deflections were noted towards the entrance between Sta. 0 and Sta. 300, while the South African and Georgia pavements showed very low deflections, indicative of stiff pavement layers.



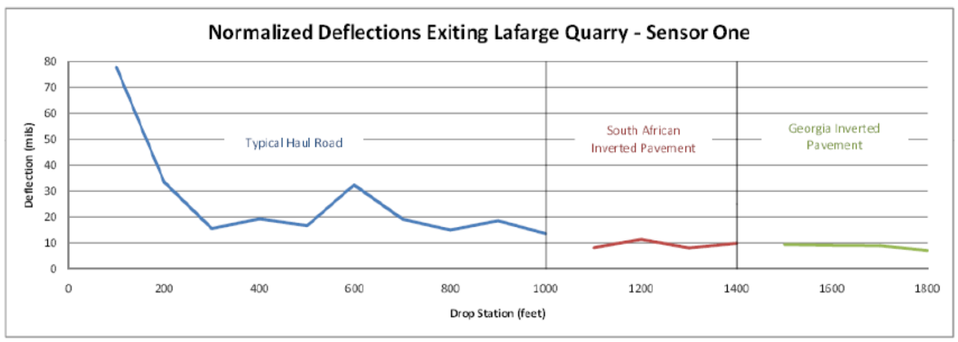


Figure 10. FWD Test Deflections conducted in Nov 2007 (after Lewis et al., 2012)

Figure 11, 12 and 13 present rutting depth measurements obtained in 2003, 2006 and 2016 respectively. The section between Sta. 0 and Sta. 300 near the highway intersection indicated high rutting behavior in the 2003 and 2006 data and consequently is understood to have undergone repairs at some stage prior to the 2016 measurements, which explains the lower readings in the 2016 study at that location. Meanwhile, the rest of the conventional pavement section seems to indicate gradual rutting increases and thus deterioration. The South African and Georgia sections are performing remarkably well after 16 years of operation. Based on the 2016 data, there may be slightly lesser rutting in the South African IBP than the Georgia IBP section, but additional measurements with the laser scanning technology after an additional period of service life would be required to confirm this.

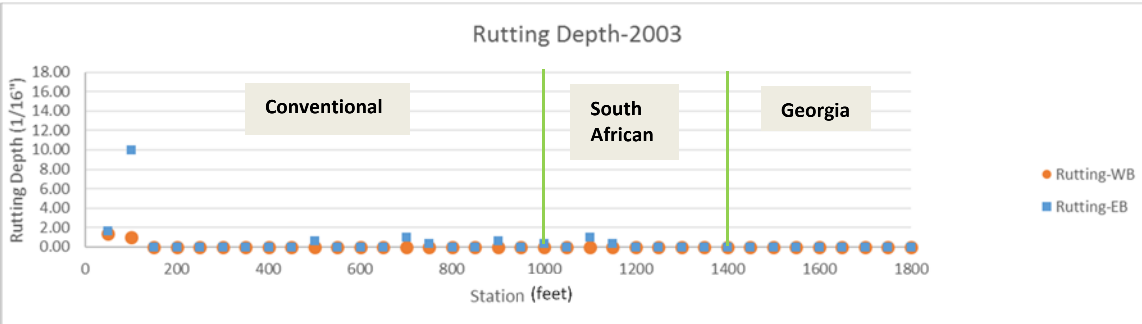


Figure 11. Rutting measurements in 2003

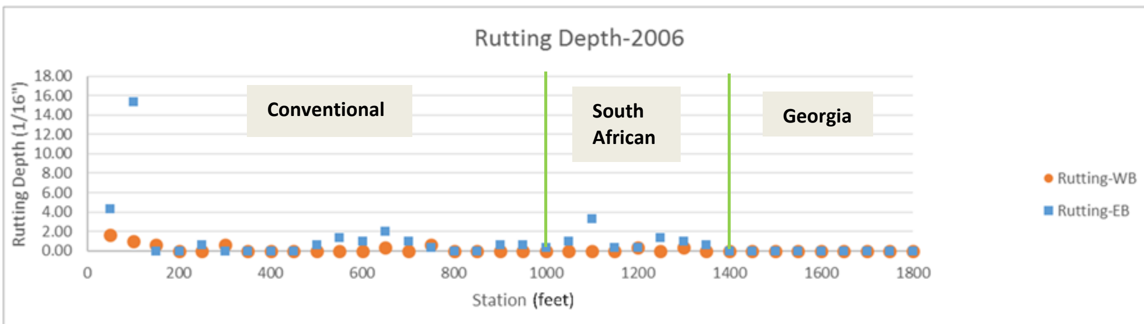


Figure 12. Rutting measurements in 2006

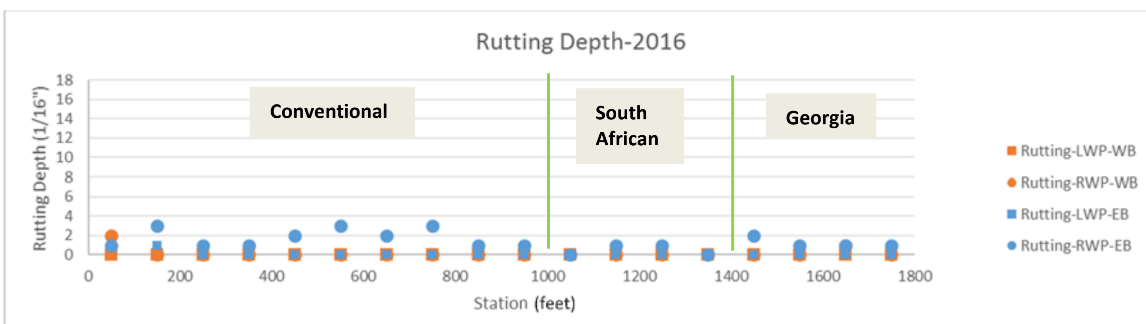


Figure 13. Rutting measurements in 2016

As indicated in the FWD measurements from 2007, the conventional section shows greater distress in various modes of cracking like load and block cracking as well. Figures 14 and

15 show Load cracking in the eastbound direction being noticeably greater in severity (levels 3 and 4) than the westbound lane, likely due to the greater stresses from loaded haul-trucks coming out of the quarry. The South African section indicates slightly better resistance to load cracking in the eastbound lane (Figure 15), while both, South African and Georgia IBP sections are clearly performing better than the conventional section in both lanes. Similarly, Figure 16 shows Block cracking being slightly severe in the conventional section where FWD deflections were the greatest, while the South African and Georgia IBP sections performed comparably better.

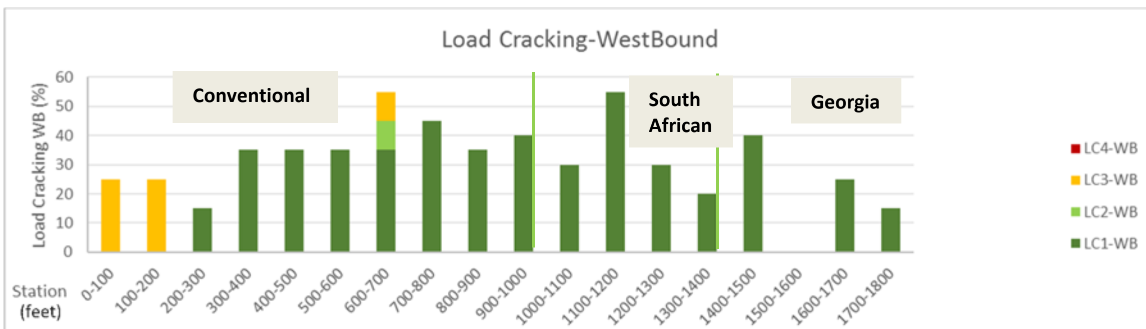


Figure 14. Load Cracking measurements in the Westbound lane (2016 measurements)

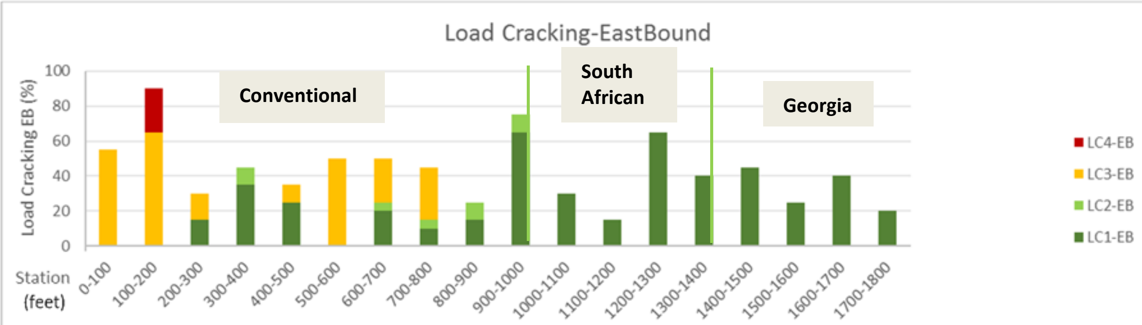


Figure 15. Load Cracking measurements in the Eastbound lane (2016 measurements)

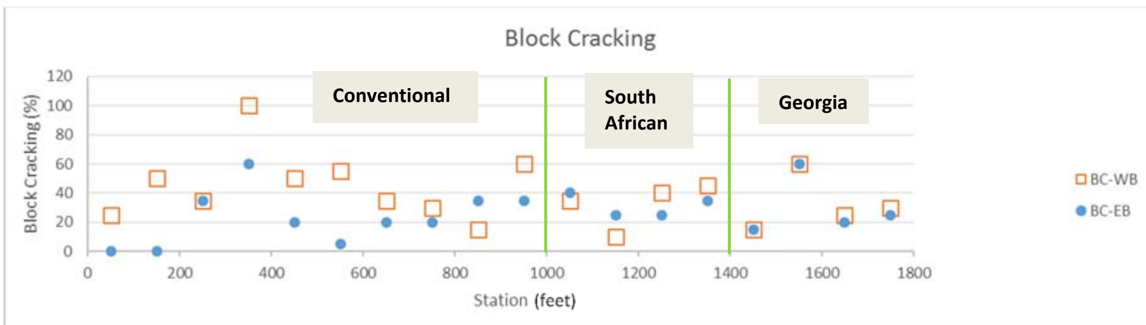


Figure 16. Block Cracking measurements (2016 measurements)

Primary observations from the Morgan County Quarry Access Road study are noted below. Data collection was conducted on April 8, 2016. The data was processed using developed algorithms and a manual review to extract distress information for every 100-ft segment. Two segments (marked at +0 ft. ~ +100 ft. and +100 ft. ~ +200 ft.) near the entrance and two segments (marked at +500 ft. ~ +600 ft. and +700 ft. ~ +800 ft.) near the crossroad, were excluded from further analysis because the stop-and-go traffic pattern in these segments had significant impact on the conditions. The pavement condition on the three test sections is summarized as follows:

- The conventional section had diverse conditions with ratings ranging from 61 to 85. The average rating is about 75 after 15 years in service. Rutting, Level 1 block cracking, and severe load cracking (Levels 2 and 3) was observed on this section. Level 1 load cracking ranging from 15% to 65% was observed in the outbound lane where the loaded trucks travel, while lesser load cracking was observed in the inbound lane. Similarly, rutting in the outbound lane is higher than in the inbound lane. Thus, the average rating (71.7) in the outbound lane is significantly lower than the rating (77.8) in the inbound lane.
- Both inverted pavement sections performed better than the conventional section. The average ratings in the South African and Georgia sections were 81.4 and 83.3, respectively. Only Level 1 load cracking (not severe), block cracking, and minor rutting was observed in these two sections.
- It is noted that the South African section had a lower rating (81.4) than the Georgia section (83.3). The difference between the inbound lane and outbound lane is smaller, compared to the other two sections. There was very limited rutting observed on the South African section in both directions, except for two segments in the outbound lane.
- The Georgia inverted pavement section performed similar to the South African section. The average ratings were 85.5 and 81 in the inbound lane and outbound lane, respectively. Cracking in the Georgia section was limited to Level 1 load cracking (20% to 45%) and Level 1 block cracking (15% to 65%). It is noted that rutting (1/16 in. – 2/16 in.) was observed on all segments in the outbound lane.

- In all three sections, the condition in the outbound lane was worse than in the inbound lane because of the loaded trucks traveling in the outbound lane. Significant difference (more than 6 points in rating) can be observed on the conventional section, while the South African section has the least difference in both directions. This may imply the slushing technique could help in the stiffness of GAB. Further investigation (e.g., FWD) is needed to study the stiffness of each section.

2.2.2. LaGrange ByPass Road

GDOT built a 3,400-ft long IP test section on Pegasus Parkway in LaGrange, Georgia. The construction began in January 2008 and was completed in April 2009 (Cortes & Santamarina, 2011). Detailed data (including laboratory and field tests on the subgrade, the cement-treated base, the asphalt concrete, etc.) before, during, and after construction were collected to gain a better understanding of the internal behavior and performance of this pavement structure. Despite the detailed information collected at this site, there has not been any survey conducted on this test section to quantitatively evaluate its performance since it opened to traffic in 2009. The objectives of this study are to 1) critically evaluate the pavement condition of this test section using quantitative measures defined in the Pavement Condition Evaluation System (PACES) developed by the Georgia Department of Transportation (GDOT, 2007), and 2) establish quantitative baseline condition data for future deterioration analysis. With these objectives in mind, a condition evaluation was performed on the outside lanes (both Eastbound and Westbound lanes) of the test section.

Full details of the site, the data collection method, data processing steps and data analysis are presented in Appendix B.

Resilient Modulus (Mr) of subgrade soil can be estimated using correlations with dynamic cone penetration rate as shown in the equation below that was developed by George and Uddin (2000).

$$M_r = a_o (PR)^{a_1} \left[{\gamma_{dry}}^{a_2} + \left(\frac{LL}{w_c} \right)^{a_3} \right],$$

where PR is the dynamic cone penetration rate, γ_{dry} is the dry unit weight, LL is the liquid limit, w_c is the water content, and a_i are fitting parameters.

Based on an extensive field and laboratory study conducted at the LaGrange Bypass test section, Cortes (2010) estimated the mean Mr to be 250 MPa with a standard deviation of 100 MPa. The resilient modulus was measured at various stations along the test section as shown in Figure 17 below, where Sta. 280+00 and Sta. 314+00 represent the extent of the Inverted Base pavement (IBP) section. The mean and one-standard deviation lines are also presented in Figure 17. From the graph, the major outliers are observed to be between Sta. 298+00 and Sta. 300+00 (weak subgrade) and between Sta. 303+00 and Sta. 305+00 (strong subgrade).

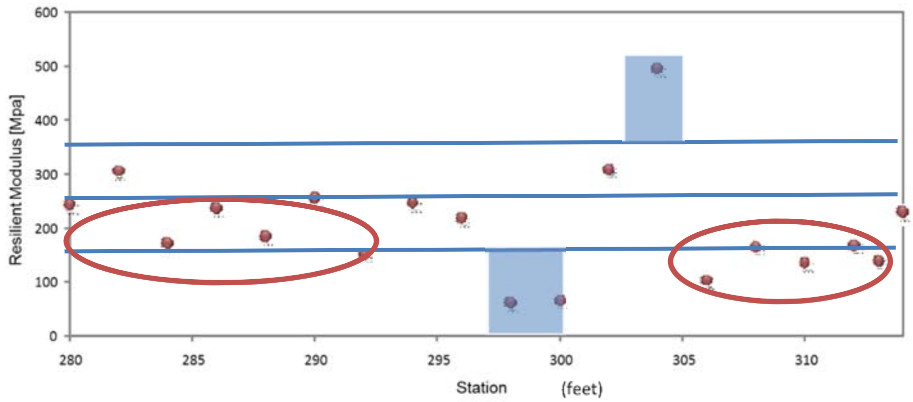


Figure 17. Resilient Modulus estimated from DCP penetration rate

Since in-situ moisture, density and porosity are some of the critical soil properties that affect resilient modulus and the quality of the subgrade material, Figure 18 presents plots of these properties along the test section (Cortes, 2010). There appears to be a correlation in the above-mentioned sections of pavement, i.e. Sta. 298+00 and Sta. 300+00 (weak subgrade) and Sta. 303+00 to Sta. 305+00.between resilient modulus and dry density (direct correlation), porosity (inverse correlation) and water content (inverse correlation). This confirms the merit of the resilient modulus values derived from dynamic cone penetrometer tests.

Following the 2016 study conducted by the Georgia Tech team to quantify the cracking of the pavement, a comparison of the observations from this study with the information from Figures 17 and 18 was made. The section between Sta. 298+00 and Sta. 300+00 indicates low PACES ratings and high load cracking as shown in Figures 19 and 20. Sta. 303+00 to Sta. 305+00 shows relatively better performance.

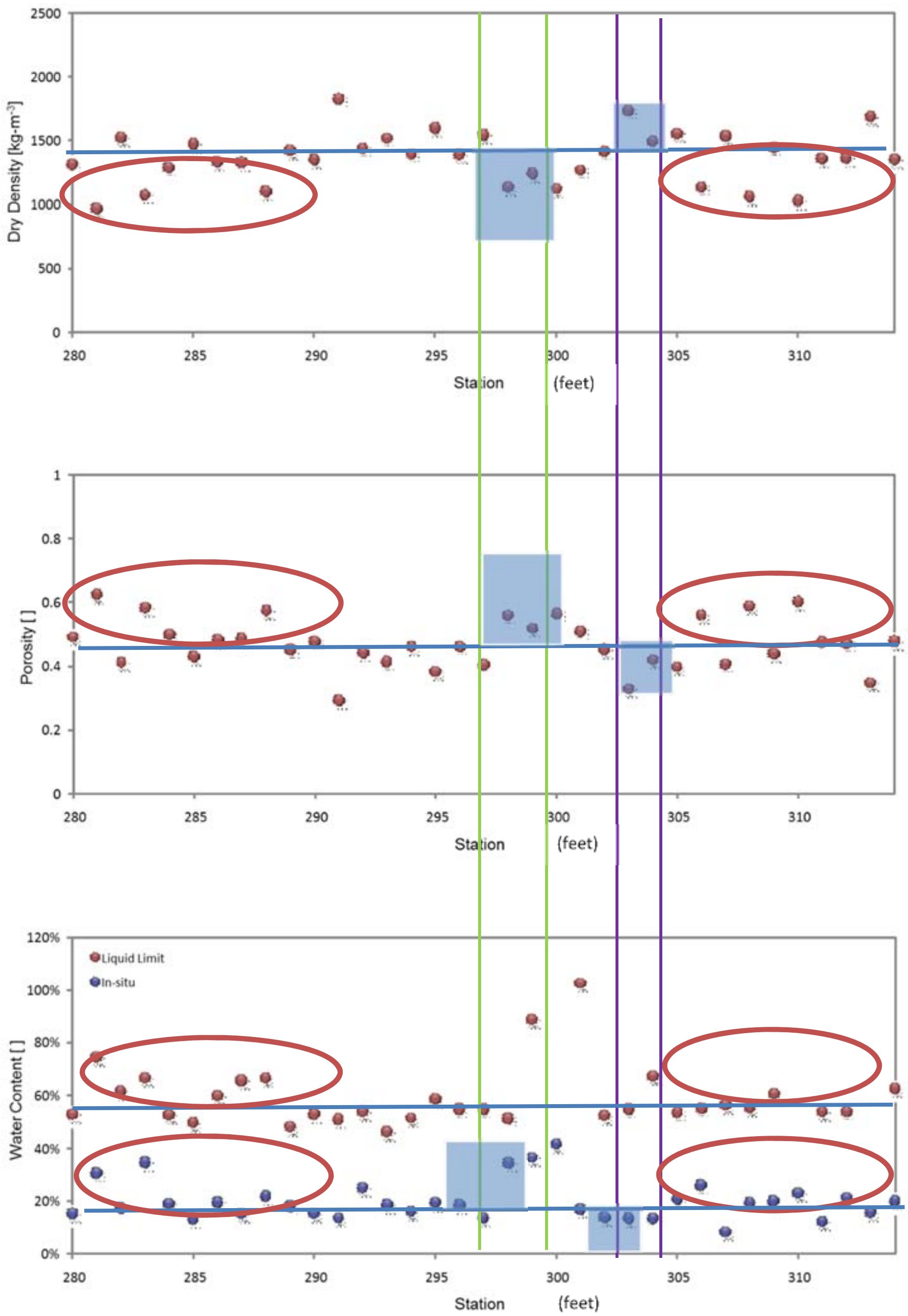


Figure 18. Soil properties measured along the pavement test section

Other regions of interest, i.e. between Sta. 280+00 to Sta. 292+00 and Sta. 305+00 to Sta. 315+00, are highlighted in the orange ellipse in Figures 17 to 21. These regions exhibit a somewhat lower resilient modulus, lower density, higher porosity, higher liquid limit and higher water content values (Figures 17 and 18), and likely, as a consequence, lower PACES ratings and relatively high load and block cracking as seen in Figures 19 to 21.

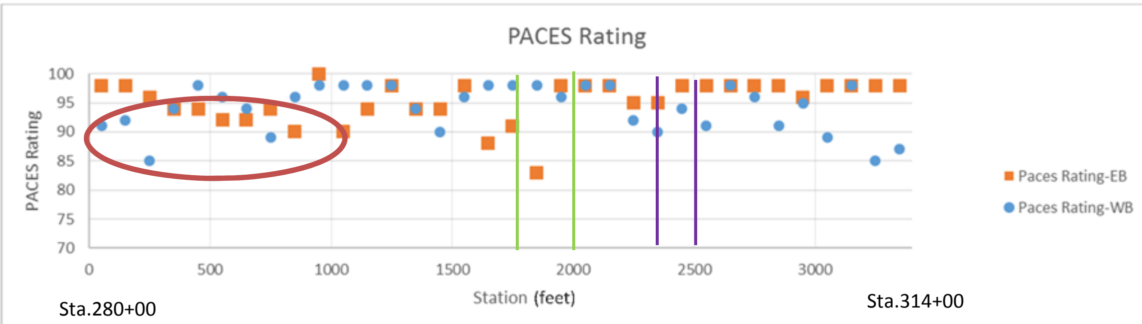


Figure 19. PACES Rating showing sections of interest (2016 measurements)

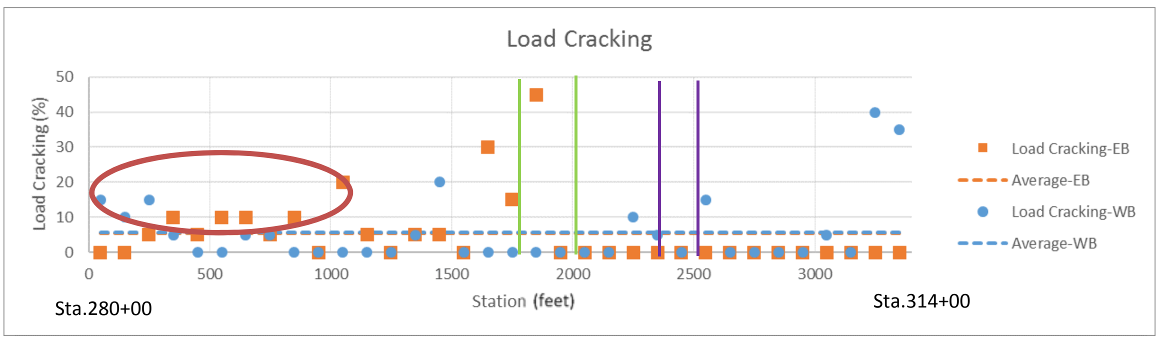


Figure 20. Load Cracking showing sections of interest (2016 measurements)

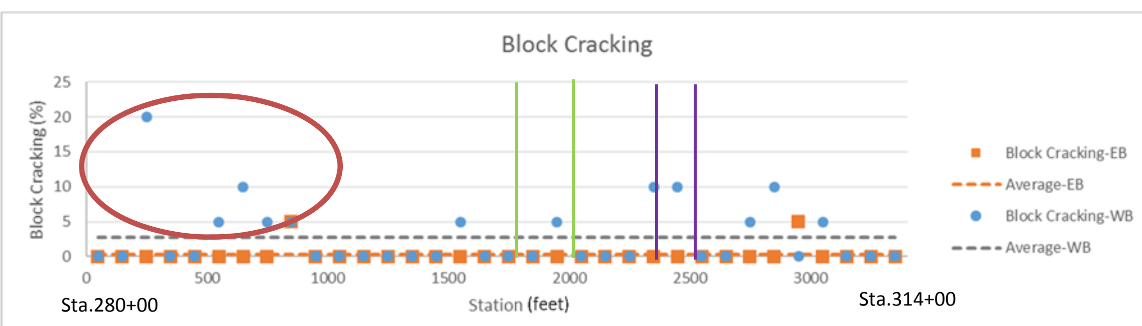
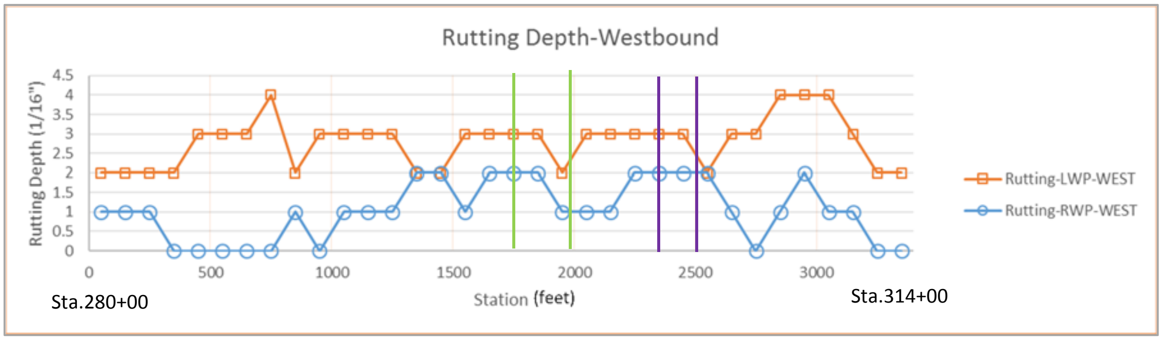


Figure 21. Block Cracking showing sections of interest (2016 measurements)

While the graphs do not indicate a definitive correlation at this stage between soil properties and observed behavior, they do indicate a possible dependency and identifies areas-of-interest to be closely monitored in the future as the pavement continues in use.

Figure 22 presents the rutting depths as measured in the 2016 study conducted using laser scanning technology. Considering ruts have a larger areal footprint than other modes of distress, they tend to develop over prolonged deterioration in a pavement zone and the current 7-year operation cycle for this test section does not indicate any stand-out trends.



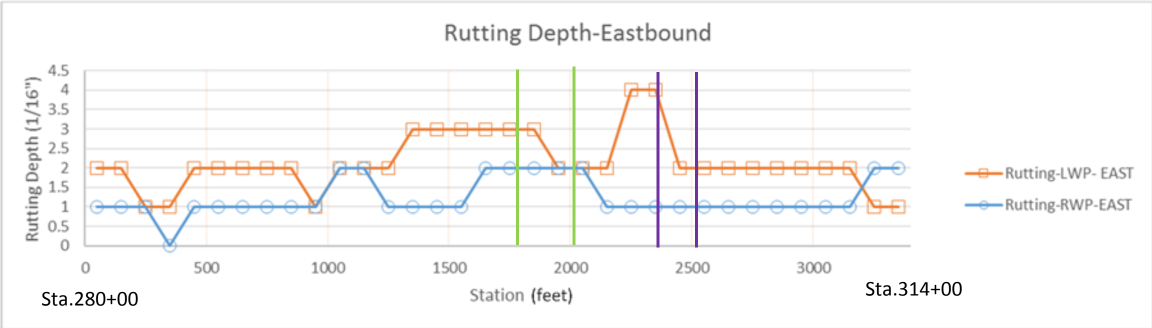


Figure 22. Rutting depth measurements made in 2016

While there is not a clear trend in rutting behavior along the pavement section, the left wheel path (near the center-line of the road) in both directions shows greater rutting than the right wheel path. Additional field distress measurements after an additional period of service life are recommended to enable performance to be monitored.

After processing these data for cracking and rutting information, the distress information for every 100 feet was aggregated. From this data, the PACES score was determined according to GDOT specifications. The scores indicate that since being opened to traffic in 2009, the IP section has performed well:

- The test section has performed well with an overall average rating of 94.7 after 7 years of service. Of the 64 segments (34 in each direction), only 6 segments had a rating less than 90. This is especially notable when considering, on average, Georgia's pavements reach a rating of 70 in 10.6 years.
- Overall, the test section showed limited and low-severity (Level 1) load cracking and block/transverse cracking and moderate rutting. The average extent for load cracking and block cracking is approximately 5.4% and 1.5%, respectively. Of the 68 segments (34 in each direction), 28 segments exhibited load cracking (ranging from 5% to 45%), while only 14 segments exhibited block cracking (ranging from 5% to 20%).
- The load cracking was distributed differently in the EB and WB lanes. For the EB lane, the load cracking was observed only on the first half of the test section (between the 2+00 and 19+00 marks). The segments approaching the 16+00-ft to 19+00-ft marks from the EB direction had significantly higher cracking than the

other segments. This higher presence of cracking may be attributed to the horizontal curve in a downhill grade from the 16+00-ft to 19+00-ft marks. For the WB lane, the load cracking was observed across the length of the test section with the segments near the west side (the 32+00 to 34+00 marks) showing the highest extent of load cracking. This may be attributed to the vehicle dynamic loading when moving from the bridge to the IP section.

- The WB lane exhibited more block/transverse cracking than the EB lane. Only two segments in the EB lane exhibited blocking cracking, while 12 segments in the WB lane were reported with block cracking. This may be attributed to the heavy truck loads in the WB lane.
- Moderate rutting was measured on the test section; in general, the WB lane had more rutting than the EB lane. The average rutting in the EB lane and WB lane was approximately 2/16 in. and 3/16 in., respectively. A 3/16 in. of rutting was reported between the 13+00-ft and 19+00-ft marks in the EB lane, where the load cracking was also high. Further study is needed to determine the causes of higher rates of rutting and cracking in these segments.
- It is noted that the rut depth in the left wheel path (inside wheel path) was higher than that in the right wheel path (outside wheel path) in both EB and WB lanes. Further analysis needs to be done to assess the potential causes.

Using sensing technology, the cracking and rutting information for all 100-ft segments was fully captured. Through thorough analysis, the current condition of cracking and rutting for the IP section has been established. The test section has performed well after 7 years of service; however, the segments with higher rates of cracking and rutting need to be monitored and studied. With this baseline information, in-depth analysis on crack deterioration can be performed in the future to assess changes in crack characteristics, such as length, width, and depth. In addition, the growth of rutting in terms of both depth and length can be analyzed to determine any problems in base or surface layers. Through this analysis, the performance of the IP section can be analyzed over time to evaluate how well this new pavement structure performs in comparison to a conventional asphalt pavement structure.

2.3. Laboratory Investigation of Slushing Technique

2.3.1. Apparatus Development

The need for better grasp of unbound granular material in pavement applications is especially important in light of the emergence of new and alternative pavement designs such as inverted-base pavements. This study aimed to supplement the field-observations supporting the superior long-term performance of inverted-base sections relative to the conventional sections at two test sections in Georgia, with laboratory simulations to replicate the underlying mechanisms. To this end, the current study also served to lay the groundwork for an extensive study on inverted base pavements in the near future by including the design and fabrication of a laboratory bench-scale setup to simulate the ‘slushing’ technique, which has been reported to further enhance the density of the packed granular base.

The slushing process is applied to the unbound aggregate base layer (UAB) of inverted base pavements, represented by the GAB layer in Figure 23, which also schematically presents the differences between a conventional flexible pavement and an inverted base pavement structure. Since the UAB layer in an inverted base pavement plays a greater structural role in load-distribution, it is critical to achieve the right composition of particles and minimize voids. Slushing helps achieve this by retroactively removing excess fine particles from an already-placed UAB layer, as opposed to traditionally adopted repeated rolling which leads to particle crushing and is detrimental to the integrity of the pavement in the long term (Figure 24). The seepage action of water through the compacted UAB layer is critical to the slushing process, as explained below.

This technique involves the following steps during compaction of the unbound aggregate base layer:

- A cement-treated base layer is compacted to ensure a stiff, low-permeability layer to support the overlying UAB layer.
- UAB layer is placed and compacted until it exhibits no (or very little) movement under the weight of a heavy roller.
- The next stage is the slushing process which involves multiple passes by a water truck, a heavy smooth-drum roller and a pneumatic rubber-tired roller, in that sequence. This combination allows the water to seep into the UAB layer and immediately being expelled back to the surface under the action of the following two rollers, while eliminating any excess air pockets and fine particles. Visually, this is observed as air bubbles and fine sediments at the surface indicating the slushing process is underway. This expelled water is removed from the pavement.

- At the end of the slushing stage, indicated by expulsion of clear water at the surface, the UAB layer should contain lesser percentage of voids than pre-slushing and an optimum ratio of coarse to fine particles, ensuring higher stiffness and durability.

- The cleaned surface is allowed to dry completely and then dry-rolled before applying the tack-coat for asphalt placement.

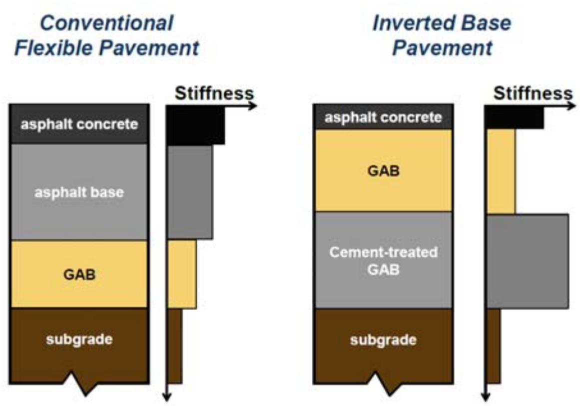


Figure 23: Comparison between conventional and inverted base pavement systems [Papadopoulos, 2014]

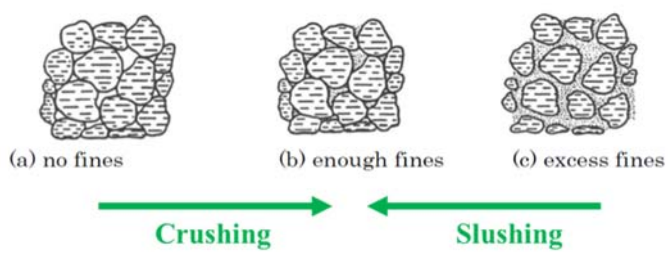


Figure 24: Crushing versus Slushing action in achieving maximum density

Method:

The ‘Slushing’ setup was designed as shown in the schematic below (Figure 25) and incorporated the following features:

- Two sets of rollers of to each act as steel and rubber-tired wheels. Varying stiffness was captured by using rubber sleeves of different hardness (90A Urethane for harder roller and 60A Vinyl for softer roller)

- Roller weight to be controlled using dead weights hanging independently off rollers

- One directional compaction, capability to retract rollers to origin while elevated from the soil surface to prevent reversal of rolling stresses

- Ability to be speed-controlled and position controlled (micro-controller driven)

- Instrumented to measure and record horizontal load, speed and number of cycles

- Water sprinkler system to spray water at a controlled rate as desired

Figures 26 and 27 show some additional schematics and photos of the device.

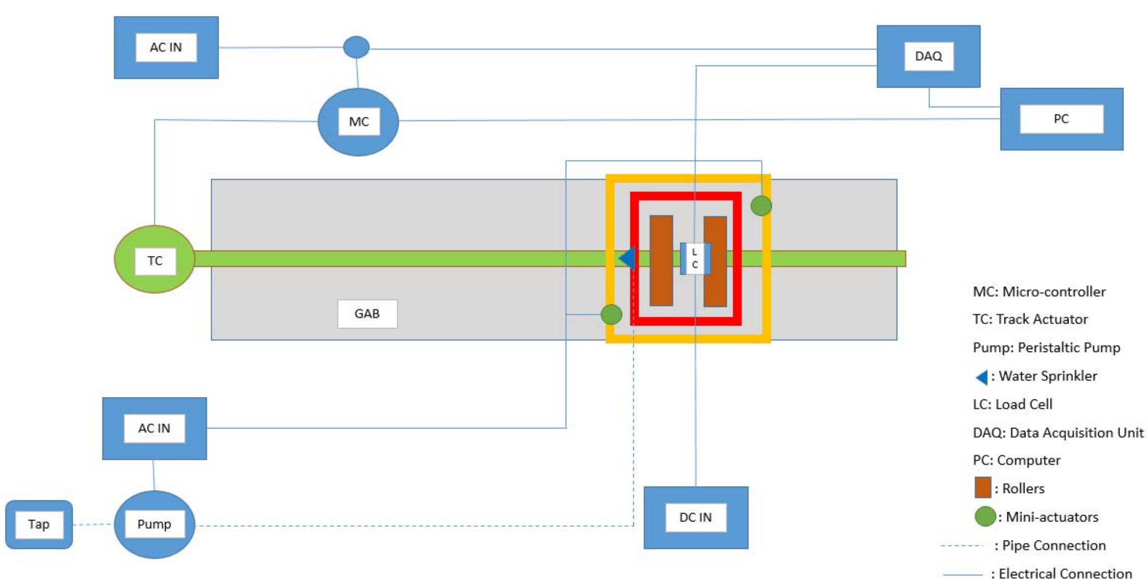


Figure 25: Schematic showing various components involved in testing process

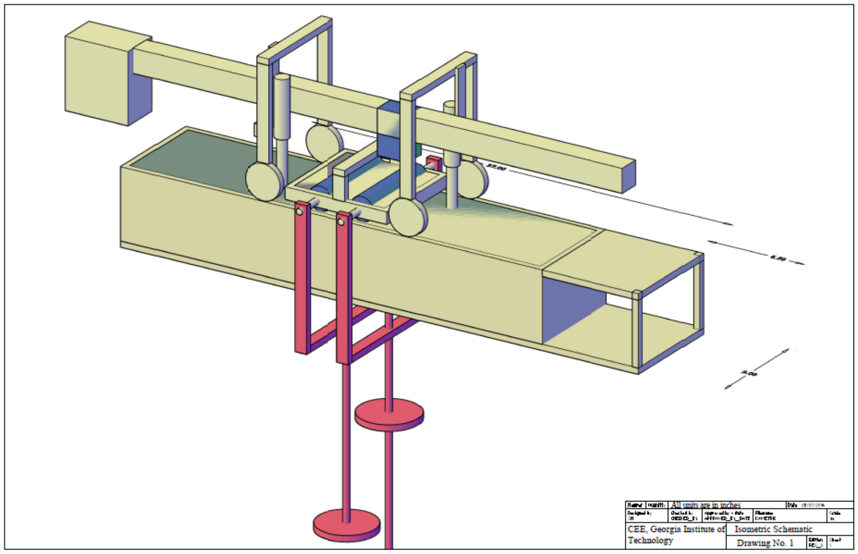


Figure 26: CAD rendering showing concept-design of slushing setup

Figure 27: Photographs of slushing device

Test Parameters:

The gradation of GAB material was modified so as to remove the coarser particles greater than ¾ inches (to scale for reduction in the laboratory roller size as well as make any subsequent core-sampling easier) as shown in Figure 28.

GAB was manually compacted during the initial placement stage in four lifts of one-inch thickness. The gab material is mixed to optimum water content (6.5%) prior to placement. This test was run in the following stages, with gradually increasing rolling stress to prevent soil 'bowing':

- Stage I: Surface Preparation: Low stress passes (20 lbs on each roller) to create even surface
- Stage II: Conventional Compaction-I: Moderate stress (36 and 31 lbs on each roller) passes
- Stage III: Conventional Compaction-II: High stress passes (55 and 40 lbs on each roller)
- Stage IV: Slushing: Similar stresses as above but accompanied by water spraying in one direction

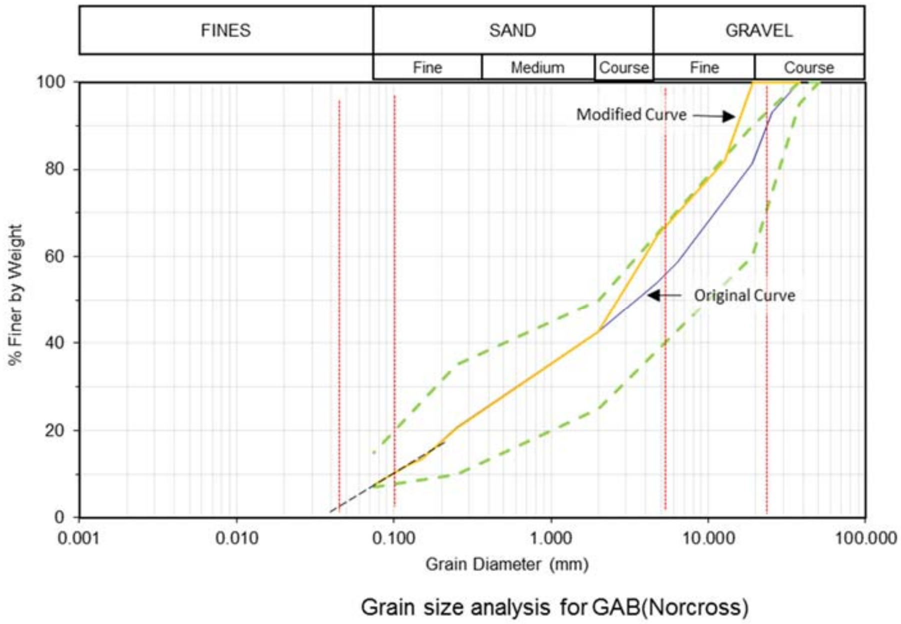


Figure 28: Grain size distribution curve for GAB material used in slushing test

2.3.2. Preliminary Simulations

The objective of this section of the study was to primarily develop a working apparatus to simulate slushing and conduct a pilot test to qualitatively observe slushing mechanisms. The following paragraphs present the result from the pilot test.

Figure 29 presents the horizontal load resistance recorded by the load cell while pushing the rollers in the forward direction. Stages I-IV comprised of one, five, five and 34 passes respectively. The varying vertical stresses on rollers for four aforementioned stages of compaction can be clearly distinguished. The default speed of rolling was set to 0.33 in/s (actuator speed 75). Horizontal drag increases upon introduction of water which explains the higher load measurements for Stage IV as seen in Figure 29. The orange-colored passes were conducted at higher speeds of 0.44 in/s (actuator speed 100) and 0.66 in/s (actuator speed 150), which is causing the even-higher load readings compared to the previous cycles of Stage IV.

Another interesting observation, which should be closely monitored for future tests is the bell-shaped load curve, with the load reading dropping in the second half of the slushing stage. This is noticed in Stage IV at all three speeds.

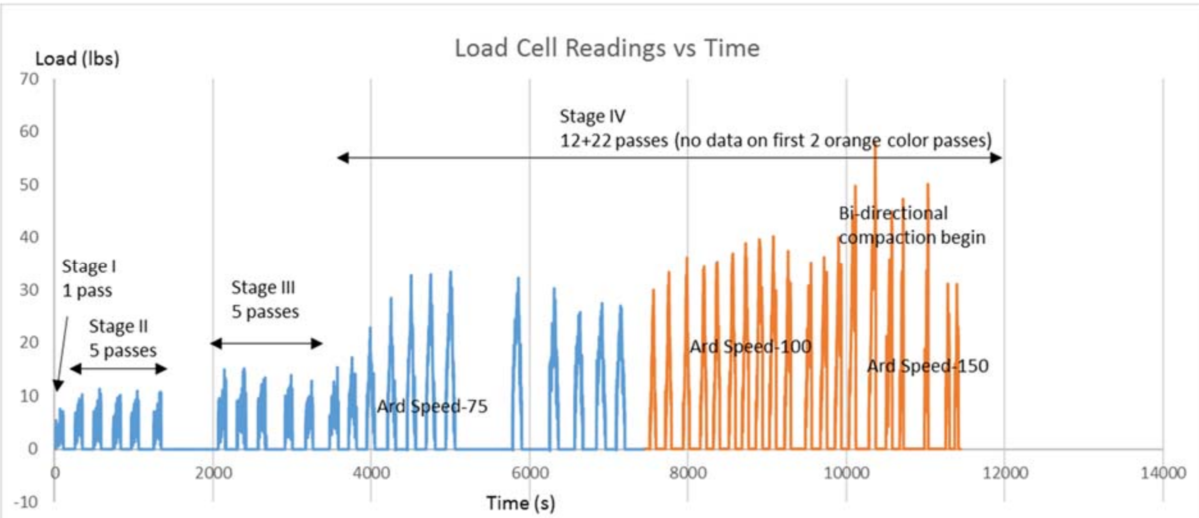
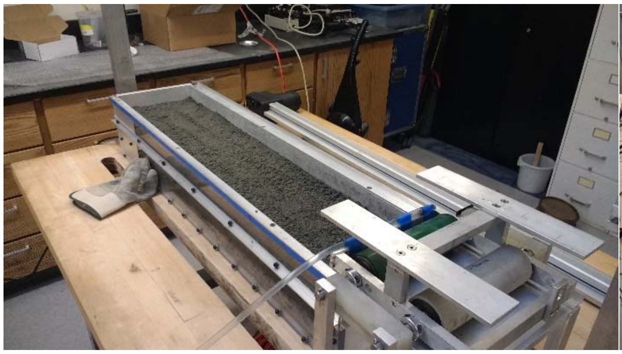
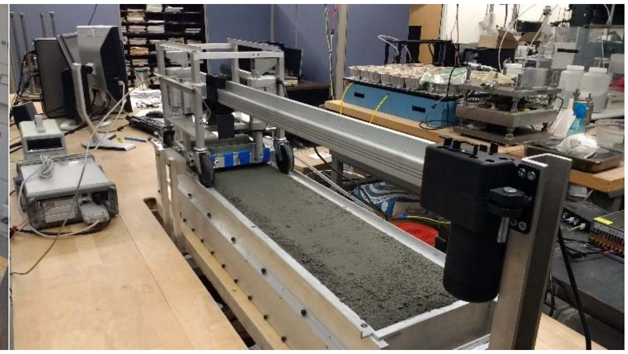


Figure 29: Horizontal load-cell readings for all cycles of compaction

Some photographs from the test are shown below in Figure 30. It should be mentioned that while air bubbles and fine particles were ejected at all across the surface, the water carrying these ejected particles was subsequently pushed to the side of the box by the following pass of the rollers. Therefore, the photos below indicate greater accumulation of fine particles along the edges of the box, as seen in Figure 30(f), (g) and (h).



(a) GAB placement and manual compaction

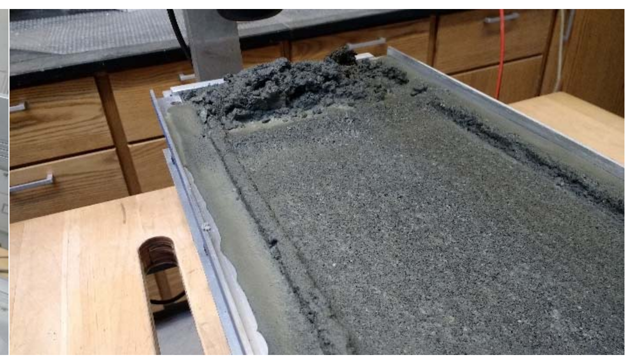


(b) Commencement of stage I compaction

(c) GAB surface pre-slushing

(d) Slushing stage underway

(e) Slushing stage in progress



(f) Fines being ejected to sides of roller

(g) GAB surface after slushing

(h) GAB surface after slushing

Figure 30: Photographs from pilot test

2.4. Promotion of Inverted Base Pavements as a Construction Alternative

As a result of the significant role that GDOT has played over the past 15 years in evaluating alternative pavement systems and in particular inverted base pavements, it also has a critical role to play in sharing the insights gained through the various studies it has participated in and in many cases led. For example, the inverted pavement test sections at the Morgan County Quarry Access Road and the LaGrange By-pass Road are amongst the best documented test sections in the country and thus performance evaluations of these test sections can provided critical evidence of the relative performance of conventional and alternative pavement systems.

To fulfill this role of promoting inverted base pavements as an alternative pavement system, several activities were undertaken as part of this project as follows:

- The project PI presented a lecture at a special session organized at the 2016 TRB Annual meeting in Washington D.C. on Inverted Base Pavements by AFP70 Mineral Aggregates sub-committee. The title of the lecture was "Performance Assessment of Inverted Pavement Test Sections". The special session was attended by more than 60 individuals including representatives from more than 20 state DOT's.

- The project PI was one of three lecturers who delivered a TRB webinar organized in July 2016 on "Inverted Pavements" by AFP70 Mineral Aggregates sub-committee. The webinar was attended by more than 300 participants with registered participants from 39 state DOT's.

3. CONCLUSIONS AND RECOMMENDATIONS

Based on this study, a number of important insights have been observed and form the basis for a framework for future studies:

a) The PUMA tests reiterated the huge significance of the molding water content on the performance of the aggregate layer system. Specimens molded wet of the optimum water content showed lower stiffness moduli (up to 50%) and larger plastic deformations (up to 3 times larger) compared to specimen molded closer (and dryer) to the optimum water content. The increased permanent deformation in wetter conditions is potentially reflective of fines-migration within the specimen in an attempt to achieve an optimized load-bearing particle matrix and also results in a higher matrix stiffness. Repeated cycles of wetting drying gradually deteriorates the particle matrix as was evident from the CBR test results.

b) Preliminary laboratory simulations of the slushing technique clearly showed the ejection of fine particles at the surface of the aggregate layer along with excess water. This establishes the effectiveness of the laboratory system towards simulating the slushing construction process as followed in the field, while enabling close control over testing conditions and electronic measurements of various metrics to quantify the improvements potentially achievable using this novel technique.

c) Combining the insights from the PUMA apparatus and the "slushing" compaction apparatus, a base layer that is compacted, within a reasonable range, close to the maximum modified-proctor dry density and optimum water content, followed by implementation of the slushing process to further enhance the stiffness of the system would potentially achieve a significant improvement in resiliency of the system. Moreover, this improvement would be achieved by minimizing void space in the unbound aggregate layer while minimizing crushing of aggregate particles, which is otherwise expected to occur with conventional high-energy low-lubrication compaction techniques.

d) The field studies undertaken as part of this project to quantitatively evaluate pavement distress and rutting at the two locations of existing inverted base pavement test sections have provided both valuable information on the relative performance of the conventional and alternative pavement sections as well as critical quantitative baseline data so that future pavement distress surveys can be quantitatively compared to the baseline data. The field measurements provided clear evidence of the significantly better performance achievable with alternative pavement structures such as inverted base pavements.

e) The interest shown through both attendance as well as active engagement in discussion at both the Special Session at the TRB 2016 Annual Meeting and the subsequent webinar, on Inverted Base Pavements” both of which were organized by the AFP70 Mineral Aggregates sub-committee provided clear evidence of the strong interest that exists nationwide amongst state DOT’s for alternative pavement structures. GDOT has been playing an important lead technical role in these efforts.

4. REFERENCES

ASTM (2009), "D6913-04 – Standard Test Method for Particle-Size Distribution of Soils Using Sieve Analysis", ASTM International, West Conshohocken, PA.

ASTM (2015), "D1557-12 – Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbs/ft3 (2,700 KN-m/m))", ASTM International, West Conshohocken, PA.

ASTM (2015), "D1883-14 – Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils", ASTM International, West Conshohocken, PA.

Alba, L.J. (1993). "Laboratory Determination of Resilient Modulus of Granular Materials for Flexible Pavement Design." Ph.D. Thesis, Georgia Institute of Technology, Atlanta.

Brown, S.F., Thom N.H. (2013). "Recent Developments in Pavement Foundation Design", Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

Cooper Technologies. Precision Unbound Material Analyzer, Manufactures Brochure, Website url: http://cooper.co.uk/wp-content/uploads/downloads/2013/08/PUMA-Precision-Unbound-Material-Analyser-Cooper.pdf

Cortes, D.D., (2010), "Inverted Base Pavements Structures", Ph.D. Thesis, Georgia Institute of Technology, Atlanta.

Lewis, D.E., Ledford, K., Georges, T., Jared, D.M. (2012), "Construction and Performance of Inverted Pavements in Georgia", Transportation Research Board 91st Annual Meeting, 12-1872.

Papadopoulos, E. (2014). "Performance of Unbound Aggregate Bases and Implications for Inverted Base Pavements." Ph.D. Thesis, Georgia Institute of Technology, Atlanta.

APPENDIX A –

Morgan County Quarry Access Road Field Measurements Report

Morgan County Pavement Condition Evaluation Report

Yiching Wu. Yichang Tsai, Geoffrey Price

1. Scope and Objective

Three test sections with different pavement designs were constructed on an entrance road to the Martin-Marietta Morgan Quarry in Morgan County, Georgia in 2001. The three test sections were 1) conventional pavement), 2) South African inverted pavement, and 3) Georgia inverted pavement. Although a visual inspection was conducted in 2006, there has been no pavement condition evaluation conducted on these three test sections. The objectives of this study are to 1) critically evaluate the pavement condition of these three test sections using quantitative measures defined in the Pavement Condition Evaluation System (PACES) by the Georgia Department of Transportation (GDOT) (GDOT, 1993) and 2) establish a quantitative baseline for future deterioration analysis.

2. Site Description

The three test sections together are approximately 1,800 ft. on a private entrance road to the Martin-Marietta Morgan Quarry located near I-20, Exit 121 off the 7-Island Road in Madison, GA. Figure 1 shows the location of the test sections. This entrance road is used by empty haul trucks entering the quarry and loaded trucks leaving the quarry. In addition, there is an unpaved crossroad intersecting with the entrance road.

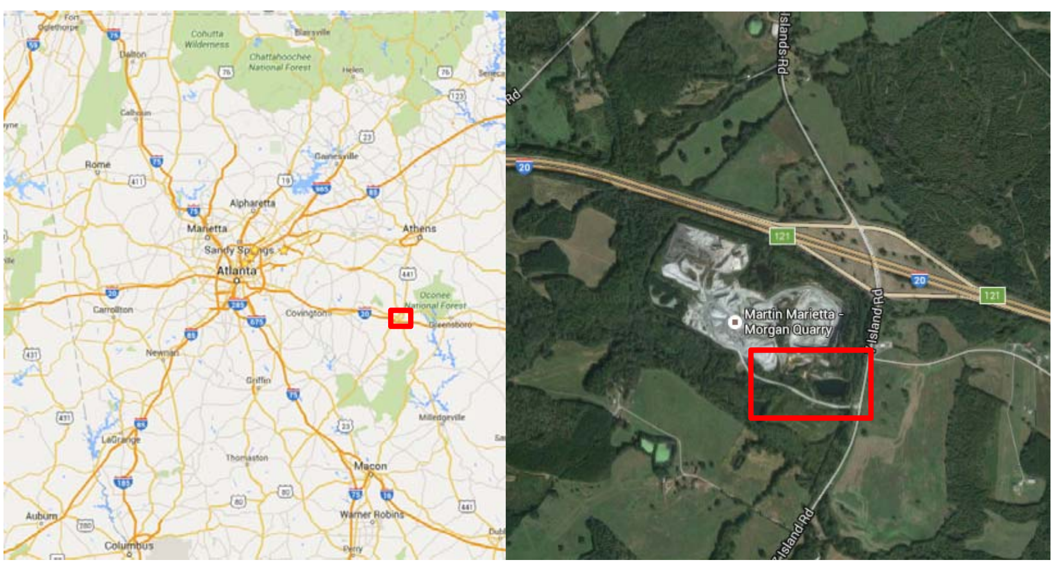


Figure 1. Site location.

The layout of the three test sections is shown in Figure 2.

- The conventional pavement section, consisting of HMA on top of 8 in. of graded aggregate base (GAB), begins at the entrance at 7 Island Road and continues in the westbound (WB) (or inbound) direction for 1000 ft. This section is mostly straight with a slight horizontal curve near the entrance. A crossroad which intersects the conventional section at approximately +680 ft, is used for trucks carrying pit overburden to a waste site. These trucks weigh over 40 tons when loaded (Cortes & Santamarina, 2012). In addition, an unpaved parking area is located around +500 ft. mark in the eastbound (EB) (or outbound).
- The South African inverted pavement section (SAIP) is 400 ft. long (from the +1000 ft. mark to the +1400 ft. mark); it is a mostly straight stretch of roadway.
- The Georgia inverted pavement section (GAIP) is also 400 ft. long, and continues from the +1400 ft. mark to the +1800 ft. mark on a curved section.

Both the inverted pavement test sections (SAIP and GAIP) were constructed with 8 in. of a cement-treated base, a 6-in. layer of GAB, and a thin, 3-in. layer of HMA on the top, the only difference being the incorporation of the“slushing” technique for the SAIP section. Slushing increases the stiffness of the GAB layer by reducing the volume of voids between the aggregate particles.

Figure 2. Layout for three test sections.

3. Data Collection

Georgia Tech's sensing vehicle, equipped with laser crack measurement systems (LCMS), GEO3D cameras, GPS, IMU (inertial measurement system), and DMI (distance measuring instrument), was used for collecting 3D pavement data, 2D images, and GPS data for extracting pavement distresses based on PACES (GDOT, 1993) standards. Data collection was conducted on April 8, 2016. Since there weren't any pavement marking on this private entrance road, location reference points were marked with fluorescent paint to help identify the 100-ft segment for use in a PACES survey. A diagram of the marking scheme is shown in Figure 3. After construction in 2001, nails were placed in the pavement's surface at +1000, +1400, and +1800 ft. to mark the different test designs. These were used as location references to mark the start and end of every section with paint. The center line was marked with a dashed line and a cross and the marking numbers were placed along the center line at every 100 ft. using the nails as references. The WB and EB travel lanes were then outlined with dashed lines. Once the lanes were outlined, the transition points between the different pavement designs were marked across the full lane. The marking, which took approximately 2 hours to finish, outlined the 100-ft segment for the PACES survey.

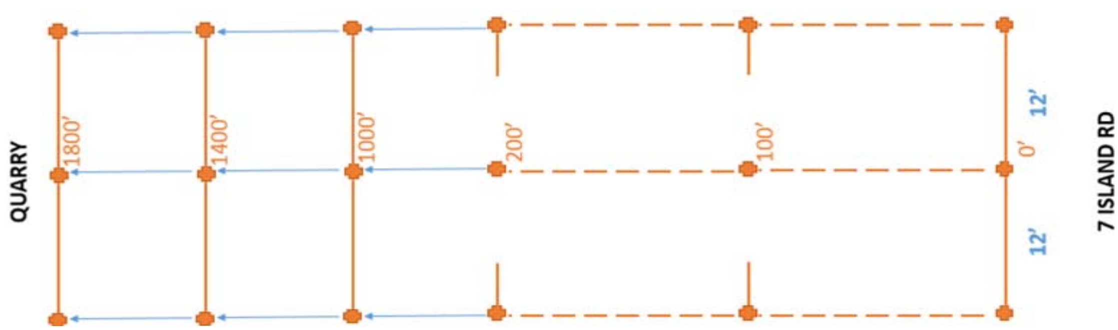


Figure 3. Layout for markings.

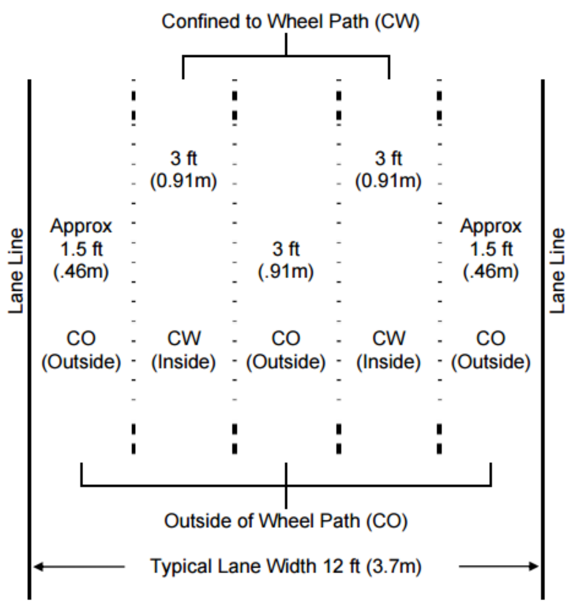
The Georgia Tech sensing vehicle, as shown in Figure 4, was driven at approximately 25 mph in both directions to collect the data at 5-meter intervals with each video log image corresponding to a single laser file. To facilitate better coverage of the access road, two runs of data were collected, and the run with better coverage of the marked lane was processed and analyzed.

Figure 4. Georgia Tech Sensing Vehicle.

4. Data Processing

Distresses on the three test sections were extracted from the sensing data based on GDOT's PACES survey standards. PACES establishes standardized nomenclature for distresses and defines their respective severity levels and measurement methods for asphalt concrete pavement. There are ten distresses surveyed in PACES including: 1) rutting, 2) load cracking (LC), 3) block/transverse cracking (B/T), 4) reflection cracking, 5) raveling, 6) edge distress, 7) bleeding and flushing, 8) corrugation and pushing, 9) loss of pavement section, and 10) patches and potholes. Cracking (including load cracking, block cracking, and reflective cracking) is measured in a 100-ft section. A PACES rating is then computed on a scale of 0 to 100 (with 100 representing pavement with no visible distresses) based on the extent and the severity level of present distresses. As pavement condition worsens and distresses begin to appear, points are deducted, and the PACES rating drops. GDOT uses a rating of 70 for triggering the need for a thin resurfacing (1.5 in.). More information on the PACES distress types and severities can be found in Appendix A.

Cracking and rutting on each 5-m interval were first extracted using an automatic crack detection algorithm (Tsai et al., 2013) and rutting algorithm (Tsai et al., 2013) from the 3D pavement data. Cracking information, including type, severity level, and extent, in each 5-m interval was then reviewed and adjusted manually to ensure the distress information was correct. It is noted that load cracking is identified by its presence in the wheel path, as shown in Figure 5(a). However, because there are no markings on this private road, trucks are likely to travel outside of the wheel paths, as shown in Figure 5(b). Thus, adjustment was made to the cracking results to reflect the true surface condition. Rutting was computed at approximately every 1 ft. and the 60th percentile rutting was reported for every 100 ft in each wheel path. The 60th percentile was chosen as the representative value because it appears to best reflect the manual PACES surveys conducted by GDOT. After reviewing and recording distresses on each 5-m interval, the information was then aggregated for each 100-ft segment, which is the sample unit length in PACES. Load cracking, block/transverse cracking, and rutting were the only distresses present on the test sections. A PACES rating was computed for each 100-ft segment based on the distresses. Tables 1 and 2 summarize the rating and distresses derived from the sensing data for each 100-ft segment of the inbound and outbound lane.



(a) Defined wheel path location (FDOT, 2015) (b) Need for adjusting wheel path locations

Figure 5: Illustration of wheel path locations.

Table 1: PACES Summary - Inbound (WB)

		Rutting (1/16")		LC1	LC2	LC3	LC4	B/T	PACES
		LWP[1]	RWP[2]	(%)	(%)	(%)	(%)	(%)	Rating
Conventional Pavement	0-100[3]	0	2	0	0	25	0	25	61
	100-200[3]	0	0	0	0	25	0	50	59
	200-300	0	0	15	0	0	0	35	85
	300-400	0	0	35	0	0	0	100	71
	400-500	0	0	35	0	0	0	50	79
	500-600[3]	0	0	35	0	0	0	55	79
	600-700	0	0	35	10	10	0	35	72
	700-800[3]	0	0	45	0	0	0	30	78
	800-900	0	0	35	0	0	0	15	84
	900-1000	0	0	40	0	0	0	60	76
South African Inverted Pavement	1000-1100	0	0	30	0	0	0	35	82
	1100-1200	0	0	55	0	0	0	10	81
	1200-1300	0	0	30	0	0	0	40	81
	1300-1400	0	0	20	0	0	0	45	83
GA Inverted Pavement	1400-1500	0	0	40	0	0	0	15	82
	1500-1600	0	0	0	0	0	0	60	89
	1600-1700	0	1	25	0	0	0	25	85
	1700-1800	0	0	15	0	0	0	30	86

1. LWP: left wheel path
2. RWP: right wheel path
3. Segments excluded from the comparison of three test sections.

Table 2: PACES Summary - Outbound (EB)

		Rutting (1/16")		LC1	LC2	LC3	LC4	B/T	PACES
		LWP[1]	RWP[2]	(%)	(%)	(%)	(%)	(%)	Rating
Conventional Pavement	0-100[3]	1	1	0	0	55	0	0	50
	100-200[3]	1	3	0	0	65	25	0	48
	200-300	0	1	15	0	15	0	35	64
	300-400	0	1	35	10	0	0	60	76
	400-500	0	2	25	0	10	0	20	72
	500-600[3]	0	3	0	0	50	0	5	46
	600-700	0	2	20	5	25	0	20	61
	700-800[3]	0	3	10	5	30	0	20	56
	800-900	0	1	15	10	0	0	35	80
	900-1000	0	1	65	10	0	0	35	77
South African Inverted Pavement	1000-1100	0	0	30	0	0	0	40	81
	1100-1200	0	1	15	0	0	0	25	86
	1200-1300	0	1	65	0	0	0	25	78
	1300-1400	0	0	40	0	0	0	35	79
GA Inverted Pavement	1400-1500	0	2	45	0	0	0	15	78
	1500-1600	0	1	25	0	0	0	60	79
	1600-1700	0	1	40	0	0	0	20	81
	1700-1800	0	1	20	0	0	0	25	86

1. LWP: left wheel path
2. RWP: right wheel path
3. Segments excluded from the comparison of three test sections.

5. Data Analyses

Identification of abnormal segments

PACES ratings for each 100-ft segment in the inbound and outbound lane are shown in Figure 6 for reviewing the trend and identifying abnormal segments. The average rating of all the 38 segments is about 74.8. It is noted the ratings of the first two segments (marks +0 ft.~+100 ft. and +100 ft.~ +200 ft. mark) close to the entrance are significantly lower than the other segments in both directions, as shown in Figure 6. The distresses contributing to the deducts are rutting, load cracking and block cracking. Figures 7 and 8 show the extent of load cracking and block cracking for each 100-ft segment. It is noted that the total load cracking (Levels 1-4) should not exceed 100%; block cracking is recorded separately with only the predominant severity level and should not exceed 100% as well. Severe load cracking (Levels 3 and 4) was observed on the two segments close to the entrance, as shown in Figures 7(a) and 7(b). This is due to the trucks' deceleration and acceleration when approaching the entrance. Truck braking and idling has a significant negative impact on pavement surface condition. Unlike typical load cracking residing only in the wheel paths, the load cracking in these two segments cover the entire lane, as shown in Figure 8. This suggests that loading has been applied across the entire lane and is likely the result of trucks not traveling directly in the lane marked. The distresses on these two segments do not represent the pavement condition under normal traffic patterns; thus, these two segments were excluded from further analysis. In addition, the PACES rating for the segments (between marks +500 ft.~+600 ft. and +700 ft.~+800 ft.) near a roadside parking space and the crossroad, is noticeably lower in the outbound direction. Severe cracking was observed before the roadside parking space and the crossroad, as shown in Figure 9. This may be the result of this section's experiencing more slowly moving loaded trucks due to that cross traffic. While severe cracking was observed mostly on the outbound direction between segments +500 ft.~+600 ft. and +700 ft.~+800 ft., this stretch in both directions (inbound and outbound) was excluded from further analysis.

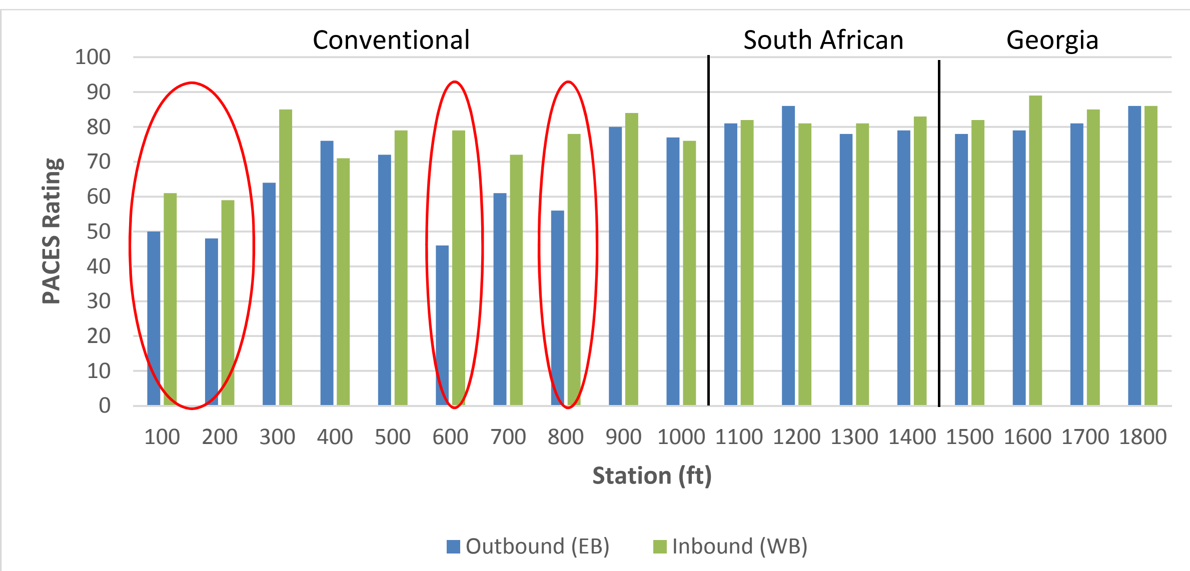
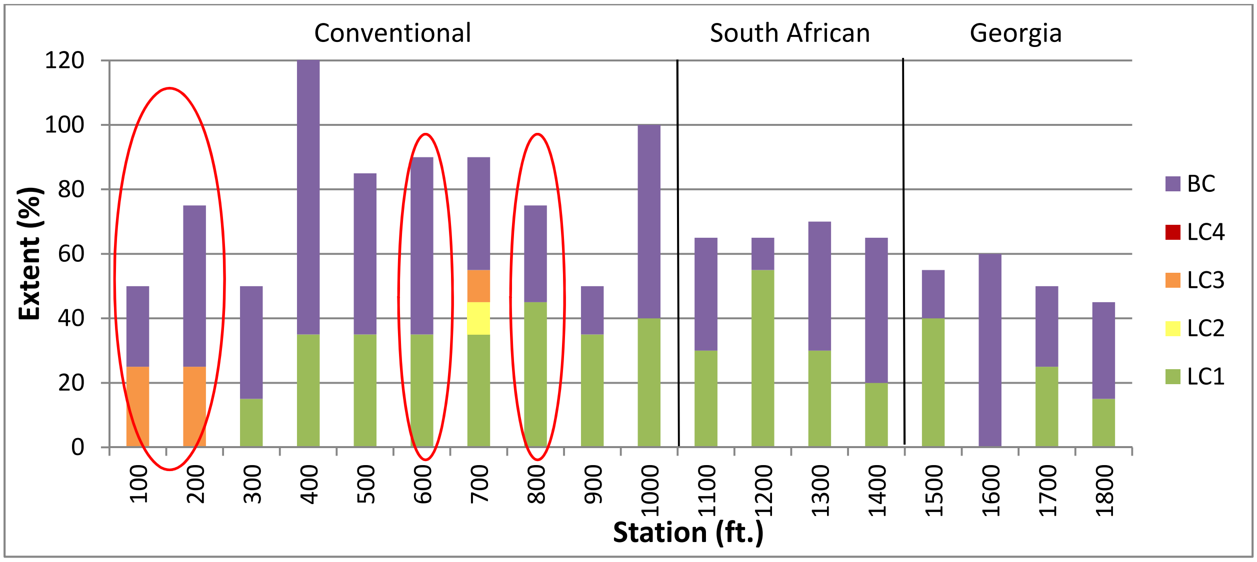
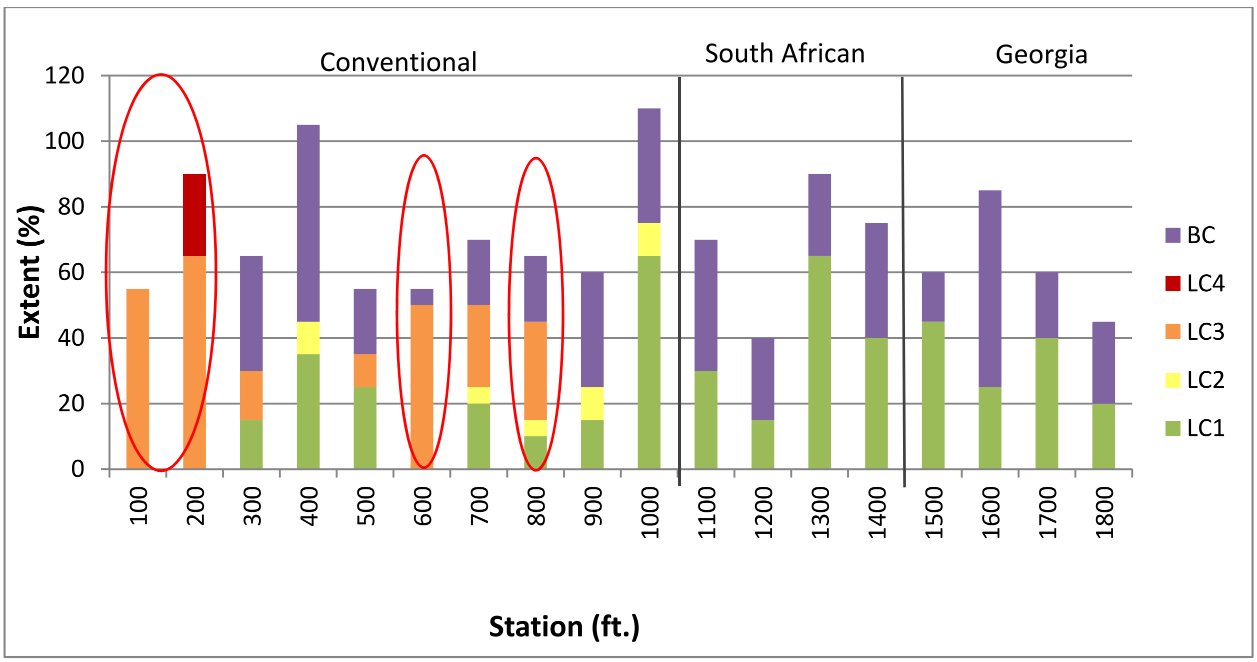


Figure 6. PACES rating in inbound and outbound lane.



(a) Inbound lane.



(b) Outbound lane

Figure 7. Distresses in inbound and outbound lane.

Figure 8. Distresses near station +100 ft.

(a) Cracking near the roadside parking (b) Cracking near the cross road

Figure 9. Severe load cracking near roadside parking space and the cross road.

Table 3 summarizes the PACES ratings and distresses for each test section after removing the abnormal segments. Rutting, load cracking, and block cracking were observed on these sections. The performance of each test section is discussed below.

Table 3. PACES summary for each test section

		Conventional		South African IP		Georgia IP	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Load Cracking	1	32.5 %	29.2%	33.8%	37.5%	20 %	32.5%
	2	1.7%	5.8 %	0	0	0	0
	3	1.7%	8.3%	0	0	0	0
Block Cracking	1	49.2%	34.2%	32.5%	31.3%	32.5%	30%
Max Rutting (1/16”)		0	2	0	1	1	2
Average Rating		77.8	71.7	81.8	81	85.5	81
Rating Range		71-85	61-80	81-83	78-86	82-89	78-86

Conventional Section

The conventional section had diverse conditions with the ratings ranging from 61 to 85. The pavement condition in the outbound lane was significantly worse than the one in the inbound lane. The average rating in the inbound and outbound lane was and 77.8 and 71.7, respectively. These low ratings can be attributed to high levels of load cracking. In addition to Level 1, Level 2 and 3 load cracking was observed in some locations in the outbound lane. It is noted the load cracking can be attributed to the poor drainage or loss of edge support. In addition to load cracking, which has the most significant impact on the PACES rating for this section, Level 1 block/transverse cracking was also observed on all segments in both directions. Figures 10 and 11 show typical distresses in the conventional section with less severe load cracking and with significant high-level load cracking, respectively. Rutting was observed in the outbound lane only. The right wheel path had a rutting of 1/16 in. to 2/16 in., and the left wheel paths had no rutting measured, which means the rutting is less than (1/16” or 1.5 mm).

Figure 10. Example of typical distresses on the conventional section with less severe cracking.

Figure 11. Example of typical distresses on the conventional section with severe load cracking.

South African Inverted Pavement Section

The South African section had an average rating of 81.8 (inbound lane) and 81 (outbound lane). Cracking in both directions was limited to Level 1 for both load and block/transverse cracking. The extent of load cracking ranged from 15% to 65%; the segment at +1200 ft.~+1300 ft. in the outbound lane had the most load cracking. The extent of block cracking ranged from 10% to 45%. Figure 12 shows an example of the typical distresses on the South African section. The inbound lane performs slightly better than the outbound lane in terms of rating and load cracking. Approximately 33.8% of Level 1 load cracking was reported in the inbound lane, which is slightly less than the 37.5% in the outbound lane. This low severity cracking, accompanied by limited rutting, suggests that the South African section is sufficient to sustain cyclic travel of trucks, both unloaded and loaded.

Figure 12. Example of typical distresses on the South African Inverted Pavement Section

Georgia Inverted Pavement Section

The Georgia inverted pavement section performed like the South African section. The average rating is 85.5 (inbound lane) and 81 (outbound lane). Similar to the South African section, cracking in the Georgia section was limited to Level 1 load and Level 1 block cracking. Load cracking ranged from 0% to 45%, and block cracking ranged from 15% to 60%. Minor rutting (1/16 in. – 2/16 in.) was observed on all segments in the outbound lane; the segments in the inbound lane reported limited rutting. Figure 13 shows an example of the typical distresses on the Georgia section.

Figure 13. Example of typical distresses on the Georgia Inverted Pavement Section

Figure 14 shows rutting reported on each 100-ft segment. In general, rutting was observed mainly in the outbound lane because of the trucks' heavy loads; very limited rutting was observed in the inbound lane. The segments highlighted in red circle are the ones excluded from the conventional section. Two segments (marked at +1100 ft.~+1200 ft. and +1200 ft.~+1300 ft.) in South African section had a rutting of 1/16 in. Compared to the Georgia section, the South African section had less rutting. This may imply the slushing could increase the stiffness of GAB. Further investigation, such as with a Falling Weight Deflectometer, is needed to verify the stiffness.

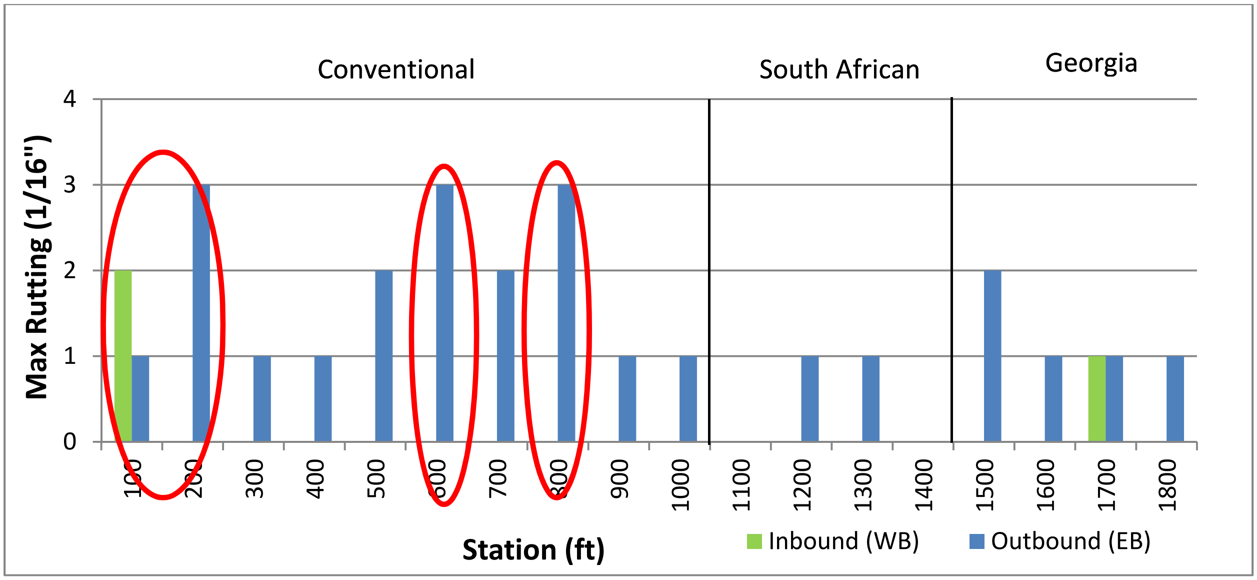


Figure 14. Max rutting for every 100-ft segments.

6. Summary

In 2001, three pavement test sections, composed of conventional pavement, South African inverted pavement, and Georgia inverted pavement, were constructed on an entrance road to the Martin-Marietta Morgan Quarry in Morgan County. Since its operation, there had been no quantitative evaluation of the performance (e.g., cracking and rutting) on these test sections, although a visual inspection was conducted in 2006. This year, Georgia Tech's sensing vehicle, equipped with a laser crack measurement system (LCMS), GEO3D cameras, GPS, IMU (inertial measurement system), and DMI (distance measuring instrument), was used to collect data to quantitatively evaluate the pavement condition on these sections according to GDOT's PACES standards. Data collection was conducted on April 8, 2016. The data was processed using developed algorithms and a manual review to extract distress information for every 100-ft segment. Two segments (marked at +0 ft.~+100 ft. and +100 ft. ~+200 ft.) near the entrance and one segment (marked at +500 ft.~+600 ft. and +700 ft.~+800 ft.) near the crossroad, were excluded from further analysis because the stop-and-go traffic pattern in these segments had significant impact on the conditions. The pavement condition on the three test sections is summarized as follows:

- The conventional section had diverse conditions with ratings ranging from 61 to 85. The average rating is about 75 after 15 years in service. Rutting, Level 1 block cracking, and severe load cracking (Levels 2 and 3) was observed on this section. Level 1 load cracking ranging from 15% to 65% was observed in the outbound lane where the loaded trucks travel, while lesser load cracking was observed in the inbound lane. Similarly, rutting in the outbound lane is higher than in the inbound lane. Thus, the average rating (71.7) in the outbound lane is significantly lower than the rating (77.8) in the inbound lane.
- Both inverted pavement sections performed better than the conventional section. The average ratings in the South African and Georgia sections were 81.4 and 83.3, respectively. Only Level 1 load cracking (not severe), block cracking, and minor rutting was observed in these two sections.
- It is noted that the South African section had a lower rating (81.4) than the Georgia section (83.3). The difference between the inbound lane and outbound lane is smaller, compared to the other two sections. There was very limited rutting observed on the South African section in both directions, except for two segments in the outbound lane.
- The Georgia inverted pavement section performed similar to the South African section. The average ratings were 85.5 and 81 in the inbound lane and outbound lane, respectively. Cracking in the Georgia section was limited to Level 1 load cracking (20% to 45%) and Level 1 block cracking (15% to 65%). It is noted that rutting (1/16 in. – 2/16 in.) was observed on all segments in the outbound lane.
- In all three sections, the condition in the outbound lane was worse than in the inbound lane because of the loaded trucks traveling in the outbound lane. Significant difference (more than 6 points in rating) can be observed on the conventional section, while the South African section has the least difference in both directions. This may imply the slushing technique could help in the stiffness of GAB. Further investigation (e.g., FWD) is needed to study the stiffness of each section.

References

Cortes, D. and Santamarina, J. C. (2012) “Inverted Base Pavement in LaGrange, Georgia: Characterization and Preliminary Numerical Analyses” Proceeding of the 91st Transportation Research Board Annual Meeting, Washington D.C.

GDOT. (1993). “Pavement condition evaluation system (PACES)” Georgia Department of Transportation, Office of Maintenance. Atlanta, GA.

Tsai, Y., Li, F. and Wu, Y. (2013) "A new rutting measurement method using emerging 3D line-laser-imaging system." *International Journal of Pavement Research and Technology*: 667.

Tsai, Y., Kaul, V., Yezzi, A. (2013) “Automating the Crack Map Detection Process for Machine Operated Crack Sealer.”Automation in Construction, Vol. 31, 10-18

Florida Department of Transportation. “2015 Flexible Pavement Condition Survey Handbook. http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/researchreports/pavement/flexiblehandbook.pdf. Accessed June 2016.

Appendix A: GDOT PACES Definitions

- **Load Cracking**

Load cracking is a product of constant loading by vehicle tires on the pavement surface. It is present in four severity levels. At the first level, longitudinal cracks begin to form in the wheel paths with short transverse cracks spurring from the main longitudinal crack.

At severity level two, there are typically two longitudinal cracks within the wheel path. As cracks spur from the original longitudinal crack, loading causes them to connect with other longitudinal cracks. Some polygons will form from cracks in the pavement surface.

At severity level three, there are typically three or more longitudinal cracks in the wheel path. They are all connected by transverse cracks. This forms a network of polygons in the wheel path. The polygons forming on the pavement surface is indicative of the base crumbling from being unable to carry the applied loads.

At severity level four, loading has caused more damage and the polygon size has reduced. At this severity, the polygons have begun to pop out of the surface. As more polygons pop-out, potholes form from the holes left behind.

- **Block/Transverse Cracking**

Block/Transverse cracking is a result of pavement weathering. As temperature changes, the pavement expands and contracts. This constant movement leads to cracks in the pavement surface. Block cracking is not confined to a particular area in the wheel path. At the lowest severity level, mostly transverse cracks are seen in the pavement surface. At this severity, the extent is computed as the total length in feet of all block/transverse cracks in the section. If the length of cracks exceeds 100 feet, the section is said to have 100% block/transverse cracking.

At severity two, block/transverse cracking develops definite block patterns. The cracks are typically wider than those at level one but may not be wide enough for sealing. Severity level two block/transverse cracking is measured in terms of area of coverage. Because it isn’t load related, this type of cracking typically covers the entire travel lane. The extent of cracking is determined by how much of the 100-ft sample area is covered by severity level two block/transverse cracking.

At severity 3 the size of the blocks has reduced and the crack width has increased. The cracks are typically wide enough to require sealing. There may also be evidence of spalling around the cracks at this severity.

APPENDIX B –

LaGrange By-Pass Road Field Measurements Report

LaGrange Bypass Inverted Pavement Condition Evaluation Report

YiChing Wu, Yi-Chang Tsai, Geoffrey Price

1. Background

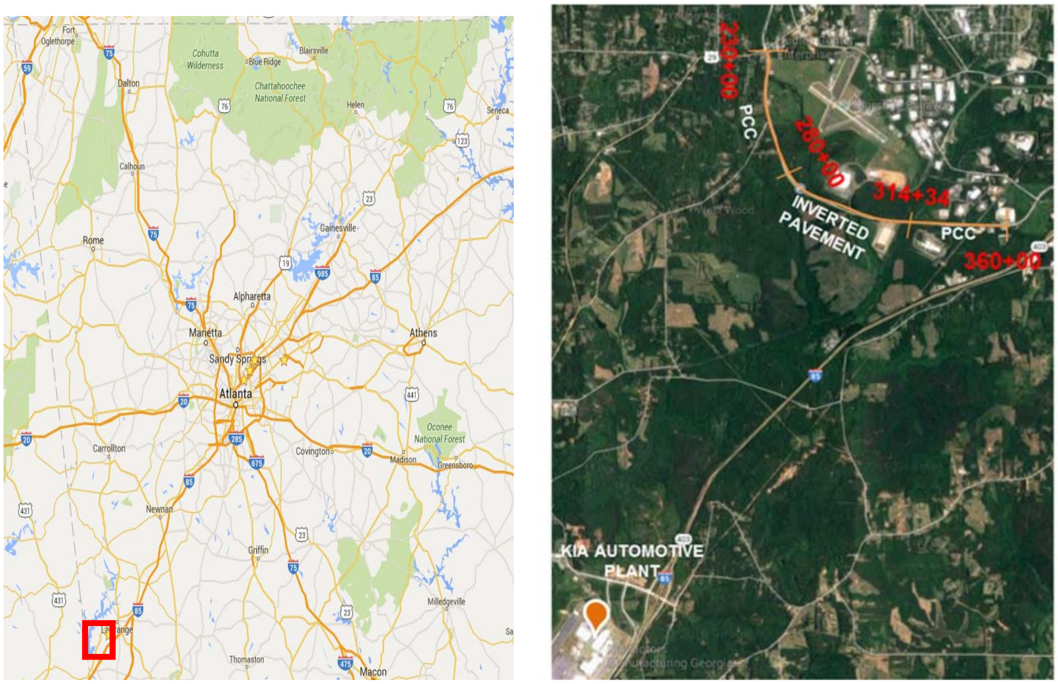
An inverted pavement (IP) structure differs from a traditional asphalt construction in that the lower, supporting pavement layers are much more rigid than the upper surface layers. This type of pavement structure has shown to be more cost-effective and more resistant to traffic loading than traditional Portland Cement Concrete (PCC) and hot mix asphalt (HMA) designs (Lewis et al., 2012). Although the pace of adopting inverted pavements in the United States has been slow, the Georgia Department of Transportation (GDOT) has taken the lead in this regard by building two IP test sections to observe their actual performance under local conditions, materials, and construction practices. The first IP test section was built on a private access road at the Lafarge Building Materials quarry in Morgan County, Georgia, in 2001. Based on the good performance observed at this test site, GDOT built a 3,400-ft long IP test section on Pegasus Parkway in LaGrange, Georgia. The construction began in January 2008 and was completed in April 2009 (Cortes & Santamarina, 2011). Detailed data (including laboratory and field tests on the subgrade, the cement-treated base, the asphalt concrete, etc.) before, during, and after construction were collected to gain a better understanding of the internal behavior and performance of this pavement structure. Despite the detailed information collected at this site, there has not been any survey conducted on this test section to quantitatively evaluate its performance since it opened to traffic in 2009.

2. Scope and Objective

The objectives of this study are to 1) critically evaluate the pavement condition of this test section using quantitative measures defined in the Pavement Condition Evaluation System (PACES) developed by the Georgia Department of Transportation (GDOT, 2007), and 2) establish quantitative baseline condition data for future deterioration analysis. With these objectives in mind, a condition evaluation was performed on the outside lanes (both Eastbound and Westbound lanes) of the test section.

3. Site Description

Pegasus Parkway is a two-lane road located near the LaGrange Callaway Airport in Troup County, as shown in Figure 1a. It is an industrial parkway intended to serve the growing car manufacturing industry in Southwest Georgia. The test section is approximately 3,400-feet long between the 280+00 and 314+00 mark, as shown in Figure 1b. Jointed plain concrete pavement (JPCP) was constructed at both ends of the test section. Figure 2 shows the pavement structures for the IP test section and the PCC section. These pavement structures were designed based on the 1972 AASHTO interim pavement design guide. They were designed to sustain approximately 4.78 million trucks in a 20-year design life, which was estimated based on an initial one-way traffic of 7,000 vehicles per day, a final one-way traffic of 11,700 vehicles at the end of design life, and 7% truck traffic (Cortes & Santamarina, 2011).



(a) Site Location (b) Test Section Location

Figure 1. Inverted pavement test section in LaGrange, GA

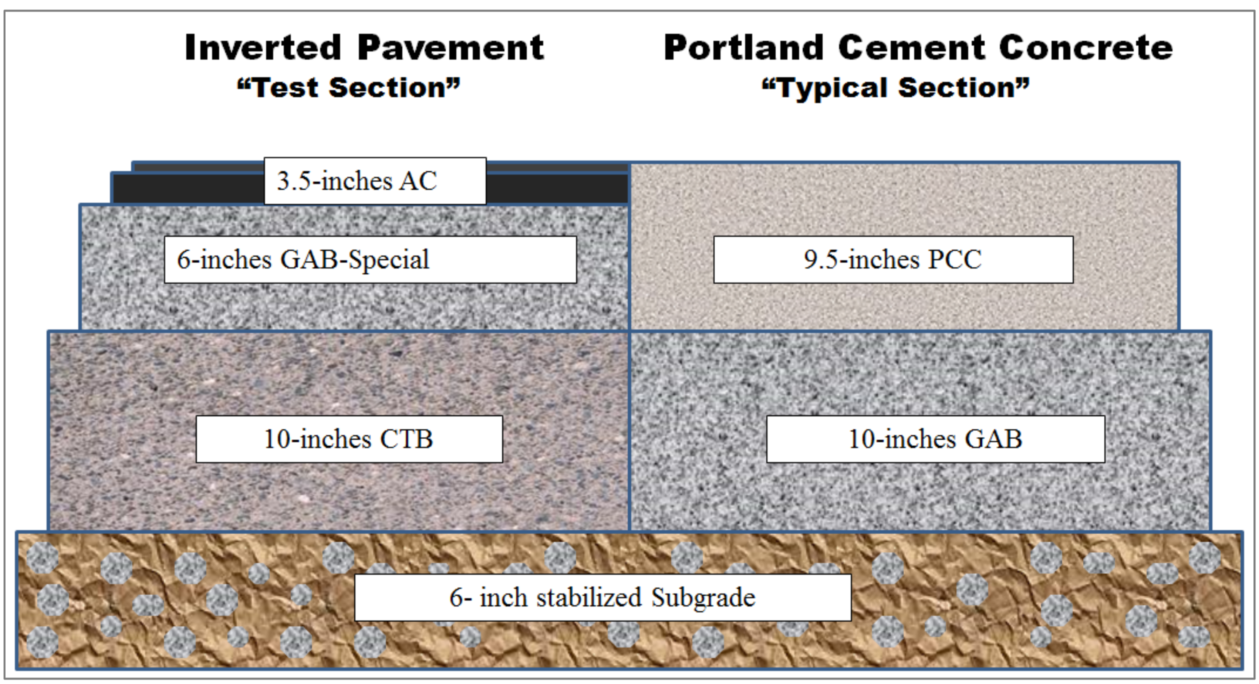


Figure 2. Pavement structures for IP test section and PCC section

4. **Data Collection**

Georgia Tech's sensing vehicle, equipped with a laser crack measurement system (LCMS), GEO3D cameras, GPS, an IMU (inertial measurement system), and a DMI (distance measuring instrument), was used for collecting 3D pavement data, 2D images, and GPS data for extracting pavement distresses based on PACES (GDOT, 1993) standards. Data collection was performed on June 30, 2016, on the outside lanes (both Eastbound and Westbound) of the test section. Prior to data collection, Dr. James Frost's research team marked the test section every 100-ft for use in a PACES survey. A diagram of the marking scheme is shown in Figure 3. A total of thirty-four, 100-ft segments were marked on the pavement. The Westbound (WB) transition point for the IP section will be referred to as the 0+00-ft mark, and the Eastbound (EB) transition point from IP to JPCP will be referred to as the 34+00-ft mark. The Georgia Tech sensing vehicle (see Figure 4), followed by a GDOT traffic control crew, was driven at approximately 30 mph on the outside lane to collect 3D pavement data, video log images, GPS data, etc. The 3D pavement data was collected at a resolution of 5-mm, 1-mm, and 0.5-mm for the *x* (driving direction), *y* (transverse direction), and *z* (depth) directions, respectively, with a full-lane width coverage (i.e., 12 ft). To facilitate better coverage of the access road, two runs of data were collected, and the run with less lateral movement (i.e., better coverage of the marked lane) was processed and analyzed.

Figure 3. Illustration of marking 100-ft segment

Figure 4. Georgia Tech sensing van (GTSV)

5. **Data Processing**

Distresses on the test section were extracted from the sensing data based on GDOT's PACES survey standards. PACES establishes standardized nomenclature for distresses and defines their respective severity levels and measurement methods for asphalt concrete pavement. There are ten distresses surveyed in PACES including: 1) rutting, 2) load cracking (LC), 3) block/transverse cracking (B/T), 4) reflection cracking, 5) raveling, 6) edge distress, 7) bleeding and flushing, 8) corrugation and pushing, 9) loss of pavement section, and 10) patches and potholes. Cracking (load cracking and block cracking) and rutting were the only distresses observed on this test section. More information on the cracking defined in PACES (types, extent and severities) can be found in Appendix A. Cracking and rutting on each 5-m interval were first extracted using an automatic crack detection algorithm (Tsai et al., 2013) and rutting algorithm (Tsai et al., 2013) from the 3D pavement data. Cracking information, including type, severity level, and extent, in each 5-m interval was then reviewed and adjusted manually to ensure the distress information was correct. Rutting was computed at approximately every 1 ft. This data was then aggregated for each 100-ft segment, which is the sample unit length in PACES. A PACES rating on a scale of 0 to 100 (with 100 representing pavement with no visible distresses) was computed for each 100-ft segment based on the extent and the severity levels of distresses present. Tables 1 and 2 summarize the rating and distresses derived from the sensing data for each 100-ft segment of the inbound and outbound lanes.

Table 1: PACES Summary (EB)

Station	Rutting (1/16")		Load Cracking Level 1 (%)	Block Cracking Level 1 (%)	PACES Rating
	LWP*	RWP*			
0-100	2	1	0	0	98
100-200	2	1	0	0	98
200-300	1	1	5	0	96
300-400	1	0	10	0	94
400-500	2	1	5	0	94
500-600	2	1	10	0	92
600-700	2	1	10	0	92
700-800	2	1	5	0	94
800-900	2	1	10	5	90
900-1000	1	1	0	0	100
1000-1100	2	2	20	0	90
1100-1200	2	2	5	0	94
1200-1300	2	1	0	0	98
1300-1400	3	1	5	0	94
1400-1500	3	1	5	0	94
1500-1600	3	1	0	0	98
1600-1700	3	2	30	0	88
1700-1800	3	2	15	0	91
1800-1900	3	2	45	0	83
1900-2000	2	2	0	0	98
2000-2100	2	2	0	0	98
2100-2200	2	1	0	0	98
2200-2300	4	1	0	0	95
2300-2400	4	1	0	0	95
2400-2500	2	1	0	0	98
2500-2600	2	1	0	0	98
2600-2700	2	1	0	0	98
2700-2800	2	1	0	0	98
2800-2900	2	1	0	0	98
2900-3000	2	1	0	5	96
3000-3100	2	1	0	0	98
3100-3200	2	1	0	0	98
3200-3300	1	2	0	0	98
3300-3400	1	2	0	0	98
Average	2.1	1.2	5.3	0.3	95.3
MIN	1	0	0	0	83
MAX	4	2	45	5	100

*LWP = Left Wheel Path

*RWP = Right Wheel Path

Table 2: PACES Summary (WB)

Station	Rutting (1/16”)		Load Cracking Level 1 (%)	Block Cracking Level 1 (%)	PACES Rating
	LWP*	RWP*			
0-100	2	1	15	0	91
100-200	2	1	10	0	92
200-300	2	1	15	20	85
300-400	2	0	5	0	94
400-500	3	0	0	0	98
500-600	3	0	0	5	96
600-700	3	0	5	10	94
700-800	4	0	5	5	89
800-900	2	1	0	5	96
900-1000	3	0	0	0	98
1000-1100	3	1	0	0	98
1100-1200	3	1	0	0	98
1200-1300	3	1	0	0	98
1300-1400	2	2	5	0	94
1400-1500	2	2	20	0	90
1500-1600	3	1	0	5	96
1600-1700	3	2	0	0	98
1700-1800	3	2	0	0	98
1800-1900	3	2	0	0	98
1900-2000	2	1	0	5	96
2000-2100	3	1	0	0	98
2100-2200	3	1	0	0	98
2200-2300	3	2	10	0	92
2300-2400	3	2	5	10	90
2400-2500	3	2	0	10	94
2500-2600	2	2	15	0	91
2600-2700	3	1	0	0	98
2700-2800	3	0	0	5	96
2800-2900	4	1	0	10	91
2900-3000	4	2	0	0	95
3000-3100	4	1	5	5	89
3100-3200	3	1	0	0	98
3200-3300	2	0	40	0	85
3300-3400	2	0	35	0	87
Average	2.8	1.0	5.6	2.8	94.1
Min	2	0	0	0	85
Max	4	2	40	20	98

*LWP = Left Wheel Path

*RWP = Right Wheel Path

6. **PACES Data Analysis**

PACES Rating

The test section has performed well with an overall average rating of 94.7 after 7-year of service. Of the 64 segments (34 in each direction), only 6 segments had a rating less than 90. It is noted that on average, the pavements in Georgia reach a rating of 70 in 10.6 years (Tsai et al., 2016). Based on typical pavement deterioration observed on Georgia's pavements, the test section with a rating of 94.6 can last approximately 8 more years before the rating drops to 70, which triggers the need for resurfacing. PACES ratings for each 100-ft segment in two directions (EB and WB) are shown in Figure 5. In general, the ratings in the EB are slightly higher than those in the WB. The average rating in the EB and WB directions is 95.3 and 94.1, respectively. This may be because traffic loads in the WB are heavier than those in the EB; traffic load data can be collected to better understand the pavement performance in the EB and WB lanes. The rating in the EB ranges from 83 to 100. The segments between the 16+00-ft and 20+00-ft marks had lower ratings (less than 90) compared to the other segments. The segments between the 19+00-ft and 34+00-ft marks had relatively high ratings (greater than or equal to 95) because no cracking or minimum cracking was observed on these segments. The rating in the WB lane ranges from 85 to 98. The segments with lower ratings are at the two ends of the test section (the 0+00-ft to 3+00-ft marks and the 30+00-ft to 34+00-ft marks), especially on the beginning of WB lane (30+00-ft to 34+00-ft marks) when transitioning from the bridge to the IP test section.

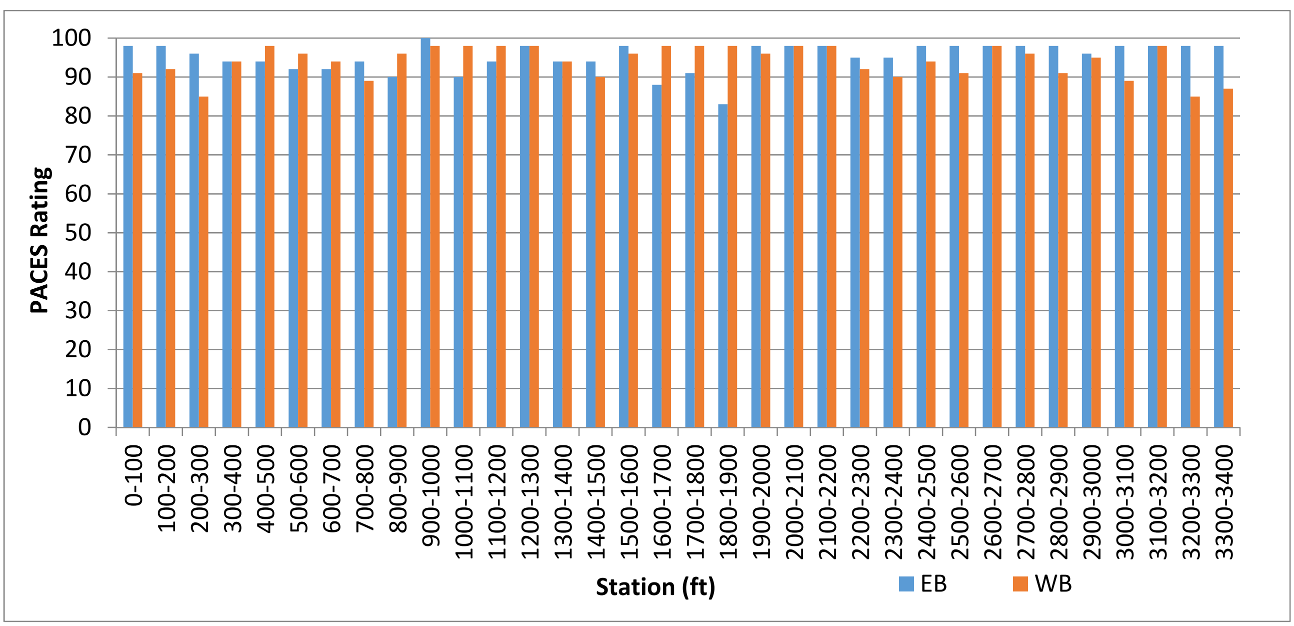


Figure 5. PACES rating in the EB and WB

Cracking

There were only Level 1 load cracking and limited Level 1 block cracking observed on the test section. Figure 6 shows examples of the cracking observed on the test section; the cracks were 4-5 mm-wide, single-line cracks. Of the 68 segments (34 in each direction), 28 segments exhibited load cracking, while only 14 segments exhibited block cracking. This level of cracking indicates that the pavement is just beginning to deteriorate and the cracks are not extensive yet. The cracking extent values for both load and block cracking in the EB and WB lanes are shown in Figures 7a and 7b. Of the EB segments (34 segments), 14 segments exhibited load cracking (ranging from 5% to 45%) and the average extent for the entire EB lane (34 segments) is approximately 5.3%. It is noted that the load cracking was observed only on the first half of the test section (between the 2+00 and 19+00 marks); there was no load cracking on the second half of the section (between the 19+00 and 34+00 marks) where the road is in a tangent (straight) with a -3% downhill vertical grade. The segments approaching the 16+00-ft to 19+00-ft marks from the EB direction have significantly higher cracking than the other segments. This higher presence of cracking may be attributed to the horizontal curve in a downhill grade from the 16+00-ft to 19+00-ft marks. As drivers approach the horizontal curve, they will likely decelerate to safely navigate through the curve. The deceleration along the horizontal curve, especially by trucks, may partially cause the increased damage to the pavement in that area. There was minimum block cracking (approximately 0.3%) in the EB lane; only two segments were observed with 5% of block cracking. Compared to the EB lane, the WB lane segments had similar load cracking in terms of the extent and more block cracking. The average load cracking extent in the WB lane is approximately 5.9%; however, the cracks were distributed differently. The load cracking was observed across the length of the test section with the segments near the west side (the 32+00 to 34+00 marks) showing the highest extents of load cracking. This may be attributed to the vehicle's dynamic loading when moving from the bridge to the IP section. Block cracking was observed on a total of 12 segments ranging from 5% to 20%. There was no load cracking observed on the curved section (the 16+00-ft to 19+00-ft marks). This may be because the curve is an uphill grade from the WB direction. The vehicle does not need to decelerate excessively to navigate through the curve. Further analysis is needed to better understand the pavement performance with respect to roadway geometry (e.g., horizontal curve, vertical grade, and super-elevation) as well as cut/fill.

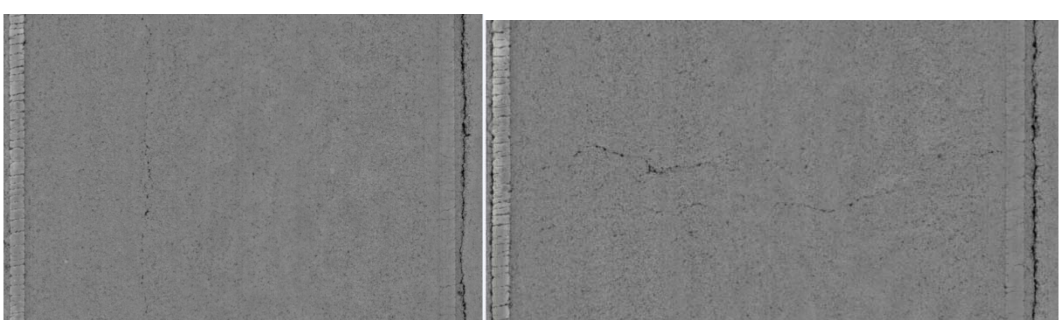
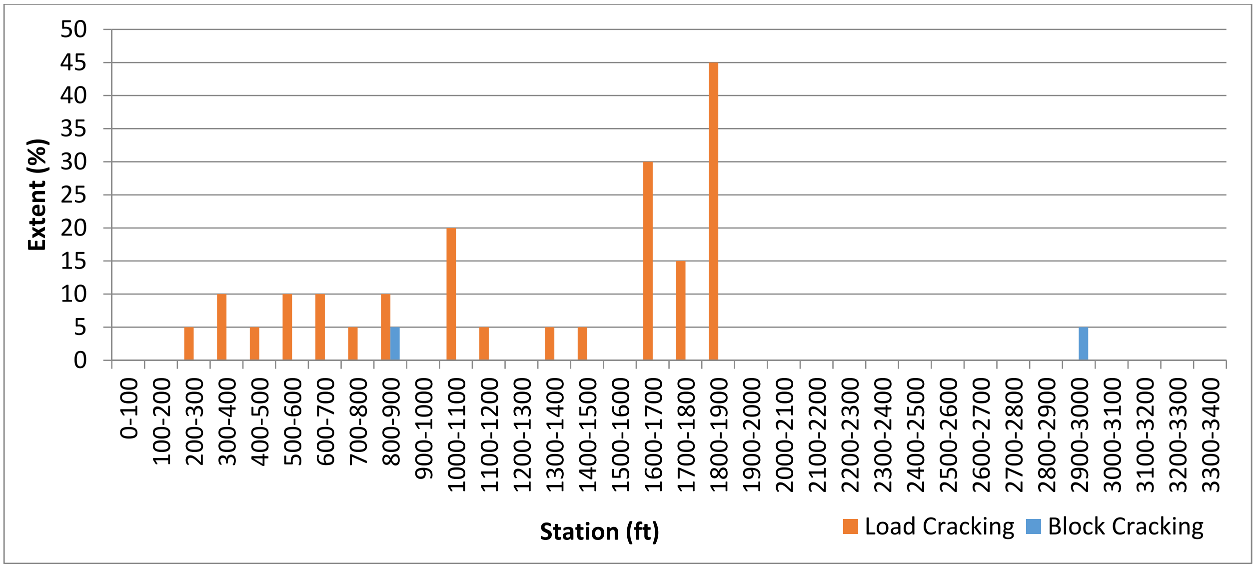
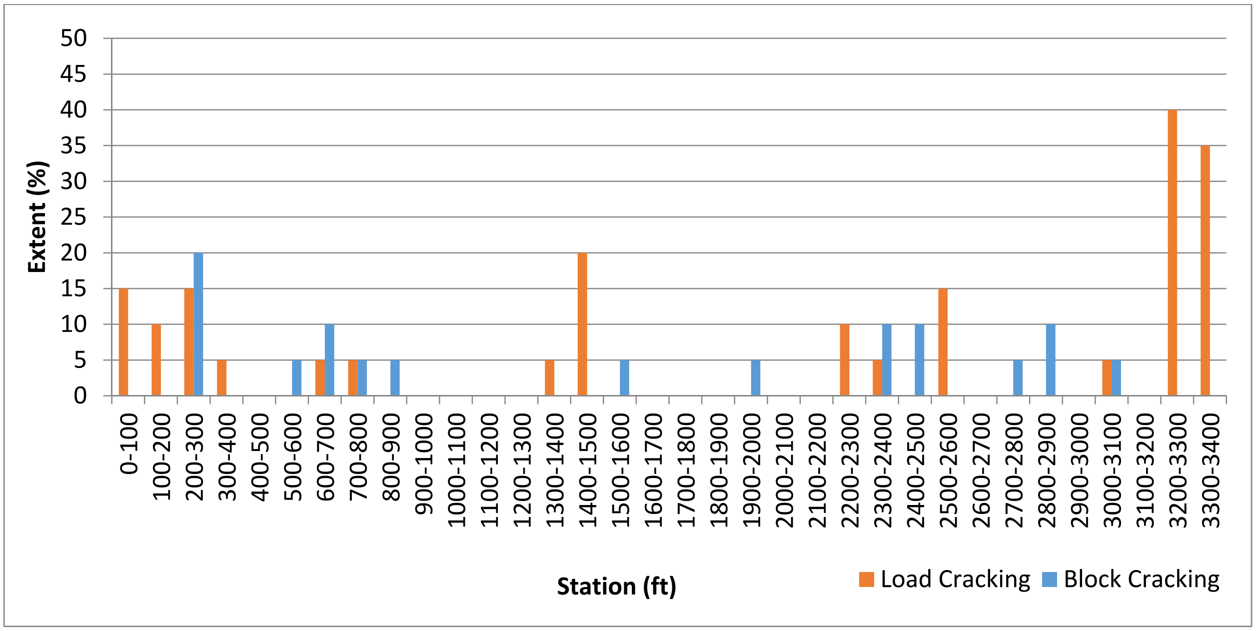


Figure 6. Examples of load cracking and block cracking observed on the test section



(a) Cracking in the EB



(b) Cracking in the WB

Figure 7. Extent of Cracking in the EB and WB

Rutting

Moderate rutting was measured on the test section; the average rutting in the EB and WB lanes is approximately 2/16 in. and 3/16 in., respectively. Figure 8 shows the maximum rut depth (between left and right wheel paths) of each 100-ft segment in both the EB and WB lanes. In general, rutting in the EB lane was slightly lower than that in the WB lane. For the EB lane, only 7 segments had a rut depth greater than or equal to 3/16 in., and 6 of them were reported on the segments between the 13+00-ft and 19+00-ft marks, where there is, also, a higher extent of load cracking. For the WB lane, however, 23 of the 34 segments exhibited rutting depths of 3/16 in. or greater. In particular, all segments between 28+00 and 31+00 showed a high rut depth (1/4 in.). It is noted that the rut depth in the left wheel path (inside wheel path) was higher than in the right wheel path (the outside wheel path) in both EB and WB lanes. Further analysis needs to be done to assess the potential causes (e.g., super-elevation, cut/fill, etc.) of higher rutting in the left wheel path.

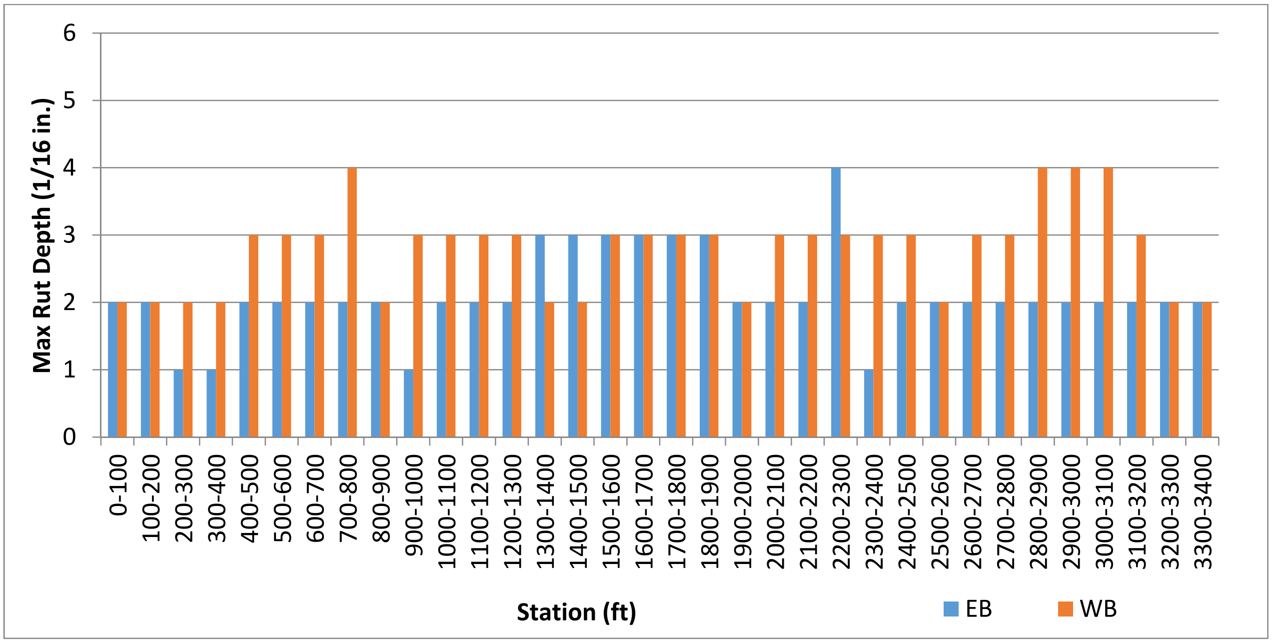


Figure 8. Maximum rutting in the EB and WB

7. **Summary**

Through the use of the Georgia Tech Sensing Van, 3D pavement and 2D video log data were collected on the section of inverted pavement on Pegasus Parkway in LaGrange, Georgia. After processing these data for cracking and rutting information, the distress information for every 100 feet was aggregated. From this data, the PACES score was determined according to GDOT specifications. The scores indicate that since being opened to traffic in 2009, the IP section has performed well:

- The test section has performed well with an overall average rating of 94.7 after 7 years of service. Of the 64 segments (34 in each direction), only 6 segments had a rating less than 90. This is especially notable when considering, on average, Georgia's pavements reach a rating of 70 in 10.6 years.
- Overall, the test section showed limited and low-severity (Level 1) load cracking and block/transverse cracking and moderate rutting. The average extent for load cracking and block cracking is approximately 5.4% and 1.5%, respectively. Of the 68 segments (34 in

each direction), 28 segments exhibited load cracking (ranging from 5% to 45%), while only 14 segments exhibited block cracking (ranging from 5% to 20%).

- The load cracking was distributed differently in the EB and WB lanes. For the EB lane, the load cracking was observed only on the first half of the test section (between the 2+00 and 19+00 marks). The segments approaching the 16+00-ft to 19+00-ft marks from the EB direction had significantly higher cracking than the other segments. This higher presence of cracking may be attributed to the horizontal curve in a downhill grade from the 16+00-ft to 19+00-ft marks. For the WB lane, the load cracking was observed across the length of the test section with the segments near the west side (the 32+00 to 34+00 marks) showing the highest extent of load cracking. This may be attributed to the vehicle dynamic loading when moving from the bridge to the IP section.
- The WB lane exhibited more block/transverse cracking than the EB lane. Only two segments in the EB lane exhibited blocking cracking, while 12 segments in the WB lane were reported with block cracking. This may be attributed to the heavy truck loads in the WB lane.
- Moderate rutting was measured on the test section; in general, the WB lane had more rutting than the EB lane. The average rutting in the EB lane and WB lane was approximately 2/16 in. and 3/16 in., respectively. A 3/16 in. of rutting was reported between the 13+00-ft and 19+00-ft marks in the EB lane, where the load cracking was also high. Further study is needed to determine the causes of higher rates of rutting and cracking in these segments.
- It is noted that the rut depth in the left wheel path (inside wheel path) was higher than that in the right wheel path (outside wheel path) in both EB and WB lanes. Further analysis needs to be done to assess the potential causes.

Using sensing technology, the cracking and rutting information for all 100-ft segments was fully captured. Through thorough analysis, the current condition of cracking and rutting for the IP section has been established. The test section has performed well after 7 years of service; however, the segments with higher rates of cracking and rutting need to be monitored and studied. With this baseline information, in-depth analysis on crack deterioration can be performed in the future to assess changes in crack characteristics, such as length, width, and depth. In addition, the growth of rutting in terms of both depth and length can be analyzed to determine any problems in base or surface layers. Through this analysis, the performance of the IP section can be analyzed over time to evaluate how well this new pavement structure performs in comparison to a conventional asphalt pavement structure.

References

Cortes, D. and Santamarina, C. Inverted Base Pavement in LaGrange, Georgia: Characterization and Preliminary Numerical Analyses. *TRB 90st Annual meeting*. 2011. http://www.dot.ga.gov/BuildSmart/research/Documents/Inverted_Base_Pavement_in_LaGrange_GA.pdf

GDOT. (2007). “Pavement condition evaluation system (PACES)” Georgia Department of Transportation, Office of Maintenance. Atlanta, GA.

Lewis, Dwane E., Keith Ledford, and E. I. T. Tanisha Georges. "Construction and Performance of Inverted Pavements in Georgia." *TRB 91st Annual meeting*. 2012.

Tsai, Y., Li, F., and Wu, Y. (2013) "A new rutting measurement method using emerging 3D line-laser-imaging system." *International Journal of Pavement Research and Technology*: 667.

Tsai, Y. and Wu, Y. (2016) "Study of Georgia’s Pavement Deterioration/Life and Potential Risks of Delayed Pavement Resurfacing and Rehabilitation." Georgia Department of Transportation, Atlanta, Georgia.

APPENDIX C –

Inverted Base Pavement Presentation Materials

Invited seminar given at

AFP70 Mineral Aggregates Sub-committee

Special Session at 2016 TRB Annual Meeting

Washington D.C.

Presenter: David Frost, Georgia Tech

Performance Assessment of Georgia Inverted Pavement Test Sections

David Frost, Georgia Tech

(with contributions from J. Cardosa, D. Cortes, S. Hanumasagar, D. Jared, D. Lewis, E. Papadopoulos, C. Santamarina, J. Tsai)

January 11th 2016

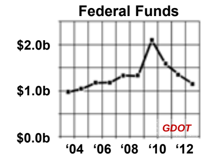
The US Road System is vast and suffers from insufficient funding.

Georgia IBP

Vast network

Wikipedia.org

Depleted funding



Poor condition

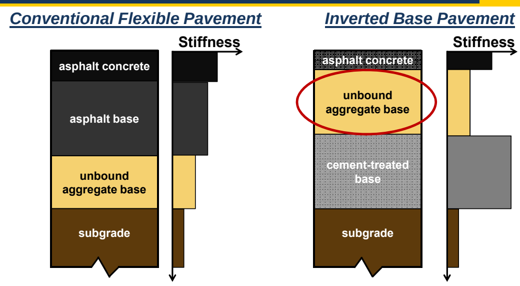
Solution Sources

- Innovative designs
- Optimal use of materials

(Adapted from Papadopoulos, 2015)

An inverted base pavement (IBP) is an innovative technology that can optimize the use of materials.

Georgia IBP

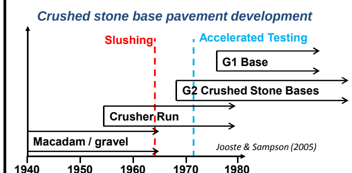


- Stiffness contrast between layers
- Granular base : close to load ➔ demand for exceptional performance

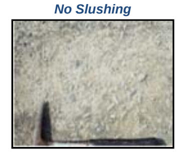
(After Papadopoulos, 2015)

South Africa has developed and utilized inverted base pavements for half a century.

Georgia IBP



No Slushing



Slushing after compaction

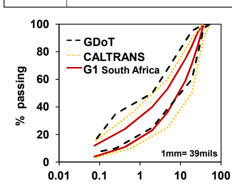
Kleyn, 2012

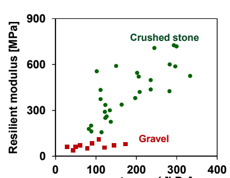
(After Papadopoulos, 2015)

Top quality unbound aggregate base is the fundamental block of IBPs.

Georgia IBP

	South Africa G1 base	CALTRANS base	GDoT GAB
Fines	LL<25%, PI<4	Sand Equivalent <21	Sand Equivalent <20
Shape	flackiness (sphericity) <35%	N/A	elongated particles <10%
Density	86-88% of apparent solid density (~102% mod Proctor)	95% of CTM 231	98% mod. Proctor



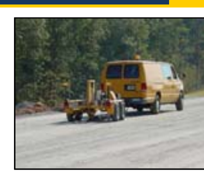


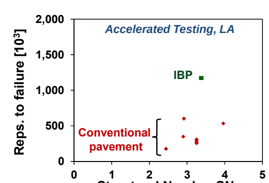
(After Papadopoulos, 2015)

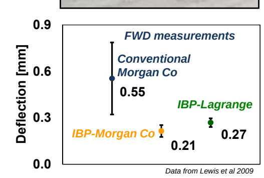
US experience with inverted base pavements had also been long but sparse.

Georgia IBP

- New Mexico (1960s)
- USACE (1970s)
- Georgia Tech (1980s)
- Louisiana (1990s)
- Morgan County GA quarry (2000s)
- Lagrange GA bypass (2000s)
- Bull Run VA highway (2010s)
- Pineville NC quarry (2010s)







(Adapted from Papadopoulos, 2015)

Georgia (led by GDoT supported activities) have continuously moved towards greater understanding of potential of IBP.

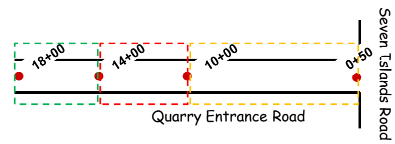
Georgia IBP

Progression of these efforts summarized within 5 Phases:

- **Phase I:** Morgan County Quarry Test Section (2000 to present)
- **Phase II:** LaGrange Bypass Test Section including detailed construction documentation (2008 to present)
- **Phase III:** Multi-faceted lab testing - field testing – compaction – modelling study (2008 to 2015)
- **Phase IV:** Field pavement distress and lab “slushing” simulation studies (2015 – present)
- **Phase V:** Proposed pooled-fund study on Inverted Base Pavements (solicitation posted – project in planning stage)

Phase I: multiple test sections with well documented loading over 15 year period.

Georgia IBP



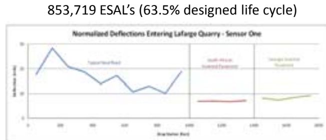
- **Station 0+50 through Station 10+00** Conventional Haul Road
- **Station 10+00 through Station 14+00** South African Base
- **Station 14+00 through Station 18+00** Georgia Base

Construction completed in 2001

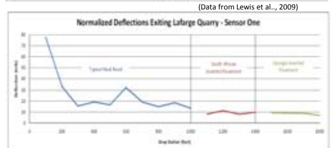
Phase I: multiple test sections with well documented loading over 15 year period.

Georgia IBP

Performance Evaluation: November, 2006
853,719 ESAL’s (63.5% designed life cycle)



(Data from Lewis et al., 2009)



No rutting and no cracking of asphaltic layer observed in IBP sections even as recently as 2015

Phase II: fully documented construction project provides basis for long-term IBP performance assessment.

Georgia IBP

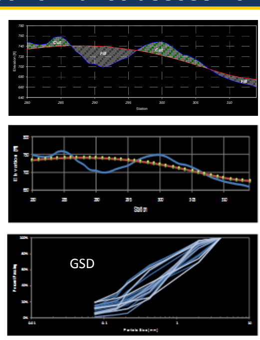
LaGrange By-Pass

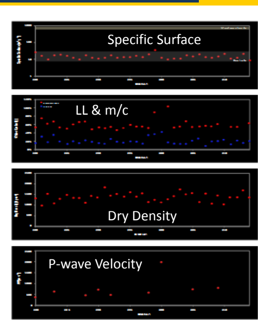
Test section:
0.65 miles long
2 lanes
PCC typical section
IBP test section

Construction completed in 2009

Phase II: fully documented construction project provides basis for long-term IBP performance assessment.

Georgia IBP

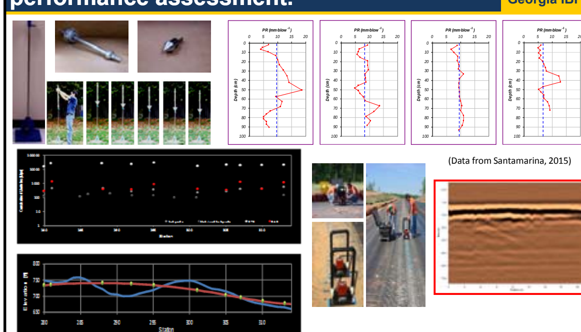




Laboratory Characterization of Subgrade
(Data from Santamarina, 2015)

Phase II: fully documented construction project provides basis for long-term IBP performance assessment.

Georgia IBP



(Data from Santamarina, 2015)

Extensive lab and field characterization studies for various layers

Phase III: comprehensive laboratory – field – numerical study that expanded understanding of IPB component performance.

Georgia IBP

Compaction

Lab Characterization

Inverted Base Pavements

In situ testing

Mechanistic analysis

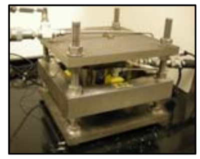
Study completed in 2014

(After Papadopoulos, 2015)

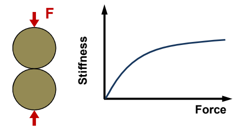
Phase III: current laboratory methods do not account for the complex nature of aggregate base stiffness.

Georgia IBP

Inherent Anisotropy



Stress-Dependent Stiffness

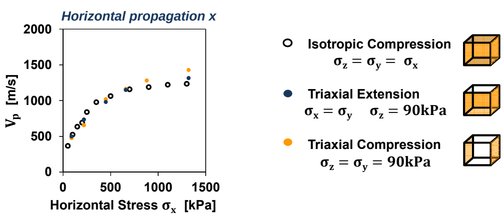


- In-chamber compaction.
- Independent control of the 3 principal stresses.
- P-wave instrumentation in each direction.

(After Papadopoulos, 2015)

Phase III: stress ratio has small influence on the small-strain stiffness as long as the material is away from failure.

Georgia IBP



Characterization of unbound aggregate base stiffness:

- Granular Bases: inherent & stress-induced anisotropy exist.
- M_{max} : function of normal stress
- Loading conditions: almost no effect on M_{max}

(Adapted from Papadopoulos, 2015)

Phase III: soil compaction is omnipresent in most geotechnical construction and has known impact on performance.

Georgia IBP

Inadequate compaction results

Post-placement changes in material

Lab-field discrepancies

(Adapted from Papadopoulos, 2015)

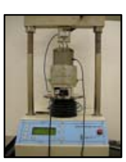
≠

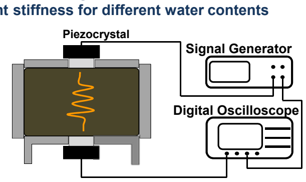
Phase III: an extensive lab study was conducted to assess the compaction process in terms of stiffness.

Georgia IBP

- Specimens compacted using Modified Proctor
- Stress-dependent stiffness for different water contents

(Adapted from Papadopoulos, 2015)





Effect of compaction on granular base stiffness:

- ρ_{dry}: not sufficient to assess compaction
- Granular base stiffness not affected by water content
- Water content affects permanent deformation
- Velocity changes reflect accumulation of deformation

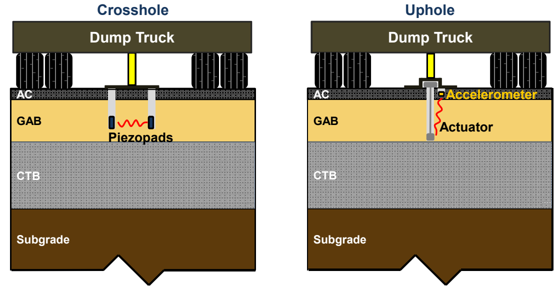
Phase III: two tests were conceived to measure the stiffness of as-built aggregate bases.

Georgia IBP

Measure the stiffness of as-built unbound aggregate bases

Crosshole

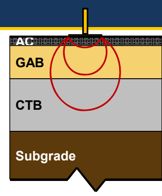
Uphole



(After Papadopoulos, 2015)

Phase III: successive forward simulations were conducted to determine the state of stress in the pavement.

Georgia IBP



Two setups to capture anisotropic stiffness – 2 case histories

- In situ GAB: anisotropic stress-dependent stiffness
- Field values ≠ lab values:
  1. Preconditioning
  2. Compaction method (Field vs. lab)
- Field-Compacted GAB: great stiffness

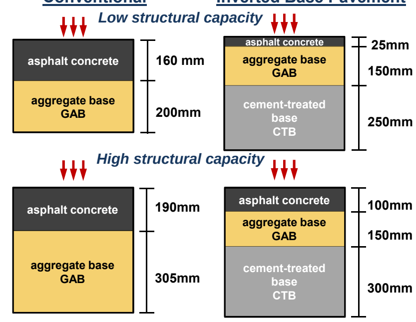
(Adapted from Papadopoulos, 2015)

Phase III: numerical simulations were conducted to compare IBPs to conventional pavements.

Georgia IBP

(Adapted from Papadopoulos, 2015)

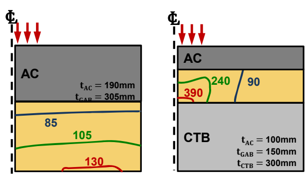
Mechanistic analysis



Phase III: aggregate base stiffness in IBPs is high due to the confinement provided by the CTB.

Georgia IBP

(Adapted from Papadopoulos, 2015)



Tangent Vertical Young's modulus E_v (MPa)

Constitutive model:
- Anisotropy, stress-dependency, shear softening

Inverted base pavements:
- Unique load-bearing mechanism

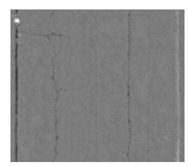
Granular base:
- Underutilized in conventional pavements
- Great contribution in inverted base pavements

Thin asphalt layers:
- Potential for economic savings
- Caution when subjected to strong shear

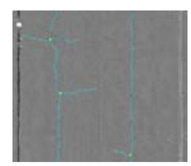
Phase IV: IBP pavement surface distress study using imaging and LiDAR.

Georgia IBP

3D Laser Imaging System



Range Image



Detected Crack Map

- **The GDOT's Pavement Condition Evaluation System (PACES) is used for conducting the annual asphalt pavement condition surveys in Georgia.**
  - Ten different distress types and their severity levels are defined.
  - Four of them are crack related distresses: load cracking, B/T cracking, edge distress, and reflective cracking.

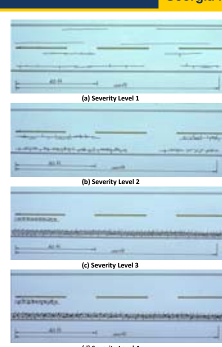
(Courtesy of James Tsai)

Phase IV: IBP pavement surface distress study using imaging and LiDAR.

Georgia IBP

- **Load cracking is caused by repeated heavy loads and always occurs in the wheel paths:**
  - **Severity Level 1** usually starts as single longitudinal cracks in the wheel path.
  - **Severity Level 2** has a single or double longitudinal crack with a number of 0-2 feet transverse cracks intersecting.
  - **Severity Level 3** shows an increasing number of longitudinal and transverse cracks in the wheel paths. This level of cracking is marked by a definite, extensive pattern of small polygons.
  - **Severity Level 4** has the definite "alligator hide" pattern but has deteriorated to the point that the small polygons are beginning to pop out.

(Courtesy of James Tsai)

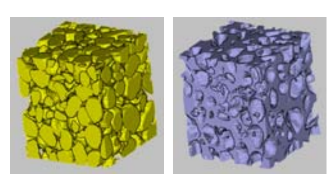


Phase IV: laboratory study of slushing effect on microstructure and load transfer.

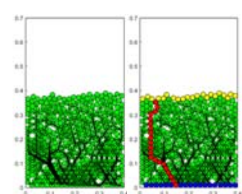
Georgia IBP

Laboratory Simulation of Slushing
Study of evolution of aggregate shape, pore structure and load path during slushing

Characterization using UI Aggregate Image Analyzer



Reconstruction of Real Particle and Pore Structures Using Optical Microscopy, Image Mosaic and Serial Sectioning to create high-fidelity geo-structures

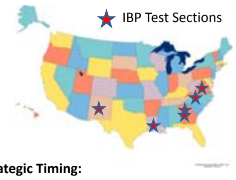


Numerical simulations of shortest load path and highest contact forces

Phase V: pooled fund study to leverage current knowledge and interest to expedite implementation of IBP design specifications for state DOT's.

Georgia IBP

GDoT proposed Pooled-Fund Study 09/25/15



Objective: To expedite the implementation of inverted base pavement design specifications for state DoT's and to make IBP a practical and reliable alternative design approach for highway pavements.

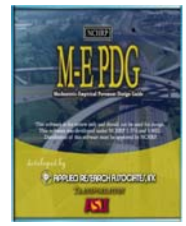
Broad Tasks:
- Further study of existing field cases with detailed construction records and long-term performance monitoring data
- Advanced material characterization and modeling with emphasis on granular base
- Numerical simulation of IBP performance
- Relevant calibrations for design within framework of Mechanistic-Empirical Pavement design Guide (MEPDG)

Strategic Timing:
- Existing field cases range between ~95% and ~0% of design life thus allow broad performance assessment
- Ability to compare IBP and conventional pavement performance under same loading histories
- High interest for use of innovative designs that optimize material use within constrained budgets

Phase V: pooled fund study to leverage current knowledge and interest to expedite implementation of IBP design specifications for state DOT's.

Georgia IBP

GAPS in knowledge:
- Improved understanding of IBP component performance, particularly of unbound granular base, through advanced material characterization and modeling
- Better understanding of relationship between construction and long-term performance of CTB, in particular, and IBP, in general, through continued assessment of test sections and associated numerical simulations



BARRIERS to implementation:
- Need for reliable framework for assessment of economics of IBP for both construction and performance stages
- Need for material model calibrations and damage functions suitable for IBP designs in MEPDG
- Guidelines for implementation through all phases of design, construction and maintenance

PROPOSED POOLED-FUND STUDY CAN RESOLVE GAPS AND ELIMINATE BARRIERS

TIMING IS STRATEGIC – TIPPING POINT HAS BEEN REACHED - PARTNERS NEEDED

Selected References

Georgia IBP

Cortes, D. D. (2010). "Inverted Base Pavement Structures." Ph.D., Georgia Institute of Technology, Atlanta, GA.

Terrell, R.G., Cox, B.R., Stokoe II, K.H., Allen, J.J., and Lewis, D. (2003). Transportation Research Record, No. 1837, pp. 50-60.

Papadopoulos, E. (2014). "Performance of Unbound Aggregate Bases and Implications for Inverted Base Pavements." Ph.D., Georgia Institute of Technology, Atlanta.

Cortes, D.D., Shin, H.S. and Santamarina, J.C. (2012), Numerical Simulation of Inverted Pavement Systems, ASCE J. Transportation Engineering, vol. 138, no. 12, pp. 1507-1519.

Cortes, D.D. and Santamarina, J.C. (2013), Inverted Base Pavement Case History (LaGrange, Georgia): Construction, Characterization and Preliminary Numerical Analyses, International J. Pavement Engineering, International Journal of Pavement Engineering vol. 14, 463-471

Lewis, D.E. and Jared, D.M. (2012). "Construction and Performance of Inverted Pavements in Georgia." *Proceedings of 91st TRB Meeting*, Washington D.C., Paper # 12-1872.

Papadopoulos, E., D. Cortes, and Santamarina J.C., (2015). "In Situ Assessment Of The Stress-Dependent Stiffness Of Unbound Aggregate Bases: Application In Inverted Base Pavements", International Journal Pavement Engineering., http://dx.doi.org/10.1080/10298436.2015.1022779

Papadopoulos, E. and Santamarina J.C., (2015). "Analysis Of Inverted Base Pavements With Thin Asphalt Layers", International Journal of Pavement Engineering, http://dx.doi.org/10.1080/10298436.2015.1007232

Papadopoulos, E., and Santamarina, J. C. (2014). "Optimization of Inverted Base Pavement Designs with Thin Asphalt Surfacing." *Geo-Congress 2014 Technical Papers*, ASCE, Atlanta, GA, 2996-3004.

Acknowledgements

Georgia IBP

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- Dwane Lewis
- Gretel Sims
- Supriya Kamatkar
- David Painter
- Tom Yu
- Mark Wayne

Georgia Tech

- Douglas Cortes
- Thymios Papadopoulos
- Carlos Santamarina
- James Tsai
- Andreina Etzi
- Alessio Contu
- Sangy Hanumasagar

Others

- John Cardosa
- Georgene Geary
- Jim Maxwell
- Erol Tutumluer
- Rick Boudreau

Webinar organized by

AFP70 Mineral Aggregates Sub-committee

Presented July, 2016

Atlanta, GA.

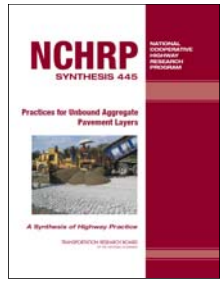
Presenters: Rick Boudreau, Boudreau Engineering; David Frost, Georgia Tech; and Kevin Vaughan, Vulcan Materials.

Inverted Pavements

A TRB Webinar

(AFP70 – Mineral Aggregates)

Why now?



The IP topic was briefly reviewed in **NCHRP Synthesis 445 – Practices for Unbound Aggregate Pavement Layers** (Erol Tutumluer, Deb Mishra and Rick Boudreau).

download from the TRB website:
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_445.pdf

We received tremendous audience feedback following the TRB Webinar presented June 24, 2015 (Erol Tutumluer, Andrew Dawson, Deb Mishra and Rick Boudreau).

Invited Speaker Session
TRB 95th Annual Meeting

Sponsored by AFP70 – Mineral Aggregates
(E. Tutumluer – Chair)

- Rick Boudreau (Moderator) – Boudreau Engr.
- Kevin Vaughan – Vulcan
- Wynand Steyn – South Africa
- David Frost – Georgia Tech
- Reza Ashtiani – UTEP
- Bryce Symons – N. Mexico

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Outline

- Introduction and Background *(Boudreau)*
- Design Considerations *(Frost)*
- Construction Methods *(Vaughan)*
- Performance Assessment *(Frost)*
- Summary Comments *(Boudreau)*

Inverted Pavement - Alias

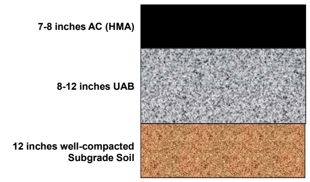
- Inverted Base Pavement (IBP)
- Inverted G1-Base Pavement (South Africa)
- Stone Interlayer Pavement (Louisiana)
- Upside Down Pavement
- Sandwich Pavement

Inverted Pavement - Defined

- Alternative flexible pavement structure
- Relatively thin upper AC layer(s)
- Layered stiffness profile does **not** decrease with depth
- Structure typically looks like this (from bottom up):
  - Compacted Subgrade
  - Cement-Treated Base (CTB w/ 2-5% cement)
  - Unbound Aggregate Base (UAB)
  - Relatively thin Asphalt Concrete (AC)

Inverted Pavement Compared to Conventional Pavement

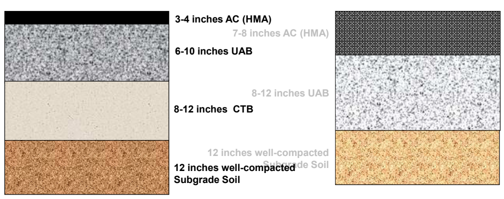
Conventional Pavement Section



Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section



Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section

Can reach up to 25% less $ to build the inverted compared with conventional for similar performance

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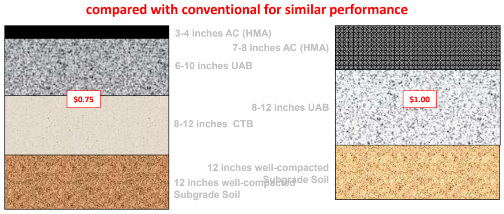
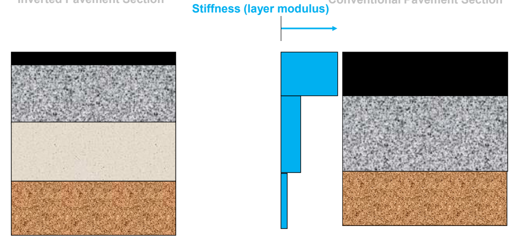


Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section



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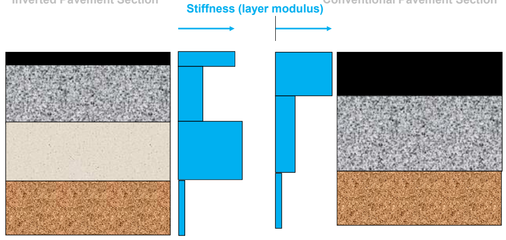
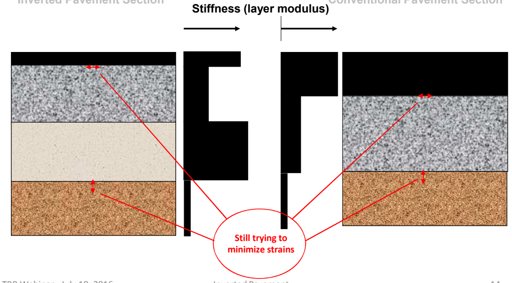


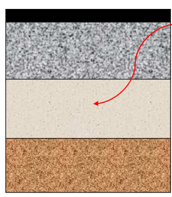
Inverted Pavement Compared to Conventional Pavement



Inverted Pavement Compared to Conventional Pavement

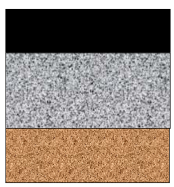
Inverted Pavement Section

Conventional Pavement Section



As a result of the stiff CTB layer, higher densities can be achieved in the UAB layer during installation.

This results in higher stiffness properties, and the UAB layer remains in compression.

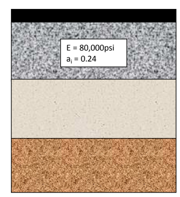


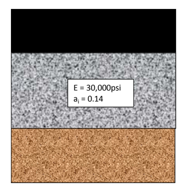
Inverted Pavement Compared to Conventional Pavement

Inverted Pavement Section

Conventional Pavement Section

1993 AASHTO Design Guide
hypothetical ***example***





Improving the Chance of Success Unbound Aggregate Base (UAB) Layer

- **Equipment:** Mixing should be accomplished by stationary plant such as a pugmill or by road mixing using a pugmill or rotary mixer. Mechanical spreaders should be utilized to avoid segregation and to achieve grade control. Suitable vibratory compaction equipment should be employed.
- **Mixing and Transporting:** The aggregates and water should be plant mixed (stationary or roadway) to the range of optimum moisture plus 1% or minus 2% and transported to the job site so as to avoid segregation and loss of moisture.
- **Spreading:** The material should be placed at the specified moisture content to the required thickness and cross section by an approved mechanical spreader. At the engineer's discretion, the contractor may choose to construct a 500-ft long test section to demonstrate achieving adequate compaction without particle degradation for lift thicknesses in excess of 13 in. The engineer may allow thicker lifts on the basis of the test section results.

Allen, et al. ICAR 501-5 (1998)

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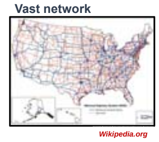
- **Slushing**: South African method to increase packing density of layer by careful over-watering during the compaction process (slush acts as a lubricant to increase density while the slush or cream exudes to the surface).

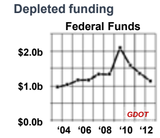
Design …………

The US Road System is vast and suffers from insufficient funding.

Vast network



Depleted funding

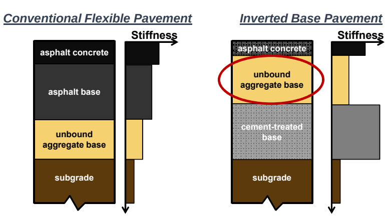


Poor condition

Solution Sources

- **Innovative designs**
- **Optimal use of materials**

An inverted base pavement (IBP) is an innovative technology that can optimize the use of materials.

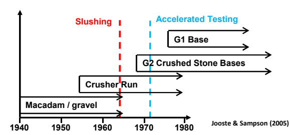


- **Stiffness contrast between layers**
- **Granular base : close to load ➔ demand for exceptional performance**

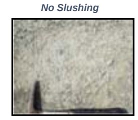
(After Papadopoulos, 2015)

South Africa has developed and utilized inverted base pavements for half a century.

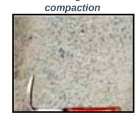
Crushed stone base pavement development



No Slushing



Slushing after compaction



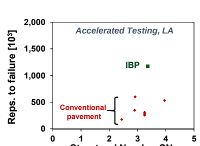
"Ping" when struck with rock hammer

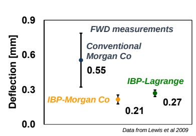
Kleyn, 2012

(After Papadopoulos, 2015)

US experience with inverted base pavements had also been long but sparse.

- New Mexico (1960s)
- USACE (1970s)
- Georgia Tech (1980s)
- Louisiana (1990s)
- Morgan County GA quarry (2000s)
- Lagrange GA bypass (2000s)
- Bull Run VA highway (2010s)
- Pineville NC quarry (2010s)

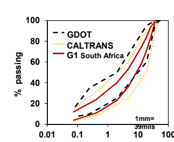


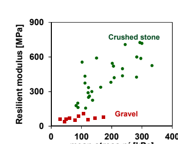


(Adapted from Papadopoulos, 2015)

Top quality unbound aggregate base is the fundamental block of IBPs.

	South Africa G1 base	CALTRANS base	GDoT GAB
Fines	LL<25%, PI<4	Sand Equivalent <21	Sand Equivalent <20
Shape	flakiness (sphericity) <35%	N/A	elongated particles <10%
Density	86-88% of apparent solid density (~102% mod Proctor)	95% of CTM 231	98% mod. Proctor

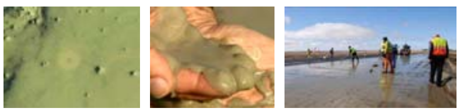




(After Papadopoulos, 2015)

Key component of Inverted Pavement construction is slushing technique

- Process to wash away excess fines to achieve optimum fine to coarse soil matrix
- Water migrates to surface by capillary action carrying excess fines



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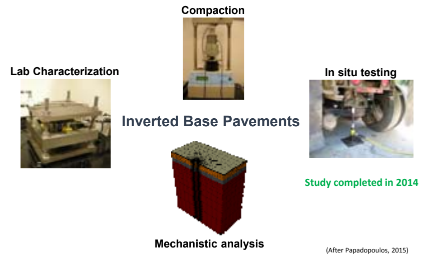
Comprehensive laboratory – field – numerical study that expanded understanding of IPB component performance.



Study completed in 2014

(After Papadopoulos, 2015)

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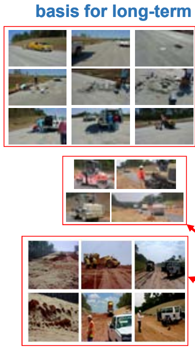
Field: fully documented construction project provides basis for long-term IBP performance assessment.



LaGrange By-Pass

Test section:
0.65 miles long
2 lanes
PCC typical section
IBP test section

Construction completed in 2009

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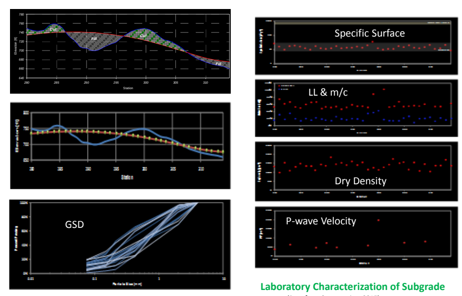
Field: fully documented construction project provides basis for long-term IBP performance assessment.



Laboratory Characterization of Subgrade
(Data from Santamarina, 2015)

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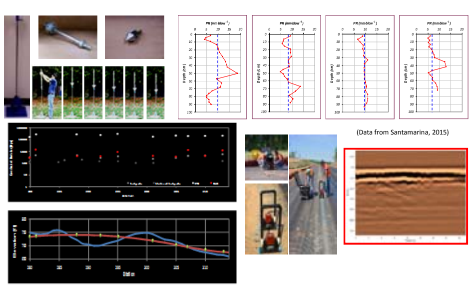
Field: fully documented construction project provides basis for long-term IBP performance assessment.



(Data from Santamarina, 2015)

Extensive lab and field characterization studies for various layers

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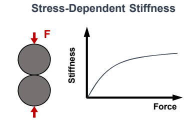
Field and Lab: current laboratory methods do not account for the complex nature of aggregate base stiffness.

Inherent Anisotropy

Stress-Dependent Stiffness



- In-chamber compaction.
- Independent control of the 3 principal stresses.
- P-wave instrumentation in each direction.

(After Papadopoulos, 2015)

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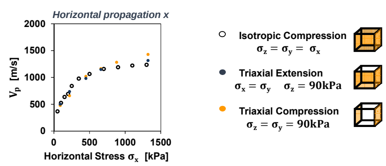
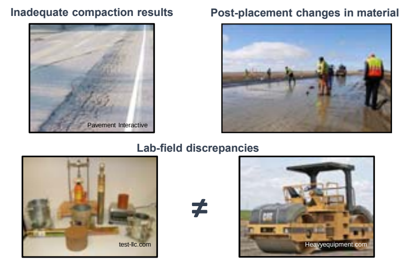
Lab: stress ratio has small influence on the small-strain stiffness as long as the material is away from failure.



Characterization of unbound aggregate base stiffness:

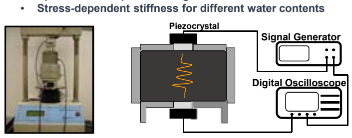
- Granular Bases: inherent & stress-induced anisotropy exist.
- M_{max} : function of normal stress (Adapted from Papadopoulos, 2015)
- Loading conditions: almost no effect on M_{max}

Field and Lab: Soil compaction is omnipresent in construction and has known impact on performance.



Lab: an extensive lab study was conducted to assess the compaction process in terms of stiffness.

- Specimens compacted using Modified Proctor (Adapted from Papadopoulos, 2015)
- Stress-dependent stiffness for different water contents

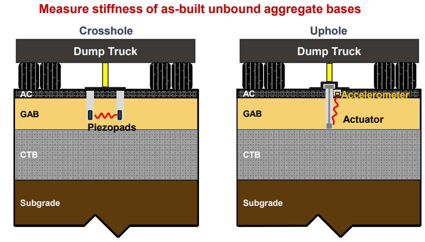


Effect of compaction on granular base stiffness:

- ρ_{dry}: not sufficient to assess compaction
- Granular base stiffness not affected by water content
- Water content affects permanent deformation
- Velocity changes reflect accumulation of deformation

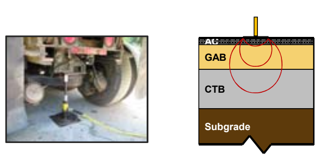
Field: Two new field tests were conceived to measure the stiffness of as-built aggregate bases.

Measure stiffness of as-built unbound aggregate bases



(After Papadopoulos, 2015)

Field: Successive forward simulations were conducted to determine the state of stress in the pavement.

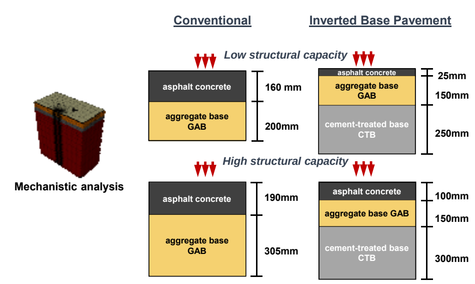


Two configurations to capture anisotropic stiffness – 2 case histories

- In situ GAB: anisotropic stress-dependent stiffness
- Field values ≠ lab values: Due to preconditioning and compaction method (field versus lab)
- Field-Compacted GAB: great stiffness

(Adapted from Papadopoulos, 2015)

Modeling: Numerical simulations were conducted to compare IBP's to conventional pavements.



(Adapted from Papadopoulos, 2015)

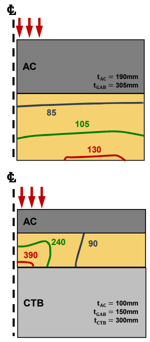
Aggregate base stiffness in IBP is high due to the confinement provided by the CTB.

Constitutive model:
- Anisotropy, stress-dependency, shear softening

Inverted base pavements:
- Unique load-bearing mechanism

Granular base:
- Underutilized in conventional pavements
- Great contribution in inverted base pavements

Thin asphalt layers:
- Potential for economic savings
- Caution when subjected to strong shear



Tangent Vertical Young's modulus E_v (MPa)

(Adapted from Papadopoulos, 2015)

Construction ....

Inverted Pavement Construction

- Standard construction methods may be used for most layers in an inverted pavement
- Subgrade, Cement Treated Base and Asphalt may be constructed in the normal way
- Unbound Aggregate Base course may take a little more effort to ensure the higher density required
  - South African methods vs. traditional

Subgrade Construction

- Generally use standard subgrade requirements
- Remove/correct saturated soils, organics, unsuitable, etc.
- Typical density requirements
- Variety of subgrades have been used in US inverted pavements

Subgrade Construction

- South Africa
  - 90% to 93% Modified Proctor
- Georgia
  - Mixed in graded aggregate base to improve CBR to 15
- New Mexico
  - Lime treated subgrade
- Luck Stone – Virginia
  - Standard VDOT subgrade requirements
- Vulcan – North Carolina
  - Standard NCDOT subgrade

Vulcan North Carolina Subgrade

New Mexico Subgrade Construction

Cement Treated Base

- Can generally use traditional CTB requirements
- Relatively low level of strength & cement
  - South Africa requires 100 to 200 psi
- Pugmill or mix in place
- Recommend spreader box to reduce segregation
- Typical density requirements

Cement Treated Base

- Pugmill system works well if available

Cement Treated Base

Cement Treated Base

- Asphalt paver used in NM for CTB
- Good control over depth and segregation

Cement Treated Base

Cement Treated Base

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Cement Treated Base

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Cement Treated Base

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Cement Treated Base

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Cement Treated Base

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Cement Treated Base

- Seal with emulsified asphalt tack coat
- Allow to cure for 7 days

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Unbound Aggregate Base

- Typical laydown
  - Spreader box should be required for thickness and consistency
- Density requirements higher than normal
- How is this achieved
  - South Africa requires “slushing”
  - Will normal methods work?

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Unbound Aggregate Base

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Unbound Aggregate Base

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Unbound Aggregate Base

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Unbound Aggregate Base

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Slushing Process

- What is slushing?
  - After initial compaction – UAB flooded with water
  - Rolled at high speed to “suck” the fines out of the UAB
    - Fines and water act as a lubricant
    - As they are removed, larger particles are consolidated for high density and stiffness
  - Excess fines collect on top of the UAB
  - Excess fines broomed off

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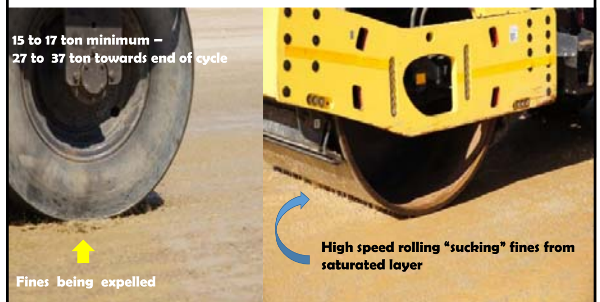
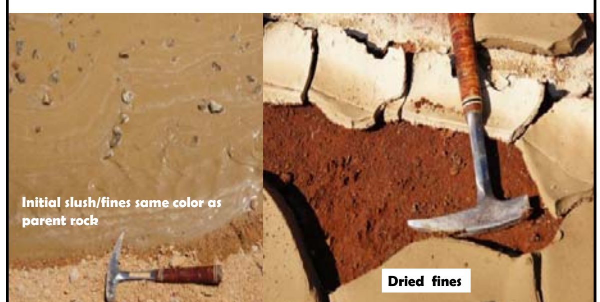
Slushing Process

Slushing Process



Slushing Process

Slushing Process



Slushing Process

Slushing Process

Unbound Aggregate Base

- To Slush or not to Slush…that is the question
- First test section in Georgia saw no benefit to slushing
- New Mexico specified slushing
- All others used traditional compaction methods
  - Easily achieved 102 to 103% of modified Proctor

Unbound Aggregate Base

- On Vulcan section, the UAB on the conventional & inverted sections compacted same time
- Density on conventional: 99.8%
- Density on inverted: 103.4%
  - 86.4% of apparent

Unbound Aggregate Base

- Used the same compaction techniques on both
- Roller operated commented that the inverted section caused more "bouncing" when compacting with vibration

Hot Mix Asphalt

- Normal HMA construction in accordance with local DOT requirements
- Nothing new

Vulcan Final Density Comparison

Inverted Layer Densities

	Required	Achieved
9.5mm A	90% of G_{mm}	90.8%
9.5mm B	92% of G_{mm}	94.3%
UAB	102% of Mod. Proc.	103.4%
CTB	97% of Mod. Proc.	99.2%

Conventional Layer Densities

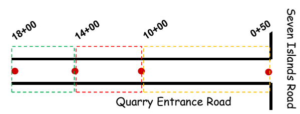
	Required	Achieved
9.5mm B	92% of G_{mm}	93.2%
19.0mm	92% of G_{mm}	93.1%
UAB	100% of Mod. Proc.	99.8%

Construction Summary

- Subgrade – standard methods
- Cement Treated Base – standard methods
- Unbound Aggregate Base – requires higher density
  - Standard methods have been shown to work
  - Slushing will work, but may not be required
- Asphalt Paving – standard methods
- QA/QC: Stiffness-based measurements vs density-based measurements
  - Intelligent Compaction (IC)
  - LWD, PLT, DCP …..

Performance Assessment

Test sections with well documented loading over 15 year period (Morgan County Quarry).



Station 0+50 through Station 10+00
Conventional Haul Road
Station 10+00 through Station 14+00
South African Base
Station 14+00 through Station 18+00
Georgia Base

Construction completed in 2001

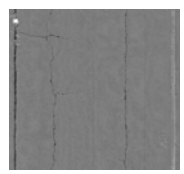
FWD evaluations of test sections (2009).

Performance Evaluation: 853,719 ESAL's (63.5% design life cycle)

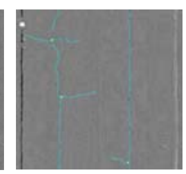
Lewis et al., 2012

Surface distress study using imaging and LiDAR (2016).

3D Laser Imaging System



Range Image



Detected Crack Map

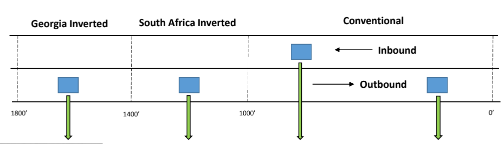
The GDOT's Pavement Condition Evaluation System (PACES) is used for conducting the annual asphalt pavement condition surveys in Georgia.

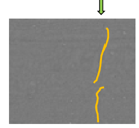
- Ten different distress types and their severity levels are defined.
- Four of them are crack related distresses: load cracking, B/T cracking, edge distress, and reflective cracking.

(Courtesy of James Tsai)

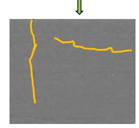
Surface distress study using Imaging (2016).

Surface distress study using Imaging (2016).

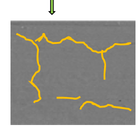




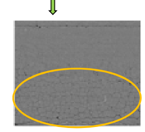
Fine transverse crack



Transverse and longitudinal crack



Block cracking

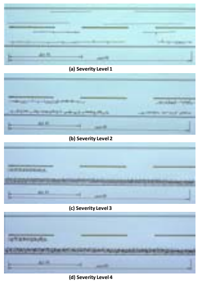


Alligator cracking

Pavement surface distress study using imaging.

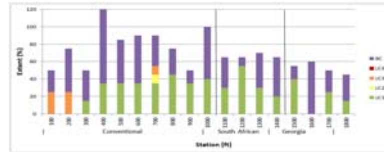
- **Load cracking is caused by repeated heavy loads and always occurs in the wheel paths**:
  - **Severity Level 1** usually starts as single longitudinal cracks in the wheel path.
  - **Severity Level 2** has a single or double longitudinal crack with a number of 0-2 feet transverse cracks intersecting.
  - **Severity Level 3** shows an increasing number of longitudinal and transverse cracks in the wheel paths. This level of cracking is marked by a definite, extensive pattern of small polygons.
  - **Severity Level 4** has the definite "alligator hide" pattern but has deteriorated to the point that the small polygons are beginning to pop out.

(Courtesy of James Tsai)

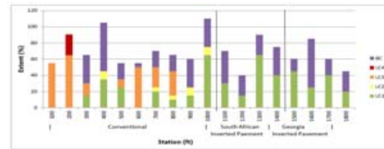


Surface distress study using imaging (2016).

Inbound



Outbound

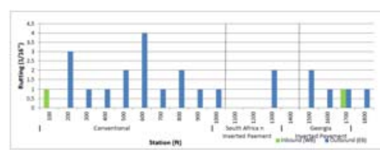


Surface distress study using imaging (2016).

		Conventional		South African IP		Georgia IP	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Load Cracking	1	32.5 %	25.8%	33.8%	37.5%	20 %	32.5%
	2	0%	5. %	0	0	0	0
	3	0%	12.5%	0	0	0	0
Block Cracking	1	52.5%	31.7%	32.5%	31.3%	32.5%	30%

Rutting study using LiDAR (2016).

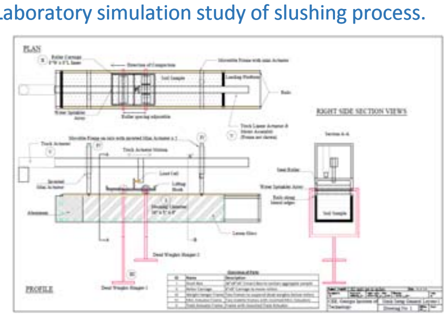
		Conventional		South African IP		Georgia IP	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
Load Cracking	1	32.5 %	25.8%	33.8%	37.5%	20 %	32.5%
	2	0%	5. %	0	0	0	0
	3	0%	12.5%	0	0	0	0
Block Cracking	1	52.5%	31.7%	32.5%	31.3%	32.5%	30%
Max Rutting (1/8")		0	4	0	0	1	2
Average Rating		79	68.7	81.8	80.5	85.5	81.5
Rating Range		71-85	43-80	81-83	76-86	82-89	79-86



Comparable rating for SA IBP and GA IBP – far superior to conventional design.

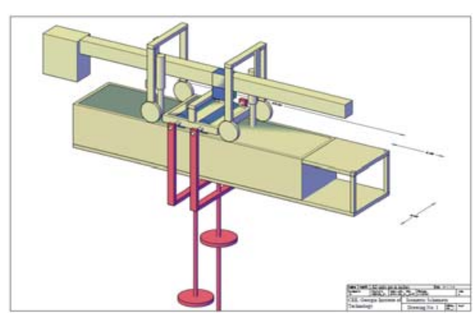
Less rutting with SA IBP than with GA IBP – possible link to benefits of slushing?

Laboratory simulation study of slushing process.



Ongoing laboratory simulation study to examine evolution of aggregate shape, pore structure and load path during slushing

Laboratory study of slushing on cracking and rutting.



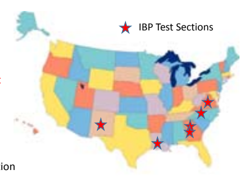
Selected References

- Cortes, D. D. (2010). "Inverted Base Pavement Structures." Ph.D., Georgia Institute of Technology, Atlanta, GA.
- Terrell, R.G., Cox, B.R., Stokoe II, K.H., Allen, J.J., and Lewis, D. (2003). Transportation Research Record, No. 1837, pp. 50-60.
- Papadopoulos, E. (2014). "Performance of Unbound Aggregate Bases and Implications for Inverted Base Pavements." Ph.D., Georgia Institute of Technology, Atlanta.
- Cortes, D.D., Shin, H.S. and Santamarina, J.C. (2012), Numerical Simulation of Inverted Pavement Systems, ASCE J. Transportation Engineering, vol. 138, no. 12, pp. 1507-1519.
- Cortes, D.D. and Santamarina, J.C. (2013), Inverted Base Pavement Case History (LaGrange, Georgia): Construction, Characterization and Preliminary Numerical Analyses, International J. Pavement Engineering, International Journal of Pavement Engineering vol. 14, 463-471
- Lewis, D.E. and Jared, D.M. (2012). "Construction and Performance of Inverted Pavements in Georgia." *Proceedings of 91st TRB Meeting*, Washington D.C., Paper # 12-1872.
- Papadopoulos, E., D. Cortes, and Santamarina J.C., (2015). "In Situ Assessment Of The Stress-Dependent Stiffness Of Unbound Aggregate Bases: Application In Inverted Base Pavements", International Journal Pavement Engineering., http://dx.doi.org/10.1080/10298436.2015.1022779
- Papadopoulos, E. and Santamarina J.C., (2015). "Analysis Of Inverted Base Pavements With Thin Asphalt Layers", International Journal of Pavement Engineering, http://dx.doi.org/10.1080/10298436.2015.1007232
- Papadopoulos, E., and Santamarina, J. C. (2014). "Optimization of Inverted Base Pavement Designs with Thin Asphalt Surfacing." *Geo-Congress 2014 Technical Papers*, ASCE, Atlanta, GA, 2996-3004.

In Conclusion …………

Pooled fund study to leverage current knowledge to expedite implementation of IBP design specifications for US state DOT's.

GDOT Led Pooled-Fund Study:
Closing Sept 25, 2016
http://www.pooledfund.org/Details/Solicitation/1416



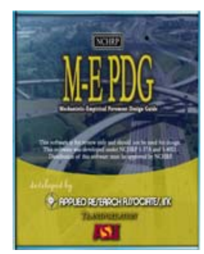
Objective:
- To expedite the implementation of inverted base pavement design specifications for state DoT's and to make IBP a practical and reliable alternative design approach for highway pavements.

Broad Tasks:
- Further study of existing field cases with detailed construction records and long-term performance monitoring data
- Advanced material characterization and modeling with emphasis on granular base
- Numerical simulation of IBP performance
- Relevant calibrations for design within framework of Mechanistic-Empirical Pavement design Guide (MEPDG)

Pooled fund study to leverage current knowledge to expedite implementation of IBP design specifications for US state DOT's.

GAPS in knowledge:
- Improved understanding of IBP component performance, particularly of unbound granular base, through advanced material characterization and modeling
- Better understanding of relationship between construction and long-term performance of CTB, in particular, and IBP, in general, through continued assessment of test sections and associated numerical simulations

BARRIERS to implementation:
- Need for reliable framework for assessment of economics of IBP for both construction and performance stages
- Need for material model calibrations and damage functions suitable for IBP designs in MEPDG
- Guidelines for implementation through all phases of design, construction and maintenance



PROPOSED POOLED-FUND STUDY CAN RESOLVE GAPS AND ELIMINATE BARRIERS