<u>YEAR ONE (2003-2004) ANNUAL PROGRESS REPORT</u>

I. COVER PAGE

A.	**Project Number:**	AR032-011
	Project Title:	INTELLIGENT ASPHALT COMPACTION ANALYZER
B.	**PI Name :**	Sesh Commuri
	Sponsoring Organization	University of Oklahoma Office of Research Administration 1000 Asp. Ave, Norman OK 73019
C.	**Co-PI Name :**	Musharraf Zaman
	Sponsoring Organization	University of Oklahoma Office of Research Administration 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
E.	**Current Funding Period**:	September 2003 – August 2006
F.	**Report Period:**	September 01, 2003 – June 30, 2004
G.	**Report Due Date:**	June 30, 2004

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, to be pursued in Year Two, the IACA will be fine-tuned to predict the density while the compactor is operating under a controlled set of conditions. The first year of the research is nearing completion and the results indicate that the Year I objectives laid out in the research plan of our proposal were successfully accomplished.

Currently, the Phase I of the research is nearing completion. Several tests were conducted to characterize the compaction process in the laboratory and the data gathered was analyzed to design and develop the Intelligent Asphalt Compaction Analyzer (IACA) prototype. 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 92.8% of the maximum theoretical density (i.e. 7.2% air voids). In the two test runs, densities of 92.9% and 92.8% of the maximum theoretical density were obtained. In the second set of tests, the IACA was required to determine when the compaction has reached 93.8% of the maximum theoretical density (i.e. 6.2% air voids). In the two test runs, densities of 93.96% and 94.01% of the maximum theoretical density were obtained. The test results, discussed in section III of the report, indicate that the IACA can consistently and accurately predict the density during compaction.

The IACA was also used to predict the density of a test pavement in the parking lot at 2821 N. Flood Avenue, Norman. Vibration data was obtained by instrumenting an Ingersoll-Rand DD 130 vibratory compactor with accelerometers and running the compactor on an existing pavement (see section III for details). The vibratory data was analyzed and the areas where the density was non-uniform were mapped out. The density across the stretch of the pavement was then mapped out using a nuclear density gauge. Results indicate good correlation between the prediction of the IACA and the areas of non-uniform density as measured by the nuclear density gauge.

In the next stage of the research, the IACA will be tested in the field under a controlled set of conditions. A test site has already been identified and the soil characterization tests and the design of the concrete slab completed. The construction of a concrete slab 200 feet long, 24 feet wide, and 1 foot deep is planned within few weeks. The construction work was interrupted by frequent rain in recent weeks. The slab has been designed to withstand the loading due to the vibratory compactor operating an asphalt mat on the surface of the slab. In the next few months, two overlays will be constructed at the test site and the data gathered during compaction will be studied. The results obtained from the aforementioned laboratory studies will be correlated against this test data. Also, results obtained from an actual construction site near Ratcliff City (off Highway 76 in Southern Oklahoma) will be used to validate the laboratory results.

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

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 will consist of a concrete pavement, to be constructed by our industry partner, Broce Construction, 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.

Key personnel in Oklahoma Department of Transportation (ODOT) have been providing invaluable assistance in the project. Dr. James Nevels Jr. and his staff have provided critical input on the selection of the test site and in pursuing the soil characterization tests. Mr. Danny Gierhart has been a great champion of the Asphalt program at OU and has been the primary source of contact for all ODOT asphalt specification-related issues.

Kirby-Smith has provided an Ingersoll-Rand dual drum vibratory compactor (DD 130) on loan to OU for the duration of the project.

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 is 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 first phase of the project (Year I) are discussed below.

1. Laboratory Study

Goals: In this study, the compaction process is studied in the laboratory using the Asphalt Vibratory Compactor (AVC) manufactured by Pavement Technologies Inc. The AVC is selected because the compaction of the asphalt mix by AVC replicates the compaction process in the field. Different asphalt mixes will be 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 will be quantified. The objective here is to understand the effect of different parameters typically experienced in the field on the vibration properties during compaction. The knowledge of these parameters will be used to model the Feature Extractor Module of the IACA.

Accomplishments:

i. Identical quantities of two different mix specimens were compacted at the same frequency, compactive pressure, and temperature and the vibratory signal was analyzed. The compacted specimen was removed from the mold and the specific gravity and density measured using the CoreLock™ apparatus using AASHTO T 166 and OHD L-45 specifications (see Appendix A.1). Accelerometers mounted on the compaction head (see Fig. 1) were used to measure the vibration of the AVC during the compaction. The spectrogram of the vibratory signal was analyzed to extract the features that are indicative of the density achieved. Five separate test runs were conducted to verify the repeatability of the data. The test results indicate that the compaction process 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 (Table 1).

ii. Identical quantities of a given mix were compacted in the AVC for increasing durations and the density of the resulting asphalt brick was measured using the CoreLock™ machine. The tests indicate that the compaction results in increasing density over time (Table 2). Further, the spectrogram of the vibratory signal indicates that the features are pronounced and can be used to predict the density of the asphalt mix during compaction (see Appendix A.2).

iii. Compaction tests were run for periods of 21,24,27,30,33,40,80,120, and 160 seconds and the compacted specimen was removed form the mold and cut into three equal vertical slices and the density of each slice was measured as before using the CoreLock machine. The test data (Table 3) indicates that while the density of the asphalt brick on the whole increases with increased duration of compaction, the same is not true within each slice. It was observed that the densification process in each slice is dependent on the initial distribution of the aggregates and binder in the mix, and on compaction, these settle at different rates causing uneven densities in the three layers.

iv. The temperature plays a significant role in the final density that can be achieved through compaction. The asphalt mix for all the tests were obtained through Oklahoma Department of Transportation (ODOT). Initially about 1000 pounds (lbs) of asphalt mix type 31 and 32 were obtained from ODOT. The specifications of these two mixes are provided in the Appendix A.1. However, the batch of mix that was obtained was oxidized and compaction at the specified temperature (139^0 C) did not result in acceptable densities. In fact, irrespective of the duration of the compaction process, densities greater than 91% (of Gmm) could not be achieved. However, when the temperature was increased to 175^0 C, densities closer to the required density (96% of Gmm) were obtained. While it is known that compacting at temperatures below the specified minimum will make it difficult to compact the mix, sometimes temperatures greater than the specified temperature must be used depending on the type of mix. Thus, temperature of the asphalt mat should be one of the factors to be used in the design of the IACA.

v. The effect of varying the speed of rotation of the eccentric weights in the AVC (frequency of the compactive impacts) could not be verified. While the AVC is designed to operate at 60 Hz, it does not have a closed-loop control of the frequency. As a result, there is a significant drift (3-5 Hz) in the frequency as the machine is loaded during the compaction process. Operation of the machine at 50 Hz is infeasible as that frequency is close to the resonant modes of the system. Operation at frequencies below 50 Hz did not result in adequate compaction of the mix.

2. Development of Feature Extraction and Analyzer Modules

The feature extraction module and the neural network classifier modules are the principal components of the IACA. The observed relationship between the process parameters and the vibrations of the AVC during the compaction process will be utilized to design the IACA. A feature extractor is first designed to extract in real-time the features indicative of this relationship. These features are then as input to the Neural Network (NN) Classifier. The number of frequencies in the spectrum that need to be considered and their amplitudes determine the number of input nodes for the neural network. The output layer of the NN will be designed to classify the input vector into one a several groups. This is done so that the NN can classify the features extracted from the accelerometer output during compaction in the field. The Neural Network will be trained on the data obtained in the tests till satisfactory classification is achieved.

Goals: Determine a process to study the vibration signals obtained from the instrumented AVC and design the feature extractor to extract the salient features in the vibratory signal. Depending on the number of features, design and train the Neural Network Classifier to predict the density of the compacted mix. Test the functioning of the classifier in real-time prediction of the density during the compaction of asphalt mix in the AVC.

Accomplishments:

i. A real-time XPC Target computer was purchased from MathWorks[1] to implement the IACA in real-time. This computational device enables the seamless implementation in real-time of visual models developed in SimuLink/MatLab[2]. This state-of-the-art tool along with the software toolboxes purchased from MathWorks significantly reduces the development time for the software implemented in the IACA prototype.

ii. The spectrogram of the vibratory signals obtained during compaction in the lab study was analyzed to determine the salient features that are indicative of the densification of the mix. It was observed that the frequency characteristics in the 20 – 50 Hz range vary as the mix is compacted. A feature extractor was developed to extract ten features in the frequency range. The neural network analyzer was then designed to predict the density based on the knowledge of the features, mix type and other proven parameters. The vibration data collected during the laboratory study was used to train the network. The training is performed in real-time and the process of training the network can be completed in a matter of minutes.

iii. The feature extractor and the neural network analyzer were tested using data collected during the laboratory tests, but not used for training the network. It was seen that the analyzer could accurately predict when the prescribed density has been reached during the compaction process.

iv. In order to verify the functioning of the analyzer in indicating when a desired level of compaction was reached, the analyzer was first trained to predict a specified density. The AVC was then run and the visual signal from the analyzer was used to shut down the AVC. The mold was removed from the AVC and the compacted sampled was cored and the density measured. It was seen that in each case, the analyzer could correctly predict when the mix was compacted to the desired density (Table 4).

[1] The MathWorks Inc., The MathWorks, Inc. 3 Apple Hill Drive, Natick, MA 01760-2098

[2] SimuLink and MatLab are registered trademarks of The MathWorks Inc.

3. Field Tests

While the analyzer could be trained to predict the density during compaction in the laboratory, the prediction process was based on data observed during compaction in the laboratory. Therefore, it was felt prudent to verify the functioning of the IACA on an existing pavement before investing a lot of time and money in the construction of a controlled test environment for the field testing of the analyzer.

Goal: To verify if the process developed in the laboratory study could be applied for determining the density of a pavement using a vibratory compactor like the Ingersoll-Rand DD 130 compactor.

Accomplishments:

i. An Ingersoll-Rand DD 130 compactor was instrumented with high bandwidth accelerometers (Cross Bow CXL100HF3, 0 -100 MHz, 0-10 G) and the compactor was operated on a bed of gravel and an existing parking lot at 2821 N. Flood Avenue, Norman. The spectrograms of the vibrations of the compactor (accelerometer outputs) was computed and displayed in real-time. From these figures, it is evident that the difference between the gravel bed and the pavement can be easily determined from the spectrograms.

ii. The spectrogram obtained during the operation of the compactor on the parking lot indicates that the density of the material is not uniform. The analyzer was trained to predict he regions where the density was below an acceptable limit. The output of the analyzer and the actual density measurements are shown in Fig. 6. It is, thus, evident that the invention is capable of predicting the density of the asphalt mat during compaction.

4. Site Identification and Construction of Test Strip

In order to manage the complexity of field trials, initial development and testing of the analyzer will be performed on a test strip of known properties. To facilitate this, a site will be identified within the OU campus in the first 3 months of the project and a test strip 200 feet long and 24 feet wide with a concrete base will be constructed to simulate controlled field conditions for tests in Phase II of the project.

Accomplishments: A test site on Mendel Pl. in Norman near Max Westheimer Airport was identified and permission obtained from the University of Oklahoma to use this site for the construction of the test strip. Soil Characterization tests were performed and the results used to design a concrete slab to withstand the dynamic loading due to the compactor. The report of this activity is provided in the Appendix A.4. The construction of the test strip is in progress and should be completed by mid-July.

V. WORK PLANS

In the remaining two months of Year One of the study, 01 July 2004 to 31 August 2004, test data from the field (Broce Construction's work site on state highway 76, 2 miles South of Ratcliff city) will be gathered and analyzed to correlate the data obtained in the laboratory with the real-life conditions prevalent in the field. The construction of the test site and the instrumentation of the Ingersoll Rand DD130 compactor provided by Kirby Smith will also be completed during this period. The project team could not utilize the services of the Post-Doc Fellow, Dr. Rafi Tarefdar, due to his taking up employment elsewhere. The project team had to train two graduate students in asphalt mix design and testing techniques to fill this gap in expertise. The team also utilized the services of a senior Ph.D student in Civil Engineering, Mr. Naji Khoury, for the design and construction of the test strip.

In the second year of the project, the IACA developed will be tested during compaction on the test strip. 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. It is also anticipated that the provisional application for the patent will also be submitted. This will enable the project team to disseminate the research findings in technical journals and workshops. YEAR TWO of the research will follow the plan enunciated in the original proposal.

VI. PUBLICATIONS

Conference and Journal submissions are being prepared based on the results of the research. *The disclosure of these results is on hold pending the approval of the provisional patent application.*

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 PI is working with Mr. Nick Rouse, Patent Attorney with Dunlap, Codding, & Rogers, to formalize the claims for submission to US Patent and Trademark Office.

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. 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 had some initial discussions with **Caterpillar**, **Ingersoll Rand**, and other companies involved in the manufacture of compaction equipment. From the discussions, it is evident that all these companies are interested in the development of technology that can predict the level of compaction achieved in the field.

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 recently 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."

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. This advantage will be leveraged in the next year to attract more state and federal funding for the asphalt program at OU.

APPENDIX

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A.1 Laboratory Compaction of Asphalt Mix Specimens

Fig. 1. Asphalt Vibratory Compactor

Fig. 2 Mold for compacting the mix

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

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OMIKL- 2003 51432

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

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Fig. 4 Mix Design Specifications

The AVC (Fig. 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 (Fig. 4), and placed in a mold (Fig. 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 Fig. 1. Accelerometers mounted on the frame of the AVC (Fig. 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. After 1 hour remove the material from oven and make batches of 6.5 kg each and place the material in separate pans and place the pans back in the oven. The mold has dimensions 29.9cm x 12.5cm and the desired lift thickness determines the quantity of the mix placed in the mold. In the experiments conducted, the maximum quantity of mix permissible was used resulting in a weight of 6.5 kilograms.
3. Clean the compacting head and coat with mineral oil so the asphalt won't stick to it. Remove the mold from the oven and place the base plates in the mold. Remove the pan which contains 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 (Fig. 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.
6. 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.

A.2 Results of Compaction Tests

Repeatability of the Test Results

The first set of tests was run to determine the repeatability of the results while compacting the mix using AVC as detailed in Appendix A.1. In this test, mix type 31 and 32(Fig.4) was compacted for different durations and the density of the resulting cores studied. The data obtained is presented below.

S. No	Compaction Time (seconds)	Density (% Gmm)
1	40	92.3
2	40	92.55
3	40	92.28

a. 6.5 Kg mix Type 31 at 175^0 C, compacted at 32 psi.

S. No	Compaction Time (seconds)	Density (% Gmm)
1	40	91.02
2	40	91.42
3	40	90.98

b. 6.5 Kg mix Type 32 at 175^0 C, compacted at 32 psi.

S. No	Compaction Time (seconds)	Density (% Gmm)
1	80	92.91
2	80	92.49
3	80	92.78

c. 6.5 Kg mix Type 31 at 175^0 C, compacted at 32 psi.

S. No	Compaction Time (seconds)	Density (% Gmm)
1	80	93.03
2	80	93.58
3	80	92.99

d. 6.5 Kg mix Type 32 at 175^0 C, compacted at 32 psi.

Table 1. Compaction of mix type 31 and 32 specimens for repeatability

S. No	Compaction Time (seconds)	Density (% Gmm)
1	24	77.14
2	24	80.08
3	24	79.67

S. No	Compaction Time (seconds)	Density (% Gmm)
1	27	87.55
2	27	86.63
3	27	86.19

S. No	Compaction Time (seconds)	Density (% Gmm)
1	30	88.23
2	30	88.31
3	30	87.63

S. No	Compaction Time (seconds)	Density (% Gmm)
1	33	89.91
2	33	89.14
3	33	89.88

S. No	Compaction Time (seconds)	Density (% Gmm)
1	40	92.3
2	40	92.55
3	40	92.28

S. No	Compaction Time (seconds)	Density (% Gmm)
1	60	92.91
2	60	92.49
3	60	92.78

Table 2. Change in density with increasing compaction time
(6.5 Kg mix Type 31 at 139^{o} C, compacted at 23.6 psi.)

Compacting beyond 60 seconds did not result in any appreciable changes in the density of the specimen. Further investigation indicated that this could be the result of using a recycled mix with excessive oxidation. To obtain higher density during compaction, the temperature of the mix was increased to 175^{0}C and the compactive pressure to 32 psi. The specimen was first compacted for 40 seconds and then rotated by 180 degrees to ensure uniform compaction. This cycle was repeated 4 times and the densities measured. This process was observed to yield densities closer to those specified in the mix design. The densities obtained after each cycle (expressed as a percentage of the theoretical maximum density – Gmm) is shown in the table below.

S. No	Cycle 1	Cycle 2	Cycle 3	Cycle 4
1	92.888	93.809	95.492	95.904

Table 3. Improved compacted density with increase in temperature
(6.5 Kg mix Type 31 at 175° C, compacted at 32 psi.)

A.3 Performance of the IACA in predicting density during compaction

The data gathered in the previous tests was analyzed to determine the key features of interest in the spectrum of the vibratory signals. This information was used to design the feature extractor and the neural network classifier components of the IACA. The neural network was trained to detect five primary regions during compaction. Data collected during a test run was used to verify the functioning of the analyzer. Fig. 5 below shows the different features extracted from the accelerometer output during the compaction process. The graph shown in straight line (Green) is the output of the classifier indicating the different regions it was trained to recognize. Thus, it is clear that the IACA can detect different stages of compaction.

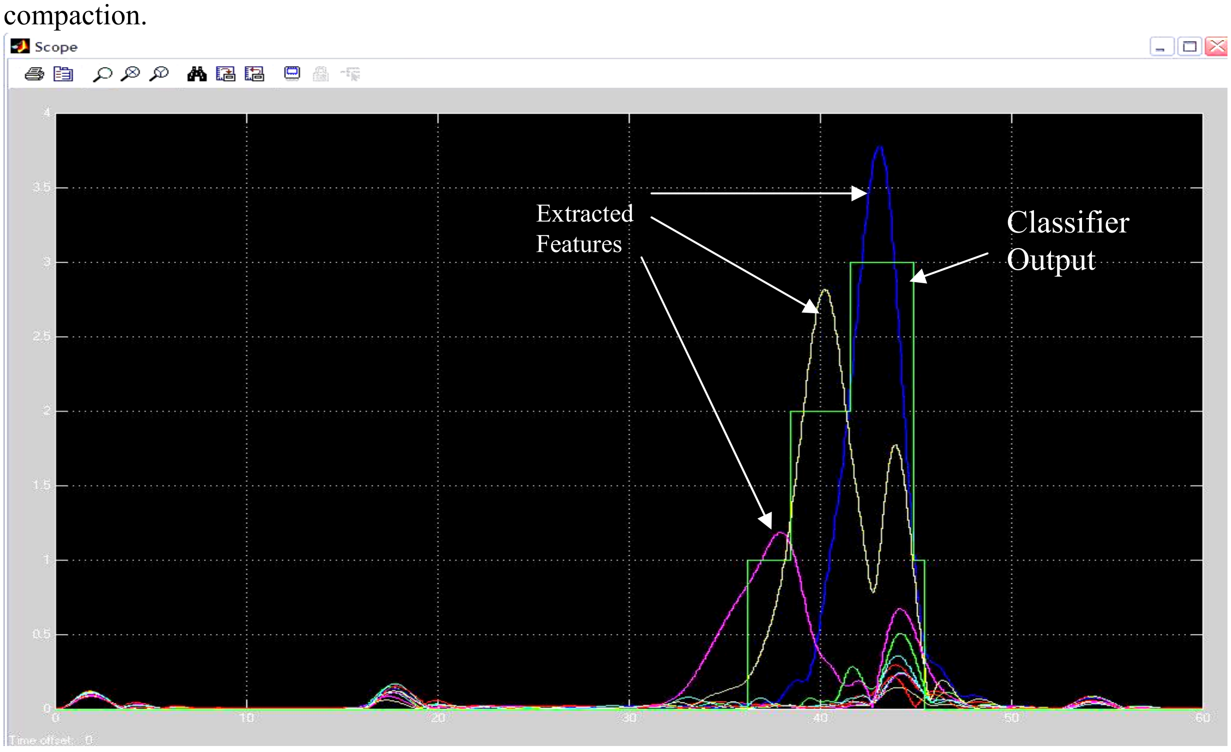

Fig. 5. Output of the Classifier

The ability of the IACA to predict the density during was also tested. The AVC was run as in the previous tests, but was manually shut down when the IACA indicated that the mix had reached the target density. 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 IACA can accurately predict the density of the mix during compaction.

S. No	Desired Density (%Gmm)	Achieved Density	
		Test 1	Test 2
1	92.888	92.889	92.829
2	93.809	93.964	94.007

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

A3. Performance of the IACA on a Vibratory Compactor in the field

The above results seem to 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 (Fig. 6). Subsequent readings using a nuclear density gauge corroborated these findings.

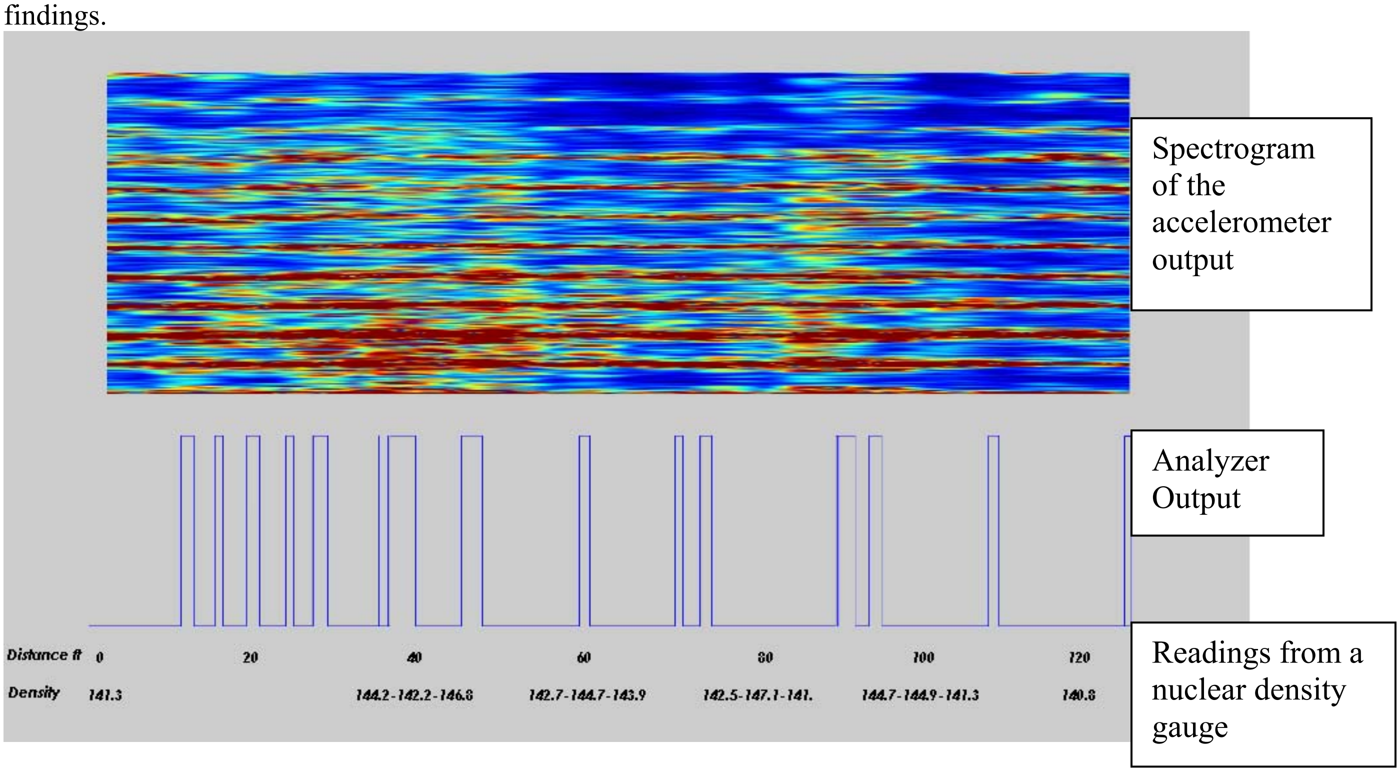

Fig. 6 Use of Analyzer to determine compaction in the field.

A.5 Design and Construction of Controlled Test Site

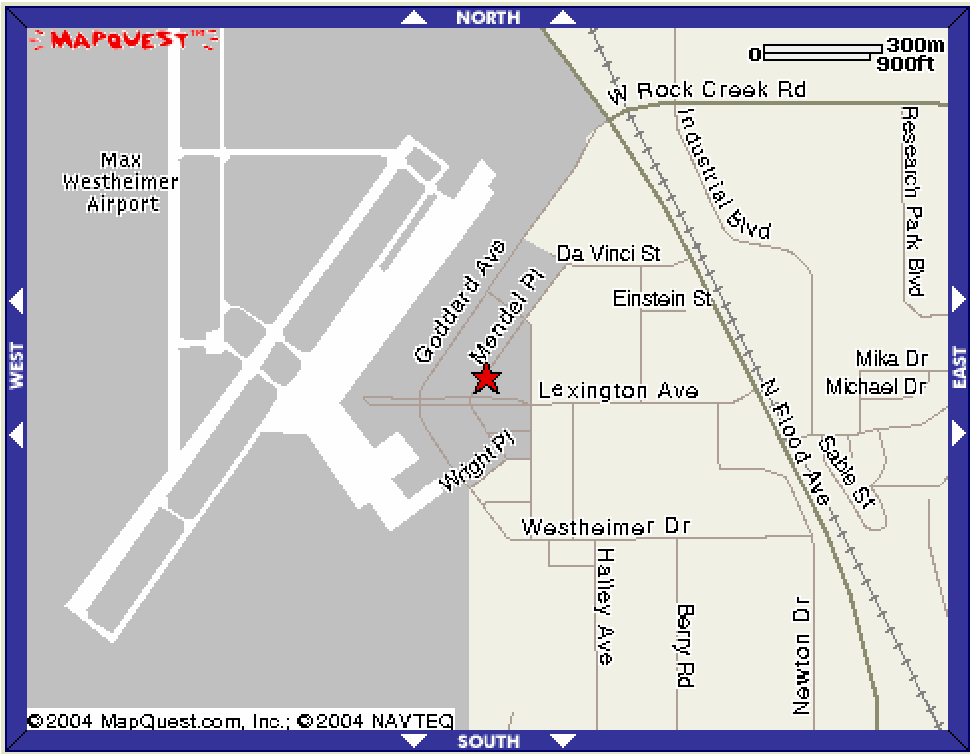

Fig. 7 Location of the test site

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 Fig. 8. The section is 24 feet wide by 250 feet long and it was divided into five stations. Fig. 9 shows a photographic view of marking down the stations using a wheel meter and an orange paint.

Fig. 8 Locating the benchmark for the project

Fig. 9 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 Fig. 10. The number of holes is supposed to give a better soil properties distribution throughout the project.

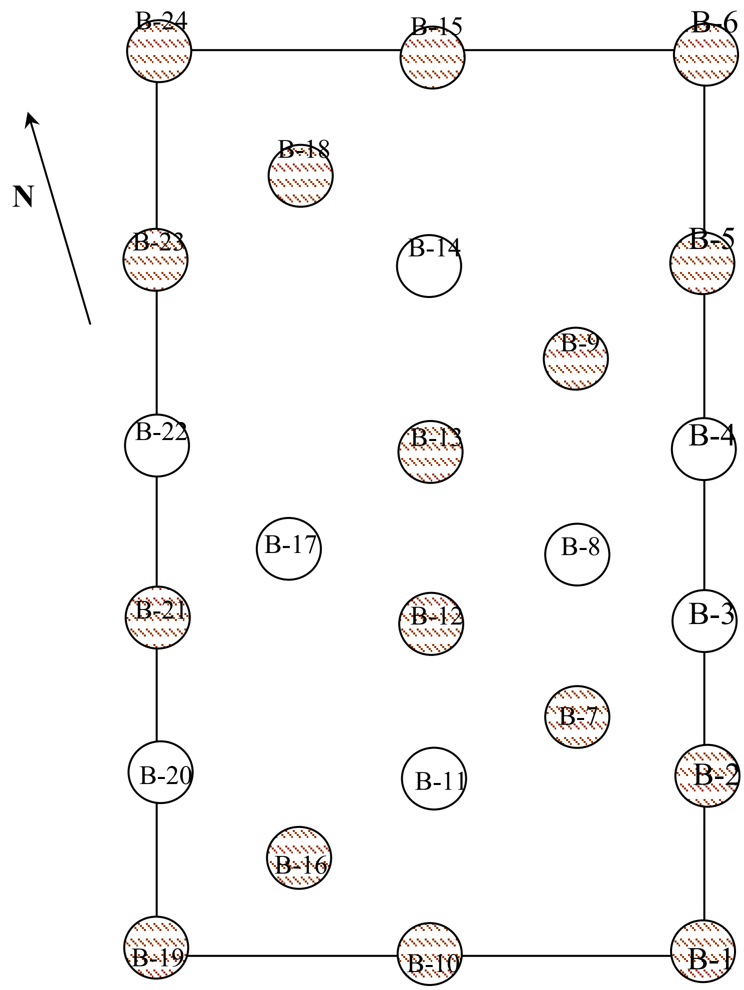

Fig. 10 Plan view of the section and boreholes numberings

Task 3: Field testing

The dynamic cone penetration (DCP) tests were performed inside each hole so that preliminary properties for soil will be available. Tests were conducted up to a depth of approximately 30 inches. After the performance of the DCP tests, bulk samples were collected from selected boreholes (shown as hashed circles in Fig. 10.) A total of sixteen holes were drilled using a hand auger, as shown in Fig.11. Bulk samples were collected every 6 inches, up to 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 (Fig.11).

Fig. 11 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 Fig. 12. From Fig. 12, 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 [Huang 2004].

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.

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				

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

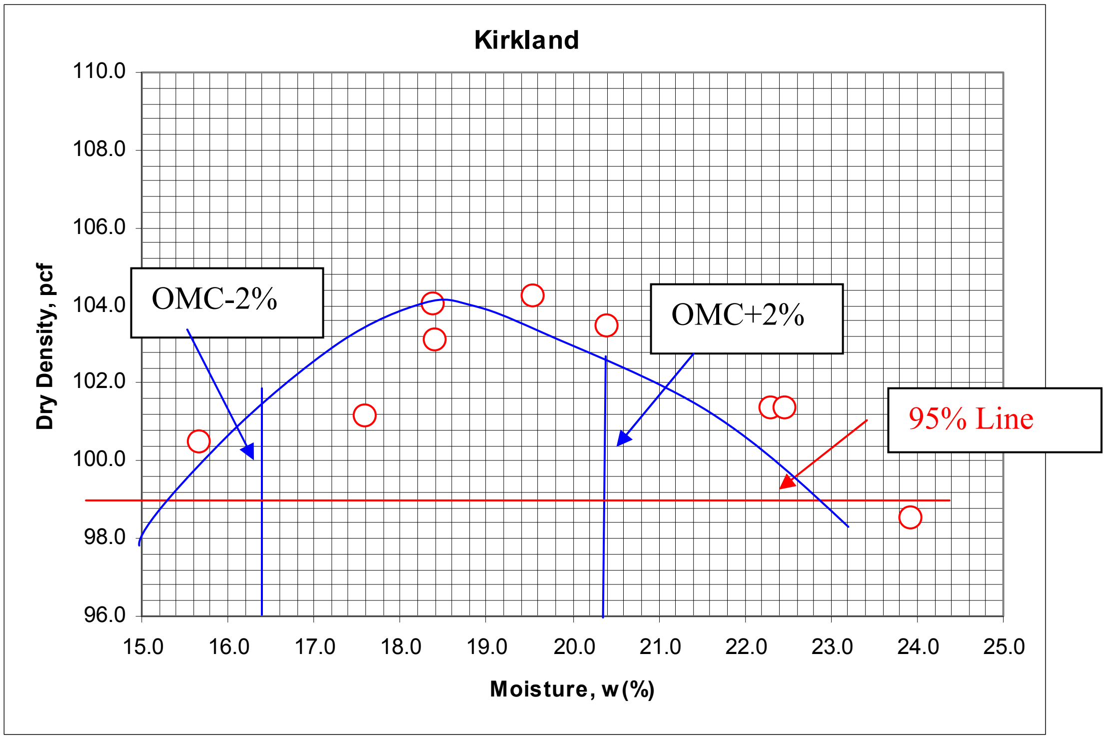

Fig. 12 Proctor test results

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 24 feet, length of 200 feet, and a thickness of 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 @ 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.

References

[1] Xang H Huang, Pavement Analysis and Design, 2nd edition, Pearson Prentice Hall, New Jersey, 2004.