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Economic Enhancement through Infrastructure Stewardship

Pavement Evaluation Using a Portable Lightweight Deflectometer

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16. ABSTRACT

The use of Zorn ZFG-3000 portable Lightweight Deflectometer (LWD) in the in-situ assessment of pavement quality was investigated in this research. A lower load and a shorter load pulse duration are used in a LWD as compared to a Falling Weight Deflectometer (FWD). LWDs are ideally suited for the structural evaluation of a single pavement layer at a time. LWDs could serve as a cost effective, non-destructive, in-situ test method for the evaluation of the mechanistic properties of the pavement and help to bridge the gap between the design and the construction of the pavements.

The performance of the Zorn ZFG3000 LWD device in measuring the stiffness of asphalt layer was studied during construction of full-depth asphalt pavements. While it was observed that the Zorn ZFG-3000 LWD was easy to use and able to determine the general trends in increasing/decreasing stiffness of the asphalt pavement layer, the researchers found very little correlation between the LWD measured modulus and the density of the asphalt mat at the test locations as determined from roadway cores. Further, very little correlation was observed between the LWD measured modulus and the dynamic modulus of the pavement at the test locations. The LWD measurements also did not appear to depend on any pavement parameters such as mix type and gradation, lift thickness, total asphalt pavement thickness, and type of construction. Based on these findings, it is concluded that the Zorn ZFC-3000 LWD is not suitable for measuring the stiffness of asphalt pavements and for use in Quality Assurance of pavements.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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Pavement Evaluation Using a Portable Lightweight Deflectometer

Research Project

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

The evaluation of the degree and uniformity of compaction is an important part in the Quality Assurance of asphalt pavements during their construction. Traditionally, acceptance quality testing of the asphalt pavements involved the use of spot testing of the density in conjunction with statistical methods. These methods are time consuming, and usually destructive in nature. In recent years, the mechanistic-empirical design techniques have been proposed for the design and analysis of pavements and their long term performance. The National Cooperative Highway Research Program (NCHRP) Project I-37A (AASHTO, 2002) recommends the use of dynamic modulus to characterize the performance of HMA mixes. With the increased emphasis on the new mechanistic-empirical (M-E)-based design procedures, predictive equations have been developed to estimate dynamic modulus of HMA layers as a function of such properties as mix type, aggregate structure, binder specifications, volumetric properties of compacted specimens, and mix temperature. However, the stiffness of the pavement layer is seldom measured during the construction process or during acceptance testing.

Falling Weight Deflectometers (FWDs) have been used for several years for evaluating the modulii of pavement layers and to assess the remediation/rehabilitation requirements of the pavement. However, the use of this device in evaluating the quality of newly constructed pavements is infeasible from a cost and logistics point of view. Thus, there is a need to determine the feasibility of using portable Lightweight Deflectometers (LWD) to evaluate the modulii of the pavement layers after their construction. LWDs use a lower load and a shorter load pulse duration as compared to FWDs and are ideally suitable for the structural evaluation of single pavement layers. LWDs could serve as a cost effective, non-destructive, in-situ test method for the evaluation of the mechanistic properties of the pavement and help bridge the gap between the design and the construction of the pavements.

The use of Zorn ZFG-3000 LWD in the in-situ assessment of pavement quality was investigated in this research. Two full-depth construction sites were identified and the performance of the LWD device in measuring the stiffness of base asphalt layer was studied at each of these sites. The performance of the LWD in measuring the stiffness of asphalt layers constructed on top of the base layer at each of these sites was also studied. The following are the key observations from the results of the study.

A. The Zorn ZFG-3000 LWD device is easy to set up and operate. It is light weight and portable and can be operated by a single operator.
B. The Zorn ZFG-3000 LWD is able to determine the general trends in increasing/decreasing stiffness of the asphalt pavement layer. The built-in software takes into account the surface temperature of the asphalt mat and provides modulus values predicted at 20^0 C (20 degrees Celsius).
C. In all the tests conducted, the researchers found very little correlation between the LWD measured modulus and the density of the asphalt mat at the test locations as determined from roadway cores.
D. In all the tests conducted, the researchers found very little correlation between the LWD measured modulus and the dynamic modulus of the pavement at the test locations as determined from the density and the dynamic modulus master curves developed through laboratory tests.
E. The correlation between the LWD estimated modulus and the density of the asphalt mat did not appear to depend on any pavement parameters such as mix type and gradation, lift thickness, and asphalt layer.

Based on these finding, it can be concluded that the Zorn ZFC-3000 LWD is not suitable for measuring the stiffness of asphalt pavements and for use in Quality Assurance of pavements.

2. INTRODUCTION

Stiffness is a key design factor that directly impacts the load bearing capacity of roadway pavements. Early deterioration of pavements due to rutting, fatigue cracking, and other types of distresses may be attributed to inadequate stiffness achieved during the compaction process (Pellinen and Witczak, 2002). The stiffness of the pavement is typically expressed in terms of its modulus, i.e., the relationship between the applied stress and the resulting deformation. While there are several ways to define the stiffness of a HMA layer, the dynamic modulus ($|E^*|$) of hot-mix asphalt (HMA) is selected as one of the fundamental inputs in the mechanistic-empirical pavement design guide (MEPDG) [NCHRP Project 1-37A]. The National Cooperative Highway Research Program (NCHRP) Project I-37A recommends the use of dynamic modulus to characterize the HMA mixes (AASHTO, 2002).

Failure to achieve the desired stiffness during the construction of the pavement is a leading cause for the early degradation of asphalt pavements. Excessive rutting, cracking, potholes etc., that are signs of failure of asphalt pavements can be avoided by using good quality control tools during the compaction process and through the adoption of better construction practices. Unfortunately, the stiffness of a pavement is seldom measured during its construction. Instead, the current quality control (QC) methods focus on the measurement of the density of the finished pavement at specific locations. The most reliable method of measuring pavement density is the extraction of cores at several locations on the finished pavement and conducting air voids tests in the laboratory as specified in AASHTO T 269-97 (AASHTO, 2003). This method of testing, however, is time consuming, costly, and destructive. Alternative methods for in-place measurement of density of hot mix asphalt (HMA) layers include the use of both nuclear density gauges and non-nuclear density gauges. The nuclear-based devices tend to have problems associated with licensing, equipment handling, and storage. In addition, both these technologies allow only point-wise measurements of density during the construction of an asphalt pavement. These manual processes of measurement are time consuming and result in unavoidable delays in the construction while not reflecting the overall quality of the pavement.

2.1 Related studies in mechanistic properties of pavements

In-situ testing of mechanical properties of pavements and underlying subgrade soils is a widely researched area. Several test devices such as the Benkelman Beam, Lacroix Deflectograph, static plate loading test, and FWD are available for nondestructive evaluation of asphalt pavements (Newcomb and Birgisson, 1999; Tayabji and Lukanen, 2000). More recently, the rolling weight deflectometer, spectral analysis of surface waves, and the Humboldt stiffness gauge have also been used to measure in-situ stiffness of pavement layers including subgrade (Newcomb and Birgisson,1999; Navaratnarajah, 2006). However, these test methods are time consuming, and costly. Therefore, their use has been limited to the evaluation of the quality of existing pavements where only a few infrequent measurements are required.

With the increased emphasis on the new mechanistic-empirical (M-E)-based design procedures, predictive equations have been developed to estimate dynamic modulus of HMA layers as a function of mix type, aggregate structure, binder specifications, volumetric properties of compacted specimens, and mix temperature etc. (Andrei et al. 2002; Ayres et al., 1998; Crovetti et al. 2005; Katicha, 2003; Tarefder, 2003;). While these tests are adequate to study the properties of the asphalt mix in the laboratory, they too are not suitable for determining the stiffness of the pavement during its construction.

The need of measuring the stiffness of a pavement during construction has motivated the industry and equipment manufacturers to develop technologies that can ensure consistent and optimal compaction of HMA pavements (Camargo et al. 2006; Landers, 2006; Moore 2006; Peterson 2005). Uniform compaction of both soil and aggregate bases is achieved through the variation of machine parameters such as amplitude and frequency of vibrations, and vectoring of the thrust. Dynamic control of machine parameters allows the application of the vibratory energy only to under-compacted areas and thereby preventing over-compaction and ensuring uniform compaction of subgrade soils and/or aggregate bases. While these intelligent compaction (IC) techniques hold promise, their performance is being evaluated by several Departments of Transportations (DOTs) and the Federal Highway Administration (FHWA) (FHWA, 2009).

In contrast to the aforementioned intelligent compaction (IC) technologies (Ammann, Asphalt Manager, Caterpillar, Asphalt Compaction, Sakai) the Intelligent Asphalt Compaction Analyzer (IACA) (Commuri et al. 2008; Commuri et al. 2009a; Commuri et al. 2009b, Commuri and Zaman, 2010) is a measurement tool that analyzes, in real time, the vibrations of a vibratory compactor to estimate the level of compaction of a HMA mat or layer during construction. Use of IACA to estimate the density of asphalt pavements during construction was demonstrated during actual construction of asphalt pavements (Commuri, 2011). In the research funded by Oklahoma Transportation Center (OTCREOS7.1-10, October 2008 - June 2010) and Volvo Construction Equipment (VCE) the ability of the IACA to accurately measure the stiffness of the pavement was demonstrated. During this research, the IACA estimates were verified using Falling Weight Deflectometer (FWD) tests on the completed pavement. While the FWD tests demonstrated the power of the IACA, conducting FWD tests at each construction site is not cost effective and will ultimately lead to difficulties in adopting IC technologies. Thus, there is a need to develop test methods and procedures for the rapid testing of the stiffness of pavement layers using inexpensive, portable, lightweight tools.

2.2 Background on the Lightweight Deflectometers

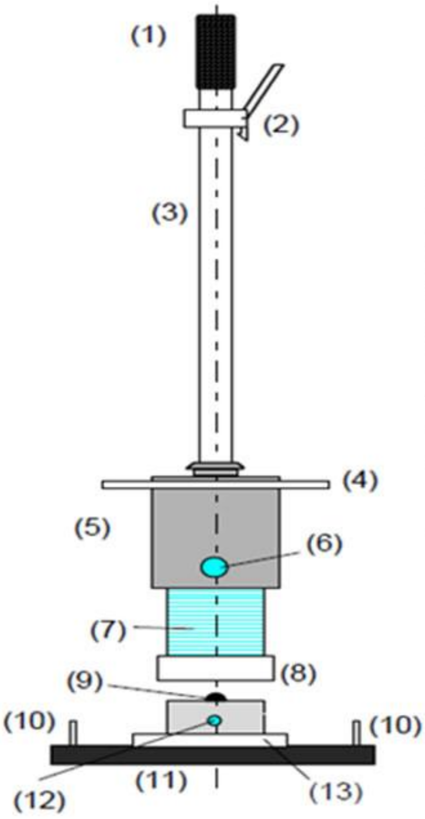
Light Weight Deflectometers (LWDs) are non-destructive testing tools used to measure the stiffness (modulus) of a pavement layer or a surface. LWDs are an alternative to static plate bearing tests and are finding more application during pavement construction due to their small foot print, portability, and the short time required for conducting each test. The LWD consists of a fixed weight that is dropped onto the pavement surface from a fixed height through a loading plate. The resulting deflection of the surface is measured either through the use of geophones or accelerometers and is used to determine ‘stiffness’ or the ‘**Surface Modulus**’ of the pavement layer. There are three commonly used LWD apparatus worldwide – ZFG2000 manufactured by Zorn Instruments, Germany; LWD 3031 manufactured by Dynatest International; and the

PRIMA100 manufactured by Cooper Industries, United Kingdom. The ZFG2000A and the associated software ZFG3000 are specifically designed for the evaluation of the surface modulus of asphalt pavement and is the focus of this research.

Figure 1. Zorn ZFG2000A asphalt tester (Zorn, 2011)

The Zorn ZFG3000 system is shown in Figure 1 and the essential components of the LWD are shown in Figure 2. The LWD drops a weight of 15 Kg from a height of 700 mm onto a loading plate. The deflection caused by the 12 mm diameter pin on the surface is measured using an accelerometer. Assuming that a constant peak force is imparted on impact, the ZFG3000 system calculates the deformation modulus of the pavement surface. It is assumed that a peak force of 10.6kN is imparted and the resulting pulse is of 17 ms duration. The modulus of the pavement at 20^0C is then calculated as

$E_{20^0 C} = (.055/s_\infty)e^{0.07(T-20^0 C)}$,where s_∞ is the measured deflection and T is the temperature of the pavement surface at the time of measurement.



1. Grip
2. Top fix and release mechanism
3. Guide rod
4. Round grip
5. 10 or 15 kg - falling weight
6. Lock pin
7. Set of steel springs
8. Anti-tipping fixture
9. Load canter ball
10. Carry grip
11. Loading plate
12. Socket for the connection to electronic device
13. Adapter Plate

Figure 2. Components of the LWD (Zorn, 2011)

2.3 Prior research on the use of LWDs for assessing pavement layers

Over the past two decades, several researchers have explored the use of LWDs in assessing the mechanistic properties of soil and aggregate bases and unbound material (Senseney and Mooney, 2010; Hossain, and Apeagyei, 2010). The results, while showing good correlation to the stiffness of the pavement layers', were not very encouraging and had high variability compared to FWD measurements (Hossain, and Apeagyei, 2010). The low peak impact forces associated with the LWDs were found to be insufficient to capture the properties of all the pavement layers. As a result, the back calculated modulus (Hossain et. al. 1992) based on layer information showed excessive variability compared to FWD test data. Fleming et. al., (2007) concluded that prior to the use of LWDs, site specific data must be factored into the LWD measurements and correlation factors have to developed to minimize the deviations from FWD measurements. Further, the seating on the LWD device and the test protocol has to be standardized to reduce variations from one test location to another (Edwards and Fleming, 2009). These issues were supposed to have been addressed in the ZFG3000 LWD and its associated software. In this research, the researchers attempt to verify the stiffness of asphalt pavement layers measured by this LWD and determine its usability in the quality assurance of asphalt pavements.

3. GOALS OF THE PROPOSED RESEARCH

The main goals of the study presented in this report are as follows:

a) Study the ease of use and accuracy of the Zorn ZFG-3000 Lightweight Deflectometer in determining the stiffness of asphalt pavement layers after construction,

b) Study the ability of the ZFG-3000 LWD to capture trends in the stiffness along the length of the asphalt pavement.

c) Study the stiffness reported by the ZFG-3000 in relation to the pavement density as determined by roadway cores extracted at the test location.

d) Study the effect of pavement layer and mix parameters on the modulus values reported by the LWD.

e) Study the effect of the underlying pavement layers on the modulus reported by the LWD device by comparing the LWD modulus with the modulus backcalculated from Falling Weight Deflectometer (FWD) tests.

In order to address these goals, two sites of full depth asphalt pavement construction will be identified. At each of these sites, test locations will be marked on top of the compacted base layer and stiffness measurements reported by the LWD will be recorded. Roadway cores will then be extracted and their density will be measured in the laboratory in accordance with the AASHTO TP-62 test procedure. Virgin asphalt mix will also be collected from the site and the dynamic modulus tests will be conducted to develop the master curves for the mix. The density information obtained from the cores and the Master Curves will then be used to predict the dynamic modulus at the test locations. Correlation between the LWD modulus and the density as well as the dynamic modulus will be studied to determine the effectiveness of the ZFG3000 LWD to estimate the stiffness of the pavement layer. In similar manner, the effectiveness of the device will also be studied during the construction of asphalt layers on top of the base layer at these two sites. The correlation obtained for each layer will then be compared to determine if the layer parameters such as mix gradation, layer thickness, influence the ability of the LWD to accurately measure the modulus of the layer. During these tests, the portability and ease of use will also be documented.

4. RESULTS OF THE RESEARCH PROJECT

4.1 Site Selection

Two full-depth construction sites were selected to evaluate the functioning of the ZFG3000 LWD on the base asphalt layer constructed on top of the prepared subgrade. The use of the LWD for measuring the stiffness during the construction of asphalt layers on top of the base layer was also studied at these two sites. Site specific details such as location, number of asphalt layers, layer thickness, and asphalt mix parameters, binder type are detailed in the following sections.

60th Street, Norman, OK

The utility of the LWD in determining the stiffness of asphalt layers was investigated during the construction of 1 mile (4 lanes) of full-depth asphalt pavement on 60th street in Norman, OK (State Project STP-155B(813)AG). The subgrade was stabilized with 10% Cement Kiln Dust (CKD) to a depth of 203.2 mm (8 inches) and compacted using an Ingersoll Rand SD-100 vibratory compactor. A base layer of 88.9 mm (3.5 inch) thickness was first compacted on top of the prepared subgrade using a 19 mm (3/4 inch) S3 PG 64-22OK asphalt mix. The mix contained with approximately 30 percent 1 inch (25 mm) rock, 10 percent 5/8 inch chips, 25 percent C-33 screenings, 10 percent sand, and 25 percent fine Reclaimed Asphalt Pavement (RAP), with 4.1 percent PG 64-22 OK binder. A second 88.9 mm (3.5 inch) thick layer was then compacted on top of the base layer using a 19 mm (3/4 inch) S3 PG 76-28OK asphalt mix. This mix comprises of approximately 30 percent 1 inch (25 mm) rock, 15 percent 5/8 inch chips, 30 percent C-33 screenings, 10 percent sand, and 15 percent fine RAP, with 4.3 percent PG 76-28 OK binder.

The GPS coordinates and the test data were recorded at each of these locations. Roadway cores were also extracted at select locations to determine the density of the pavement. The asphalt pavement was compacted using Hamm HD90 vibratory compactor equipped with OU Intelligent Asphalt Compaction Analyzer (IACA).

Apple Valley, Oklahoma City, OK

The second site selected for this project was located in Apple Valley, Edmond, OK. A 0.7-mile (2 lanes) long full-depth asphalt pavement was constructed on Apple Valley Road (State Project STP-155B (813) AG). The subgrade was first stabilized by mixing 10% CKD to a depth of 304.8 mm (12 inches) and then compacting it using an Ingersoll-Rand SD-100 vibratory compactor. A 76.5 mm (3 inch) thick base layer was first compacted on top of the prepared subgrade using a 19 mm (3/4 inch) S3 PG 70-28OK asphalt mix. The mix contained approximately 26 percent 1 inch (25 mm) rock, 25 percent manufactured sand, 22 percent screenings, 12 percent sand, and 15 percent RAP, with 4.3 percent PG 70-28 OK binder. A second 76.5 mm (3 inch) thick base layer was then compacted on top of the base layer using the same mix. A final 50.8 mm (2 inch) thick surface course was then compacted atop of the intermediate layer using a S4 PG70-28OK mix. This mix contained approximately 35 percent 5/8 inch (15.6 mm) chips, 25 percent manufactured sand, 13 percent C-33 screenings,12 percent screenings, and 15 percent sand, with 4.9 percent PG 70-28 OK binder. The asphalt pavement was compacted using an Ingersoll Rand DD118HFA.

4.2 Initial Demonstration

The LWD was initially tested during the construction of an asphalt overlay on Hefner Road in Edmond, OK. The mix and the pavement design at this site were similar to the base layer in the Apple Valley Project. Several test locations were marked on top of the asphalt base (Figure 3) and LWD readings were taken at these locations. The LWD readings were then compared with the density of cores extracted from these locations. It was discovered during these tests that incorrect assembly of the device prevented the processing of the collected data. The research team then contacted the manufacturing company, Zorn for assistance in data collection and analysis. An expert team from Zorn visited OU in September 2011 to reassemble the device and train the research staff in the use of the LWD device. After initial training, the LWD was found to be easily transportable to the site and easy to operate by a single individual (Figure 4).

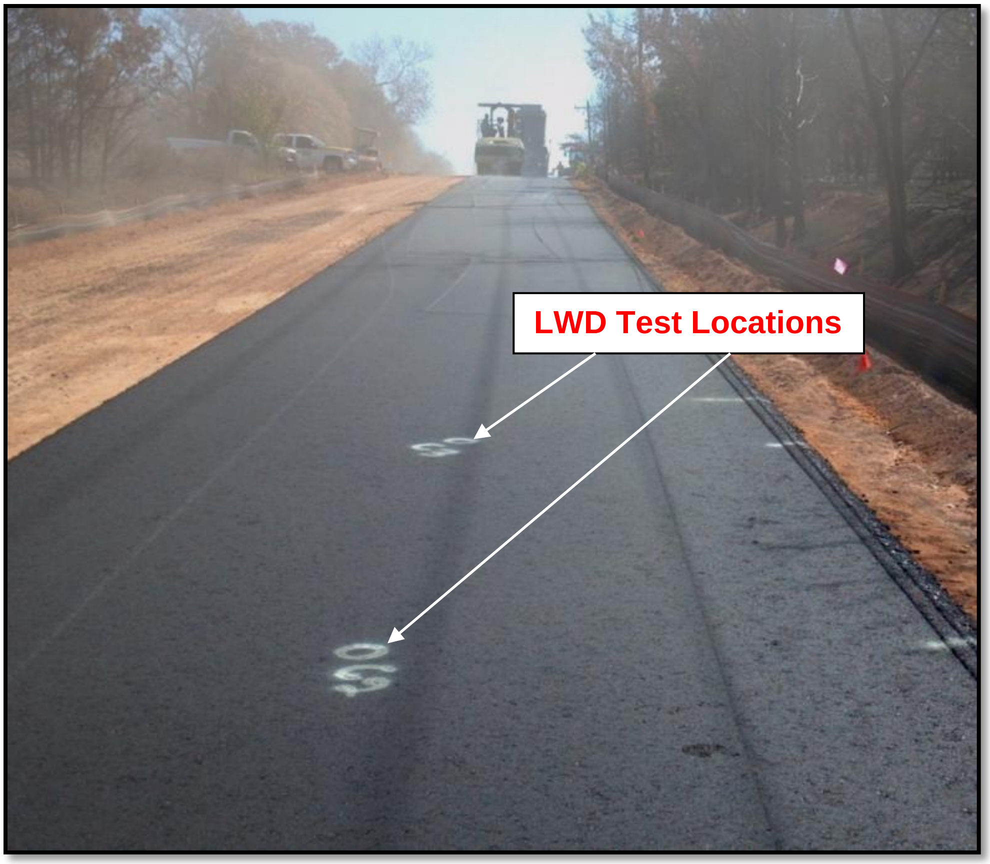


Figure 3. Representative LWD test locations at Apple Valley Road Project in Edmond, OK.

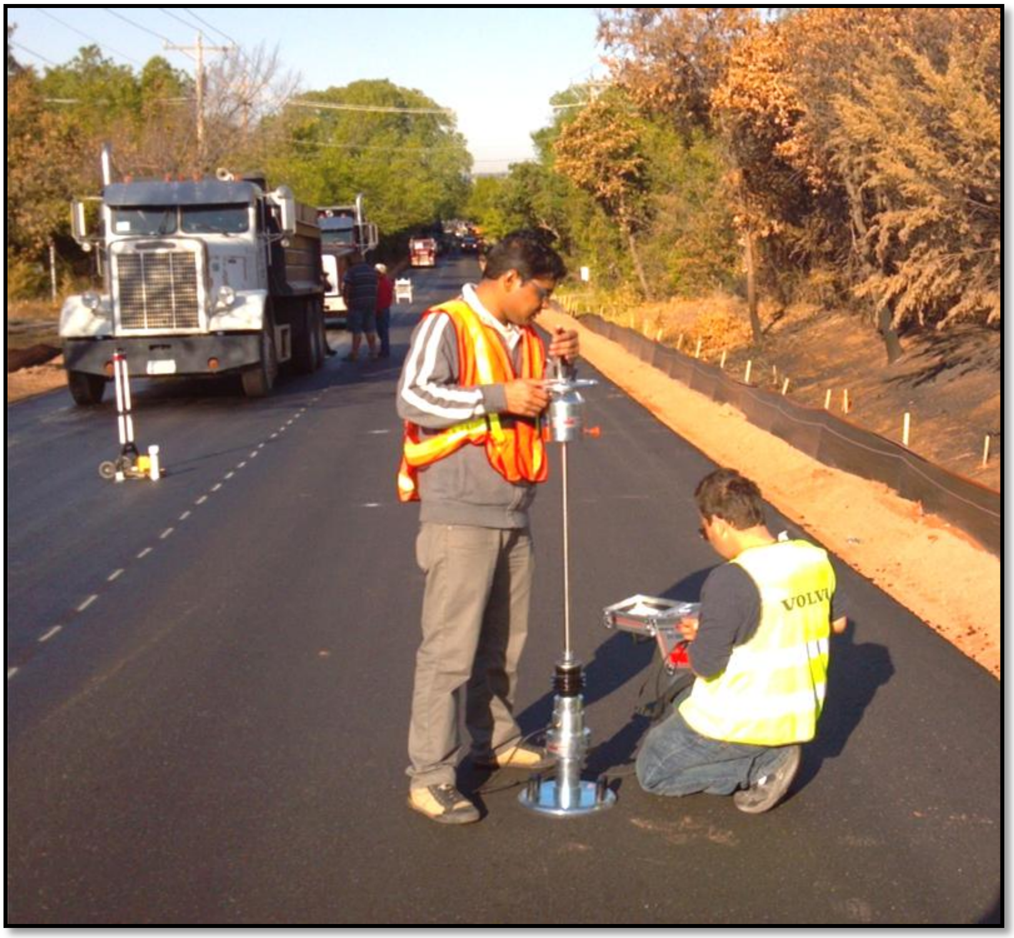


Figure 4. LWD Testing in progress at Apple Valley Road Project in Edmond, OK

4.3 Results from Tests on 60th Street in Norman, OK

The ability of the Zorn ZFG3000 LWD to ascertain the stiffness of asphalt pavement layers was studied during the construction of a full-depth asphalt pavement at the 60th street in Norman, OK. After the soil subgrade was stabilized and compacted, asphalt mix of Nominal Maximum Aggregate size (NMA) of 19 mm was placed to a thickness of 88.9mm and compacted using a dual steel drum vibratory compactor. After the construction of the full-depth asphalt layer at this project, test locations were marked 3 meters apart along the center line of the pavement. GPS readings of these locations were noted and the pavement density was also recorded using a Humboldt Nuclear Density Gauge. After the pavement had cooled down to ambient temperature, LWD tests were conducted at the test locations and the LWD modulus at the ambient temperature as well as at 20^0C were recorded. Cores were extracted at the test locations and the density of the cores was determined in the laboratory in accordance with the AASHTO T-166 method. Virgin mix was also collected from the site and the dynamic modulus master curves were developed in accordance with the AASHTO TP-62 test procedure. The densities of the cores were used in conjunction with the master curves to estimate the dynamic modulus of the asphalt pavement at the test location. The data collected during these tests is shown in Table 1. LWD tests were also conducted on the surface layer that was constructed atop the base. Table 2 presents the corresponding test results.

LWD measured modulus and the density measured from cores extracted from the test locations for the base layer is shown in Figure 5. It can be seen that there LWD readings follow a similar trend as the density measurements at the test locations. However, it can be seen in Figure 6 that the correlation between the actual density measured from the cores and the pavement stiffness determined by the LWD is very poor (R^2 = 0.003). In case of surface layer, no clear trend between density and LWD modulus was observed (Figure 7). Further, Figure 8 shows that very little correlation (R^2 = 0.07) exists between the density measured from the cores and the LWD modulus reported at the corresponding test locations. Comparison of the LWD measured modulus at each of the test locations on the first and second asphalt layers (Figure 9) does not indicate any clear pattern. This could be due to the fact that the properties of the two layers are not uniform at all test locations. Therefore, no conclusions can be drawn regarding the effect of base on the overlay as seen from LWD measurements.

The comparison between LWD measured stiffness and the dynamic modulus that was determined from the master curves is shown in Figures 10 and 11. Once again, no appreciable correlation was found between the LWD measured modulus and the dynamic modulus at the test locations for either the base layer or for the surface layer.

Table 1. LWD measured modulus, density and dynamic modulus at test locations on base layer.

60th Street, Norman (88.9mm thick, 19mm S3 PG64-22OK)			
Test Location	Density (% MTD)	Estimated Modulus (Mpa) at 20^{o}C and 10Hz	LWD Modulus (Mpa) at 20^{o}C
L1S4C2	91.3	6387	7093
L1S4C1	93.4	8063	2458
C4	92.4	7372	5934
C5	92.7	9140	4259
C6	92.9	9140	5035
L2S2C1	92.1	6387	5258
L2S2C2	93.4	9645	3778
L2S2C3	92.7	7991	3654
L1S3C2	92.1	7306	2493
L1S3C3	91.8	7306	5282.5
L1S2C3	91.3	7306	3212
C1	91.6	4192	3147.5
C2	91.9	4795	3549.5
C3	91.4	8432	3589.5
L1S2C1	91.6	6330	4203
L1S1C3	93.4	6218	3899.5
L1S1C2	94.6	5485	5702.5
L1S2C1	91.6	5534	3297.5
L1S1C1	93.4	4926	3214.5
L1S2C2	90.3	5893	2762

Note: MTD- Maximum theoretical density.

Table 2. LWD measured modulus, density and dynamic modulus at test locations on Surface Layer .

60th Street, Norman (88.9mm thick, 19mm S3 PG76-28OK)			
Test Location	Density (%MTD)	Estimated Modulus (Mpa) at 20^{o}C and 10Hz	LWD Modulus (Mpa) at 20^{o}C
C7	93.2	10271	4724
C8	92.8	9501	3899
C9	93	9802	6907
L1S1C1	96.0	7448	4070
L1S1C2	94.3	6718	3149
L1S3C3	96.2	10703	9364
L1S4C1	92.6	10175	3765
L1S4C2	93.8	12724	1766
L2S1C1	95.6	8467	13945
L1S1C3	95.8	7595	4043
L1S2C1	94.6	8067	3734
L1S3C2	94.3	10779	4410
L1S4C3	93.4	7729	10945
L2S1C2	95.4	6671	3841
L2S1C3	95.2	7291	3724
L1S2C2	92.1	9050	3015
L1S2C3	93.7	10812	3896
L1S3C1	95.5	11255	5624

Note: MTD- Maximum theoretical density.

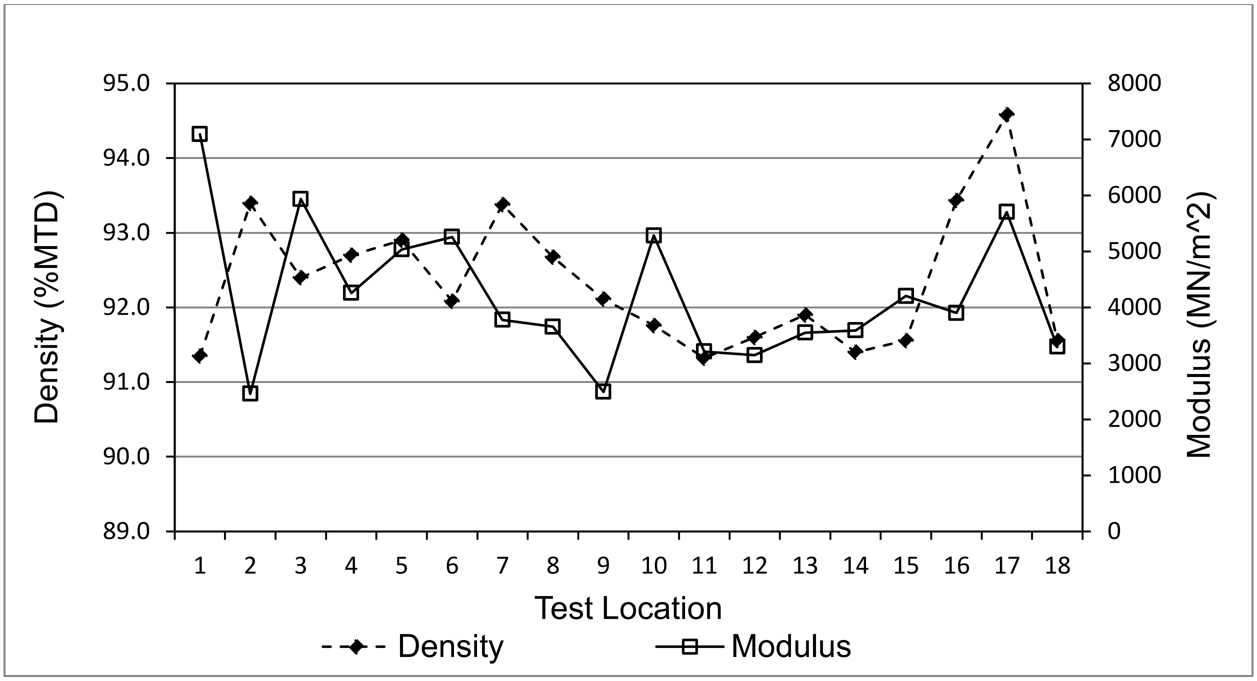


Figure 5. Density and LWD measured modulus at test locations on base layer of asphalt pavement on 60th street in Norman, OK.

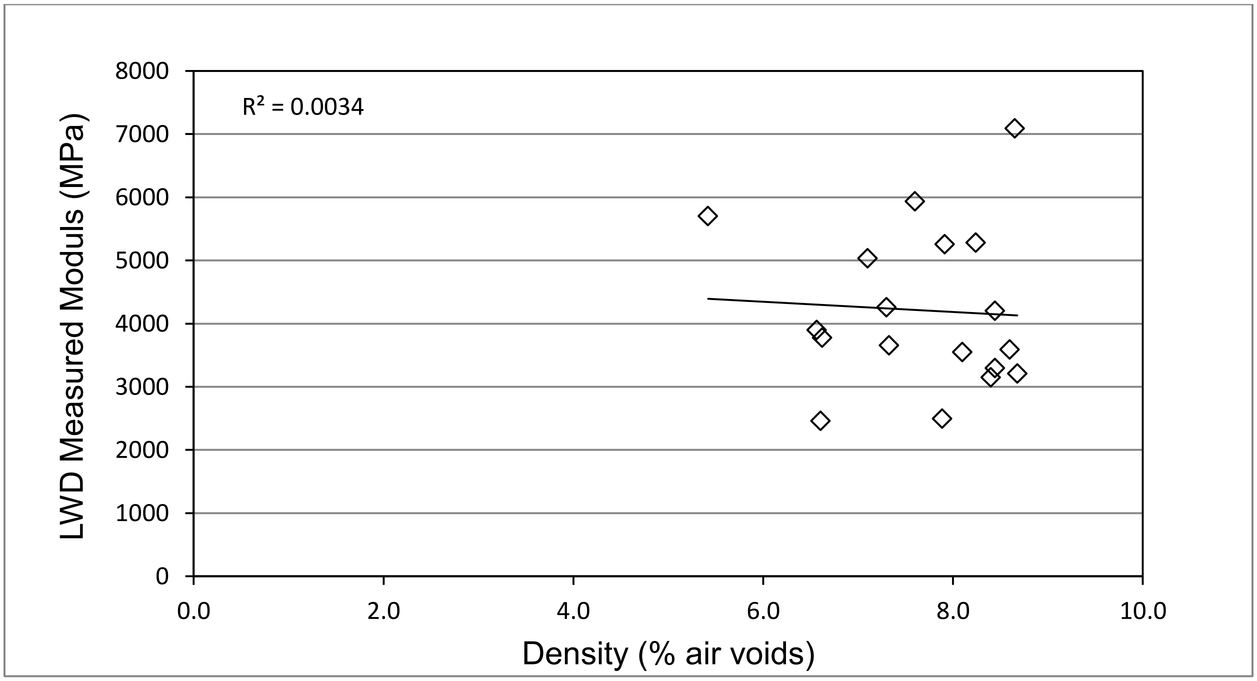


Figure 6. Comparison of roadway density and LWD measured modulus at test locations on base layer of asphalt pavement on 60th street in Norman, OK

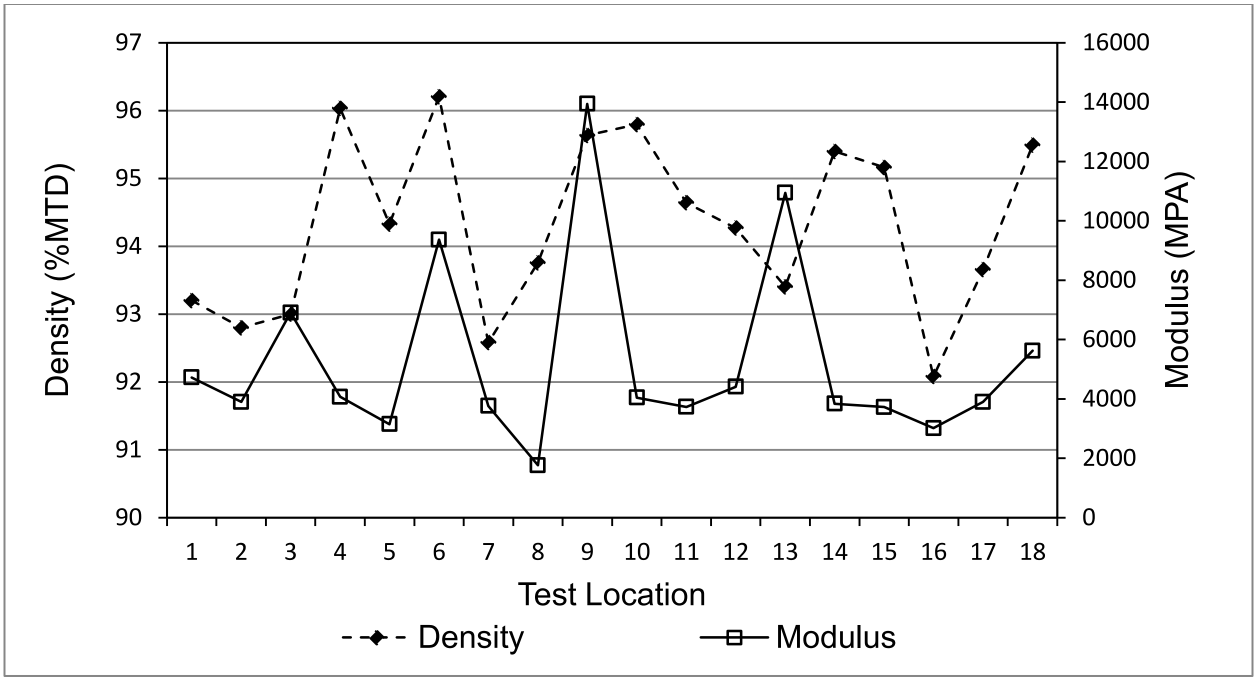


Figure 7. Density and LWD measured modulus at test locations on second layer of asphalt pavement on 60th street in Norman, OK

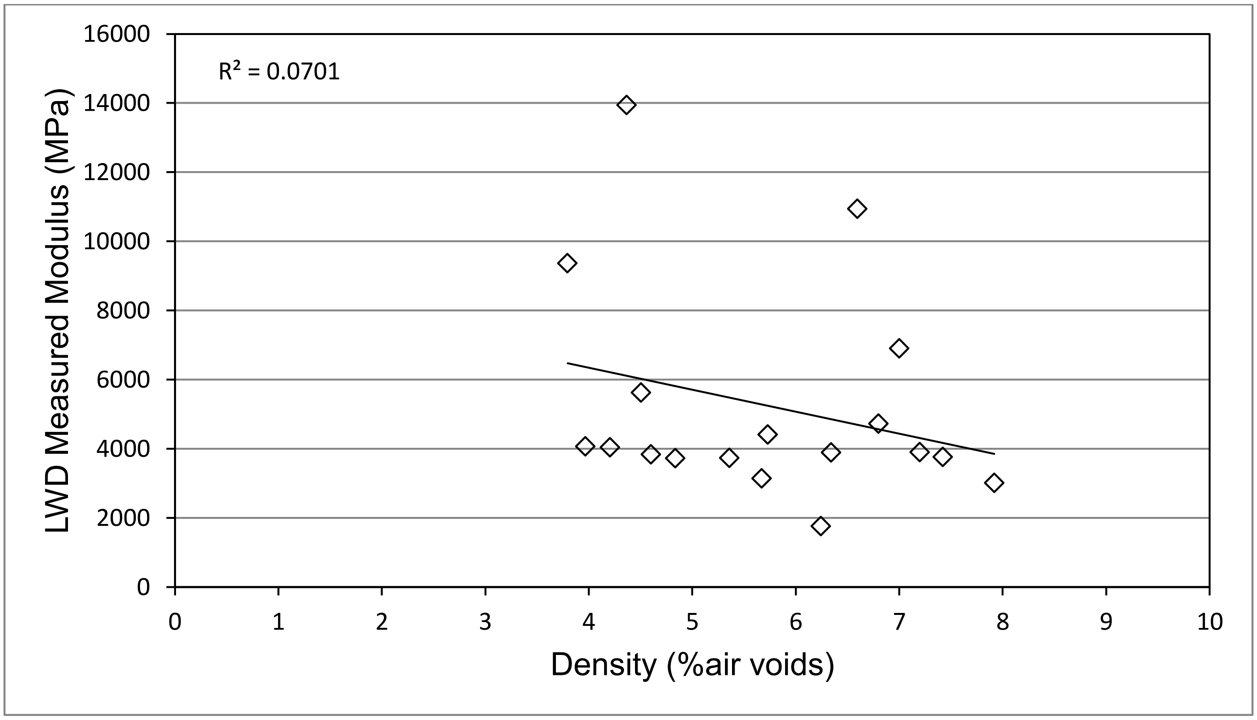


Figure 8. Comparison of roadway density and LWD measured modulus at test locations on second layer of asphalt pavement on 60th street in Norman, OK.

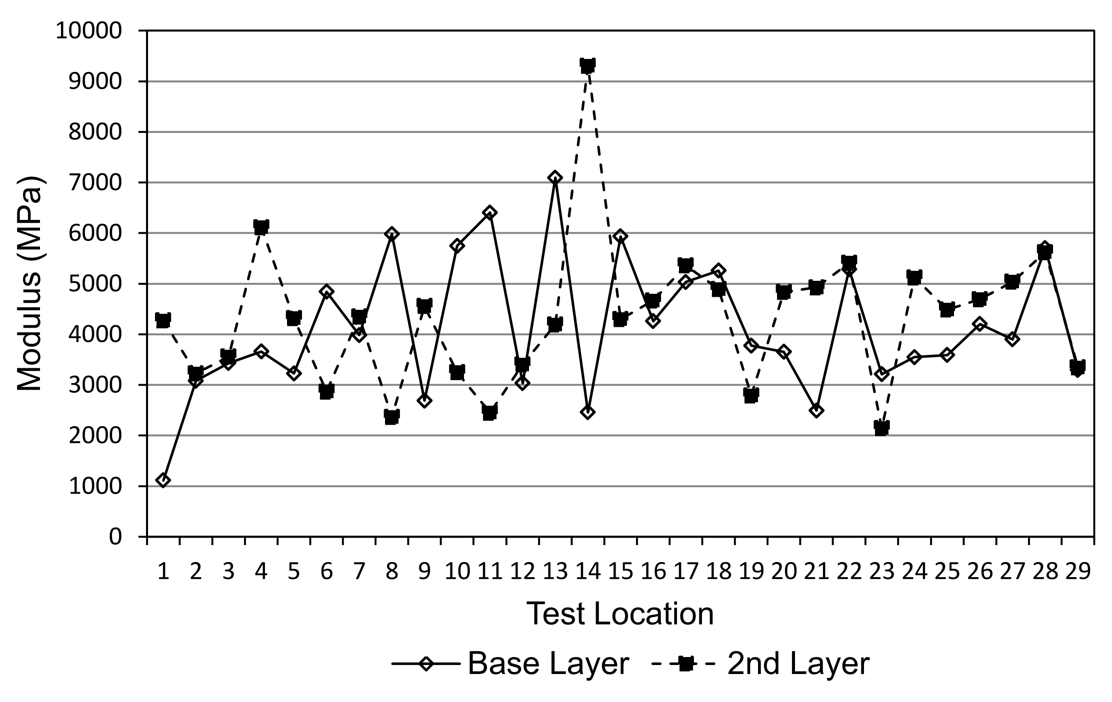


Figure 9. LWD Modulus of asphalt pavement at test locations on Layer 1 and Layer 2 of 60th street in Norman, OK.

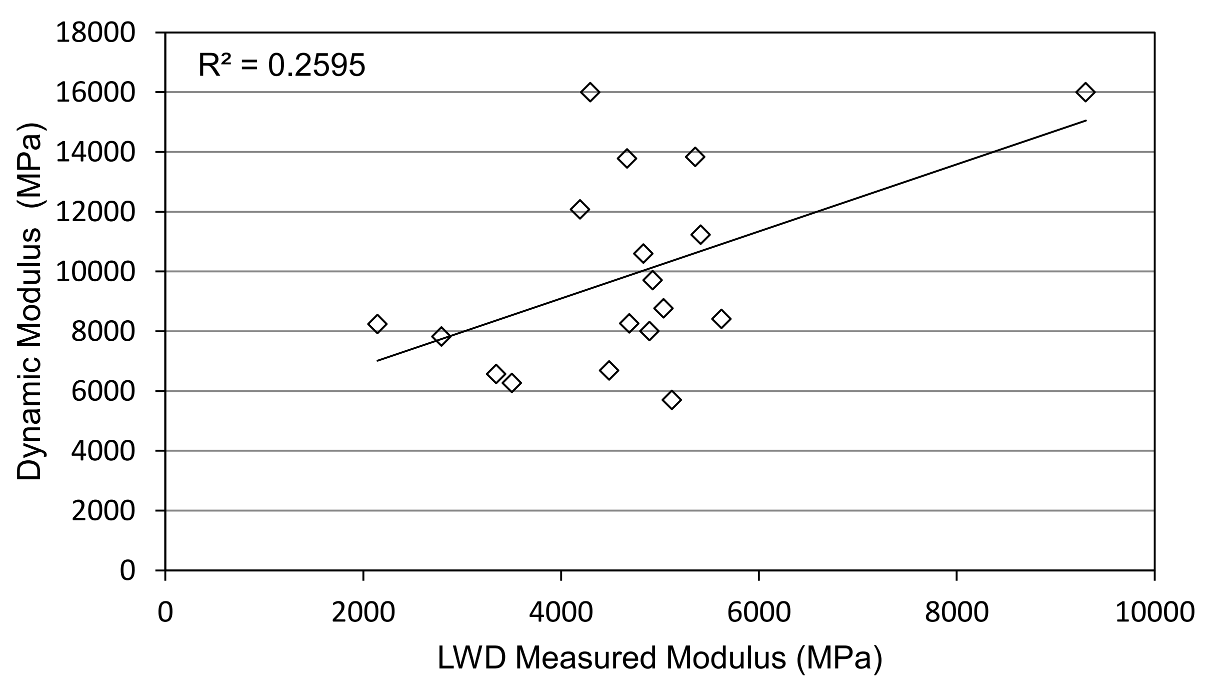


Figure 10. Comparison of LWD modulus and dynamic modulus at test locations on the asphalt base of 60th street in Norman, OK.

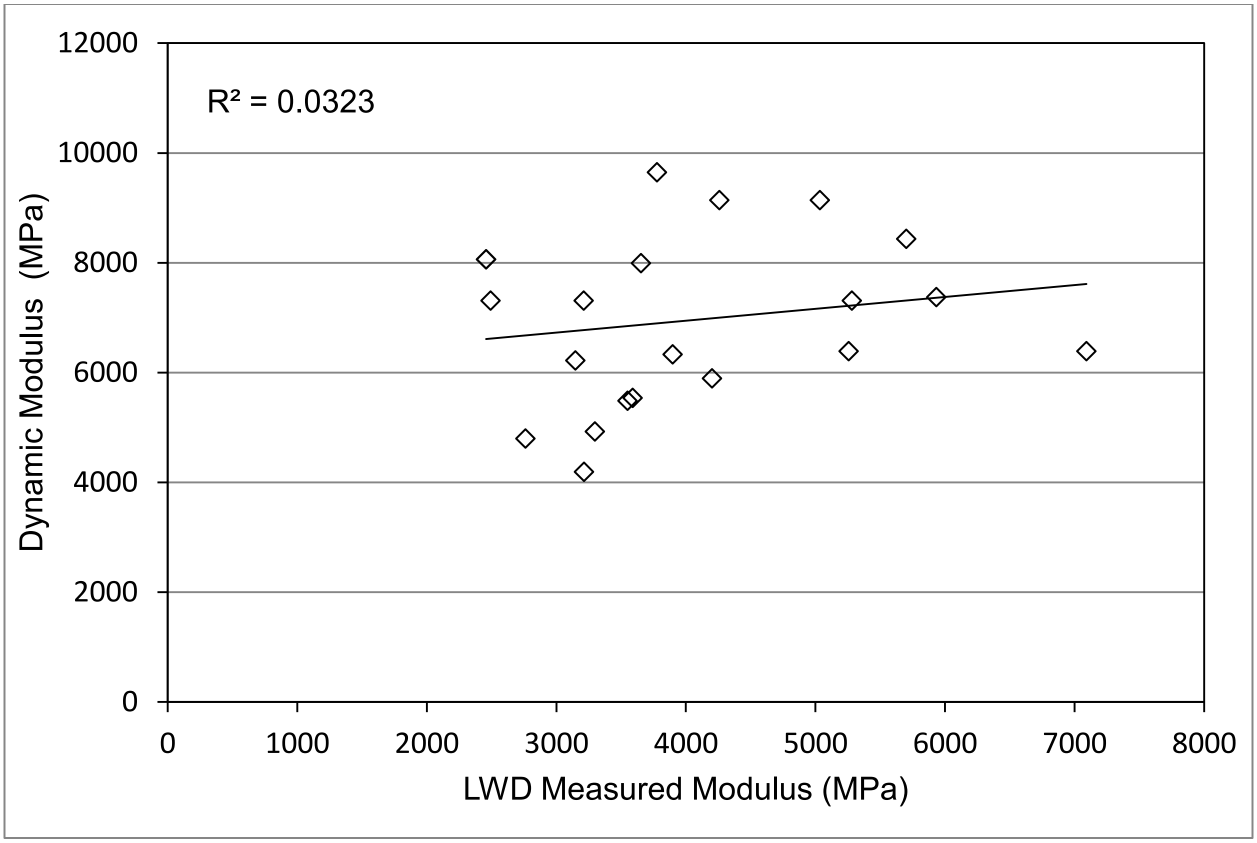


Figure 11. Comparison of LWD modulus and dynamic modulus at test locations on asphalt overlay on 60th street in Norman, OK.

4.4 Results from Tests on Apple Valley Road in Edmond, OK

The ability of the Zorn ZFG3000 LWD to ascertain the stiffness of asphalt pavement layers was also studied during the construction of a full-depth asphalt pavement at the Apple Valley Project in Edmond, OK. After the soil subgrade was stabilized and compacted, asphalt mix of Nominal Maximum Aggregate size (NMA) of 19 mm was placed to a thickness of 76.5mm and compacted using a dual steel drum vibratory compactor. Similar to the process described in the previous section, test locations were selected and NDG and GPS readings were recorded at these locations. After the pavement had cooled down to ambient temperature, LWD tests were conducted at the test locations and the LWD modulus at the ambient temperature as well as at 20^0C were recorded. Cores were extracted at the test locations and the density of the cores was determined in the laboratory in accordance with the AASHTO T-166 method. Virgin mix was also collected from the site and the dynamic modulus master curves were developed in accordance with the AASHTO TP-62 test procedure. The densities of the cores were used in conjunction with the master curves to estimate the dynamic modulus of the asphalt pavement at the test location. The data collected during these tests are shown in Table 3. The same test procedure was also followed for the construction of two asphalt layers at this site as described in section 4.1 and the corresponding data is shown in Tables 4 and 5.

LWD measured modulus and the density measured from cores extracted from the test locations for the base layer is shown in Figure 12. It can be seen that there that there is very little correlation (R^2 ~ 0.2) between the actual density measured from the cores and the pavement stiffness determined by the LWD. Similarly, no clear correlation between density and LWD modulus was observed in asphalt layers atop the base layer at this site (Figures 14 and 16). The comparison between LWD measured stiffness and the dynamic modulus that was determined from the master curves is shown in Figures 13, 15, and 17. Once again, no appreciable correlation was found between the LWD measured modulus and the dynamic modulus at the test locations for any of the asphalt layers.

Table 3. LWD measured modulus and dynamic modulus at test locations on the asphalt base on Apple Valley Road in Edmond, OK.

Apple Valley (76.5mm thick, 19mm S3 PG70-28OK)				
Points	Direction	Density (%)	Estimated Modulus (Mpa) at 20^{o}C and 10Hz	LWD Modulus (Mpa) at 20^{o}C
M1	East Bound	92.5	5854	1743
M2		92.7	5918	3009
M3		92.4	5803	1810
M4		91.7	5531	1810
M5		91.7	5544	1658
M6		91.0	5244	1683
C1		92.1	5674	1593
C2		93.6	6276	1549
C3		92.5	5841	1408
393+00		92.6	5873	1558
400+93		92.2	5726	1664
441+51		93.5	6228	1557
M7	West Bound	92.7	5943	2685
M8		93.5	6240	2506
M9		93.0	6056	2479
M10		93.8	6336	2481
M11		92.3	5764	1343
M12		90.8	5179	1315
383+00		94.9	6732	2227

Table 4. LWD measured modulus and dynamic modulus at test locations on second asphalt layer on Apple Valley Road in Edmond, OK.

Apple Valley (76.5mm thick, 19mm S3 PG70-28OK)				
Points	Direction	Density (%)	Estimated Modulus (Mpa) at 20^{o}C and 10Hz	LWD Modulus (Mpa) at 20^{o}C
M1	East Bound	95.4	6885	2965
M2		93.1	6069	2450
M3		94.5	6596	1731
M4		91.5	5440	1778
M5		94.6	6639	3919
M6		92.2	5739	2660
C1		93.1	6081	1062
C2		93.0	6056	2432
C3		93.4	6204	2116
393+00		93.8	6336	1916
400+93		94.2	6508	1804
441+51		NA	NA	NA
C4		92.7	5918	1879
C5		93.7	6300	2884
C6		93.3	6143	2604
387+07		96.5	7137	2732
393+17		95.4	6876	2371
414+61		94.5	6610	1932
M7	West Bound	93.9	6371	1431
M8		95.0	6752	1934
M9		94.2	6486	1589
M10		94.6	6639	1453
M11		94.3	6530	1651
M12		94.0	6433	1601
383+00		NA	NA	NA
400+61		94.7	6653	2456
400+41		94.4	6560	2367
392+20		93.0	6044	2610

Table 5. LWD measured modulus and dynamic modulus at test locations on the surface layer on Apple Valley Road in Edmond, OK.

Apple Valley (50.8mm thick, 12.5mm, S4 PG70-28OK)				
Points	Direction	Density (%)	Estimated Modulus (Mpa) at 20°C and 10Hz	LWD Modulus (Mpa) at 20°C
M1	East Bound	91.9	4605	1519
M2		93.1	5016	2205
M3		92.7	4866	1567
M4		91.3	4419	1424
M5		92.9	4952	1854
M6		94.0	5277	1650
C1		91.9	4605	1651
C2		93.1	5005	1280
C3		93.1	5016	1289
393+00		93.6	5174	1492
400+93		93.6	5153	1682
441+51		NA	NA	NA
C4		93.0	4963	1508
C5		92.1	4659	1452
C6		92.4	4779	1279
387+07		NA	NA	NA
393+17		93.3	5069	828
414+61		NA	NA	1919
C7		91.3	4408	1272
C8		92.4	4768	1294
C9		92.0	4648	1250
412+86		93.7	5195	1573
400+61		94.2	5368	1641
397+00		93.8	5219	1443
357+96		NA	NA	
M7	West Bound	90.5	4147	1769
M8		89.2	3712	1571
M9		90.3	4082	1839
M10		90.8	4223	1570
M11		92.0	4648	1524
M12		93.6	5164	1450
383+00		NA	NA	1934
400+61		NA	NA	1641
400+41		94.3	5388	1600
392+20		91.7	4528	1906
414+61		92.7	4855	
404+50		94.7	5514	2070
388+00		92.2	4703	1934
381+00		92.9	4952	1469
363+82		93.1	5005	2664

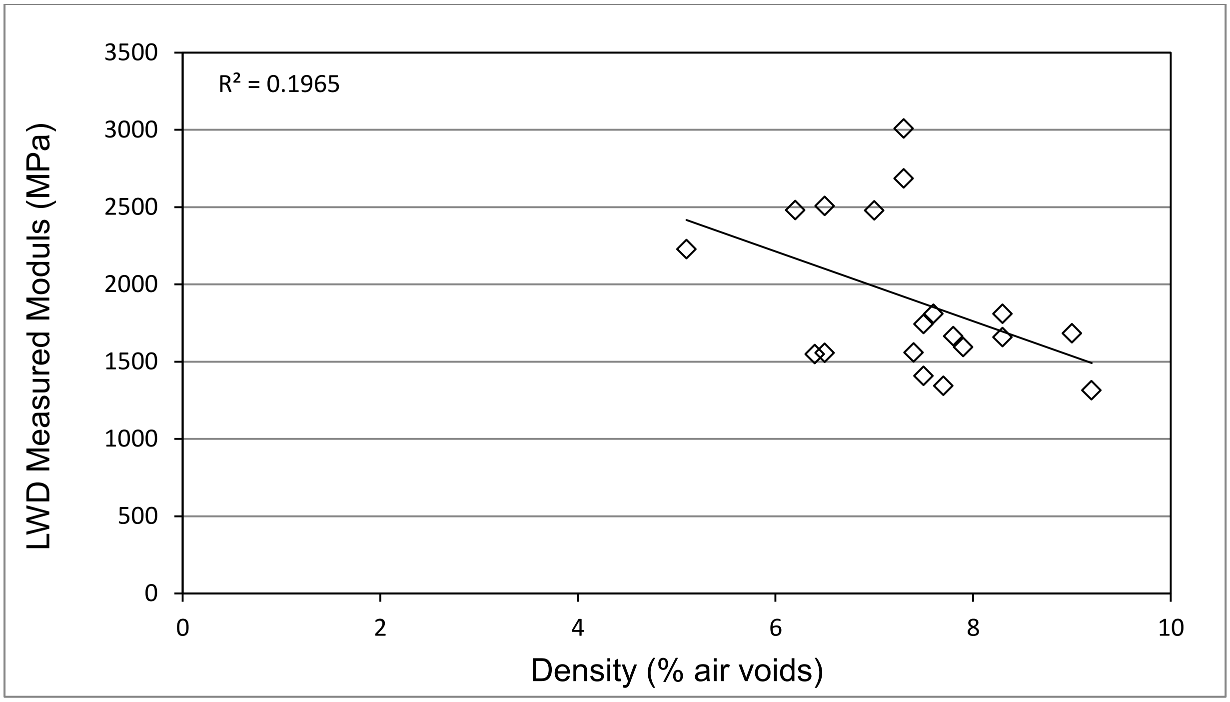


Figure 12. Comparison between roadway core density and LWD measured modulus at test locations on base layer of asphalt pavement on Apple Valley Road in Edmond, OK.

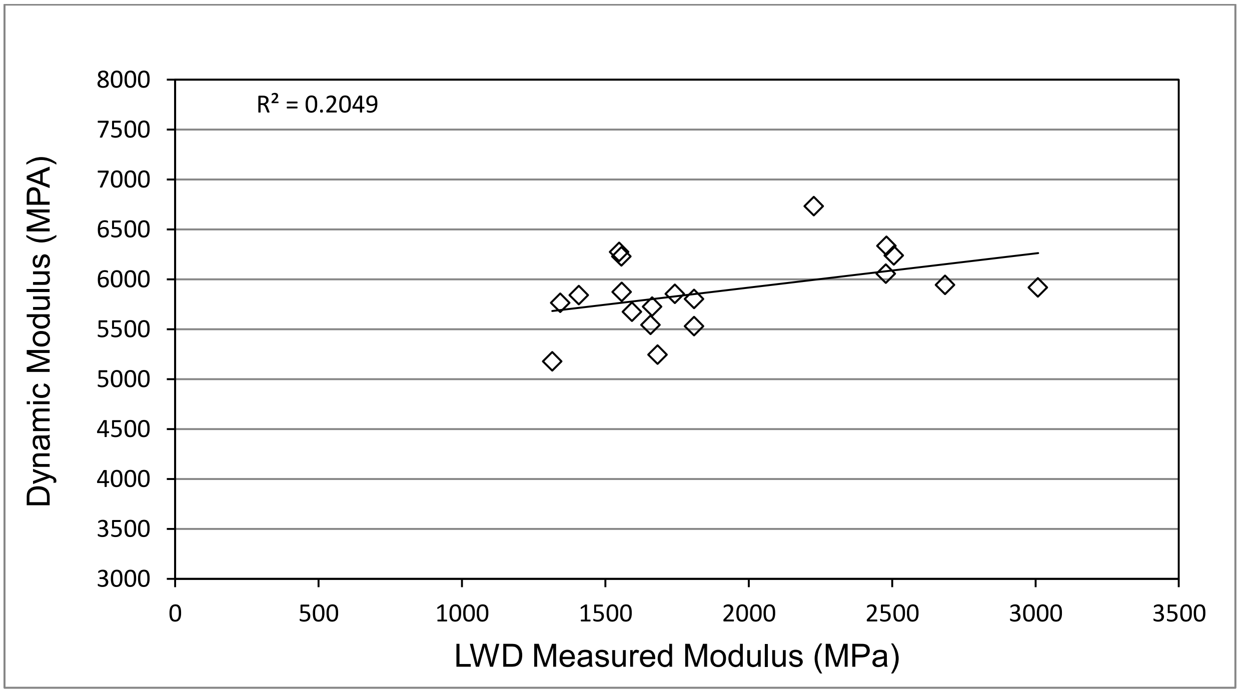


Figure 13. Comparison between LWD measured modulus and dynamic modulus at test locations on base layer of asphalt pavement on Apple Valley Road in Edmond, OK.

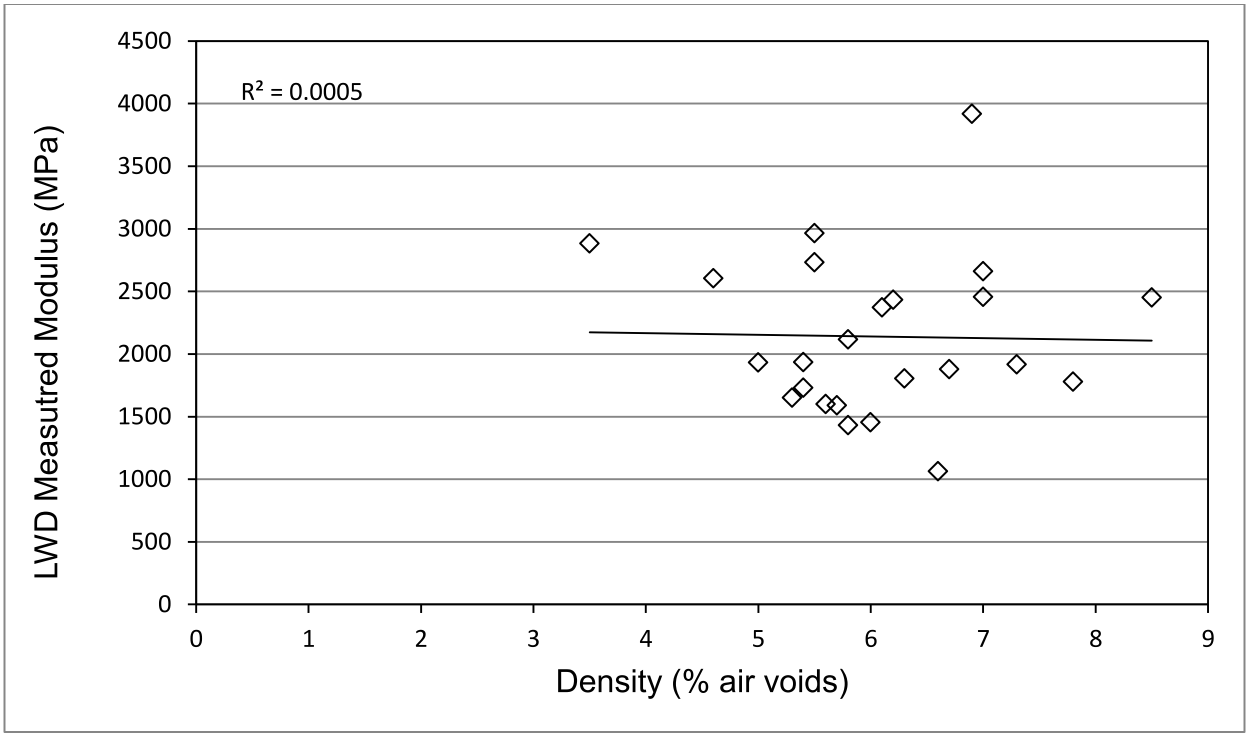


Figure 14. Comparison between roadway core density and LWD measured modulus at test locations on base layer of asphalt pavement on Apple Valley Road in Edmond, OK.

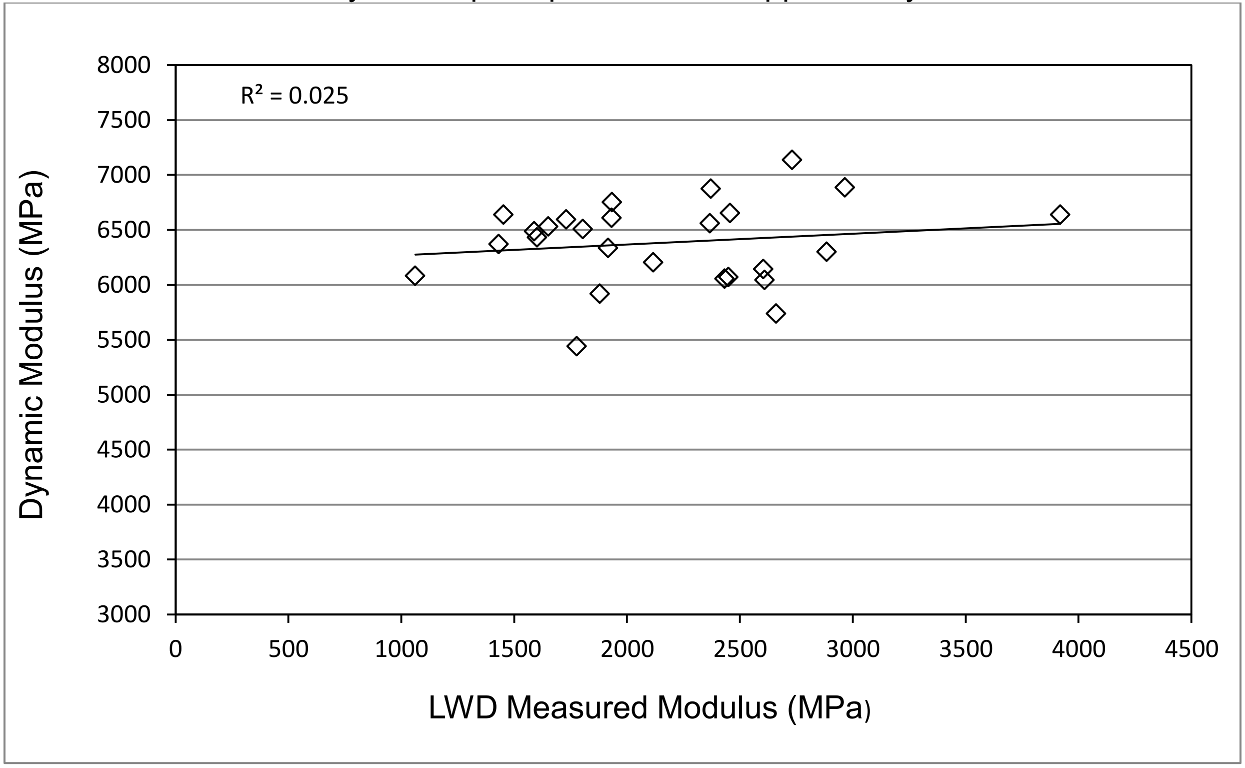


Figure 15. Comparison between LWD measured modulus and dynamic modulus at test locations on second layer of asphalt pavement on Apple Valley Road in Edmond, OK.

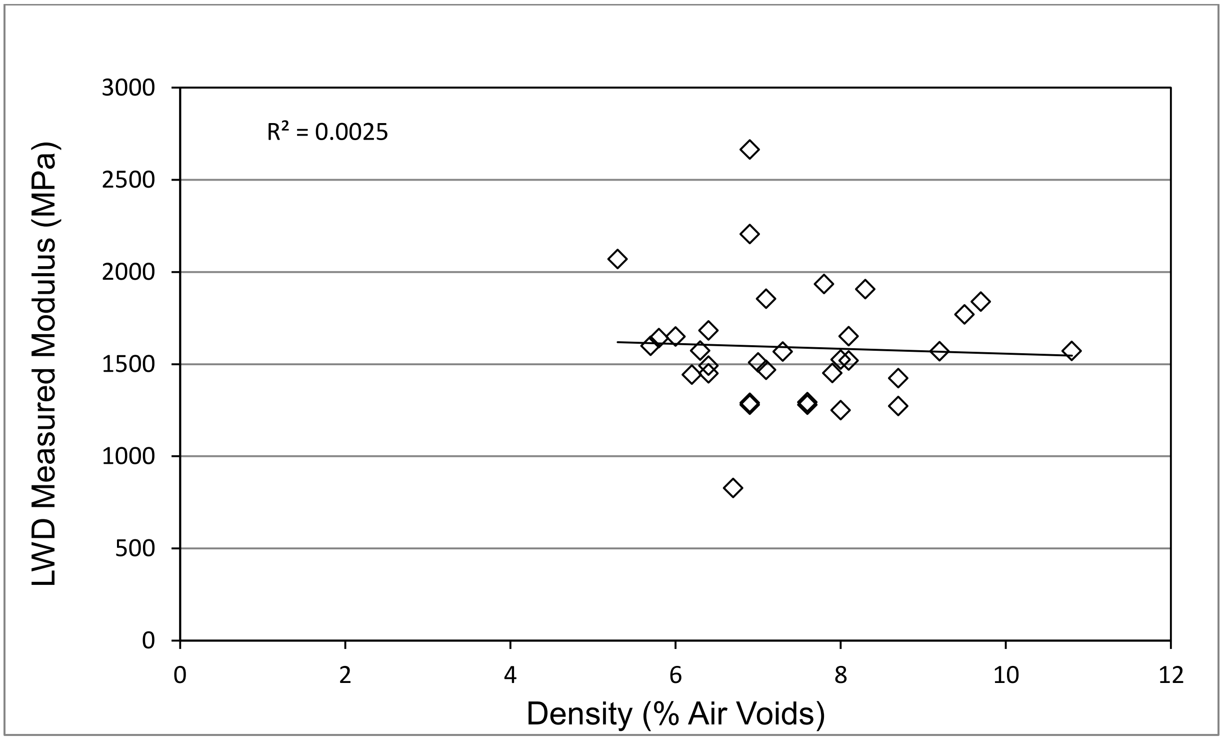


Figure 16. Comparison between roadway density and LWD measured modulus at test locations on surface layer of asphalt pavement on Apple Valley Road in Edmond, OK.

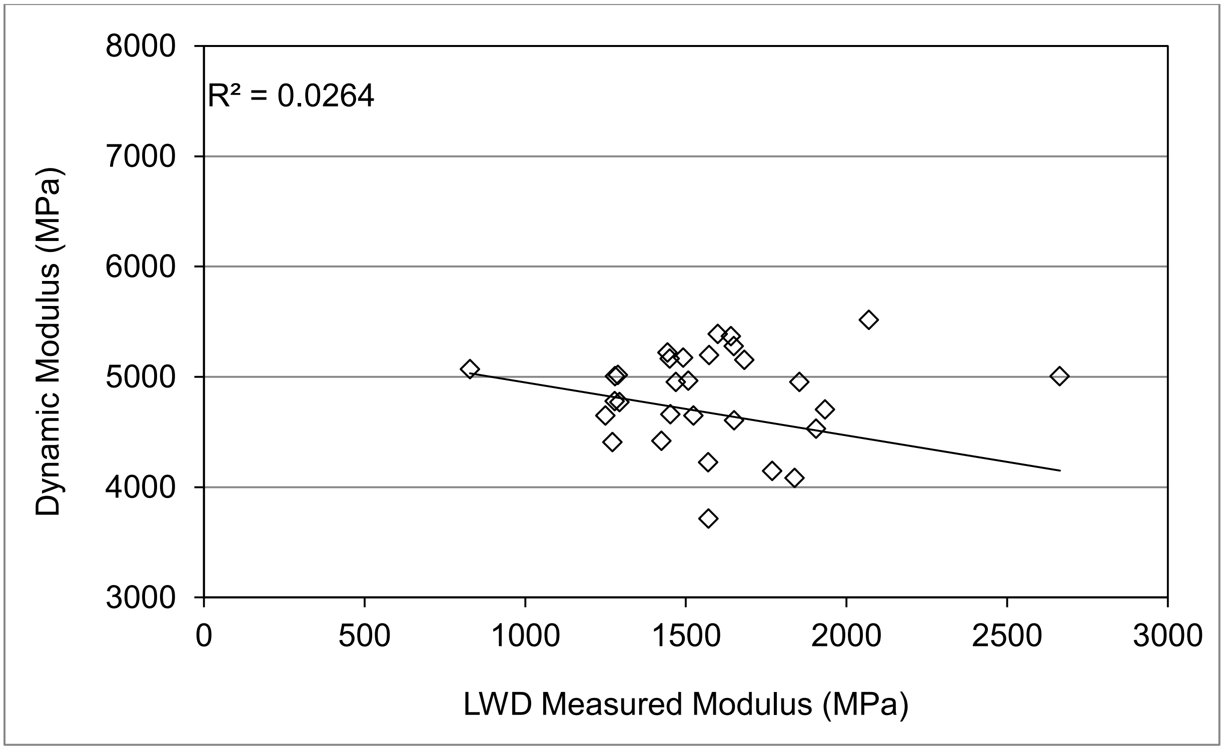


Figure 17. Comparison between LWD measured modulus and dynamic modulus at test locations on surface layer of asphalt pavement on Apple Valley Road in Edmond, OK.

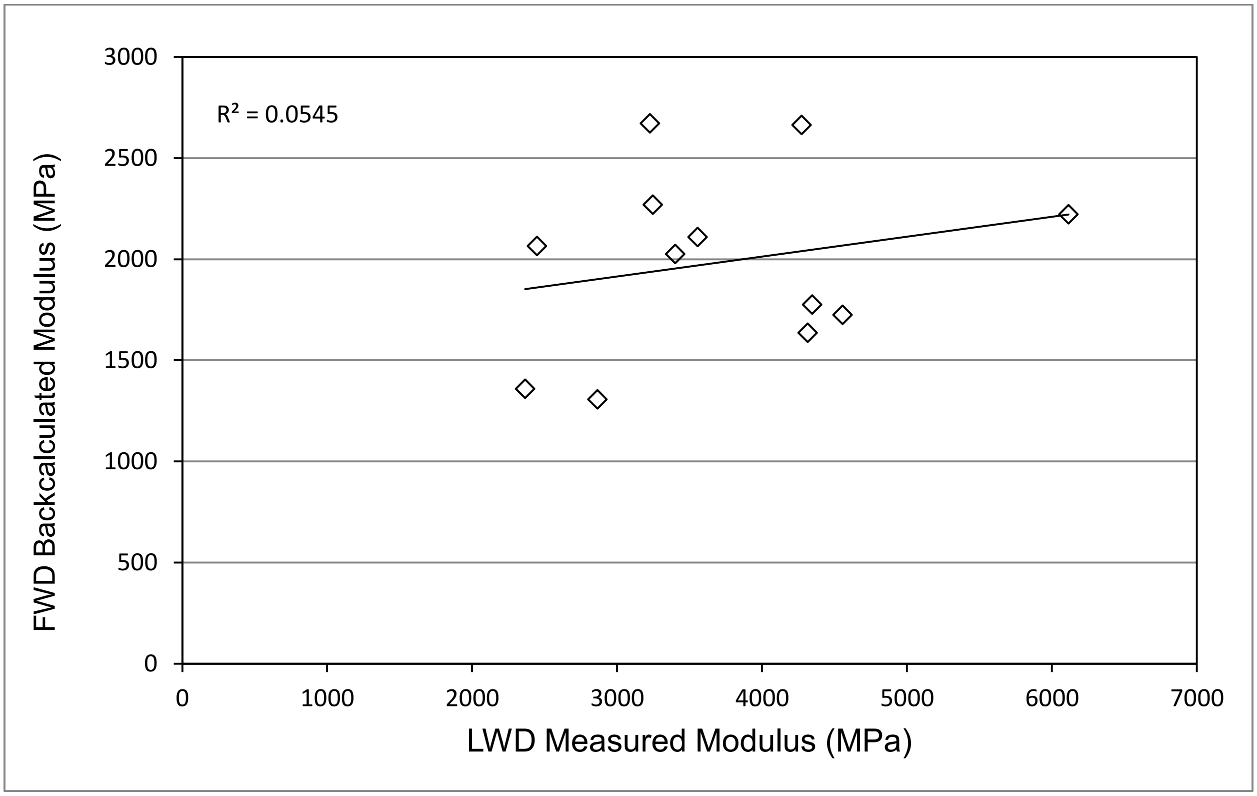


Figure 18. Comparison between LWD measured modulus and FWD backcalculated modulus at test locations on surface layer of asphalt pavement on Apple Valley Road in Edmond, OK.

5. SUMMARY OF RESULTS AND CONCLUSIONS

The use of Zorn ZFG-3000 LWD in the in-situ assessment of pavement quality was investigated in this research. Two full-depth construction sites were identified and the performance of the LWD device in measuring the stiffness of base asphalt layer was studied at each of these sites. The performance of the LWD in measuring the stiffness of asphalt layers at each of these sites was also studied. The following are the key observations from the results of the study.

A. The Zorn ZFG-3000 LWD device is easy to set up and operate. It is light weight and portable and can be operated by a single operator.

B. The Zorn ZFG-3000 LWD is able to determine the general trends in increasing/decreasing stiffness of the asphalt pavement layer. The built-in software takes into account the surface temperature of the asphalt mat and provides modulus values predicted at 20^0 C.

C. In all the tests conducted, the researchers found very little correlation between the LWD measured modulus and the density of the asphalt mat at the test locations as determined from roadway cores. The coefficient of correlation, R^2 was less than 0.1 in most of the cases studied in this research.

D. In all the tests conducted, the researchers found insignificant correlation between the LWD measured modulus and the dynamic modulus of the pavement at the test locations as determined from the density and the dynamic modulus master curves developed through laboratory tests. The correlation between LWD measured stiffness and the Dynamic Modulus values determined in the laboratory was slightly better for base asphalt layers (R^2 ~ 0.25-0.30) as compared to other layers. In case of intermediate and surface layers very poor correlation between LWD reported modulus and dynamic modulus ($R^2 < 0.10$) was observed.

E. The correlation between the LWD estimated modulus and the density of the asphalt mat did not appear to depend on any pavement parameters such as mix type and gradation, lift thickness, or asphalt layer. Very poor correlation was observed between pavement stiffness values backcalculated from Falling Weight

Deflectometer tests and the stiffness measured by the Zorn ZFG3000 LWD at the same test locations.

Based on these finding, it can be concluded that the Zorn ZFC-3000 LWD is not suitable for measuring the stiffness of asphalt pavements after construction and is not recommended for use in Quality Assurance of pavements.

6. TECHNOLOGY TRANSFER SUCESSES

Volvo Construction Equipment (VCE) has partnered with OU in the development of Intelligent Compaction technologies and is committed to providing 51% of all the development costs pertaining to this technology. <u>Since 2008, VCE has contributed over $1.2M towards royalty payments and for refining this technology</u>. This has also resulted in additional leveraged funding of $831,119 over the same period. VCE is currently supporting the OU Research team in the systematic evaluation of the Intelliigent Asphalt Compaction Analyzer (IACA) that was developed at OU for estimating the stiffness of asphalt pavements as well as the stiffness of modified soils and soil subgrades (OTCREOS 10.1-11: Real-time measurement of quality during the compaction of subgrade soils). VCE and OU are collaborating to introduce the IACA technology to the market in the near future.

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