# YEAR TWO (2004-2005) ANNUAL PROGRESS REPORT

# I. COVER PAGE

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|---|---|---|
| **A.** | **Project Number:** | AR032-011 |
| | **Project Title:** | INTELLIGENT ASPHALT COMPACTION ANALYZER |
| B. | **PI Name :** | Sesh Commuri |
| | **Sponsoring Organization** | University of Oklahoma<br>Office of Research Administration<br>1000 Asp. Ave, Norman OK 73019 |
| C. | **Co-PI Name :** | Musharraf Zaman |
| | **Sponsoring Organization** | University of Oklahoma<br>Office of Research Administration<br>1000 Asp. Ave, Norman OK 73019 |

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.

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| E. | **Current Funding Period**: | September 2003 – August 2006 |
| F. | **Report Period:** | July 1, 2004 – August 31, 2005 |
| G. | **Report Due Date:** | August 31, 2005 |

# II. EXECUTIVE SUMMARY

The goal of the present research is to develop an Intelligent Asphalt Compaction Analyzer (IACA) that will be able to predict the density of the asphalt mix in real-time during the compaction process in the field. The process variables including the temperature of the mix, the lift thickness, and their effect on the observed vibration of the compactor will first be studied in the laboratory. The data obtained in this study will be used to identify key components in the machine vibrations that are indicative of the density of the asphalt mat being compacted. The extracted features are then used to develop the IACA. The performance of the IACA is verified during actual compaction process in the laboratory, as well as during the compaction of an asphalt pavement using a vibratory compactor in a controlled field setting. The project is undertaken in phases with the first phase involving the development of the IACA using data obtained from laboratory equipment (asphalt vibratory compactor). In the second phase, being pursued in Year Two, the IACA will be fine-tuned to predict the density during compaction in the field. This report covers the activities and results of the Second Year of the research. These results demonstrate that the research team is making good progress and is looking forward to an early commercialization of the technology.

Currently, the second Year of the research is nearing completion. During the past year, a test facility was constructed at the site identified in Phase I of the project. The test strip consists of a 300 feet long, 14 feet wide, 6 inch thick continuously reinforced concrete pavement (CRCP) with a compressive strength of over 4000 PSI. The structural rigidity of the base and compaction issues arising from the use of vibratory rollers on stiff sub-grades was studied. The IACA was also equipped on compactors used by our industry partners in the field and the laboratory modeling of the compaction process and the research methodology was validated. Preliminary results obtained using the IACA are extremely encouraging and demonstrate the ability of the analyzer to predict the quality of compaction achieved in the field in real-time.

The IACA was used at numerous 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. This data is vital to the formulation of effective construction techniques to guarantee adequate and uniform compaction of the asphalt pavement. The neural network classifier was trained using the data obtained in the field and was shown to be effective in predicting regions of inadequate compaction. These results were verified against measurements taken using a nuclear density gauge. The results of field tests also demonstrated the ability of the IACA to identify structural problems in the road foundations that could lead to early failures in the asphalt pavement. In the road construction project at Miami, Oklahoma, this information was used to corroborate sub-grade failure that led to the repaving of an entire section of the road. This information is crucial to the early detection and remediation of asphalt pavements.

The results of this project were communicated to the pavement community comprising of the state and federal department of transportation personnel, local industry, and equipment manufacturers. The research was met with enthusiasm and has consistently received enormous support. The Road Development Division of Ingersoll-Rand (IR) Company has shown tremendous interest in the project and has provided the research team with a state-of-the-art research prototype DD-130 compactor. IR is in the process of negotiating with the University of Oklahoma exclusive licensing of the technology being developed. The research team is currently investigating a scaled version of the IACA that can be commercialized and licensed by early spring of 2006.

In the final year of the research, the IACA will be calibrated and tested on the test strip under a controlled set of conditions. Field testing will also be accelerated in order to meet the commercialization goals.

# III. PROJECT PARTICIPANTS

The participants in this project are:

1. University of Oklahoma
2. Broce Construction Inc., Norman
3. Oklahoma Department of Transportation
4. Haskell Lemon Construction Company, Oklahoma City, Oklahoma.
5. Kirby-Smith Equipment Inc., Oklahoma City
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 is the primary participant in the research. The PI and the Co-PI are primarily responsible for the technical developments of the project. The PIs are 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 has 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 will be compacted and the ability of the compaction analyzer to predict the density will be verified.

Broce Construction is responsible for providing matching contribution towards the project. In addition to the actual match, Broce construction also brings an enormous amount of practical field expertise in pavement construction to the project team. Broce Construction also provides access to its technical personnel, equipment, and work sites as needed during the course of this project. Haskell Lemon Construction Company has kindly provided access to its construction sites on I-35-Highway 9 interchange for data gathering and testing of the IACA.

Key personnel in Oklahoma Department of Transportation (ODOT) have been providing invaluable assistance in the project. The ODOT residency in Purcell have been instrumental in providing field support including traffic management, during construction activities near Davis, Highway 9, and near Elmore City.

Kirby-Smith has provided an Ingersoll-Rand 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. 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. In the Year I of the project, extensive tests were conducted in the Laboratory and a prototype of the IACA was constructed. The research conducted in the second year of the project validated the parameters used in the design of the IACA. The IACA was used in a number of construction projects across the state of Oklahoma and the instrumentations needs were addressed. A process was created to integrate high precision GPS measurements with the vibration and density measurements thus enabling the team to depict density in spatial coordinates in real-time. This continuous measurement of density will aid the operator of the vibratory compactor to ensure uniform compaction of the pavement during the construction process. The following are the high lights of the work accomplished during the past year.

## A. Construction of a Test Strip for Controlled Field Testing and Calibration of the IACA

In order to test and calibrate the IACA, it is desired to eliminate the effects of changing subgrade properties in the vibratory response of the compactor. A test strip with a 6 inch thick continuously reinforced concrete pavement (CRCP) as the subgrade was constructed for this purpose. While the original design called for a 12 inch thick CRCP base, it was felt that the original design was over engineered and the loading factor was not as high as originally anticipated. After discussion with our industry partners and ODOT, it was decided that a 6 inch thick CRCP with a 2 inch asphalt overlay would be adequate for the test strip.

The sub-grade layer was first prepared by milling and removing the existing pavement and clearing the ground of any organic material (see Figures 1a, 1b). The subgrade was then stabilized with fly ash (Figure 2a) and compacted (Figure 2b). A steel reinforcement mesh of #4's bars was placed with a longitudinal spacing of 24 inches and a transverse spacing of 6 inches (Figure 3). Concrete was poured and a vibrating beam screed was dragged over the concrete to eliminate any air voids (Figure 4). A tamper was then used to tamp down the concrete to the correct level and smooth out the surface. On curing (Figure 5), transverse grooves were cut in the concrete slab to allow for differential expansion and contraction due to temperature changes. The concrete used in the construction was collected in cylinders and tests conducted to measure the compressive strength and the modulus of elasticity of the constructed base (Figure 6). The results of these tests (Table 1) indicate that the design requirement of 4000 PSI is met. The completed test strip is shown in Figure 7.

## B. Validation of the Compaction Analyzer in the Field

In the Year I of the research, it was shown that the IACA prototype that was developed was capable of predicting density during compaction in the laboratory. Over the past year, data was collected from a number of construction sites across Oklahoma to ensure reliable and accurate collection of data as well as to validate the correlation between machine vibrations and the density achieved. In the first set of experiments were conducted at the construction sites near Davis, and Norman, Oklahoma. The GPS tracks of the compactor during the compaction process are shown in Figures 8a, 8b. From the rolling pattern seen in the figure, it can easily be seen that there are portions of the pavement near the shoulder that are not adequately compacted. This was verified in the field where the density readings were consistently lower towards the shoulder of the road.

Figures 9a, 9b show the spectrogram of the vibratory signals as the compaction progresses. It can be seen from these figures that as the compaction process progresses, the vibration energy gets clustered around key frequencies that are dependent on the density achieved. As the density increases, one observes bands of energy, indicated in red in the spectrograms. These features are similar to those observed during the laboratory studies and validate the research methodology.

In order to verify the suitability for application in real-life conditions, an Ingersoll Rand DD130 compactor was instrumented with accelerometers, a differential GPS system, and the compaction analyzer and was tested during the road construction project near Elmore City, Oklahoma. The differential GPS system used was capable of accurately measuring (to within 2 cm) the location of the compactor. The output of the accelerometer was collected over different passes on a stretch of the road during construction and correlated with the GPS data. After each pass, density readings were taken at specific locations on the pavement using a Troxler nuclear density gauge. The features extracted from the vibration data at these locations along with the measured densities were used to train the NN as described in the previous section. After the NN was trained, the performance of the analyzer was tested on different sections of the roadway. Figure 10 shows the output of the analyzer on a section of the road 15 feet (4.6 meters) long and 7 feet (2.1 meters) wide. The predicted density is shown as a graph where the region in 'red' represents adequate compaction (density greater than 92% of the GMM value) while the lighter shading indicates inadequate compaction. Actual readouts from a nuclear density gauge at test locations on the road are also shown in Figure 10, and validate the density predicted by the compaction analyzer.

The compaction analyzer was also tested during the construction of a roadway in Miami, Oklahoma. During the construction, it was observed that on a particular stretch of the road, adequate compaction was not achieved. 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 11) 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 the failure of the subgrade in this section of the road. From the spectrogram data, it was predicted that the subgrade failed on the section between 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 451-507 feet from the east end of the constructed roadway.

# V. WORK PLANS

During the final of this project, the IACA will be further refined and calibrated during compactions on the test strip and in the field. Asphalt overlays will be constructed on the test strip as discussed in the original proposal and the design and performance of the IACA will be refined. Compaction data will also be collected from the field to validate the results from the laboratory study and from tests run on the controlled field site. An application for patent based on the developed technology is pending with the US PTO office. The work will proceed as laid out in the project proposal.

The preliminary results have been communicated to the local industry, Oklahoma Department of Transportation personnel, and equipment manufacturers. The research being conducted at the University of Oklahoma has consistently met with enthusiasm and support. Many local contactors including Haskell-Lemon Construction Company and DOT residencies have come forward to share their experiences and resources with the project team. The project team has visited Ingersoll-Rand (IR) Corporation at their Road Development Center in Shippensburg, Pennsylvania in March 2005 and subsequently in August 2005. IR has expressed their desire to enter into an exclusive licensing agreement with the University of Oklahoma to commercialize the technology. As part of this process, the project team is developing an intermediate product that will meet the immediate needs of IR based on the technology being developed. Towards this end, the schedule is being modified to accommodate more field testing and trials in the next few months. This is being done in addition to the testing at the test strip on campus.

# VI. PUBLICATIONS

1. S. Commuri, M. Zaman, J. Nino, D. Yerrabommanahalli, "A Neural Network-Based Compaction Analyzer for Density Measurement during the Construction of an Asphalt Pavement," Annual Meeting of the Transportation Research Board, January 2006, *submitted.*
2. S. Commuri, M. Zaman, J. Nino, D. Yerrabommanahalli, "Intelligent Asphalt Compaction Analyzer – Design and Performance," Journal of Pavement Engineering, *in preparation.*

# VII. INTELLECTUAL PROPERTY DEVELOPMENT

The University of Oklahoma has contracted with the law firm of Dunlap, Codding & Rogers, P.C. for filing a provisional patent application based on the Intelligent Asphalt Compaction Analyzer (Appendix A.6). The approval of the patent application is pending review by the USPTO.

# VIII. COMMERCIALIZATION ACTIVITIES AND PLANS

Broce Construction Inc. is actively involved in all stages of this research and development. As part of the match, Broce is providing access to its work sites and personnel for the testing of the invention. It is Broce's ultimate goal to use this technology in all their construction projects, as well as to commercialize the technology. Current negotiations are underway with Ingersoll-Rand for the commercialization of the technology. The commercialization plan was provided in detail in the original proposal.

# 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.

The PI is working with **Ingersoll Rand** to bring to market a preliminary version of the proposed technology for beta testing. It is anticipated that an initial product for evaluation would be available in early spring of next year (2006).

# X. LEVERAGED SUPPORT

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 project team is working with Broce Construction to pursue SBIR funding from federal agencies to further pursue this research.

# APPENDIX

# LIST OF TABLES



# LIST OF FIGURES

**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

Table 1. Results from the Compressive Strength Tests of the Concrete Base used in the Construction of the Test Strip.


(a)


(b)

Figure 1. Preparation of site for the construction of the Test Strip.


(a) (b)

Figure 2. Stabilization and Compaction of the Subgrade.

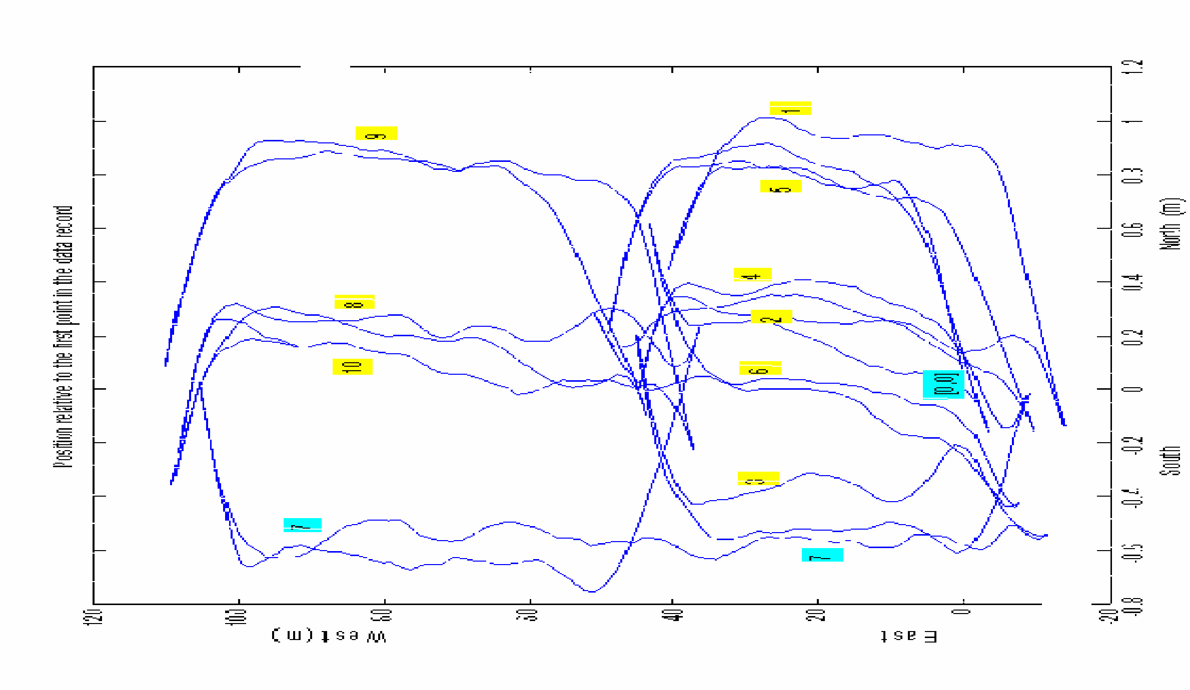

Figure 3. Steel reinforcement for CRCP Base.


Figure 4. Construction of the Concrete Base For the Test Strip.

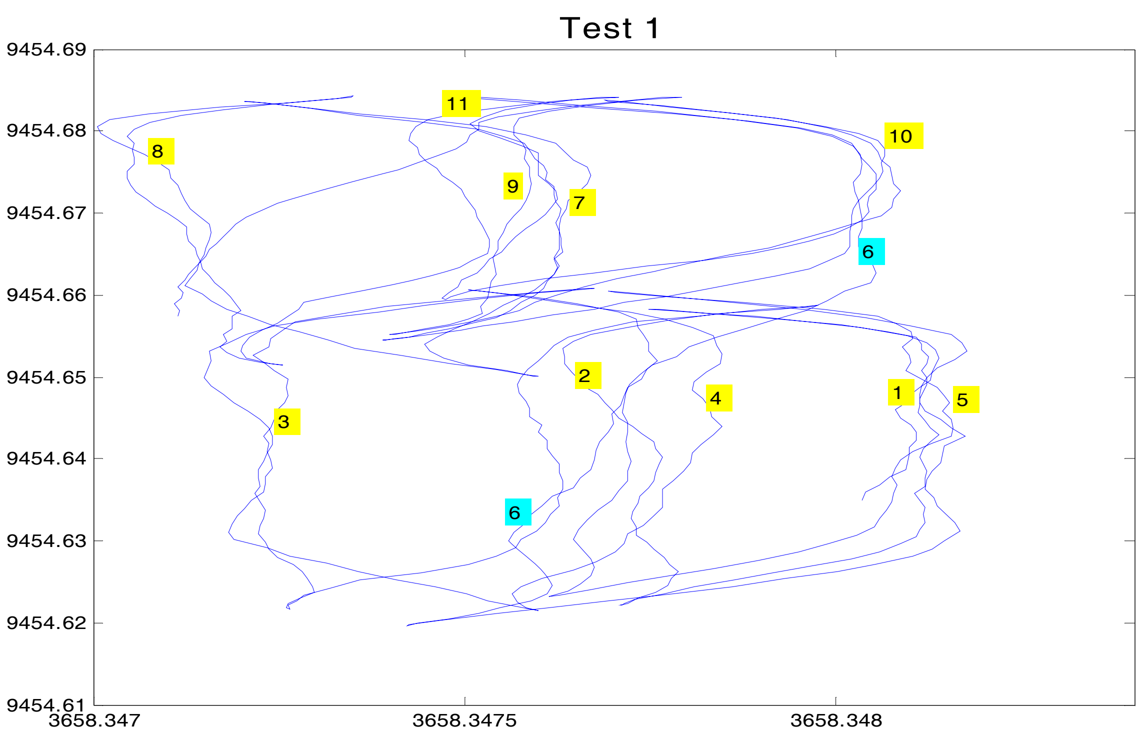
Figure 5. Curing of the Concrete Base.


Figure 6. Collection of Concrete specific for Testing.

Figure 7. Completed Test Strip for Controlled Field Testing.




(a)




(b)

Figure 8. GPS Tracks Showing the Location of the Compactor During Pavement Construction (a) Miami, Oklahoma; (b) Highway 9, Norman.

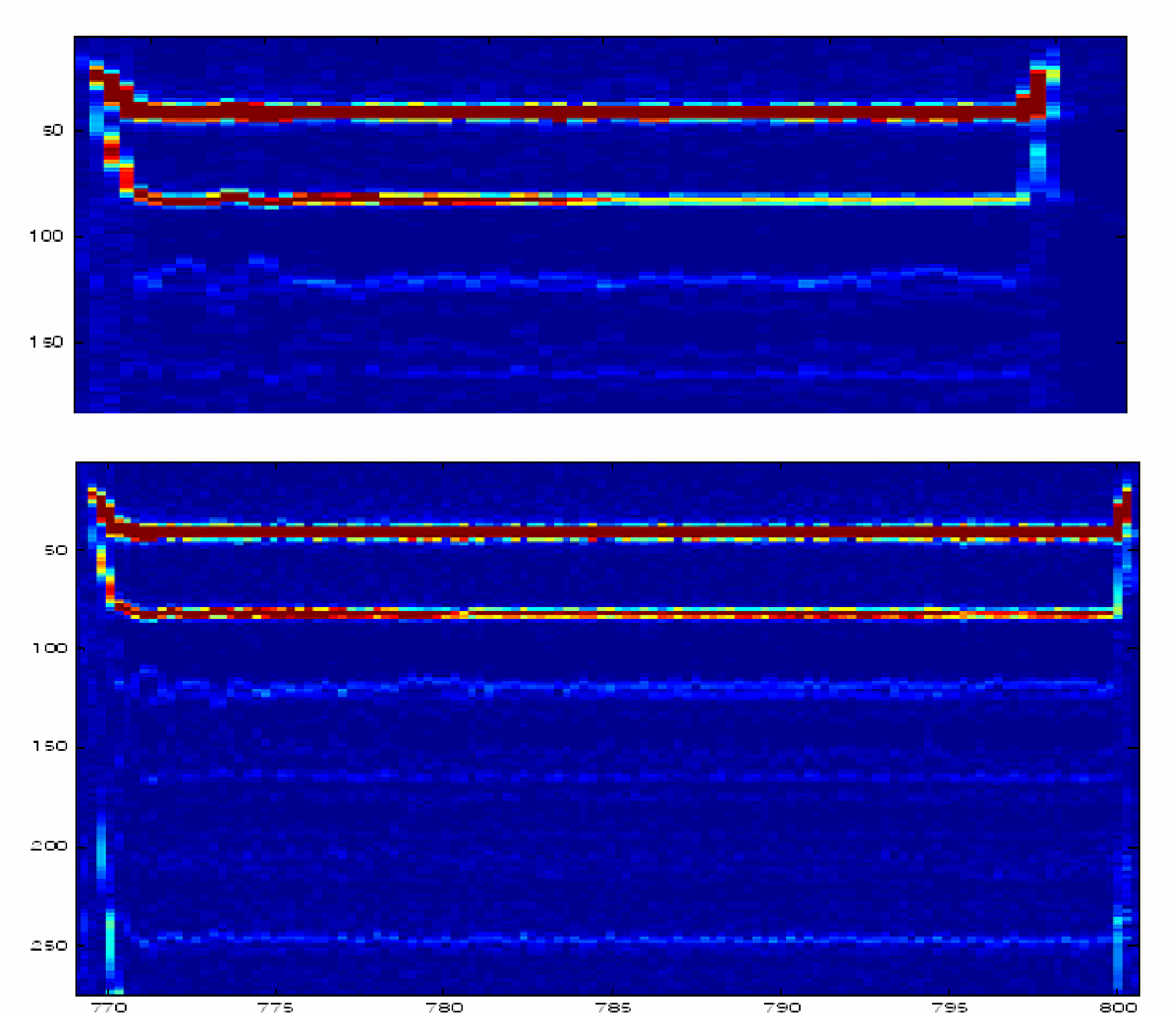



Figure 9. Spectrogram Showing the Progress of Compaction During Two Successive Passes Over the Same Stretch of the Pavement.

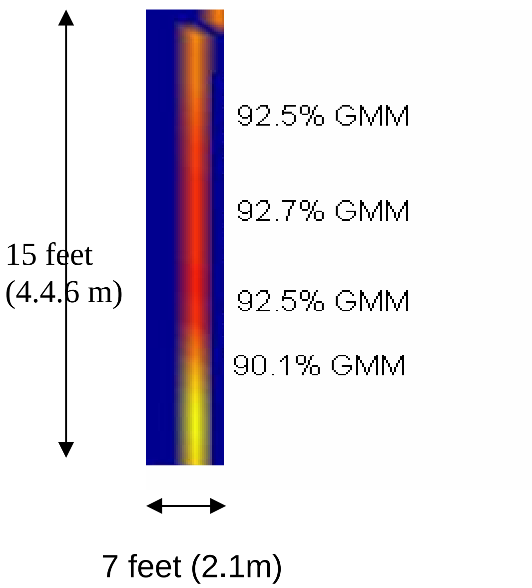



Figure 10. Output of the Compaction Analyzer Along with Actual Density Measurements Obtained from a Nuclear Density Gauge.

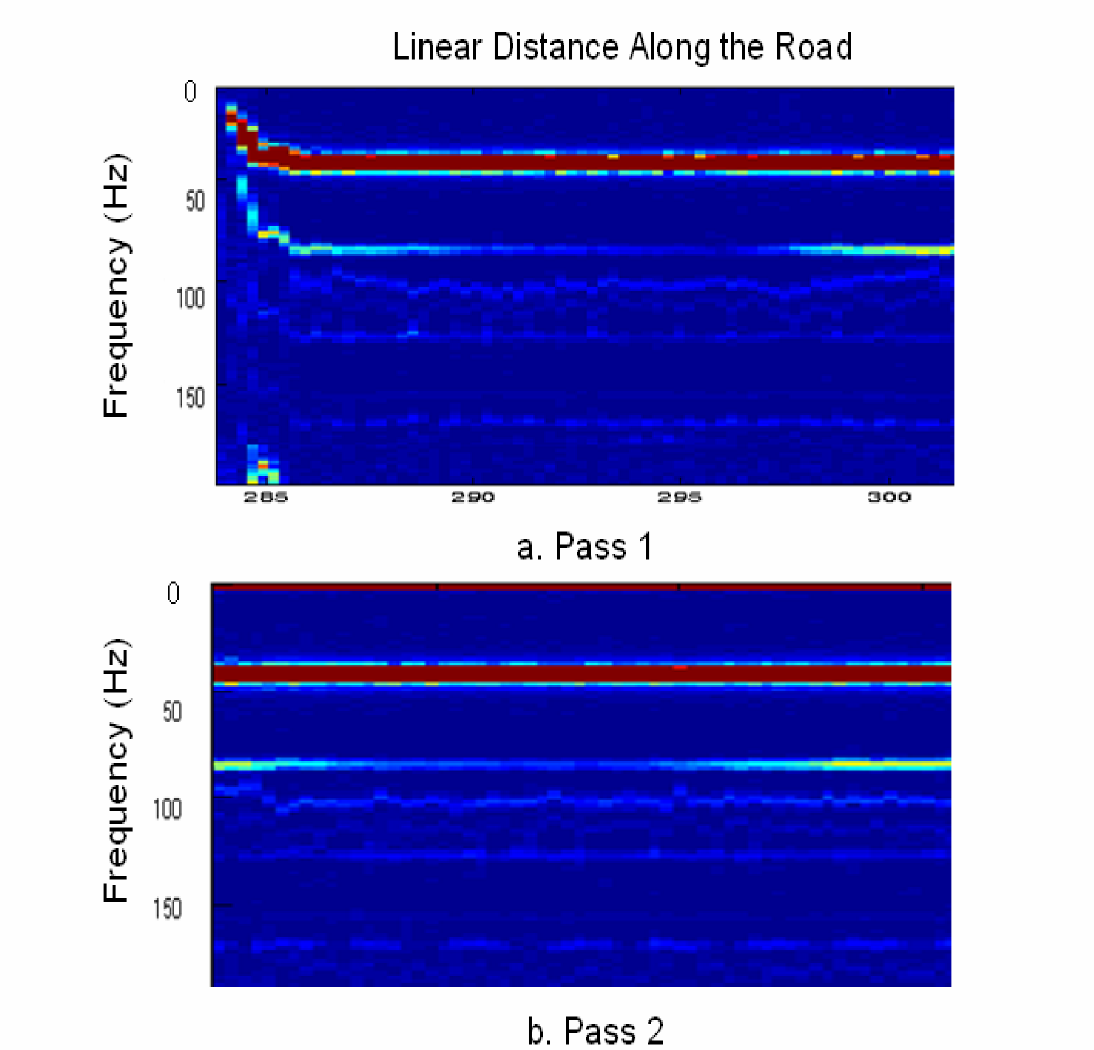



Figure 11 Spectrogram of the Vibrations of the Compactor Over Subsequent Passes Over the Same Section of the Pavement During Construction.