<u>**FINAL PROGRESS REPORT**</u>

I. COVER PAGE

A.	**Project Number:**	AR032-011
	Project Title:	INTELLIGENT ASPHALT COMPACTION ANALYZER
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D. **Other Organizations Providing Project Resources**

Broce Construction Inc., Norman, Oklahoma
Oklahoma Department of Transportation, Oklahoma City, Oklahoma
Kirby-Smith Machinery Inc., Oklahoma City, Oklahoma
Haskell-Lemmon Co., Oklahoma City, Oklahoma
Ingersoll-Rand Company, Road Development Division
Shippensburg, Pennsylvania

E.	**Current Funding Period**:	September 2003 – October 2006
F.	**Report Period:**	September 01, 2003 – October 30, 2006
G.	**Report Due Date:**	January 19, 2007

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II. EXECUTIVE SUMMARY

The successful design and validation of an Intelligent Asphalt Compaction Analyzer (IACA) is presented in this report. The IACA addresses the lack of adequate tools to continuously measure the density of an asphalt pavement during its construction. The lack of adequate quality control tools results in improper compaction of asphalt pavements leading to their early deterioration and the degradation of critical transportation infrastructure. The IACA can predict the density continuously, in real-time during the construction of the asphalt pavement. The knowledge of the achieved density can be used to remedy the compaction problems during the construction when the asphalt is still hot and pliable, thereby ensuring the quality and longevity of the pavement.

The IACA is based on the hypothesis that a vibratory compactor and the hot mix asphalt (HMA) mat form a coupled system having unique vibration properties that can be identified by an analysis of the power spectrum distribution of the coupled system. Vibration signals from an accelerometer and the process parameters like lift thickness, mix type, type of compactor, etc., are used to extract relevant features from the power spectrum of the vibrations. These features are then classified and a neural network-based pattern recognition approach used to continuously predict the degree of compaction in real time.

In the Phase I of the research several tests were conducted to characterize the compaction process in the laboratory and the data gathered was analyzed to design and develop the prototype IACA. The performance of the prototype was then verified through tests in the laboratory. In order to verify the ability of IACA to predict when a specified target density was achieved during compaction, two different sets of tests were conducted. In the first set, the IACA was required to determine when the compaction has reached 92% of the maximum theoretical density (i.e. 8% air voids). In the second set of tests, the IACA was required to determine when the compaction has reached and 94% of the maximum theoretical density (i.e. 6% air voids). The test results indicate that in both the cases, there is a 95% confidence that the achieved density is within 1.25% of the target density. This compares very favorably with both the Troxler Nuclear density gauge (measurement accuracy of 2.5%) and the Transtech PQI 301 gauge (measurement accuracy of 1.7%) used for quality control in the field.

Field testing of the IACA was conducted under a controlled set of conditions during the second phase of the project. In order to minimize the effect of variations in the subgrade on the compaction process, a test facility was constructed at the site identified in Phase I of the project. The test strip consists of a 91.44 m (300 feet) long, 4.2672 m (14 feet) wide, 15.24 cm (6 inch) thick continuously reinforced concrete pavement (CRCP) with a compressive strength of over 27,580 kPa (4000 psi). The structural rigidity of the base and the issues arising from the use of vibratory rollers on stiff sub-grades were studied. The vibration data gathered during the overlays on the concrete base was correlated with the densities obtained from roadway cores and used to train the IACA. During compaction on the test strip, the density predicted by the IACA was found to correlate well with those of the cores extracted from the completed pavement, as well as the PQI readings taken during the compaction.

The IACA was used at several construction sites in Oklahoma and the data collected was used to study the rolling patterns employed by the operators of the vibratory compactors and its effect on the quality of the pavement under construction. While the field testing was conducted on a limited basis, the preliminary results indicate very good correlation with the density measurements taken using the PQI 301 gauge as well from roadway cores. The IACA was found to be as effective as currently existing density measurement tools with the added advantage of providing continuous measurement of density in real time. The IACA was also successful in identifying regions of subgrade failure that could potentially affect the quality of the completed pavement.

Discussions are currently underway with OEMs to license this technology. The PIs are also aggressively pursuing commercialization of the IACA technology.

III. PROJECT PARTICIPANTS

The participants in this project are:

1. University of Oklahoma
2. Broce Construction Inc., Norman
3. Oklahoma Department of Transportation
4. Kirby-Smith Equipment Inc., Oklahoma City
5. Haskell Lemon Construction Company, Oklahoma City, Oklahoma.
6. Ingersoll-Rand Company, Road Development Division, Shippensburg, Pennsylvania

The University of Oklahoma, Norman (OU) through the Schools of Electrical and Computer Engineering and Civil Engineering and Environmental Science was the primary participant in the research. The PI and the Co-PI jointly handled the technical developments of the project. The PIs were assisted by graduate students in the research, development and testing of the Intelligent Asphalt Compaction Analyzer (IACA). In addition to providing access to the Broce Asphalt Laboratory and the required computational facilities, the university also extended access to a stretch of an unused road (Mendel Plaza, near Max Westheimer Airport in the University Research Park in North Campus) for the construction of controlled test facility. This test facility consists of a continuously reinforced concrete pavement, on top of which asphalt overlays were compacted and the ability of the compaction analyzer to predict the density was verified.

Broce Construction was responsible for providing matching contribution towards the project. In addition to the actual match, Broce construction also bought an enormous amount of practical field expertise in pavement construction to the project team. Broce Construction also provided access to its technical personnel, equipment, and work sites as needed during the course of this project. Haskell Lemon Construction Company had several construction projects in the Oklahoma City area and the access to the projects and construction crew was instrumental in validating the performance of the IACA during compaction in the field. Broce Construction and Haskell Lemon Construction Company together provided access to 10 construction projects at different locations in the state of Oklahoma where several miles of asphalt pavement were constructed on different subgrades using different types of asphalt mixes.

Key personnel in Oklahoma Department of Transportation (ODOT) have provided invaluable assistance in the project. The ODOT residencies across the state have provided field support including traffic management, during construction activities. Mr. Danny Gierhart and Mr. Reynolds Toney in the Materials division of ODOT in Oklahoma City have provided key technical support at various stages of the project. Ms. Dawn Sullivan, Planning Engineer, ODOT has also been very supportive of the project team and had made available critical resources during the life of the project.

Ingersoll-Rand provided a dual drum vibratory compactor (DD 130) on loan to OU for the duration of the project. This machine was subsequently upgraded to a research prototype compactor with integrated electronics and sensors for the measurement of pavement density. Kirby-Smith provided service and maintenance for the compactor. Ingersoll-Rand is also negotiating with the University of Oklahoma to license the technology.

IV. WORK ACCOMPLISHED

The objective of the proposed study is to develop an onboard "Intelligent Asphalt Compaction Analyzer (IACA)" that can predict the relative density of an asphalt mat in real-time during compaction in the field. Towards this end, the project was conducted in phases where the results of each phase would form the foundation for the next phase. This process is adopted for minimizing the risk and providing the flexibility needed to streamline the research for maximum efficiency and effectiveness. The goals and accomplishments of each of the tasks planned for the project are discussed below.

1. Laboratory Study (Phase I)

The compaction process was studied in the laboratory using the Asphalt Vibratory Compactor (AVC) manufactured by Pavement Technologies Inc. Different asphalt mixes were compacted and the relationship between various process parameters like the sample thickness, mix types, vibration frequency, compaction pressure etc., and the vibratory responses of the equipment during compaction were quantified. The repeatability and consistency of the test results were verified and the test data was used to design a Feature Extraction module. The extracted features were used to train and calibrate a neural network analyzer. The ability of the analyzer to predict density during compaction in the laboratory was verified. The following are the findings of the study on compaction in the laboratory.

Compaction process in the laboratory is repeatable and the vibratory signals are consistent in all the tests and contain significant distinguishing characteristics or features that are indicative of the type of material and the density achieved. The study also shows that while the vibration signatures are consistent for a given set of process parameters and compacted density, these signatures are different when the process parameters change. The vibration signatures were used to design and train a Neural Network to classify the extracted frequency bands into classes of representative compacted densities.

Significant Achievements:

It is clear from this study that the compaction analyzer can be used to predict the density of the asphalt mix during compaction in the laboratory. The results in Table 4 indicate that for a specified target density of 92%, the compacted specimen reached a mean density of 92.7% with a standard deviation of 0.304. The 95% confidence interval for the first set of tests obtained using the Student's t-distribution is $\left[92.7 \pm 0.38\right]$, i.e. [92.32, 93.08]. Similarly when the specified target density is 94%, the compacted specimen was found to have reached a mean density of 93.9% with a standard deviation of 0.313. The 95% confidence interval in this case was [93.48, 94.25]. The results indicate that in both the cases, there is a 95% confidence that the achieved density is within 1.25% of the target density. This compares very favorably with both the Troxler Nuclear density gauge (measurement accuracy of 2.5%) and the Transtech PQI 301 gauge (measurement accuracy of 1.7%) used for quality control in the field.

2. Construction of Test Site for Controlled Field Testing of IACA (Phase I)

In order to manage the complexity of field trials, initial development and testing of the analyzer was performed on a test strip of known properties. To facilitate this, a site on Mendel Pl. in Norman near Max Westheimer Airport was identified within the OU campus and a 106.68 m by 4.2672 m (350 feet by 14 feet) continuously reinforced concrete base with a thickness of 15.24 cm (6 inches) was constructed to simulate controlled field conditions for the project. Soil Characterization tests were first performed and the results were used to design a concrete slab to withstand the dynamic loading due to the compactor.

Significant Achievements:

The test strip provided a controlled environment for the compaction of HMA mixes. Eight different overlays were performed on the test strip over the past two years. The results of these compaction studies have shed new light on the compaction process and the effect of subgrade and machine parameters on the compaction process. Leveraged funding has also enabled the calibration study of the Transtech PQI 301 non-nuclear density gauge. This study has provided insight into the accuracy and variability in the functioning of the gauge and has already had an impact in the Quality Control specifications of Oklahoma DOT for density measurement in the field.

3. Development and Validation of IACA Prototype for Use in Simulated Field Tests (Phase II)

In the Phase I of the research, it was shown that the IACA prototype that was developed was capable of predicting density during compaction in the laboratory. In order to test the prototype during compaction of a HMA pavement, an Ingersoll-Rand DD-138 compactor was first instrumented with high bandwidth accelerometers (Cross Bow CXL100HF3, 0-100 MHz, 0-10 g) and GPS navigational system (ZX – Sensor by Thales Navigation). The differential GPS unit mounted on the roller communicates with the GPS base station through a dedicated two way radio link to provide measurements with a spatial accuracy of a few centimeters. A real-time data acquisition system (xPC Target, Mathworks Inc.) was used to sample the vibration signals of the accelerometers during compaction operations. The spectrogram of the vibration signal was computed and the variations in spectral characteristics of the signal for each roller pass were studied. Density readings were taken at specified locations on the roadway after each pass of the roller and the relationship between the observed density and the spectrogram of the vibration signals were studied. The data was used to design and train a neural network classifier.

In the period between July 2005 and November 2006, 8 different overlays were constructed and the data was analyzed to validate the functioning of the IACA. The following are the findings of the study under simulated field conditions.

i) Compaction of a HMA overlay on a concrete subgrade results in significantly high vibrations in the roller compared to compaction on a compacted soil subgrade.
ii) Compaction of the HMA mat on the concrete pad requires a smaller amplitude setting of the vibratory motors on the compactor compared to compaction on a stabilized soil subgrade. The impact of the underlying subgrade on the vibrations of the compactor can be seen in Figure 19.
iii) The progress of the compaction process is very rapid when the subgrade is a concrete pad. Thus, fewer roller passes are sufficient to achieve the required density. It can be seen from Figure 22 that maximum density occurs by the third pass of the roller and further compaction results in "roll over" or reduction in density. The 'roll over' would typically occur after 5 passes in the field and is used to establish the rolling pattern.

The vibration and the spatial location of the roller were collected for each roller pass on the HMA mat. After each roller pass, density measurements were also taken at specific points on the mat using PQI 301 non-nuclear density gauge. Typical spectrogram of the vibration signals for the first two roller passes is shown in Figure xx. Fast Fourier Transform (FFT) of the vibration signals corresponding to regions of known density were used to train a neural network. Figure 24 shows the PQI measured density at specific locations and the predicted density of the Neural Network. The predicted and measured densities correlate well and the corresponding R-squared value is 0.9628. From this figure, it can be seen that the IACA can predict the density in real-time with reasonable accuracy.

Significant Achievements:

A mobile laboratory equipped with GPS base station has been developed for rapid setup and use in the field. This mobile lab has been used to successfully acquire vibration data in the field and calibrate the IACA for use in the field. The prototype IACA is equipped with LED indications that provide the operator with a visual indication of the level of compaction obtained. An as-built map can be generated that depicts the final density over the complete stretch of the compacted pavement. The "play back" of the roller path superimposed with the density provides a valuable tool for studying the rolling pattern and the resulting compaction. This technique has provided valuable insight into the effect of rolling pattern on the shoulders and in between lanes of roadways during construction where the pavement is usually under compacted.

4. Validation of IACA Prototype in Limited Field Trials

The IACA was used in 10 different construction projects at sites across Oklahoma. Data was collected and analyzed from projects on Interstate Highway I-35 (near mile marker 70), and State Highways (HWY 77 near Davis, HWY 29 near Elmore City, HWY 412 near Woodward, HWY 283 near Mangum, Hwy 10 near Miami, HWY 9 / I-35 Ramp in Norman, HWY 152 in Oklahoma City). The data from these sites was used to integrate the various components of the IACA and evaluate the impact of the various process parameters (subgrade type, mix type, lift thickness etc.) on the vibration characteristics of the compactor. The IACA was refined in the laboratory and its ability to predict the density of the asphalt mat was verified using the data collected in the field. The final validation of the IACA was conducted during construction of taxiways at Will Rogers International Airport (Figure 26). The IACA was trained with the data from the field to predict three different levels of compaction, namely 90%, 92%, and 94% of compacted density. This was done to investigate if the quality controls that exist today can be satisfied using the IACA. DOT regulations require a compaction of 94% relative density, while a relative density of 92% is the minimum acceptable value. Density values below 92% are unacceptable and will result in significant penalties to the contractor.

The output of the IACA was used to generate an "as-built" map that shows the density of the mat over the entire stretch of the roadway. The density of the mat was also measured at several locations using the PQI 301 gauge. The measured densities as well as the density measured from roadway cores are shown in Figure 31.

Significant Achievements:

The ability of the IACA to predict the density of the asphalt pavement continuously, in real-time was validated during construction projects. The IACA was able to classify the vibrations into regions corresponding to known density values. Further, the IACA was successful in predicting density even in situations where the PQI 301 was not successful in accurately measuring the density. The IACA has been successful in identifying problems with underlying subgrade that can affect the quality of the pavement being constructed.

V. WORK PLANS

The IACA prototype has been successfully validated in the laboratory and in controlled field conditions. Limited testing of the IACA in the field has also demonstrated the ability of the IACA to accurately predict the density of the asphalt mat continuously, and in real time. Currently the IACA can be trained to predict three distinct levels of compactions. These levels were set as initial compaction (corresponding to 10% air voids in the mix), acceptable compaction (8% air voids in the mix), and good compaction (6% air voids in the mix). This was done to provide the roller operator with a visual indication that good compaction was achieved. For compaction in the field, the target density is typically set at 94% (6% air voids) and 92% compaction (8% air voids) is the threshold below which the paving contractor is penalized by the DOT. In the next year, the PIs anticipate further refinement of the prediction process. The PIs also plan to automate the training process for the IACA so that an operator with minimal training can train, calibrate, and use the analyzer. Development of auxiliary hardware and software that supports the customization of the display to suit operator preferences and the generation of reports is also planned.

The IACA prototype currently consists of a number of off-the-shelf modules that are cumbersome to connect together and install on a compactor. The first step towards commercialization of the IACA will involve the redesign of the IACA onto a single electronic module that is rugged enough to withstand the climatic variations and one that can be mounted on a roller for extended periods of time.

The field testing of the IACA revealed the potential of using the IACA for evaluating compaction of soil embankments and in detecting failures in underlying subgrade due to improper design or site preparation. The PIs are working on filing additional patents to cover these technologies.

VI. PUBLICATIONS AND PRESENTATIONS

1. S. Commuri, M. Zaman, "Intelligent Asphalt Compaction Analyzer – Design and Performance," Journal of Pavement Engineering, (*to appear*) 2007.
2. S. Commuri, M. Zaman, "Field Validation of Intelligent Asphalt Compaction Analyzer," Journal of Pavement Engineering, (*under preparation*) 2007.
3. S.Commuri, "Oklahoma Innovations," (science radio magazine) KTOK AM 1000, 5:00 p.m. – 6:00 p.m., Sunday, February 11, 2007.
4. S. Commuri, M. Zaman, "IACA – Performance and Validation," presented to Vice President Research, Ingersoll-Rand Road Development Company, Shippensburg, Pennsylvania, February 20, 2007.
5. S. Commuri, M. Zaman, "Advances in Intelligent Compaction of AC Pavements," 30th Anniversary of Transportation Research Day, Oklahoma Department of Transportation, Oklahoma City, Oklahoma, September 19, 2006.
6. S. Commuri, M. Zaman, "Overview of OU Asphalt Program," Oklahoma Transportation Center, Oklahoma, February 01, 2006.
7. Johann G. Nino, "Design and Development of a Real-time Neural Network Based Compaction Analyzer," Masters Thesis, School of Electrical and Computer Engineering, University of Oklahoma, May 2006.

VII. INTELLECTUAL PROPERTY DEVELOPMENT

The University of Oklahoma has contracted with the law firm of Dunlap, Codding & Rogers, P.C. for filing a patent application based on the Intelligent Asphalt Compaction Analyzer. The patent application is entitled "Method and Apparatus for Predicting Density of Asphalt," and has been published in November 2005 (USPTO, S. No. 11271575). The patent application is currently under review by the United States Patents and Trademarks Office.

VIII. COMMERCIALIZATION ACTIVITIES AND PLANS

The project team has been in communication with the local industry, Oklahoma Department of Transportation personnel, and equipment manufacturers regarding the technology. The research being conducted at the University of Oklahoma has consistently met with enthusiasm and support.

The results of the IACA in the limited field trials have demonstrated the ability of the IACA to continuously predict the density of the asphalt mat during compaction. The research team plans to conduct extensive field tests over the next year to validate the prototype. The PIs are in contact with Mr. John Rice, Program Manager, Ingersoll Rand Road Company and Dr. Ulf J. Lindqwister, Technology Manager, Caterpillar Incorporated to explore the possibility of licensing the technology. The PIs are also in discussions with the Oklahoma Technology Commercialization Center, OCAST; Office of Technology Development, University of Oklahoma; and venture capitalists to help commercialize the technology.

Along with the efforts to commercialize the technology, the PIs are actively seeking funding to refine the technology and conduct elaborate field testing of the prototype. Showcasing the technology in trade shows and with state Departments of Transportation are also being planned.

IX. ECONOMIC IMPACT ASSESSMENT

In the year 2002, over $5 billion was spent on projects involving asphalt compaction. Nationally paving contractors spend about $250 million annually to rectify paving problems resulting from not achieving the desired level of compaction in the field. The intelligent compaction technology we propose to develop would be able to significantly reduce, if not eliminate, this loss currently suffered by paving contractors/asphalt producers. In FY 2002, Oklahoma spent over $150 million for the maintenance of its Interstates and National Highways. The savings achieved through the development of technologies that guarantee better quality roads will enable these crucial resources to be spent on improving other crucial transportation infrastructure. The successful development and marketing of this technology will also generate new jobs in the state of Oklahoma.

X. LEVERAGED SUPPORT

A proposal entitled "Monitoring of Long Term Pavement Performance" requesting $300,203 was submitted by the PI to Oklahoma Transportation Center. The PI also is exploring other avenues to leverage existing support to further research in the design, construction, and performance of Asphalt Pavements. A workshop addressing these topics is also planned with internationally renowned experts committing to participate in the effort. This effort will be supported by the Oklahoma Transportation Center. The Co-PI, Professor Musharraf Zaman, was awarded $95,000 by the Oklahoma Transportation Center for a period of one year to study the "Effects of Anti-Stripping Additives on Performance Graded Binders in Oklahoma." In addition, leveraged funding of over 100,000 was obtained in 2006 from the Oklahoma Transportation Center and ODOT for compaction related projects.

The accelerometers, real-time computers, density measuring equipment, GPS receivers and radios purchased as part of the project are vital resources that further the existing capability of the Broce Asphalt Laboratory at OU. The upgrades to the AVC and the construction of the controlled test strip make OU on of the few universities nation-wide with the resource capability to lead the research in the area of Asphalt Pavement Engineering. The PIs are working on joint proposals to federal and local agencies to help refine the IACA and lay the pathway for commercialization.

APPENDIX

Appendix A

Intelligent Asphalt Compaction Analyzer – Phase I Laboratory Study

A.1 Laboratory Compaction of Asphalt Mix Specimens

The AVC (Figure 1) is an asphalt vibratory compactor that is well-suited for compacting small quantities of hot mix asphalt in the laboratory. Studies have shown that the compaction process using the AVC is similar to that of the compaction of hot mix asphalt mat in the field using a vibratory drum compactor. During Lab compaction, the desired mix is heated to the temperature specified in the mix design specifications (Figure 4), and placed in a mold (Figure 2) and compacted using the AVC. The pressure exerted by the compaction head and the frequency of its vibration can be set using the control console shown in Figure 1. Accelerometers mounted on the frame of the AVC (Figure 3) are used to measure the vibrations of the AVC during compaction. Using a data acquisition card, the output of the accelerometers is read into a real-time computer for analyzing the effect of the mix on the vibrations of the AVC. The complete procedure for the compaction process is given below.

1. Place the material to be compacted, the mold, base plates and the pans in the oven and set the temperature in the oven to 175^{0} C (temperature specified in the mix design).
2. Remove the material from oven after one hour and divide into batches of 6.5 kg each. The material should be placed in separate pans and put back in the oven. The dimensions of the mold are 29.9cm x 12.5cm and the quantity of the mix placed in the mold is determined by the desired lift thickness. In the experiments conducted, the maximum possible amount of mix corresponded to a weight of 6.5 kilograms.
3. Clean the compacting head and coat with mineral oil to prevent the asphalt from sticking to the head. Remove the mold from the oven and place the base plates in the mold. Remove the pan containing 6.5 kg of material and mix the material quickly (to avoid segregation) and pour into the mold. Ensure that the temperature is still within the limits specified for compaction.
4. Load the mold onto the AVC (Figure 3) and set the desired compaction time and frequency. Run the AVC and collect data as the compaction process continues.
5. On completion of the run, wait till the head retracts upward and rotate the mold 180 degrees and start the compactor again. This process is repeated till the desired density is reached or the mix has cooled down to a point where further compaction is not possible.

After the Compactor is run for desired number of cycles, the specimen (compacted sample) is extracted from the mold and allowed to cool down at room temperature. The specimen is then cored and the density of the core is measured in accordance with the AASHTO T 166 and OHD L-45 specifications.

Figure 1. Asphalt Vibratory Compactor

Figure 2. Mold for compacting the mix

Figure 3. Accelerometers mounted on the frame of the AVC to measure the vibrations of the compaction head

04/09/04 10:35 ODOT MATERIALS DIVISION → 405 325 7066 NO.029 P02

RECYCLE

A.D. No.	001-029-001	Asph. Conc. Type B Insol. Recycle	**Design No.** 3012-TJC-20013
Project No.	IMG-35-3(271)129TR	19582(04) **Hwy.** I-35	**Avg. Daily Traffic** 0.3M+
Contractor:	J & R Sand Company Inc.	**Producer** T. J. Campbell Const. Co.	

MATERIAL	**SOURCE**	**% USED**
5/8" Chips	Hanson Rock @ Davis, Okla.(5008)	25
Screenings	Hanson Rock @ Davis, Okla.(5008)	45
Sand	G.M.I.(Sooner Pit) @ Oklahoma City, Okla.	15
Milled Asph. Pav.(MAP)	Plant Site	15
Asphalt Cement PG64-22OK	Wynnewood Refinery @ Wynnewood, Okla.	

Laboratory No. **Aggregate** **Percent Passing**	**5/8" Chips**	**Scrns**	**Sand**	**MAP**	**Combined Aggregate**	**Job Formula**	**JMF Tolerance**
3/4"	100			100	100	100	±0
1/2"	91			90	96	96	±7
3/8"	54	100		83	86	86	±7
No. 4	4	78	100	74	62	62	±7
No. 10	2	41	96	49	41	41	±4
No. 40	1	17	80	29	24	24	±4
No. 80	1	11	43	17	14	14	±4
No. 200	0.7	7.0	5.0	8.0	5.3	5.3	±2
% Asphalt Cement PG64-22OK				4.5		4.7	±0.4
Mix Temperature @ discharge from Mixer, °F						305	±20
Optimum Roadway Compaction Temperature, °F						290	

Tests on Asphalt Cement:

	Found	**Required**
Abs. Visc. @ 140°F	....	
Kin. Visc. @ 275°F	....	
Spec. Grav. @ 77°F	1.01 Est.	

Tests on Aggregates:

	Found	**Required**
Sand Equivalent	68	45 Min.
L.A. Abrasion % Wear	15.1	40 Max.
Durability (DC)	76	40 Min.
IOC	0.92	
Insoluble Residue (Cal)	78.5	30 Min.
Fractured Faces	100	75 w/2
ESG	2.674	
Hveem Wt.	1225	

Tests on Compressed Mixtures:

Percent Asphalt	**Spec. Grav. Specimen**	**Max. Theo. Spec.Grav.**	**Dens. % of Max. Theo.**	**Dens. % Req'd. of Max. Theo.**	**V.M.A. (%)**	**V.M.A. (Min.%)**	**Hveem Stab.**	**Hveem Stab.(Min.)**
4.2	2.357	2.501	94.2		15.6		51	
4.7	2.375	2.482	95.7	95-97	15.4	15	54	40
5.2	2.441	2.463	99.1		13.5		46	

Retained Strength 83% *75% Mininum Required*
Compacted Wt. 109.2 *lbs./sq.yd./1" thickness*
Recommended 4% *New Asphalt Cement PG64-22OK*

NOTE: This design is to be used on shoulders only.

MEETS SPECIFICATION REQUIREMENTS

04/09/04 FRI 11:30 [TX/RX NO 6773]

Figure 4. Mix design specifications

A.2 Experimental Procedure

The IACA is based on the hypothesis that a vibratory compactor and the hot mix asphalt (HMA) mat form a coupled system having unique vibration properties that can be identified by an analysis of the power spectrum distribution of the coupled system. The first step in the validation of this hypothesis is the determination of the important process parameters and their effect on the density achieved through compaction of the mix. A S3 type mix (see Table 1) was used in this part of the study and the compaction carried out for a range of design and operational parameters. From Table 1, it is seen that the aggregates have a nominal size of 0.75 inch (19 mm). Pertinent mix design parameters are presented below, with the acceptable values indicated in parenthesis: Voids in Mineral Aggregates, VMA =13.9% (> 13%); Voids Filled with Asphalt, VFA = 76.2% (70-80%); and optimum Asphalt Cement (AC) content = 5%. PG 64-22 type binder was used in the mix. Additional details on the mix properties are given by Nino (2006)[1].

In the first set of tests, 14.33 lbs. (6.5 kg) of loose mix asphalt was compacted in the AVC at a compaction pressure of 120 psi (827.4 kPa). The loose mix was heated to 305.6^{o}F (152^{o}C) and compacted in the AVC for different durations. After compaction, the specimen was cooled and cores extracted. The density of the compacted specimen was measured according to AASHTO T-166 method. Results in Table 2 show that the density achieved after compaction is consistent over repeated trials. The density increases with compaction time, as expected. Tests were also conducted to study the effect of compaction pressure on the final density achieved (PR1-PR8 in Table 2). Lowering the compaction pressure increased the air void content in the compacted specimen. For instance, reducing the forward pressure from 827.4 kPa (120 psi) to 551.6 kPa (80 psi) resulted in an increase in the air void content from 6.4% to 17.9% for the same 80 seconds of compaction. Further, at the lower pressure of 551.6 kPa (80 psi), increasing the duration of compaction did not result in a significant change in the air void content. The effect of lift thickness was studied by compacting different amounts of loose mix. It was found that for the limited range of thickness considered, the lift thickness did not play any significant role in achievable densities. However, for low lift thicknesses, sometimes it was found difficult to obtain a desired compaction level without damaging the aggregates. Tests also reveal the difficulty in compacting the mix at lower temperatures. It was found that lowering the temperature or the compacting pressure resulted in less compaction for the same duration of compaction (Tables 2 and 3). For example, at a mix temperature of $152\,^0C$, the maximum allowed according to the mix specification, 60 seconds compaction resulted in an air void content of 6%. On the other hand, reducing the mix temperature to $122\,^0C$ resulted in an air void content of 8.8% for the same duration of compaction.

The data gathered in the previous tests was analyzed to determine the key features of interest in the spectrum of the vibratory signals (Figures 5-8). This information was used to design the feature extractor and the NN classifier components of the compaction analyzer. The NN was trained to detect four primary regions corresponding to different densities during compaction. The four regions selected are a) free vibrations of the compactor corresponding to zero compaction; b) vibrations corresponding to compaction head in initial contact with the loose mix, i.e. start of the compaction process; c) vibrations corresponding to 92% compaction; and d) vibrations corresponding to 94% compaction of the specimen. Here, 100% compaction implies that the density of the specimen is equal to its theoretical maximum density. The functioning of the compaction analyzer was verified by presenting it with vibration data collected while compacting a specimen during different tests. The different features extracted from the accelerometer output during the compaction process and the estimates of the density are shown in Figure 9.

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[1] Nino, Johann G., "Design and Development of a Real-time Neural Network Based Compaction Analyzer," Masters Thesis, School of Electrical and Computer Engineering, University of Oklahoma, May 2006.

The ability of the compaction analyzer to predict the density was tested by manually shutting down the AVC when the analyzer indicated that the mix had reached the target density. The target densities were selected as the density of the specimen corresponding to the four regions that the NN was trained to recognize. Table 4 shows the density specified in each case and the density actually achieved during test runs. It is clear from these tests that the compaction analyzer can be used to predict the density of the mix during compaction in the laboratory.

The results in Table 4 indicate that for a specified target density of 92%, the compacted specimen reached a mean density of 92.7% with a standard deviation of 0.304. The 95% confidence interval for the first set of tests obtained using the Student's t-distribution is $[92.7 \pm 0.38]$, i.e. [92.32, 93.08]. Similarly when the specified target density is 94%, the compacted specimen was found to have reached a mean density of 93.9% with a standard deviation of 0.313. The 95% confidence interval in this case was [93.48, 94.25]. The results indicate that in both the cases, there is a 95% confidence that the achieved density is within 1.25% of the target density.

A.3 Conclusions of the Laboratory Study

The following are the main conclusions from this work:

- The density of the specimen is a property of the asphalt mix. Different types of mix, i.e. coarse, intermediate, or surface mix, have different specifications, having as a result different interaction between the specimen and the AVC.
- During compaction, the density of the specimen affects the vibrations of the compacting equipment. For given equipment, mix, compaction parameters and density, the vibrations have specific frequency features, thus, changes in the spectrum reveal the changing density of the specimen (Figures 5-8).
- Laboratory studies indicate that the temperature of the mix does not play a big role in the vibrations of the compactor. Mix temperature lower than the cessation temperature will not result in further compaction but does little to affect the vibrations of the AVC. This fact is also validated by anecdotal evidence from the field.
- The compacting pressure directly affects the final density that can be achieved during compaction. However, the vibration features are similar to the features seen for the mix at the specified density level.
- The frequency of the vibratory motors affects the amount of densification achieved in a given duration of time. Lower compaction was observed when the frequency of the motors was at 45 Hz, while adequate compaction was achieved at 60 Hz. The AVC was not capable of operation beyond 60 Hz. Within this range of frequencies, it was not possible to correlate changes in the density with varying spectrograms of the AVC. Since in practice, the frequency of the motors is adjusted based on the ground speed of the compactor to give approximately 12 impacts per linear foot of the pavement, the variation in frequency in the field is minimal and play a minor role during the compaction.
- The vibration characteristics of the AVC are similar to the vibrations of a vibratory compactor during the construction of asphalt pavements in the field.
- The spectral features extracted from the vibrations produced during the compaction of an asphalt specimen can be successfully classified using a MLP neural network trained with standard back propagation or similar technique. The classification results correlated very well with the density values obtained in other tests.
- The trained MLP neural network has been shown to have excellent generalization capabilities and it was able to classify unknown vibration data in the right category corresponding to density close to the values it was trained to predict.

Table 1. Gradation for mix S3

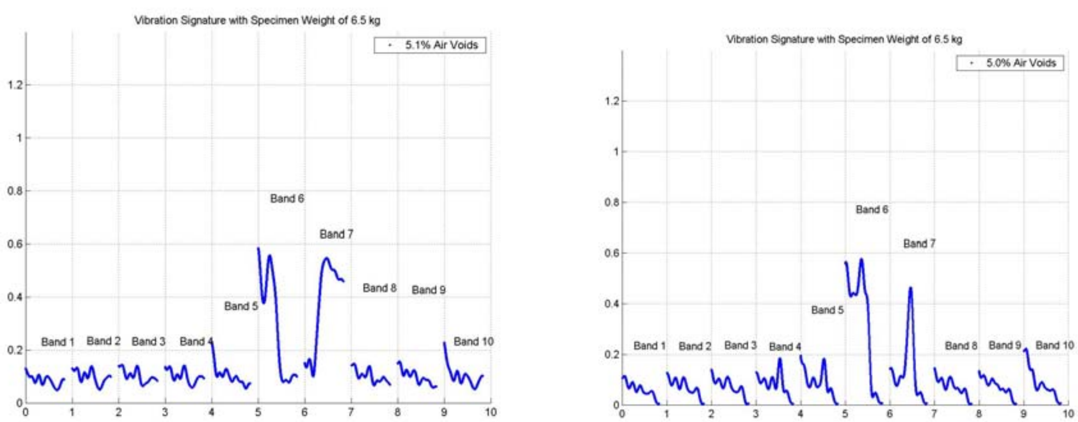
Sieve No.	Job Formula (% passing sieve)
25.4 mm (1 in)	100
19 mm (0.75 in)	98
12.7 mm (0.5 in)	88
9.52 mm (0.375 in)	72
No. 4; 4.75 mm (0.187 in)	40
No. 8; 2.36 mm (0.0929 in)	30
No. 16; 1.18 mm (0.0464 in)	21
No. 30; 0.6 mm (0.0236 in)	16
No. 50; 0.3 mm (0.0118 in)	11
No. 100; 0.15 mm (0.0059 in)	8
No. 200; 0.075 mm (0.0029 in)	4.2

Table 2. Summary of tests

Test ID	Time s	Temperature ^oC (^oF)	Pressure kPa (psi)	Specimen Weight kg (lb)	Frequency Hz	% Air Voids
TI1	40	152 (305.6)	827.4 (120)	6.5 (14.33)	60	16
TI2	40	152 (305.6)	827.4 (120)	6.5 (14.33)	60	17.5
TI3	45	152 (305.6)	827.4 (120)	6.5 (14.33)	60	7.5
TI4	45	152 (305.6)	827.4 (120)	6.5 (14.33)	60	6.7
TI5	50	152 (305.6)	827.4 (120)	6.5 (14.33)	60	6.6
TI6	50	152 (305.6)	827.4 (120)	6.5 (14.33)	60	6.9
TI7	55	152 (305.6)	827.4 (120)	6.5 (14.33)	60	4.7
TI8	55	152 (305.6)	827.4 (120)	6.5 (14.33)	60	4.9
TE1	60	122 (251.6)	827.4 (120)	6.5 (14.33)	60	8.8
TE2	60	122 (251.6)	827.4 (120)	6.5 (14.33)	60	10.0
TE3	60	132 (269.6)	827.4 (120)	6.5 (14.33)	60	6.6
TE4	60	142 (287.6)	827.4 (120)	6.5 (14.33)	60	7.3
TE5	60	142 (287.6)	827.4 (120)	6.5 (14.33)	60	6.5
TE6	60	152 (305.6)	827.4 (120)	6.5 (14.33)	60	5.5
TE7	60	152 (305.6)	827.4 (120)	6.5 (14.33)	60	6.4
PR1	60	152 (305.6)	551.6 (80)	6.5 (14.33)	60	18.0
PR2	60	152 (305.6)	551.6 (80)	6.5 (14.33)	60	17.9
PR3	60	152 (305.6)	620.5 (90)	6.5 (14.33)	60	12.1
PR4	60	152 (305.6)	620.5 (90)	6.5 (14.33)	60	10.8
PR5	60	152 (305.6)	689.5 (100)	6.5 (14.33)	60	9.2
PR6	60	152 (305.6)	689.5 (100)	6.5 (14.33)	60	8.5
PR7	60	152 (305.6)	758.4 (110)	6.5 (14.33)	60	8.7
PR8	60	152 (305.6)	758.4 (110)	6.5 (14.33)	60	8.2
WE1	60	152 (305.6)	827.4 (120)	3.5 (7.71)	60	8.6
WE2	60	152 (305.6)	827.4 (120)	3.5 (7.71)	60	5.6
WE3	60	152 (305.6)	827.4 (120)	4.5 (9.9)	60	5.4
WE4	60	152 (305.6)	827.4 (120)	4.5 (9.9)	60	6.8
WE5	60	152 (305.6)	827.4 (120)	5.5 (12.1)	60	5.5
WE6	60	152 (305.6)	827.4 (120)	5.5 (12.1)	60	4.5
WE7	60	152 (305.6)	827.4 (120)	6.5 (14.3)	60	5.1
WE8	60	152 (305.6)	827.4 (120)	6.5 (14.3)	60	5.0

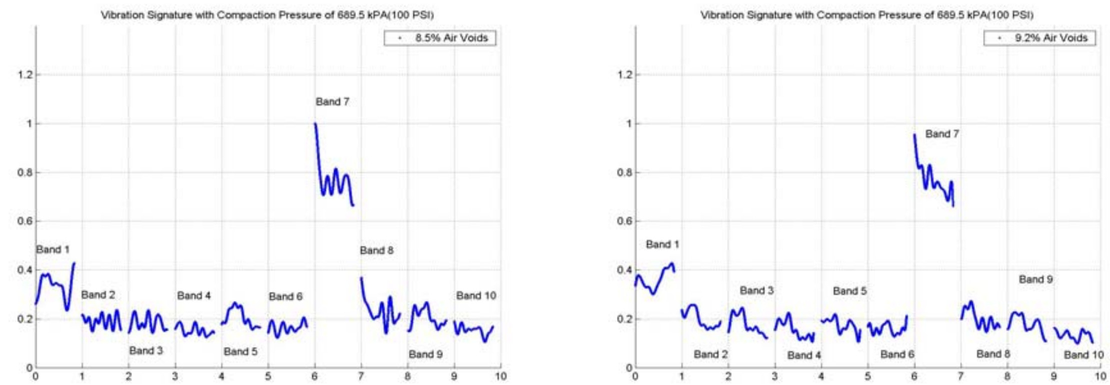
Table 3. Variation of density with AVC frequency
Parameters: 6.5 kg (14.44 lb), 152 ^{o}C (305.6 ^{o}F) and 827.4 kPa (120 psi).

Test ID	AVC Frequency (Hz)	Compaction Time (secs)	Compacted Specimen Density Average % air voids
FR1	20	40	17.7
FR2	20	80	17.5
FR3	20	120	16.2
FR4	40	40	9.5
FR5	40	80	9
FR6	40	120	8.8
FR7	60	40	8.6
FR8	60	80	7.2
FR9	60	300	5.4



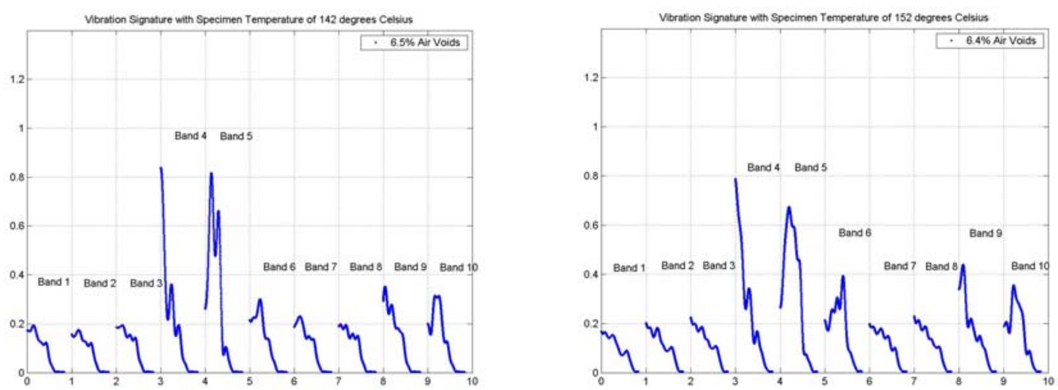
(a) (b)

Figure 5. Vibration signature of identical tests run at 120 psi (827.4 kPa)
(a) Test WE7; (b) Test WE8



(a) (b)

Figure 6. Comparison of vibration signatures for identical tests run at 100 psi (689.5 kPa): (a) Test PR5; (b) Test PR6



(a) (b)

Figure 7. Vibration signature of tests TE5 and TE7 at different temperatures: (a) Test TE5; (b) Test TE7

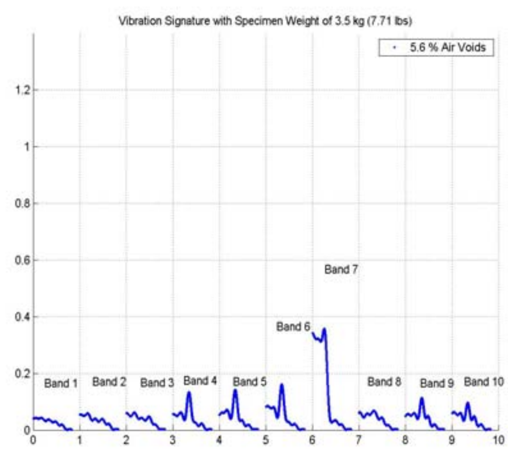


Figure 8. Vibration signature of test WE2

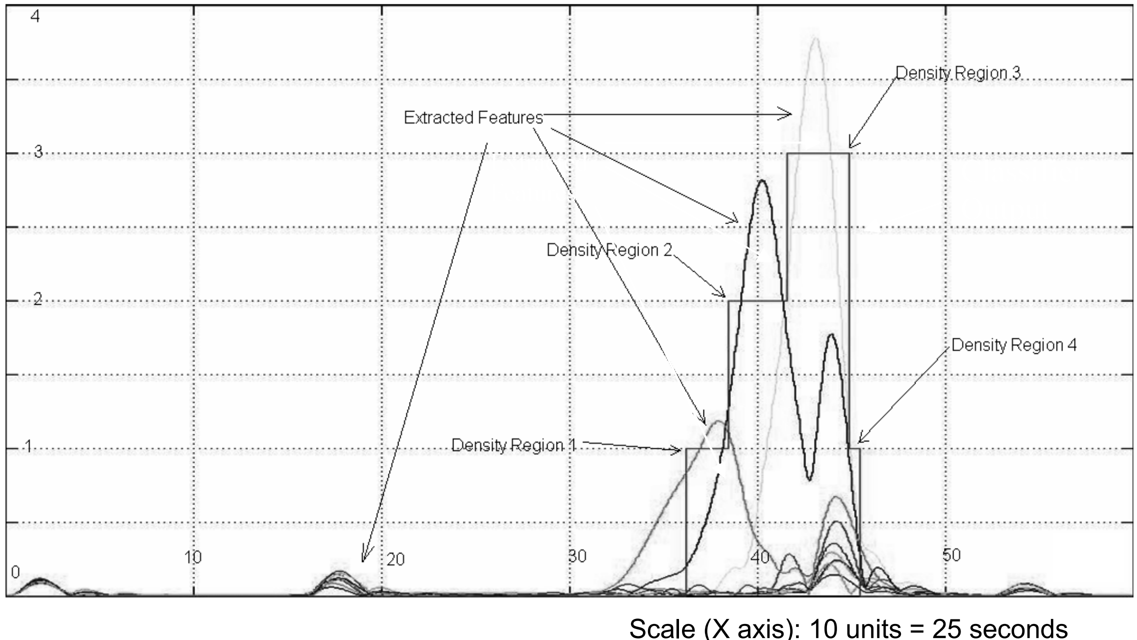


Figure 9. Output of the classifier showing the prediction of different density levels

Table 4. Use of the analyzer in compacting asphalt mix to a desired density

S. No	**Desired Density (%Gmm)**	**Achieved Density**				
		Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
1	92.0	92.9	92.9	92.2	92.8	92.9
2	94.0	93.6	94.2	94.2	93.7	93.6

A.4 Design and Construction of Controlled Test Site

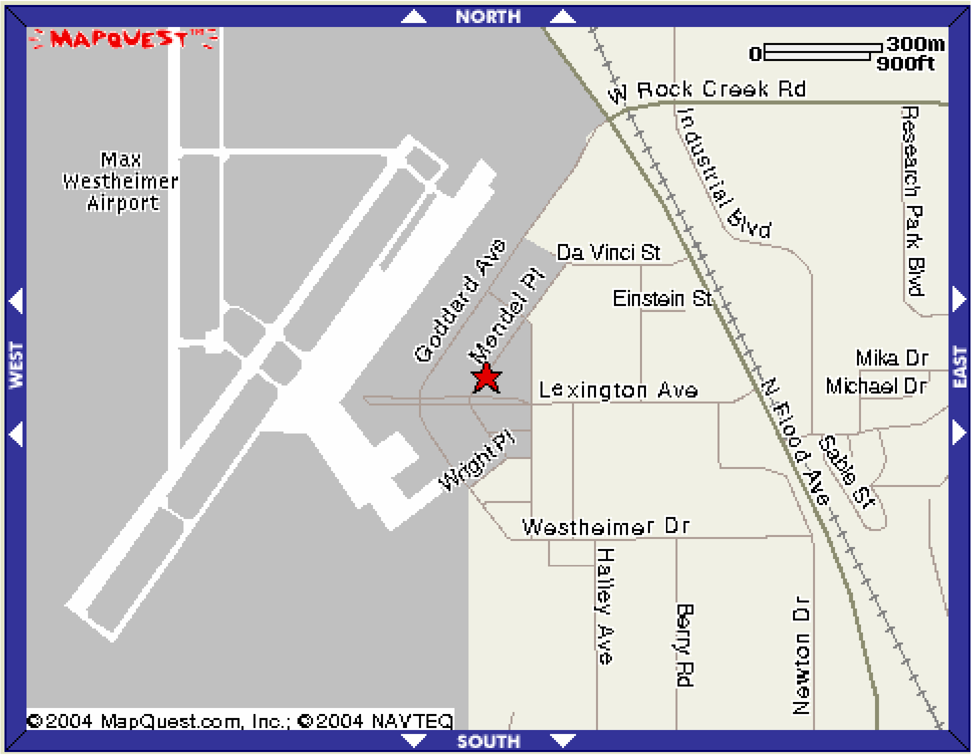


Figure 10. Location of the test site

This section details the location of the test site and the soil characterization tests performed at the site as part of the test strip design. The test site selected was a stretch of unused road on Mendel Plaza near Max Westheimer Airport in Norman. This asphalt road is part of the University Park in North Research Campus and has been provided to the research team for the duration of the project. The various tasks accomplished as part of the design are discussed below.

Task 1: Surveying

The project section is located on Mendel Pl, in Norman, Oklahoma. The center line of the street was located using surveying instrument as shown in Figure 11. The section is 7.3152 m (24 feet) wide by 76.2 m (250 feet) long and it was divided into five stations. Figure 12 shows a photographic view of marking down the stations using a wheel meter and an orange paint.

Figure 11. Locating the benchmark for the project

Figure 12. Marking down the stations

Task 2: Identification of the number of boreholes

A total of 24 boreholes were selected and marked down as shown in Figure 13. The number of holes is supposed to give a better soil properties distribution throughout the project.

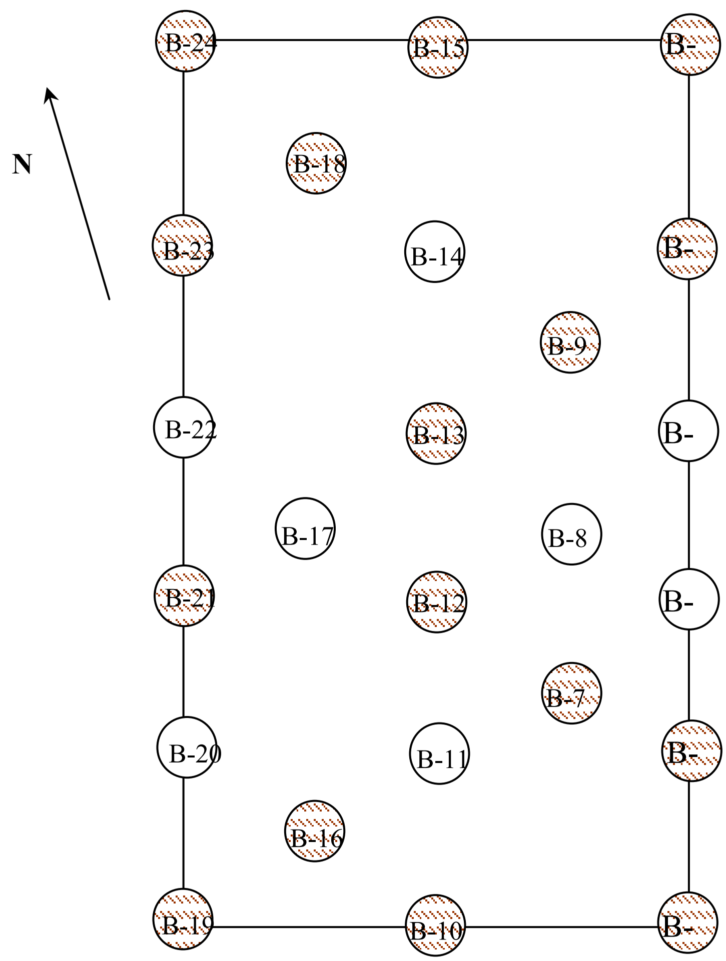


Figure 13. Plan view of the section and boreholes numberings

Task 3: Field testing

The dynamic cone penetration (DCP) tests were performed inside each hole to check the preliminary properties of the soil. Tests were conducted up to a depth of approximately 76.2 cm (30 inches). After the performance of the DCP tests, bulk samples were collected from selected boreholes (shown as hashed circles in Figure 13.) A total of sixteen holes were drilled using a hand auger. Bulk samples were collected every 15.24 cm (6 inches), up to 91.44 cm (36 inches); a total of 6 different bulk samples were collected from each hole, each sample representing a different depth. The moisture content for each six inches was measured by collecting moisture content samples. All the bulk samples were placed in bowls for drying out prior to processing (Figure 14).

Figure 14. Drying out the bulk samples prior to processing

Task 4. Design of the Concrete Slab for the Test Strip

This section summarizes the results of the proctor tests and the design procedure for constructing a concrete slab on Mendel Place, at Westheimer Field, Norman Oklahoma. The soil mapped by the Natural Resource Conservation Service, NRCS (formerly the Soil Conservation Service or SCS) is Kirkland, Urban land, Pawhuska complex, 0-3 percent slopes. Kirkland composite “B” Horizon bulk samples were collected and brought to our laboratory facilities. Samples were air-dried at room temperature, processed, and used for laboratory testing.

Proctor Test Results

The standard proctor tests were performed on the collected bulk samples. Tests were performed according to the AASHTO T 99 test method. The moisture-density relationship is illustrated in Figure 15. From Figure 15, the maximum dry density (MDD) is approximately 104.4 pcf, and the optimum moisture content (OMC) is approximately 19%. The subgrade soil should be pulverized and compacted to at least 95 percent of standard proctor density; the target density that needs to be achieved in the field will be specified in the proposed design. The moisture content of the subgrade material at the time of compaction shall be within two points of the optimum moisture content as determined by AASHTO T 99.

Design of the Concrete Slab

Three different design methods were used to determine the thickness of the slab: (1) Kenslabs, (2) ANSYS; and (3) Machine Foundations.

Kenslabs is a computer program based on finite element method, in which the slab is divided into rectangular finite element with a large number of nodes. The slab is considered as a liquid foundation also known as a Winkler foundation, with the force-deflection relationship characterized by an elastic spring.

ANSYS is another finite element program used to model the slab resting on soil medium. The third method used to design the foundation under dynamic loading, was the machine foundations procedure.

A summary of the input parameters for the design of the slab is presented in Table 5. The modulus of elasticity of the soil, also known as resilient modulus (Mr), is determined from the laboratory Mr tests. The modulus of the subgrade reaction is estimated from Mr value using the equation $k = Mr/19.44$. The shear modulus is calculated from $G = E[2(1+\nu)]$; where E is the resilient modulus. The Poisson ratio is assumed. The unit weight of the soil is determined from the Proctor and is equal to MDD*[1+OMC (%)/100]. The modulus of elasticity (Es) and ν for the concrete slab are assumed. The applied load on the slab is determined from the weight of the compactor and is assumed to be 111, 000 lbs.

Table 5. Input parameters for the design of the slab

Description		Thickness	Deflection, in	Stress in the concrete slab, psi
Method	Kenslabs	12	0.03952	-274
		18	0.0296	-160
		24	0.02364	-93
	ANSYS	12	0.0065	N/A
	Machine Foundations	12	0.016*	N/A
*Function of the compactor operating frequency				

Table 6. A summary of the deflection of the slab as well as the flexural stress in the slab

Layer	Parameters description	Method		
		Kenslabs	ANSYS	Machine Foundations
Subgrade (Kirkland soil series)	Modulus of Elasticity (Mr) (psi)	N/A	10, 000	N/A
	Modulus of Subgrade Reaction (pci)	500	N/A	500
	Poisson ratio	0.45	0.45	0.45
	Shear Modulus (psi)	N/A	N/A	3450
	Unit weight (pcf)	124	N/A	124
Slab (Concrete)	Thickness (in)	12, 18, & 24	12	12
	Modulus of Elasticty, Es, psi	4, 000, 000	4, 000, 000	N/A
	Poisson ratio	0.15	0.15	0.15
The length of the slab is 250 feet and the width is 24 feet				

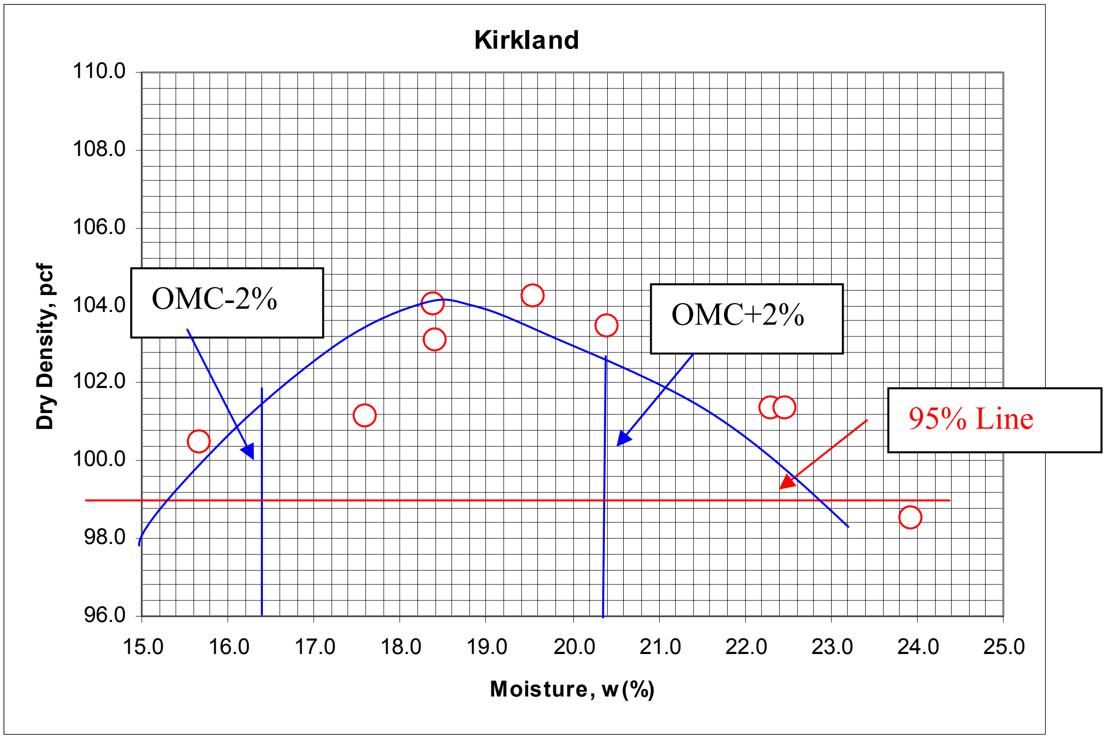


Figure 15 Proctor test results

A summary of the deflection of the slab and the flexural stress in the slab, using the three different design procedures is presented in Table 5. From the aforementioned results, the following steps are proposed:

1. Subgrade density should be approximately 104.4 pcf, at the time of compaction.
2. Subgrade moisture content shall be within two points of the optimum moisture content (19%).
3. The slab should have a width of 7.3152 m (24 feet), length of 60.96 (200 feet), and a thickness of 0.3048 m (12 inches).
3. The modulus of elasticity of the slab should be 4, 000, 000 psi.
4. The flexural strength of the concrete should be at least 350 psi.
5. A total of 24 bars of No. 8 @ 0.3048 m (1 foot) intervals in the transverse direction and a total of 200 bars of No. 3 @ 1 foot intervals in the longitudinal direction are required for the control of shrinkage and thermal cracking.

Figure 16. Preparation of site for the construction of the test strip

Figure 17. Completed test strip for controlled field testing

Table 7. Results from the compressive strength tests of the concrete base used in the construction of the test strip

7 Day Compressive Strength, psi

	Cylinder 1	Type of Break	Cylinder 2	Type of Break	Cylinder 3	Type of Break	Avg.
Truck # 3	4378	chip	4227	chip	4111	shear	4239
Truck # 4	4811	chip	4603	cone & shear	4700	cone & split	4705
Truck # 5	4482	chip	4304	chip	4011	end	4266
Truck # 6	4663	cone & split	4159	chip/end			4411

15 Day Compressive Strength, psi

	Cylinder 1	Type of Break	Cylinder 2	Type of Break	Cylinder 3	Type of Break	Avg.
Truck # 3	4366	---	4510	chip	4097	chip	4324
Truck # 4	5333	---	5235	end			5284
Truck # 5	4732	columnar	4428	cone & shear	4388	chip/end	4516
Truck # 6	4701	chip/end	4291	end			4496

28 Day Compressive Strength, psi

	Cylinder 1	Type of Break	Cylinder 2	Type of Break	Cylinder 3	Type of Break	Avg.
Truck # 3	4768	cone & split	5023	cone & split	4727	cone & split	4839
Truck # 4	5757	chip	5204	chip	5502	chip	5488
Truck # 5	5200	cone & split	5166	chip	5067	cone & split	5144
Truck # 6	5313	cone & split	5443	cone	4767*	chip	5378

* Inaccurate measurement

Appendix B

Intelligent Asphalt Compaction Analyzer – Phase II
Field Testing and Validation of IACA Prototype

B.1. Verification of IACA Hypothesis in the Field

The compaction tests conducted in the laboratory (Appendix A.2) indicate that the analyzer can successfully predict the density of the specimen during compaction in the laboratory. In order to verify the suitability for application in real-life conditions, the IACA was installed on an Ingersoll Rand DD130 compactor. Accelerometers were mounted on the frame of the compactor and the compactor run on gravel as well as a pre-compacted asphalt parking lot. The spectrograms in the two cases showed that the nature of the material in the two cases was totally different and the output of the accelerometer could be used in identifying the material underlying the compactor. Further, the analyzer predicted regions where the density of the pavement was below a threshold (Figure 18). Subsequent readings using a nuclear density gauge corroborated these findings.

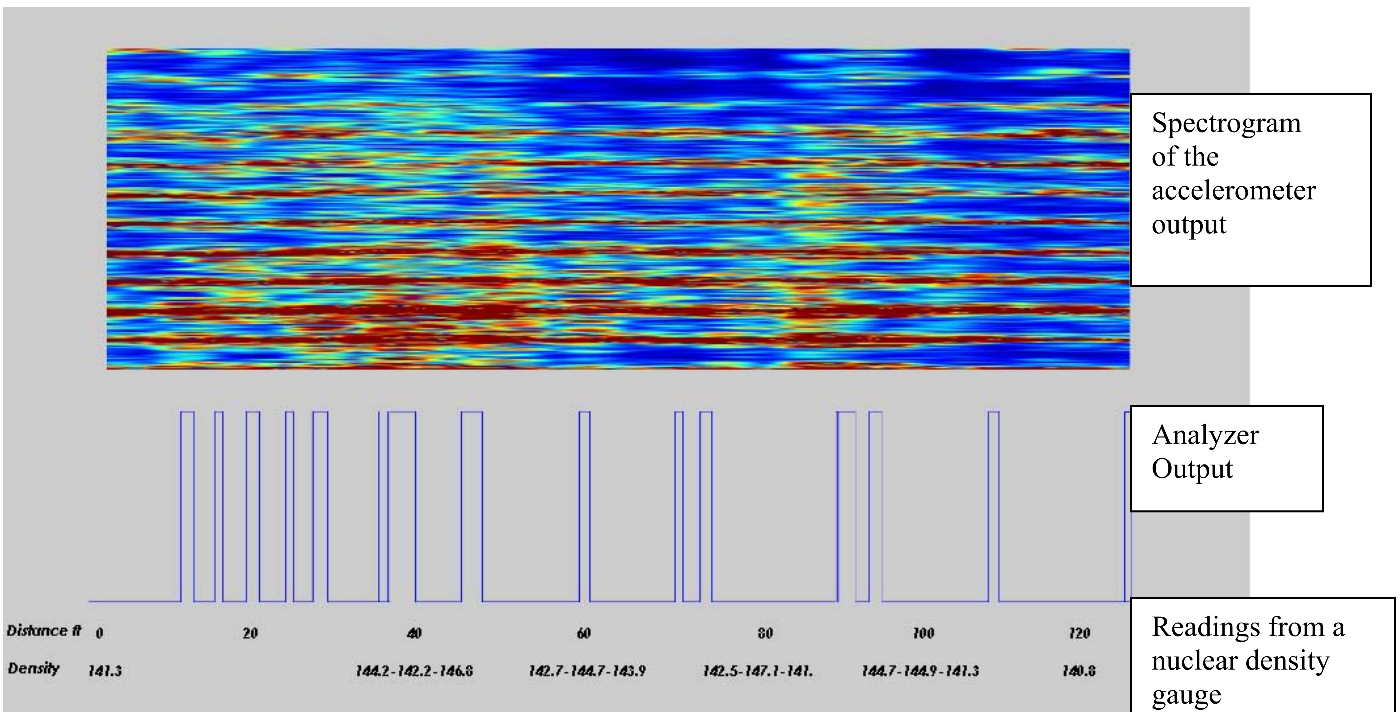
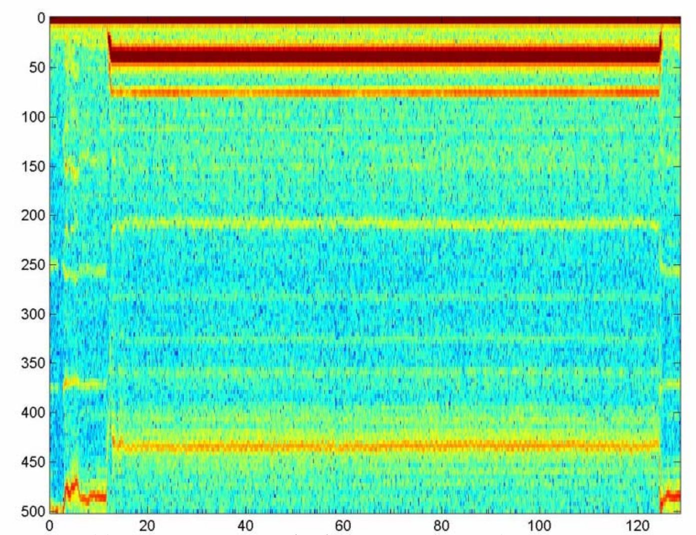
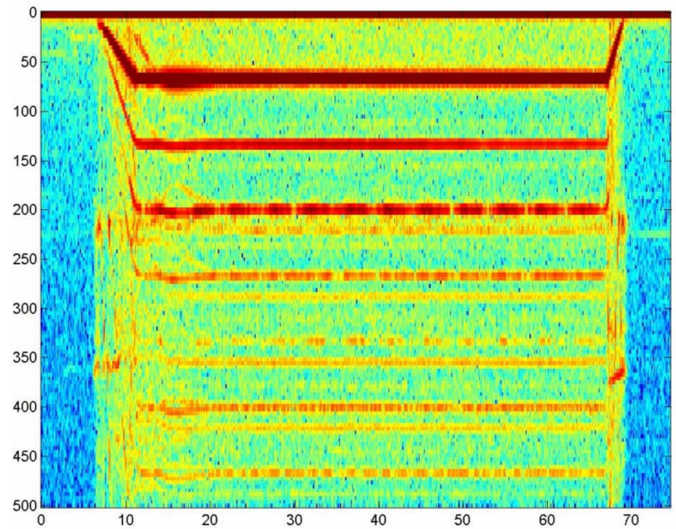


Figure 18 Use of analyzer to determine compaction in the field

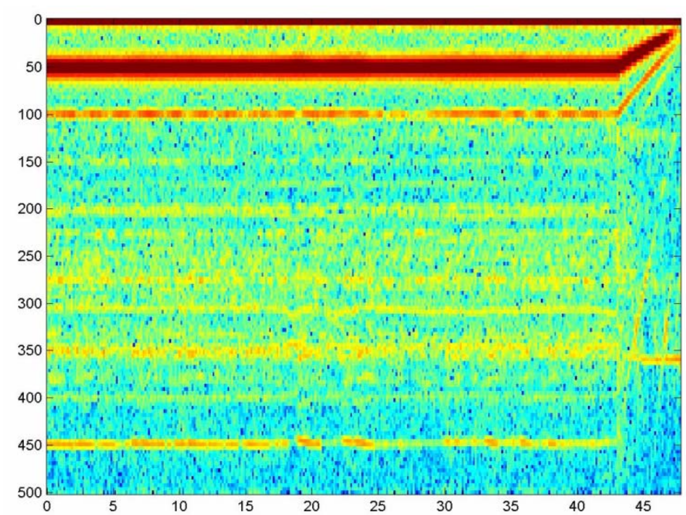
Data from several construction sites across Oklahoma was collected and studied to determine the effect of the process parameters (lift thickness, mix type, subgrade, etc.) on the vibrations of the compactor during the compaction of the asphalt pavement. The spectrograms for some typical parameters are shown in Figure 19. It can be seen that the vibration characteristics are impacted by the process parameters. Our study indicated that the spectrograms, while showing differences between different projects, remain consistent over the course of a single construction for a given set of construction parameters (lift, lift thickness, compactor vibration settings, etc.). Further, the spectrogram in Figure 20 shows the effect of the changing density on the vibration characteristics of the compactor for two passes over the same stretch of the pavement under construction. The intensity of the colors in the spectrogram indicates the power density associated with the vibrations. Regions with the maximum power intensity, shown in red in the spectrograms were visually located and their locations correlated with the GPS measurements. Figure 21 shows the power spectral density of the measured vibrations and the density of the roadway (in the center of the roller path) measured using a Troxler Nuclear density gauge. It can be seen that the observed spectral densities do indeed correlate with the measured density.



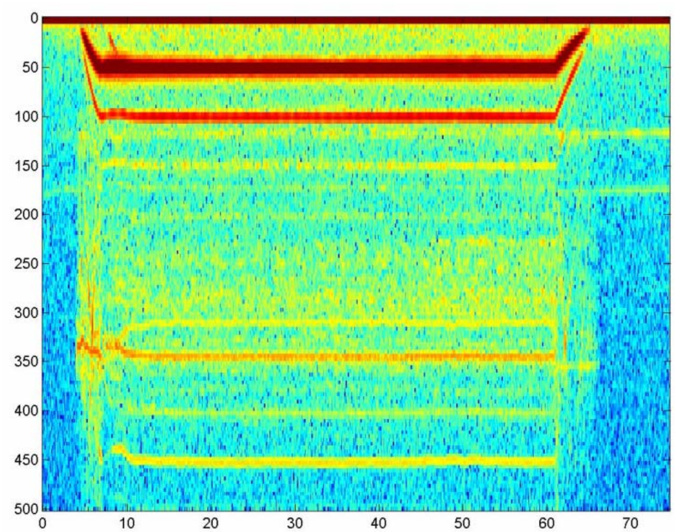
(a) Interstate I-35 2-inch (S3 – PG 64-22)



(b) 3-inch (S3 – PG 64-22) on 6 inch Concrete base



(c) 4-inch (S3 – PG 64-22) on compacted subgrade



(d) 2-inch (S4 – PG 70-28 OK) on 8 inch S3

Figure 19. Spectrograms of the vibrations of the compaction for different process parameters

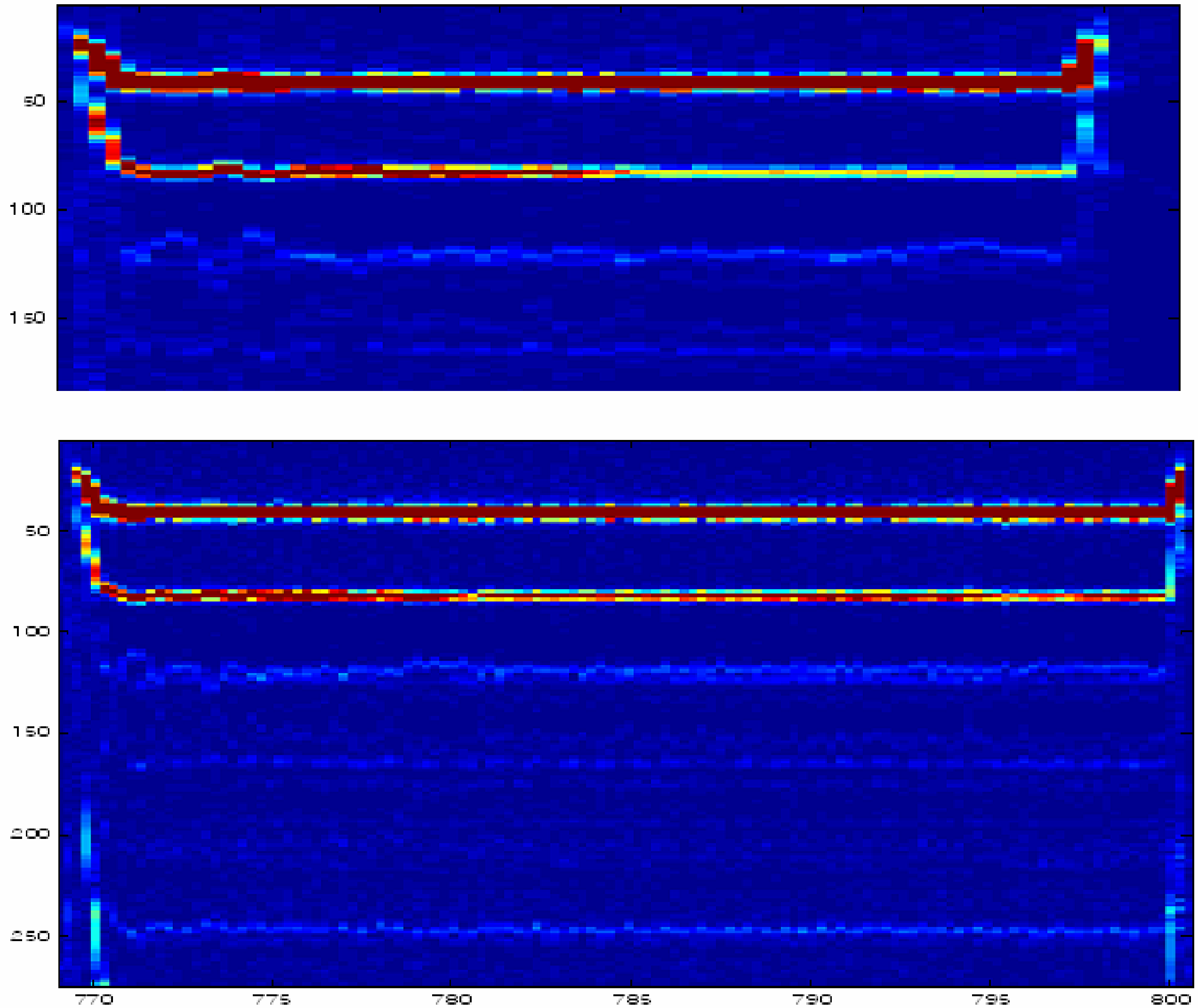


Figure 20. Spectrogram showing the progress of compaction during two successive passes over the same stretch of the pavement

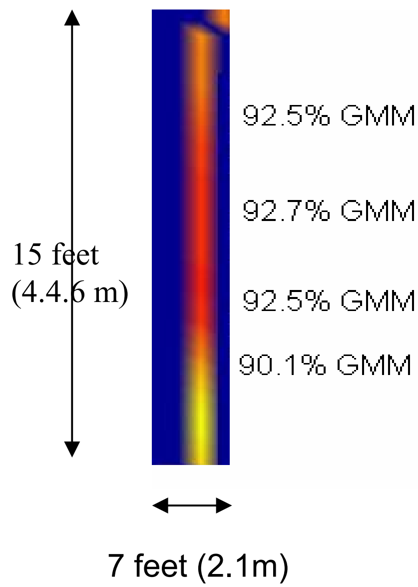


Figure 21. Output of the compaction analyzer along with actual density measurements obtained from a nuclear density gauge

B. 2 Testing of IACA under controlled Field Conditions

The IACA prototype that was developed in Phase I was refined during compaction of asphalt mixes on the controlled test strip that was constructed at Mendel Place, Norman. Initially, several overlays of 7.62 cm (3 inch) lift were constructed using the S3 mix with characteristics similar to those listed in Figure 3 and also in Table 1. During each of these lifts, the vibrations of the machine were collected and the corresponding spectrograms were computed. After each compaction, several cores were extracted and their density measured in the laboratory in accordance with the AASHTO T 166 and OHD L-45 specifications. The vibrations in the vicinity of the core locations were used to extract the features need to train the neural network. The core densities were also used to calibrate a PQI 301 non-nuclear density gauge. The training and validation of the IACA is described in this section.

The IACA was trained using data obtained during the construction of an asphalt pavement on the test strip. The pavement was 91.44 m (300 feet) long, 3.6576 m (12 feet) wide, 7.63 cm (3 inch) thickness and constructed using a S3 (PG64-22OK) mix. The vibrations of the compactor were measured using a triaxial accelerometer mounted on the axial shaft of the drum. The output of the accelerometer and the GPS measurements of the location of the compactor were collected and the spectrogram was plotted against the distance traveled by the compactor for each roller pass. After each roller pass, the density was measured at specific points on the asphalt mat using the PQI 301 gauge (Table 8). The densities measured after each pass are shown in Figure 22. It can be seen from this figure that the density increases after each pass. However, “roll over” occurs after the third pass and subsequent roller passes cause a reduction in the density of the compacted pavement. The spectrogram of the vibrations of the compactor over the first two passes is shown in Figure 23, where the effect of increased density on the vibration of the compactor can be easily seen.

The data from Table 8 was used to train the IACA to extract the relevant features from the vibration signal and predict the density. The predicted output of the IACA during the final pass of the first stretch is shown in Figure 24. It can be seen that the predicted density correlates very well with the densities measured using the PQI 301 gauge. Figure 35 shows the final compacted density of the entire test strip as predicted by the IACA. Comparison with the densities measured from the cores extracted from the completed pavement show a very good correlation between the measured and predicted densities.

B. 3 Field Testing and Validation of the IACA

The ability of the IACA to predict density using compaction operations in the field was investigated at Will Rogers International Airport, Oklahoma City. Figure 26(a) shows the construction area and Figure 26(b) depicts the different overlay regions. The project involved stabilization of the subgrade with Cement Kiln Dust (CKD) and the construction of 10.668 m (35 feet) Asphalt shoulders on either side of the Taxiway for dust abatement. The shoulder was constructed in three separate lifts with two 7.62 cm (3 inch) lifts of S3 (PG 64-22OK) mix followed by a surface layer of 5.08 cm (2 inch) S4 (PG64-22OK) type mix. The details of the paving section are shown in Figure 27 and the mix design sheets are given in Figures 28 and 29. The data and analysis presented here refer to the construction of the base layer of the 457.2 m (1500 feet) section (Section A) in Figure 26(b).

The taxiway shoulders were 10.668 m (35 feet) wide and 457.2 m (1500 feet) long and were constructed as two lanes. The base layer of the northern lane was 5.4864 m (18 feet) wide was constructed first and the base layer of the southern lane 2.1336 m (17 feet wide) was then constructed. The density readings were collected after each roller pass at periodic intervals along both the lanes using a PQI 301 non-nuclear density gauge. The vibrations measured by the accelerometer mounted on the compactor were also measured using the IACA. The features extracted from the vibration signals were correlated with the GPS measurements of the spatial location of the compactor and were used to predict the level of compaction reached after each roller pass. As in the previous case, the IACA was calibrated to recognize and classify the features in the vibration signals as those corresponding to 90%, 92% or 94% of the theoretical maximum density of the mix. Figure 30 shows the spectrogram and the predicted density during one of the passes of the roller. It can be seen from the figure that the compactor begins to move from 396.24 m (1300 feet) to 405.384 m (1330 feet) at which point the vibration motors are turned on. The predicted density over the stretch from 405.384 m (1330 feet) to 445.008 m (1460 feet) was predicted to be between level 2 and level 3, i.e. between 92% and 94% compaction.

Figure 31 shows the final as-built density map over the complete stretch of the pavement. Data below 121.92 m (400 feet) could be reproduced as a glitch in the GPS measurement led to a loss of spatial information for the northern lane from 0 to 121.92 m (400 feet). It can be seen from the figure that the PQI readings indicate uniformly good compaction (~ 93%) on the southern lane. While the northern lane was also well compacted (~ 93%), the variations in density were more significant (91– 94%). The density predicted by the IACA correlates well with the PQI measurements, as well as the density obtained from roadway cores. The as-built map in Figure 31 is depicted as the IACA output over the entire width of the drum. The spectrograms of the compactor vibrations and the IACA output over the region from 259 – 274 m (850 – 900 feet) are shown in Figure 32. It can be seen that the density predicted by the IACA both on the northern and southern lanes correlates well with the density measured by the PQI 301 gauge (Figures 34 and 35). Four roadway cores were extracted and the densities measured. The locations of the cores and the measured density as well as the density predicted by IACA are shown in Figures 31, 35, 36 and in Table 9. It can be seen from these results that the IACA is able predict the density continuously and in real-time during the compaction of the pavement. The prediction accuracy is comparable to the accuracy of the PQI 301 non-nuclear density gauge.

B. 4 Application of IACA in the identification of Design and Process Issues in Compaction

The IACA was used in several construction projects across Oklahoma. In the initial applications, the IACA was primarily used to gather vibration data to study the repeatability and consistency of the data. These field experiments were useful in identifying problems in GPS measurement and synchronization of the vibration data with the GPS information. One of the benefits realized from the analysis of the GPS information was identifying construction processes that lead to quality problems in the field. Figure 38 shows the path followed by the compactor during the construction of a stretch of highway near Elmore City (SH 19, West of I -35 near Elmore City, OK). The path of the roller indicates that the north shoulder of the highway (3.6576 m (12 feet) wide West bound Lane) is unevenly compacted. Further, the vibration data indicated that the roller operator had turned the vibration motors off while compacting the northern shoulder of the highway. Density measurements using the Troxler nuclear density gauge revealed several locations where the density was below 90%. Similar characteristics can be seen from Figure 39 showing the roller paths over several passes during the construction of the ramp at the Highway 9 / I-35 interchange in Norman, OK.

Figure 40 shows the spectrograms for two passes of the roller over the same stretch of the pavement during the construction of Highway 10 near Miami, OK. During the construction, it was observed that adequate compaction was not achieved on this particular stretch of the road. Repeated passes over the stretch did not result in any appreciable change in the density readings. Analysis of the spectrograms of the vibrations on this stretch of the road indicated that for every pass on this stretch (290-300 feet in Figure 40) the high frequency harmonics in the 80-90 Hz band were attenuated. Since this feature was consistent in every pass, it was surmised that this attenuation was due to the characteristics of the subgrade in this section of the road. From the spectrogram data, it was predicted that the subgrade failed on the section between 139.29 – 144.78 m (457 and 475 feet) from the East end of the construction. Subsequent investigation revealed that inadequate drainage had led to the failure of the subgrade between 137.47 – 154.53 m (451-507 feet) from the east end of the constructed roadway.

Figure 31 shows to significant regions of under compaction at 152.4 m (500 feet) and 320.04 m (1050 feet) of the North shoulder of the Taxiway at Will Rogers International Airport. These regions arise due to the presence of concrete bunkers at these locations for routing the cables for navigation lights on the taxiway (Figure 37). These concrete bunkers show up as uncompacted regions on the IACA output as the vibration motors of the roller are turned off when on the concrete bunkers.

Table 8. Pass by pass density reading using PQI 301

Pass	Point	Left			Center			Right		
		Moisture (%)	Density (pcf)	Relative Density (%)	H20	Density (pcf)	Relative Density (%)	H20	Density (pcf)	Relative Density (%)
1	1	4.6	143.2	92.2				4	142.8	91.9
	2	5	144.1	92.8				4.6	143.6	92.5
	3	4.9	144	92.7						91.9
	4	4	142.5	91.8						
	5									
2	1	4.4	143.8	93.1				4.8	147.5	93.1
	2	4.9	144.8	93.4	4.8	144.4	93	4.7	144.9	93.4
	3	5	144.7	93.2	5	144.2	92.9	4.8	144.7	93.3
	4	4.8	144.3	93.3	5.4	145.3	93.6	4.8	145.1	93.5
	5	5.1	145.3	93.6	5.3	143.5	92.5	6.7	147	94.1
3	1	4.3	144.8	93.3	4.3	144.2	92.9			
	2	4.9	145.1	93.5	4.1	143.9	92.7			
	3	5	145.4	93.7	4.7	144.3	92.8			
	4	4.9	145.3	93.4	5.1	145.2	93.6			
	5	5.4	146.6	94.4	5.4	143.4	92.4			
4	1	3.9	143.6	92.5	3.5	142.9	92.1	4.2	145.8	93.5
	2	4.9	144.8	93.2	4.1	143.8	92.7	4.4	144.9	93.4
	3	4.7	145	93.1	4.6	145.4	93.4	4.2	144.5	93.1
	4	4.3	144.7	93.2	6.3	146.4	93.3	4.6	145.5	93.5
	5	4.9	144.5	93.1	5.3	144.1	93.8	7.7	145.6	94.1
5	1	4.4	144.6	92.9	3.4	143.1	92.1			
	2	5.1	145.7	92.8	4.1	144.1	92.9			
	3	4.6	142.8	93.1	4.9	146.3	94.2			
	4	4.4	144.8	93.3	4.5	145.3	93.1			
	5	5	145.8	92.1	5.6		93			

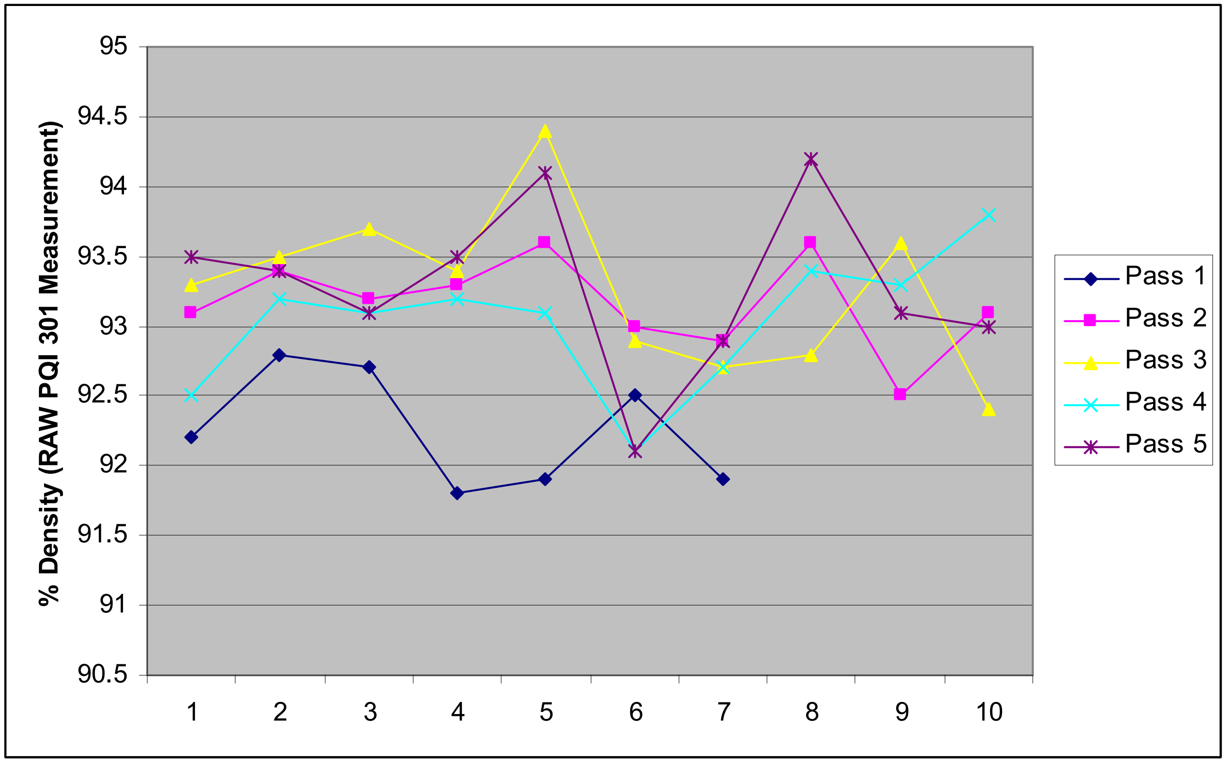


Figure 22. Changes in the density of the asphalt mat over successive roller passes

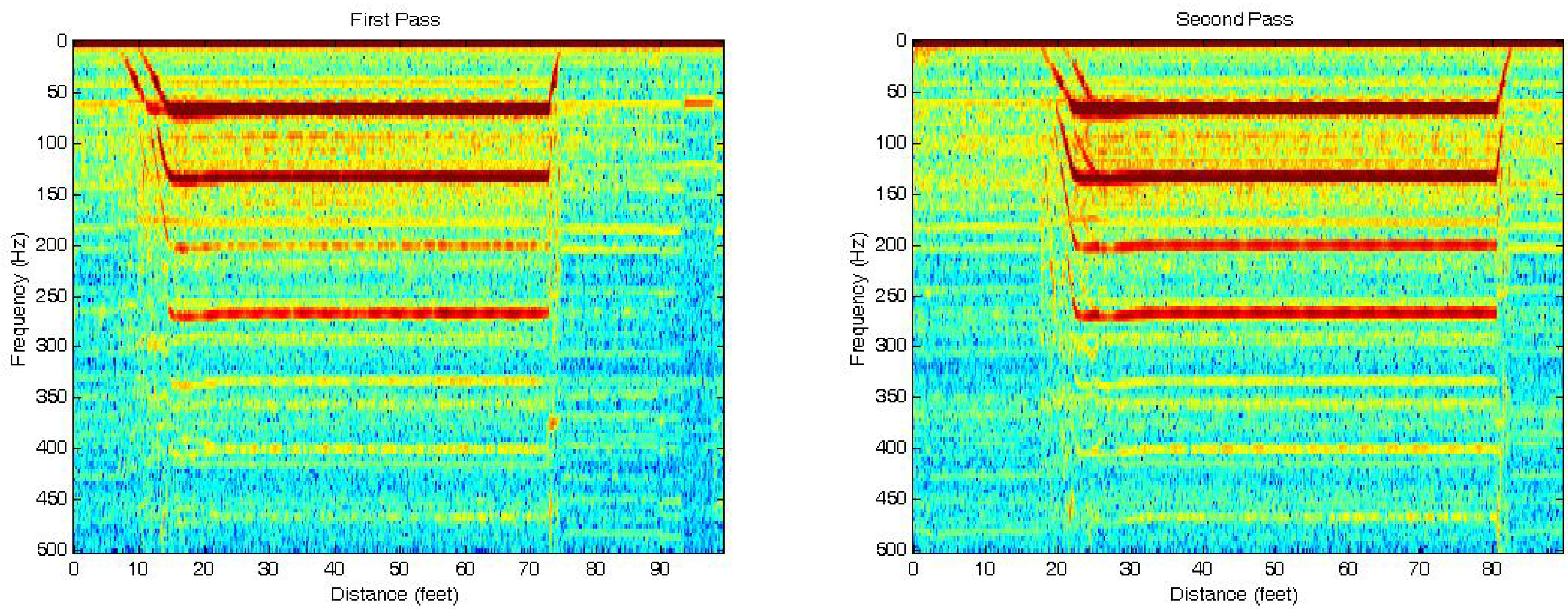


Figure 23. Spectrogram showing the effect of changes in density between the first pass and the second pass

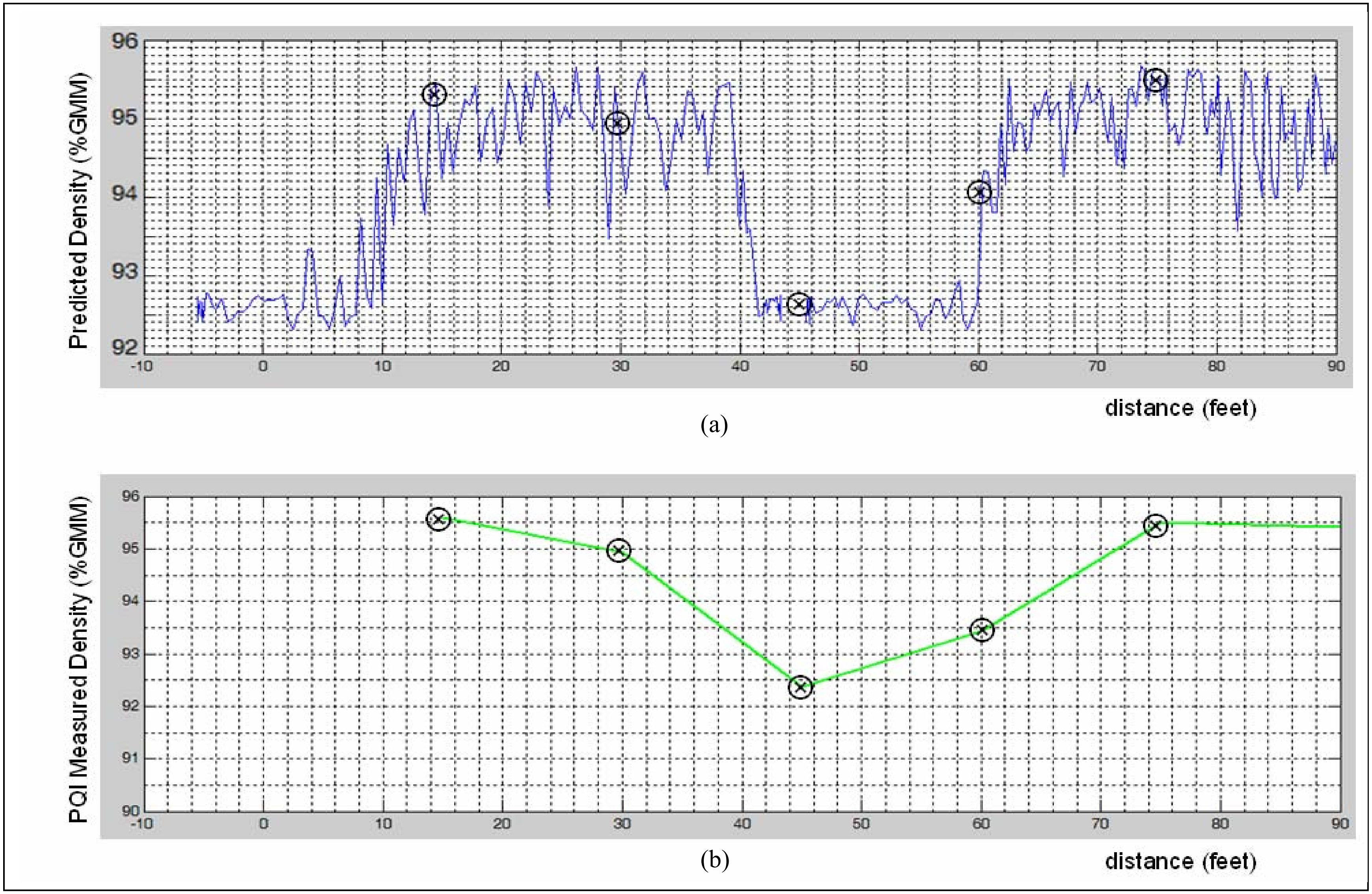


Figure 24. Comparison of predicted and measured density (a) Density predicted by the IACA; (b) Density measured by PQI 301

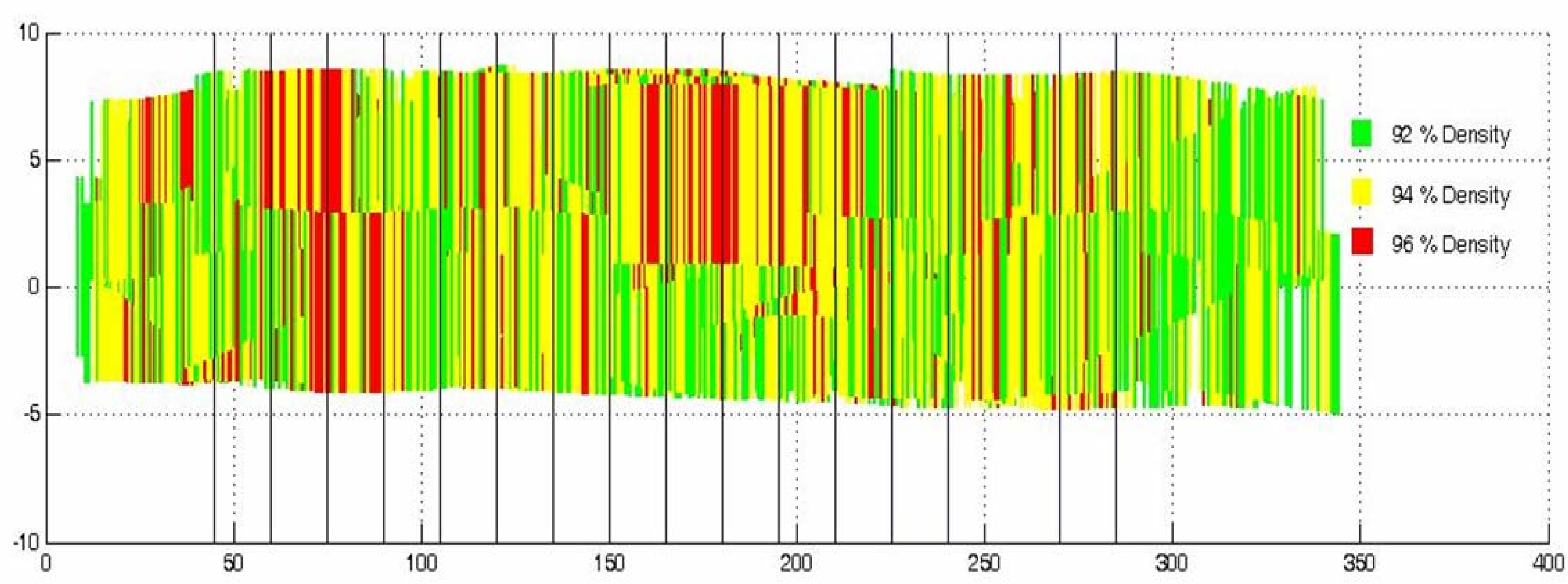
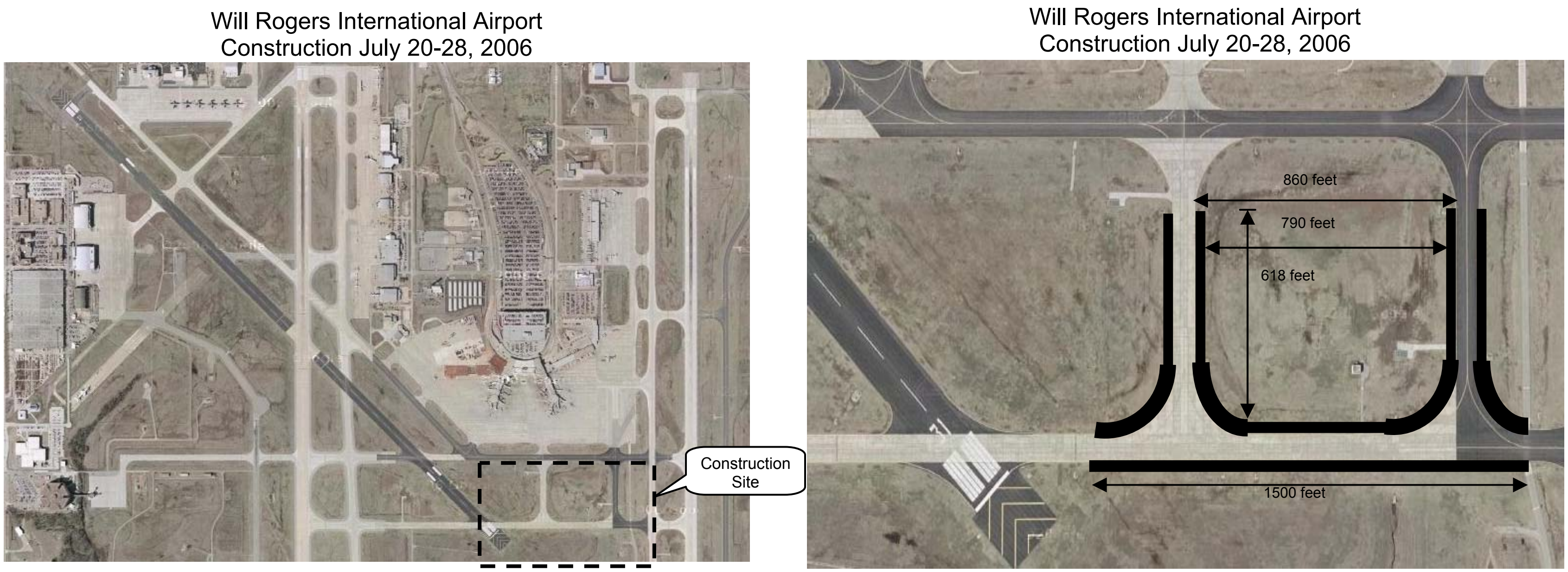


Figure 25. IACA predicted density over the entire test pavement for the final pass (As-built Density)



(a) (b)

Figure 26. Test location for the field validation of the IACA

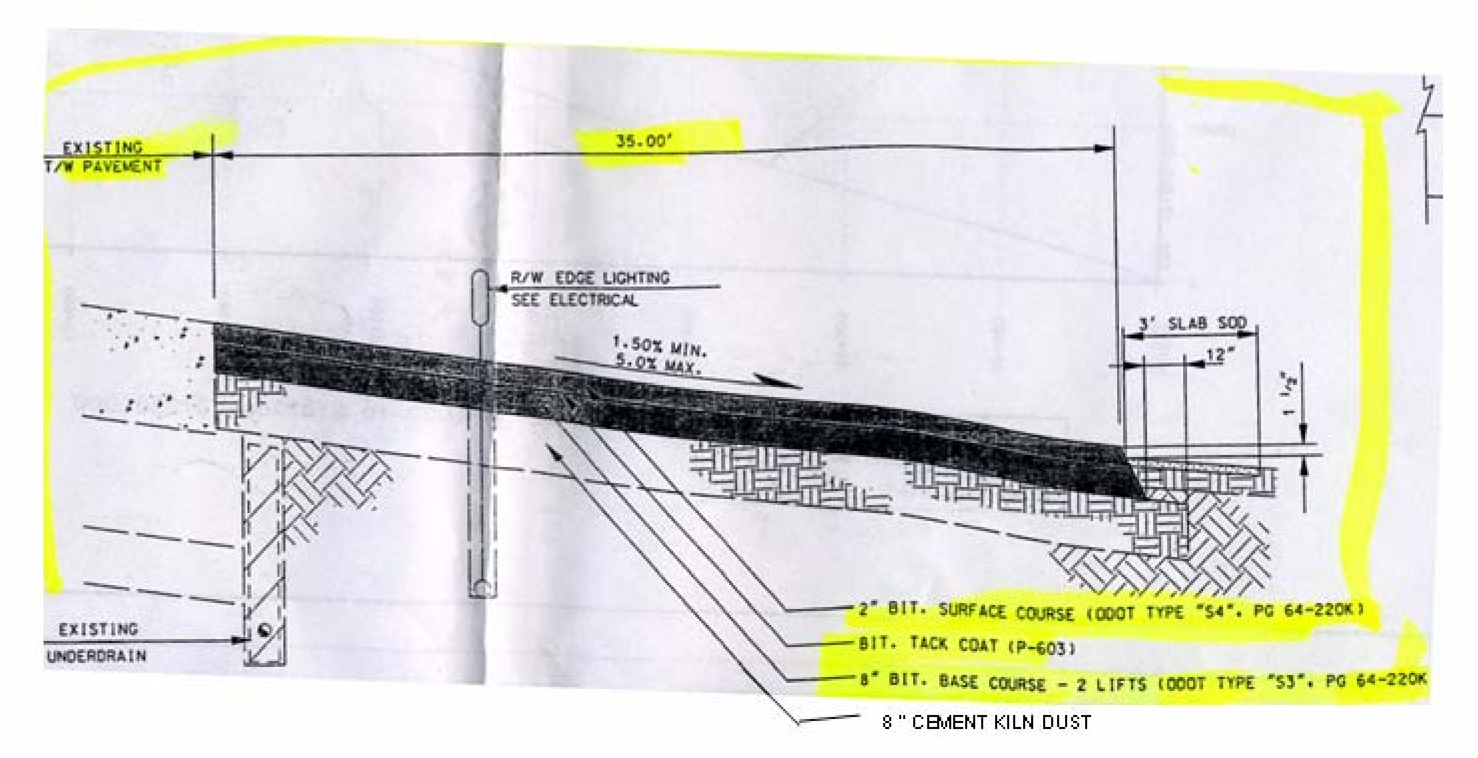
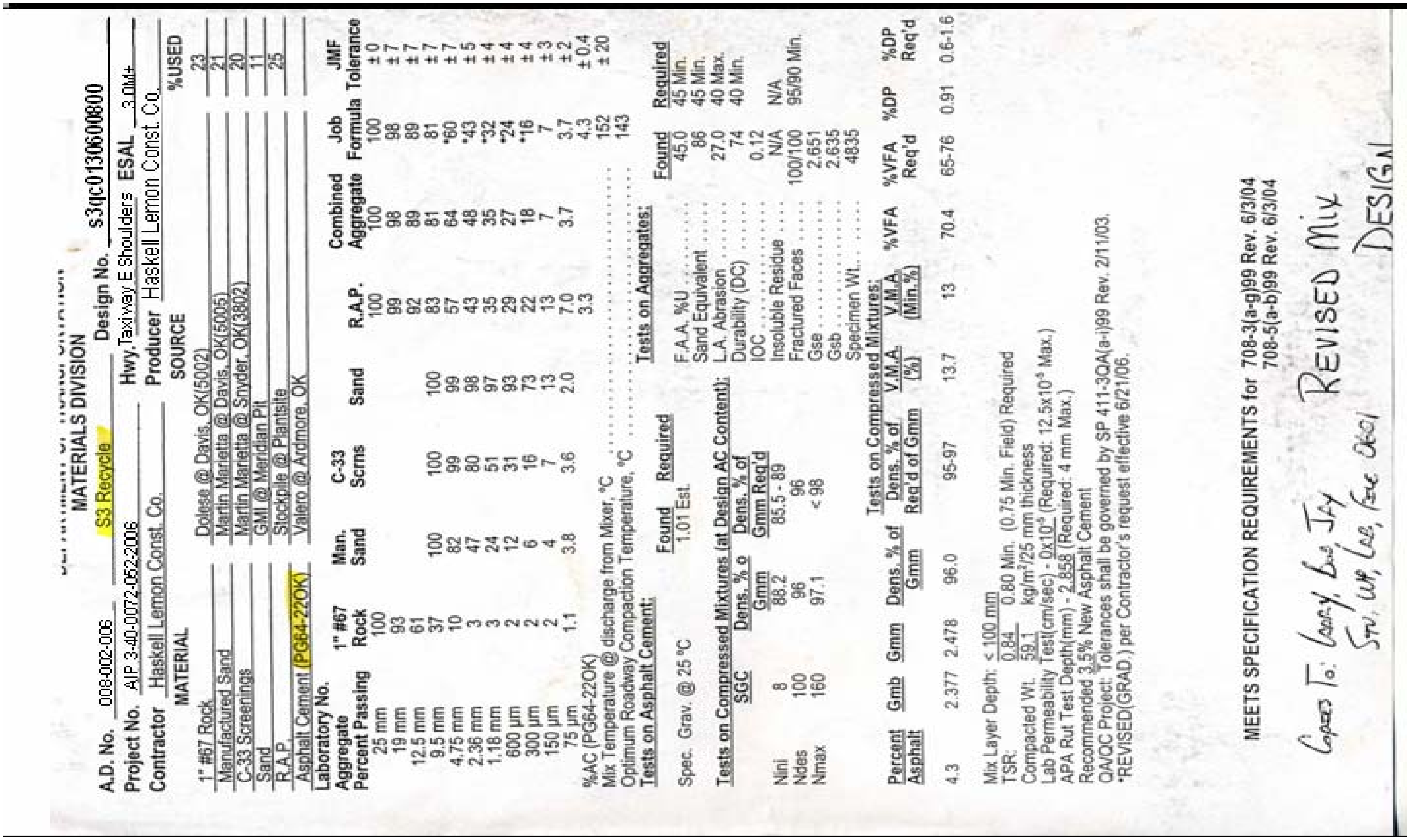


Figure 27. Construction specification for the taxiway shoulder



DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION

A.D. No. 008-002-006 S3 Recycle Design No. s3qc0130600800
Project No. AIP 3-40-0072-052-2006 Hwy. Taxiway E Shoulders ESAL 3.0M+
Contractor Haskell Lemon Const. Co. Producer Haskell Lemon Const. Co.

MATERIAL	SOURCE	%USED
1" #67 Rock	Dolese @ Davis, OK(5002)	23
Manufactured Sand	Martin Marietta @ Davis, OK(5005)	21
C-33 Screenings	Martin Marietta @ Snyder, OK(3802)	20
Sand	GMI @ Meridian Pit	11
R.A.P.	Stockpile @ Plantsite	25
Asphalt Cement (PG64-22OK)	Valero @ Ardmore, OK	

Laboratory No.

Aggregate Percent Passing	1" #67 Rock	Man. Sand	C-33 Scrns	Sand	R.A.P.	Combined Aggregate	Job Formula	JMF Tolerance
25 mm	100				100	100	100	± 0
19 mm	93				99	98	98	± 7
12.5 mm	61				92	89	89	± 7
9.5 mm	37	100	100	100	83	81	81	± 7
4.75 mm	10	82	99	99	57	64	*60	± 7
2.36 mm	3	47	80	98	43	48	*43	± 5
1.18 mm	3	24	51	97	35	35	*32	± 4
600 µm	2	12	31	93	29	27	*24	± 4
300 µm	2	6	16	73	22	18	*16	± 4
150 µm	2	4	7	13	13	7	7	± 3
75 µm	1.1	3.8	3.6	2.0	7.0	3.7	3.7	± 2
%AC (PG64-22OK)					3.3		4.3	± 0.4
Mix Temperature @ discharge from Mixer, °C							152	± 20
Optimum Roadway Compaction Temperature, °C							143	

Tests on Asphalt Cement:

	Found	Required
Spec. Grav. @ 25 °C	1.01 Est.	

Tests on Compressed Mixtures (at Design AC Content):

	SGC	Dens. % o Gmm	Dens. % of Gmm Req'd
Nini	8	88.2	85.5 - 89
Ndes	100	96	96
Nmax	160	97.1	< 98

Tests on Aggregates:

	Found	Required
F.A.A. %U	45.0	45 Min.
Sand Equivalent	86	45 Min.
L.A. Abrasion	27.0	40 Max.
Durability (DC)	74	40 Min.
IOC	0.12	
Insoluble Residue	N/A	N/A
Fractured Faces	100/100	95/90 Min.
Gse	2.651	
Gsb	2.635	
Specimen Wt.	4835	

Tests on Compressed Mixtures:

Percent Asphalt	Gmb	Gmm	Dens. % of Gmm	Dens. % of Req'd of Gmm	V.M.A. (%)	V.M.A. (Min.%)	%VFA	%VFA Req'd	%DP	%DP Req'd
4.3	2.377	2.478	96.0	95-97	13.7	13	70.4	65-76	0.91	0.6-1.6

Mix Layer Depth: ≤ 100 mm
TSR: 0.84 0.80 Min. (0.75 Min. Field) Required
Compacted Wt. 59.1 kg/m²/25 mm thickness
Lab Permeability Test(cm/sec) - 0x10⁻⁵ (Required: 12.5x10⁻⁵ Max.)
APA Rut Test Depth(mm) - 2.858 (Required: 4 mm Max.)
Recommended 3.5% New Asphalt Cement
QA/QC Project: Tolerances shall be governed by SP 411-3QA(a-i)99 Rev. 2/11/03.
*REVISED(GRAD.) per Contractor's request effective 6/21/06.

MEETS SPECIFICATION REQUIREMENTS for 708-3(a-g)99 Rev. 6/3/04
708-5(a-b)99 Rev. 6/3/04

Copies To: Larry, Bud, Jay
Stv, WP, Lab, File 0601

REVISED MIX
DESIGN

Figure 28. Mix specification for the base and intermediate layers of the shoulder

Will Rogers AIRPORT

A.D. No. 008-002-005 **Mix Type** S4 Insoluble **Design #** 3074-HLCC-05313
Project # AIP 3-40-0072-052-2005 **Location** Taxiway E Shoulders **ESALs** 3.0M+
Contractor Haskell Lemon Construction Co. **Producer** Haskell Lemon Construction Co.

Aggregate Type	Aggregate Used	% USED
5/8" Chips	Martin Marietta @ Snyder, Oklahoma (3802)	32
Washed Screenings	Martin Marietta @ Davis, Oklahoma (5005)	33
C-33	Martin Marietta @ Snyder, Oklahoma (3802)	20
Asp. Sand	GMI Meridian Pit	15
PG 64-22 OK	Valero @ Ardmore, Oklahoma	

Sieve Size	5/8" Chips	Washed Screenings	C-33	Asp. Sand	Comb. Agg.	JMF	% Tol.	Control Points
1 1/2"	100	100	100	100	100	100	0	
1"	100	100	100	100	100	100	0	
3/4"	100	100	100	100	100	100	0	100
1/2"	94	100	100	100	98	98	± 7	90-100
3/8"	68	100	100	100	90	90	± 7	90 max.
No. 4	10	80	99	93	63	63	± 7	
No. 8	4	47	79	89	46	46	± 5	34-58
No. 16	3	24	49	85	31	31	± 4	
No. 30	3	12	28	76	22	22	± 4	
No. 50	3	6	14	54	14	14	± 4	
No. 100	2	5	6	16	6	6	± 3	
No. 200	1.6	4.5	4.0	1.7	3.1	3.1	± 2	2-10
% Asphalt Cement						5.1	± 0.4	4.6 Min.
Mix Temperature @ discharge from Mixer, Deg. F						305		
Optimum RoadwayCompaction Temperature, Deg. F						290		

Tests on Asphalt Cement
Specific Gravity 1.0174

Tests on Compressed Mixtures (at Design AC Content)

	SGC	Dens. % of Gmm	Dens. % of Gmm req'd
Nini	8	87.9	85.5-89
Ndes	100	95.9	96
Nmax	160	96.6	<98

Tests on Aggregates

		Req.
Sand Equivalent	82	45 min.
Fine Aggregate Angularity	45.0	45 min.
L.A. Abrasion	21.6	40 max.
Insolubility	64.0	40 min.
Durability Index	82	40 min.
IOC	0.26%	
Fractured Faces	100/100	85/80
Gsb	2.630	
Gse	2.640	
Specimen Weight	4765	
Flat and Elongated Particles	0	10 max.

Tests on Compressed Mixtures :

% AC	Gmb	Gmm	Dens. % of Gmm	Density Req.	V.M.A.	Air Voids	V.F.A.	V.F.A. Req'd	% DP	% DP Req.
4.6	2.317	2.459	94.2		16.0	5.8	63.7		0.70	
5.1	2.340	2.441	95.9	95-97	15.6	4.1	73.4	65-76	0.62	0.6-1.6
5.6	2.363	2.423	97.5		15.2	2.5	83.5		0.57	

Tensile Strength Ratio: 0.89 0.80 Min. (0.75 Min. Field) Required
lbs/sy/1" thick = 107.4 @ 5.1 % Asphalt Cement
Mix Layer Depth: Less than 4"

MEETS SPECIFICATION REQUIREMENTS

Figure 29. Mix specification for the top layer of the shoulder

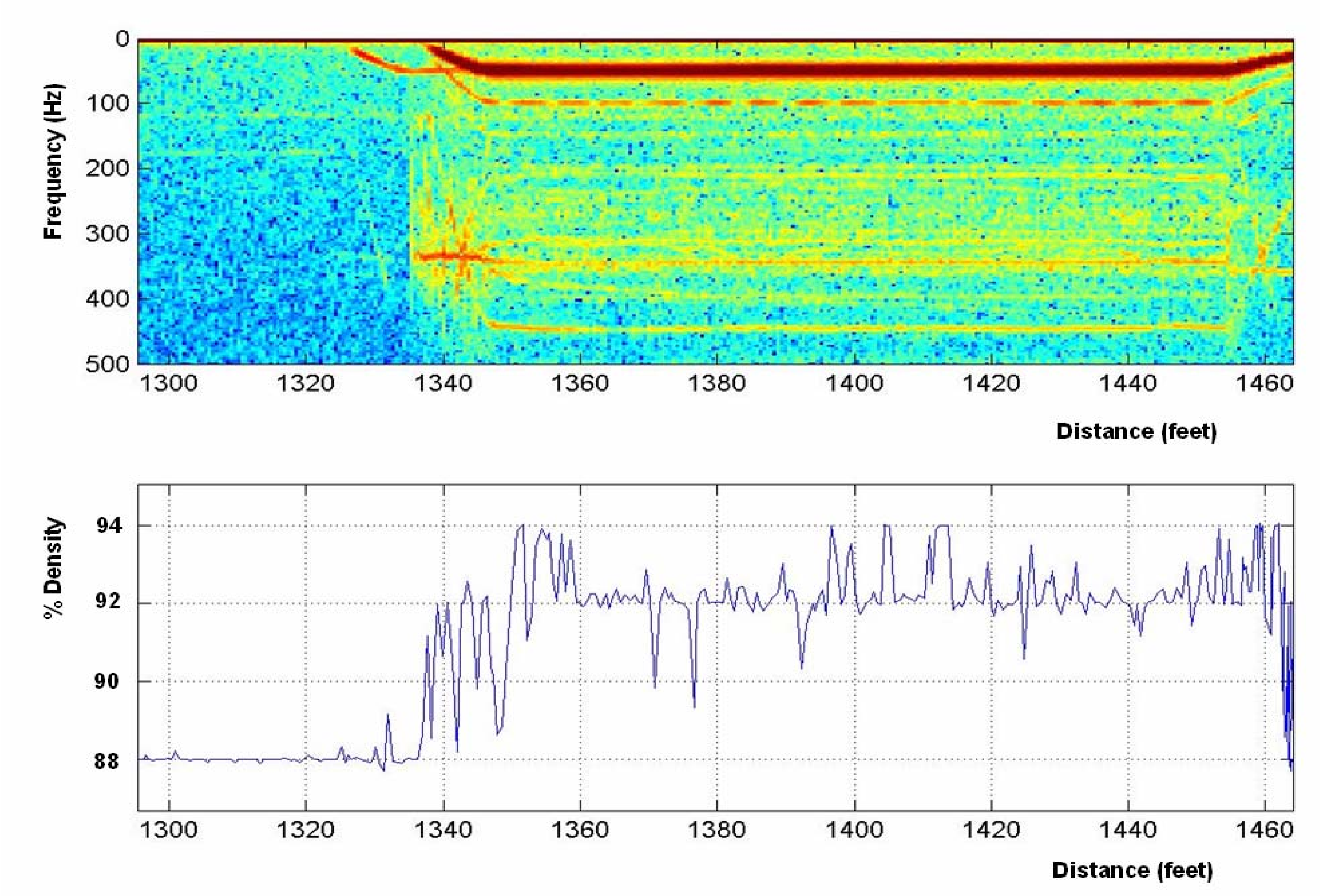
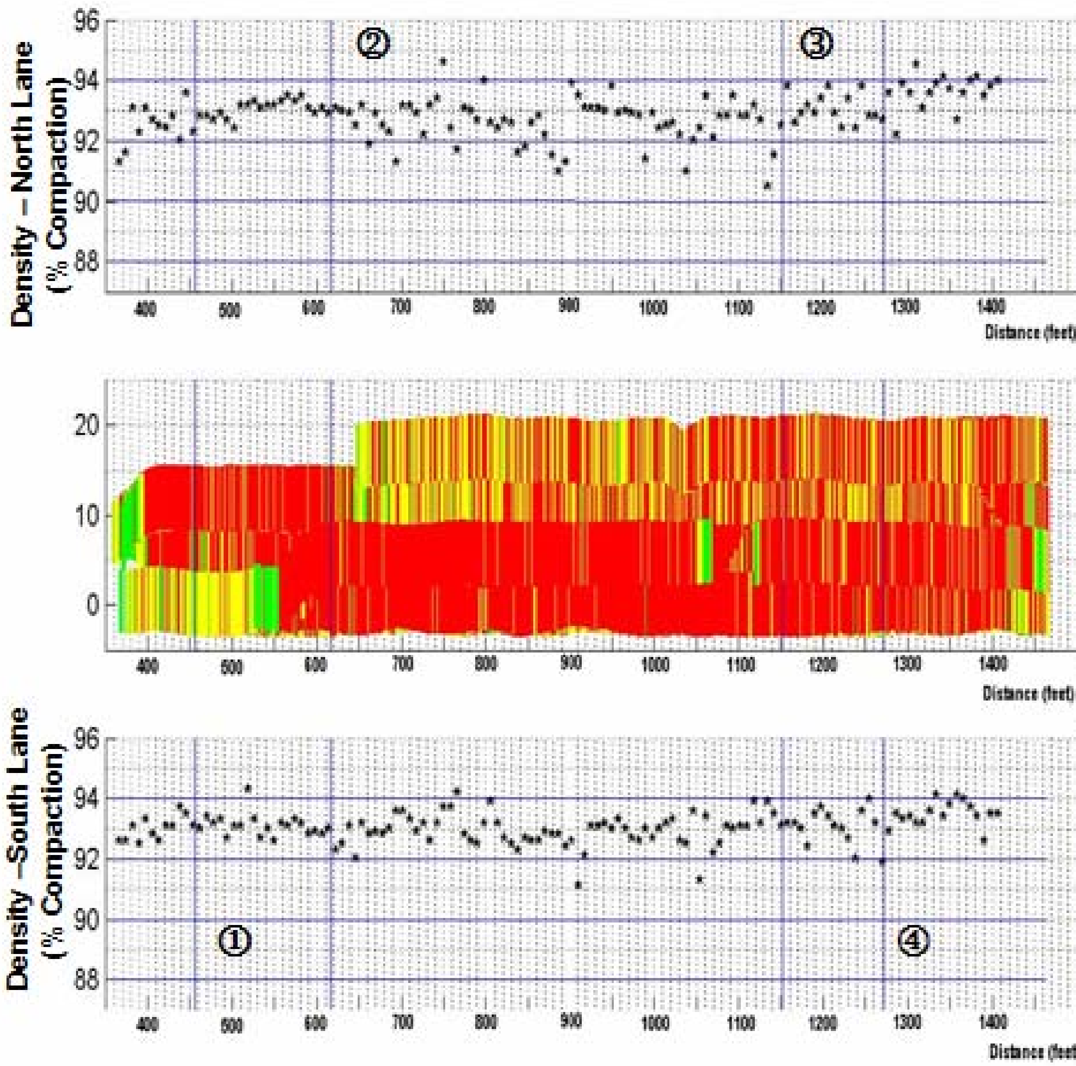


Figure 30. Spectrogram of the compactor vibration and the predicted density along a roller pass during the construction



Loc.	Core	PQI	Vicinity
1	93.2	93.3	92.7 – 93.7
2	93.5	93.2	92.6 – 93.2
3	92.5	92.8	92.1 – 92.8
4	92.1	93.1	92.4 – 93.6

Figure 31. As-built density map with PQI readings and roadway core densities

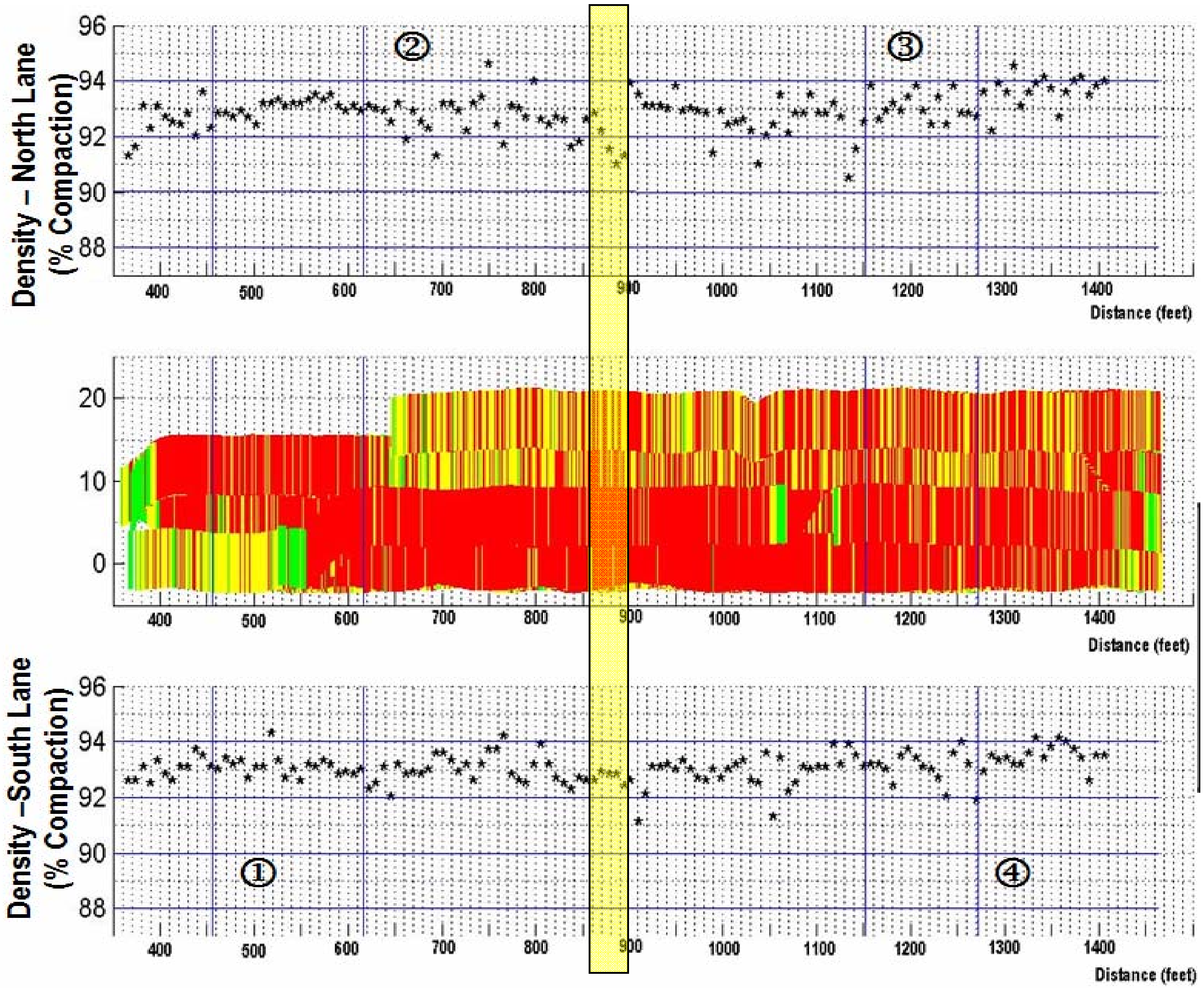


Figure 32. Region showing different compaction levels on the north and south lanes of the shoulder

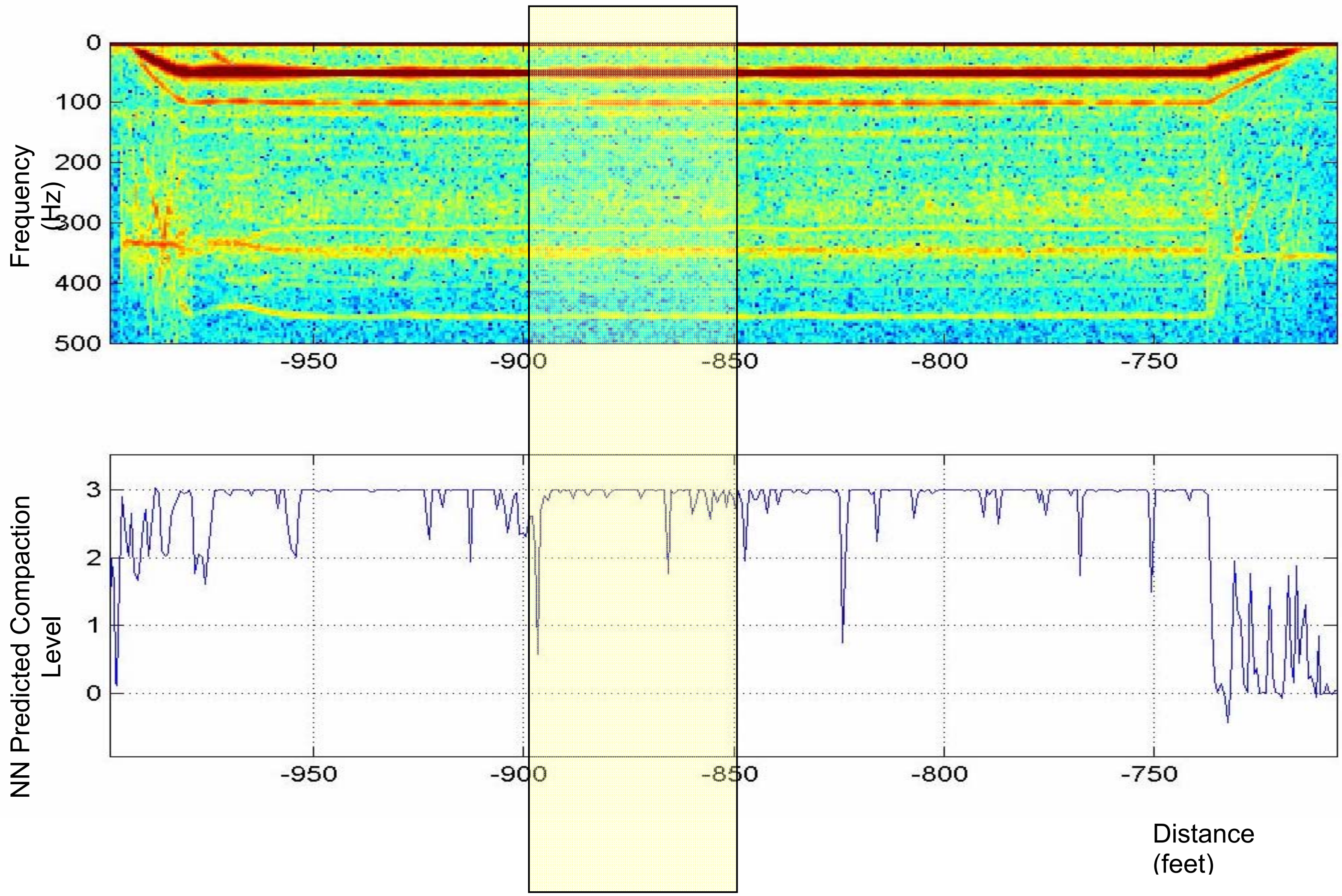


Figure 33. IACA predicted density on the south lane corresponding to region in Figure 32

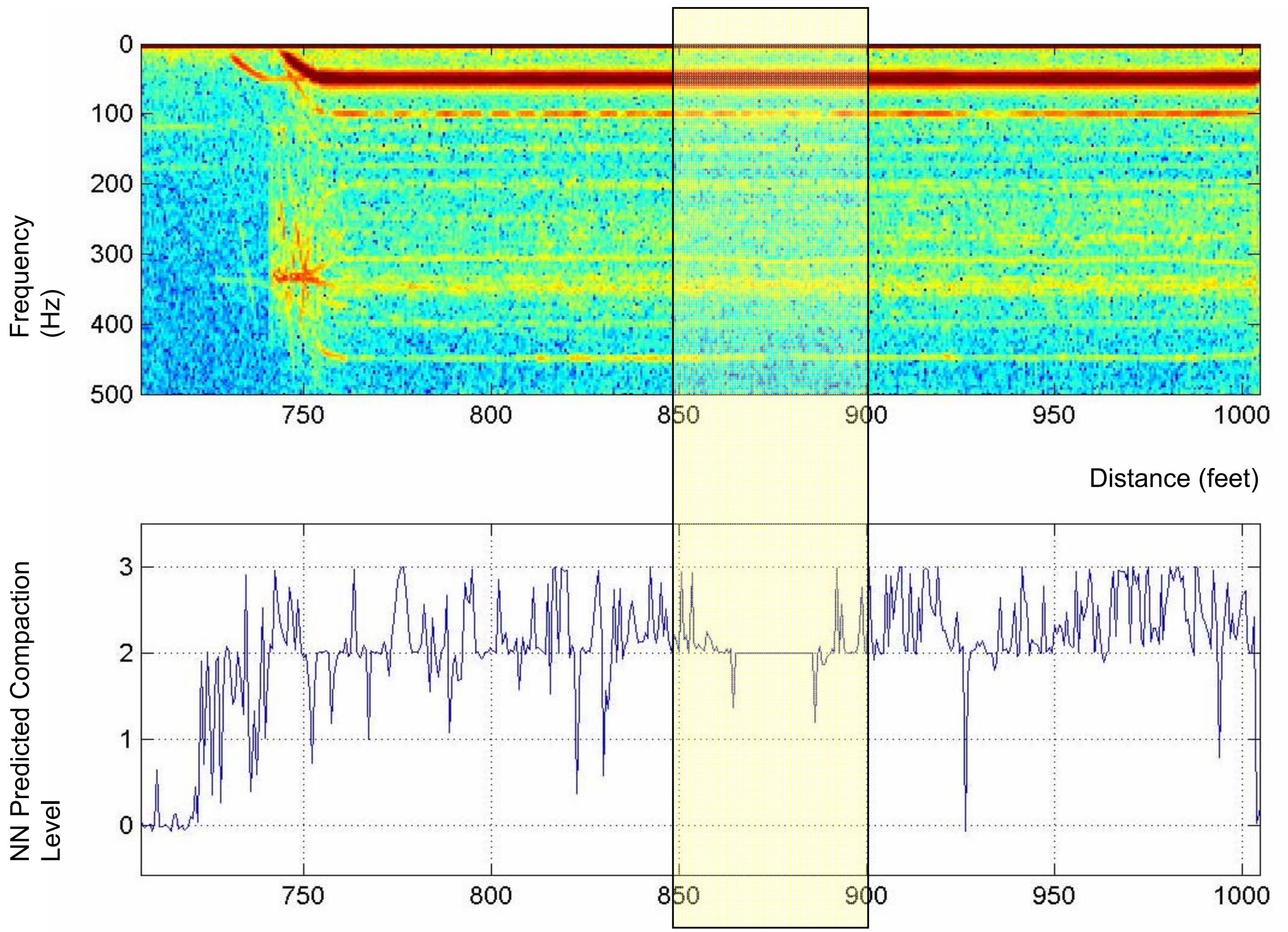
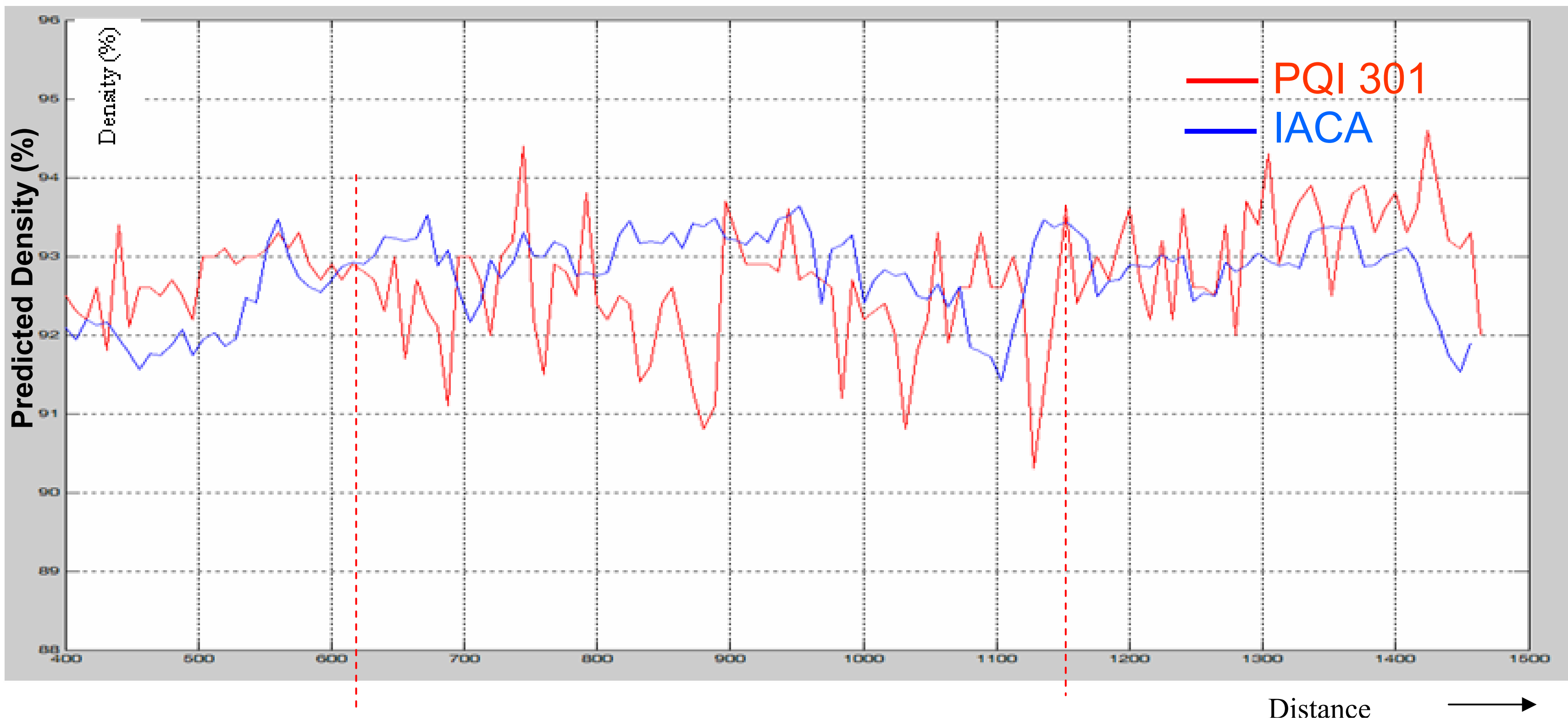


Figure 34. IACA predicted density on the north lane corresponding to region in Figure 32



Location 2
Core – 92.5
PQI – 92.9
IACA – 92.9

Location 3
Core – 92.1
PQI – 93.6
IACA – 93.4

Figure 35. Density Measurements on the north shoulder of the compacted 3” base layer

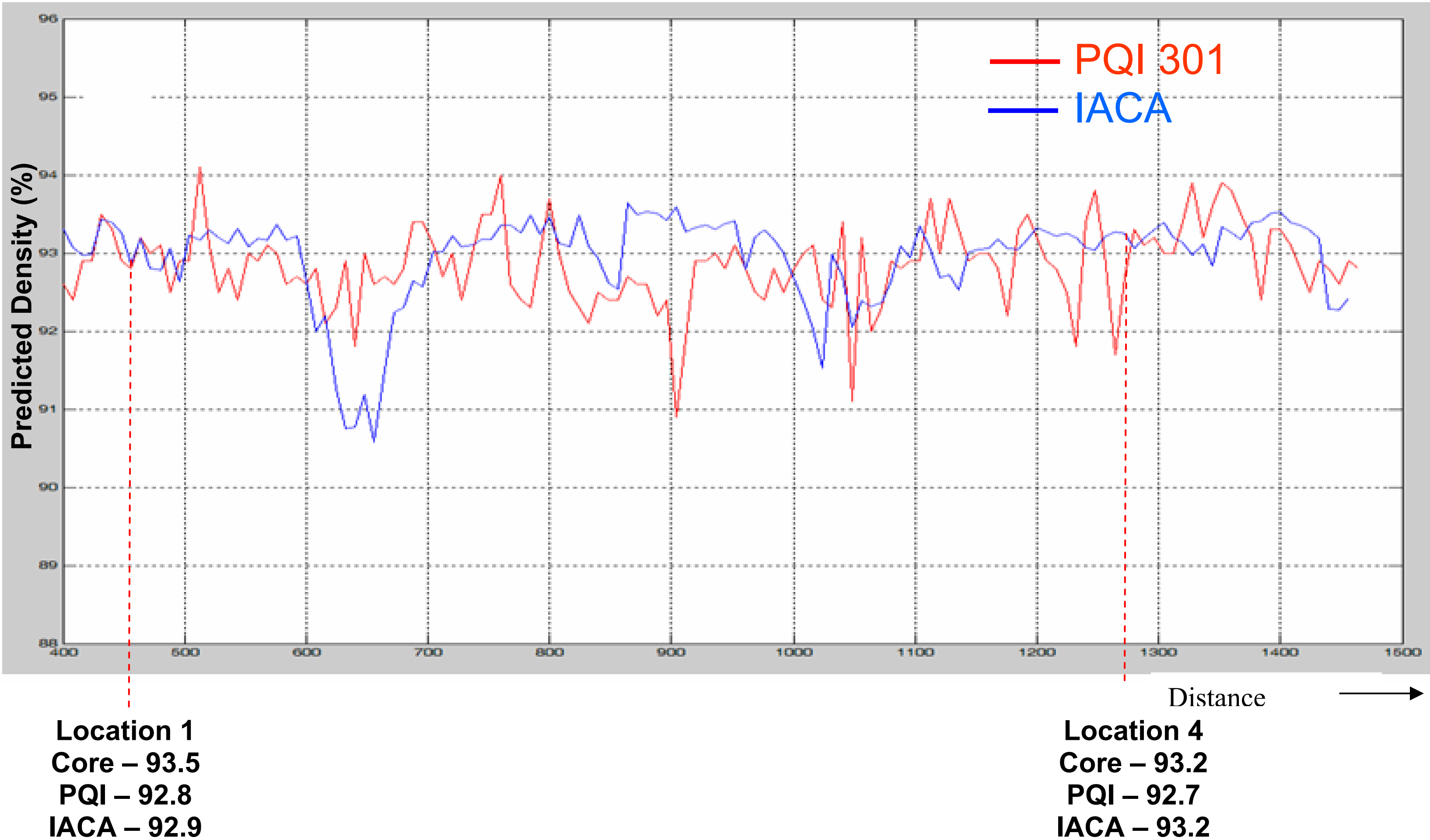


Figure 36. Density Measurements on the south shoulder of the compacted 3” base layer

Table 9. PQI and IACA density values at roadway core locations

S. No	Location (feet)	PQI Reading (%)		IACA (%)		Core Density (%)
		North Lane	**South Lane**	**North Lane**	**South Lane**	
1	456	92.6	92.8	91.6	92.9	93.5
		Range: 92.1 – 93.4		Range: 91.6 – 93.4		
2	616	92.9	92.1	92.9	92.2	92.5
		Range: 92.1 – 92.9		Range: 92.0 – 92.9		
3	1152	93.6	93	93.4	93.0	92.1
		Range: 92.8 – 93.6		Range: 93.0 – 93.4		
4	1272	93.4	92.7	92.9	93.2	93.2
		Range: 91.7 – 93.4		Range: 92.5 – 93.3		

Relief Features in Subgrade

Figure 37. Relief features in subgrade that show up as under compacted regions in Figure 32

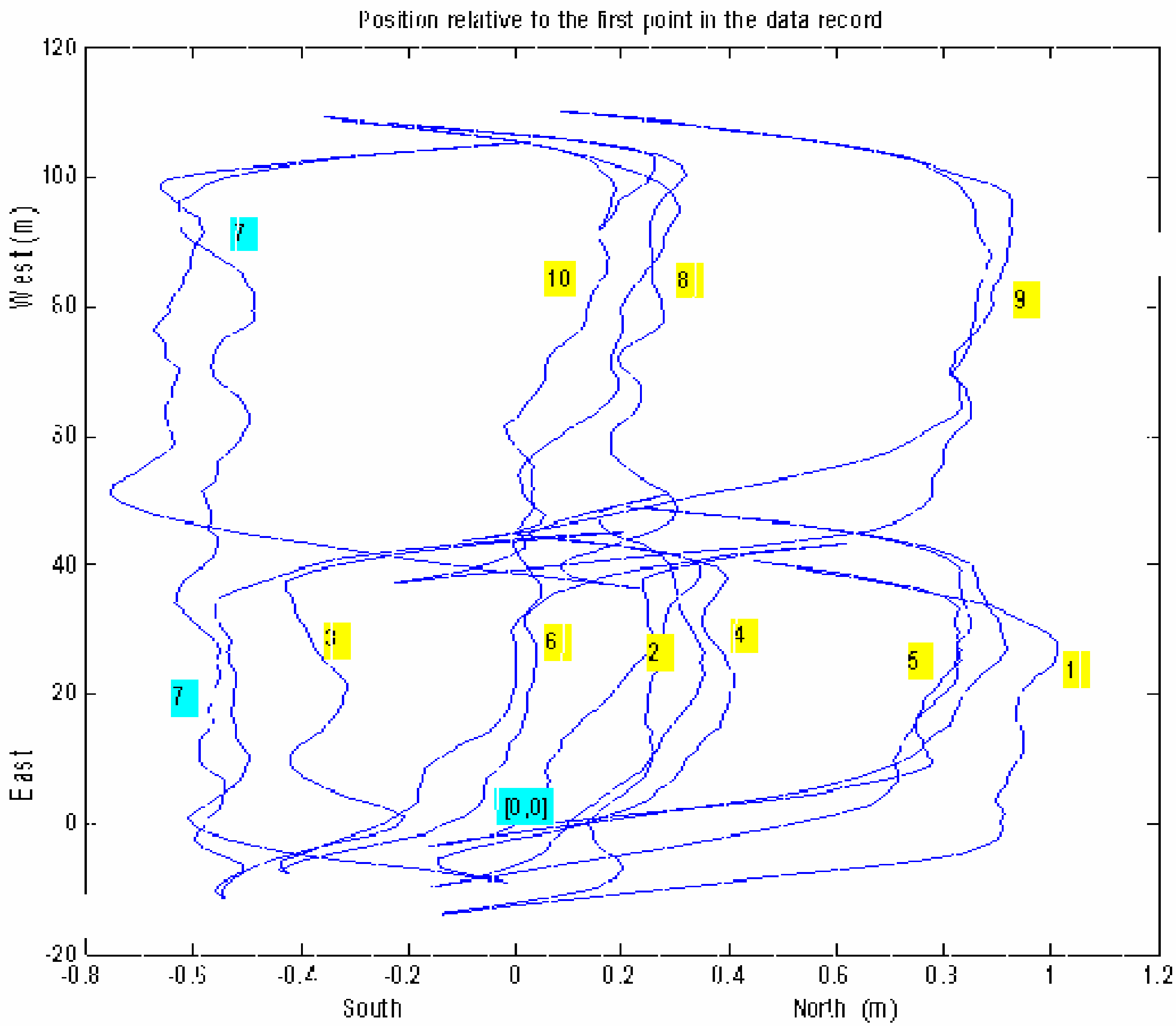


Figure 38. GPS tracks showing the location of the compactor during pavement construction at Miami, Oklahoma

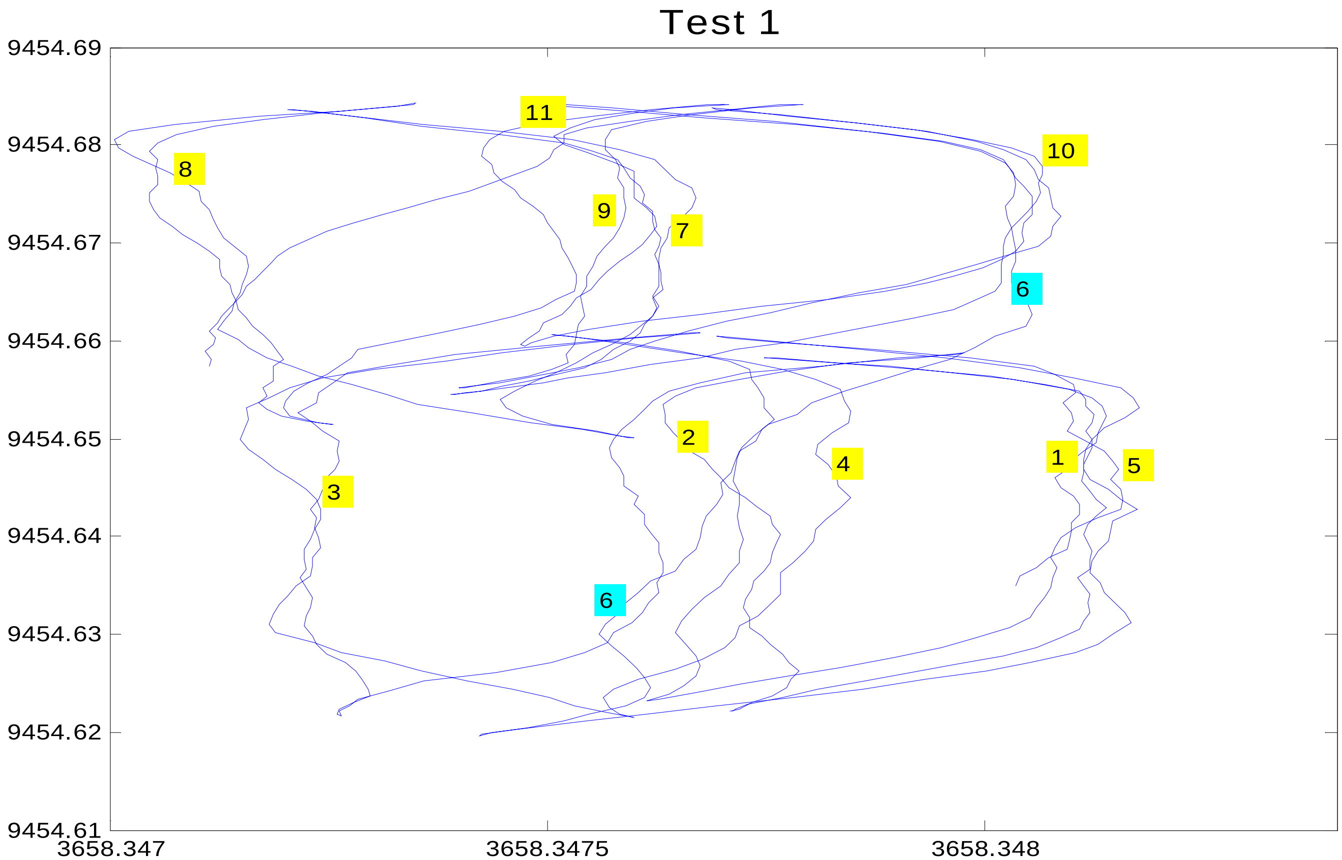


Figure 39. GPS tracks showing the location of the compactor during pavement construction on Highway 9, Norman

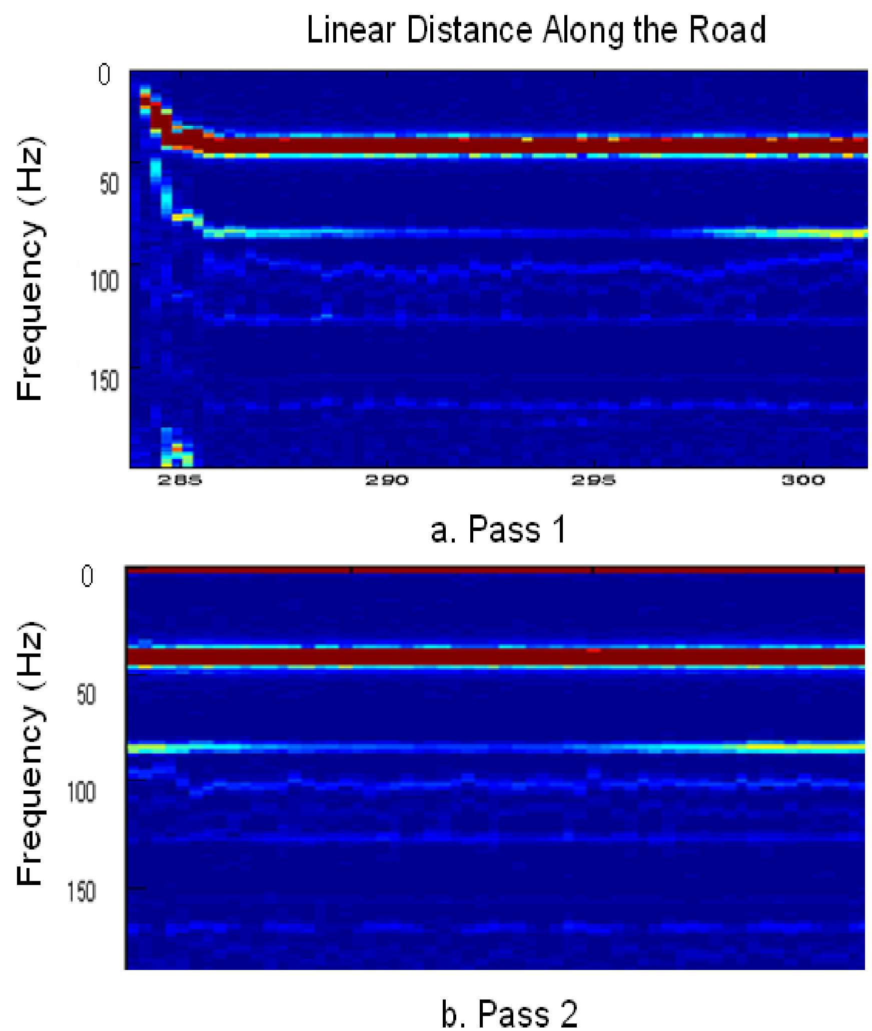


Figure 40. Spectrogram of the vibrations of the compactor over subsequent passes over the same section of the pavement during construction