In-Place Response Mechanisms of Recycled Layers Due to Temperature and Moisture Variations

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16. Abstract

The use of recycled pavement layers in highway rehabilitation is becoming increasingly popular; however, the in-place properties of recycled materials can be significantly different from those of traditional unbound granular materials, and can differentially change with variations in temperature and moisture conditions. To effectively design pavements using recycled materials, a better understanding of their in-place properties is needed. The objectives of this study were to determine the in-place properties of recycled materials common to the New England region and to evaluate the changes in these properties with changes in temperature and moisture. Five instrumented pavement sections with base layers containing recycled materials were evaluated over the course of the study. Falling weight deflectometer (FWD) testing was conducted throughout the year and at frequent intervals during the spring to capture thaw weakening and recovery behavior of the materials. Modulus values for the layers were initially backcalculated from the FWD data using the BAKFAA software program, and were further refined using a forward calculation procedure. Results of this study show that the in-place modulus values of base layers containing recycled materials can vary significantly depending upon the material type and the recycling method. The results also show that materials that are classified similarly can have very different modulus values. Furthermore, the relative sensitivity of the different materials to changes in temperature and moisture also varied. The reported modulus values can be used to more efficiently design pavements and evaluate various alternatives to ensure adequate performance over the design life of the pavement.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F

°F 32 98.6 212 °F

-40 0 40 80 120 180 200

-40 -20 0 20 40 60 80 100

°C 37 °C

* SI is the symbol for the International System of Measurement

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1. Introduction

1.1. Project Background and Objectives

New England State transportation agencies have adopted the use of recycled pavement layers in highway rehabilitation. Techniques such as full depth reclamation (FDR) with or without stabilization additives, plant mix cold recycled asphalt pavement (RAP), blending RAP with unbound subbase layers and substitution of unbound subbase layers with RAP are being used effectively. The in-place properties of these materials can be significantly different than traditional unbound granular materials, and change significantly with variations in temperature and moisture conditions during different seasons. To effectively design pavements using recycled materials, an understanding of the in-place properties of these materials is needed. The primary objective of this research project was to determine the in-place properties of recycled materials common to the New England region, and to relate changes in those properties to variations in temperature and moisture. The resulting properties can be used by transportation agencies to more efficiently design pavements and evaluate various rehabilitation alternatives to ensure adequate performance over the design life of the pavement.

1.2. Project Approach

The project focused on determining the in-place properties of pavement layers containing recycled materials and therefore the emphasis was on obtaining field data from pavements that had been constructed with different types of recycled materials. The pavement sites required instrumentation to record changes in temperature and regular non-destructive testing to monitor the seasonal variation in pavement stiffness due to temperature and moisture. The tasks conducted by the research team to meet the objectives of the project are summarized below.

Task 1: Conduct Survey and Identify Potential Test Sites

The research team conducted a survey (Appendix A) of all the NETC states to obtain information about the pavement recycling methods and materials typically utilized, including stabilization and/or other special construction techniques. Through this process, and with knowledge of the research team, two existing instrumented sites were identified in New Hampshire: Warren Flats and Kancamagus. The Warren Flats site is a sandwich construction using a recycled asphalt layer. The Kancamagus site has three sections with full depth reclamation with and without cement stabilization and conventional reconstruction with virgin materials.

The survey results also indicated that plant RAP and foamed asphalt with RAP were commonly used options in New England and identification of new construction sites focused on these materials. The research team was able to identify two sites in Maine: Auburn and Waterford that fit with the project schedule in terms of construction time frame. The Auburn site used foamed asphalt and the Waterford site used plant RAP material. The research team was not able to find sites in other states that met the project criteria and timeline.

Task 2: Site Instrumentation

The Warren Flats and Kancamagus sites had been instrumented as part of prior research projects. The Warren Flats site was still an active research site; data from the instrumentation was being collected regularly and was able to be shared with this project. The Kancamagus site required some maintenance and replacement of parts to allow temperature information to be collected from the existing instrumentation using long term data loggers. The loggers were installed in the fall and retrieved after the spring thaw and recovery for downloading temperature data.

The research team investigated various alternatives for temperature and moisture data collection for the new construction sites. It was determined that available instrumentation for collecting moisture data was not appropriate for the coarse grained foamed asphalt and plant RAP materials, so moisture sensors were not installed at those sites. Thermistor strings were installed to depths of 75-80" to reach below frost depths. The data collection was done remotely via satellite uplink and was accessible online at any time. The research team was also able to adjust the frequency of data collection during different seasons to increase the resolution during the spring thaw and recovery period.

Task 3: Monitor Instrumentation and Conduct In-Place Testing

The research team monitored the instrumentation at the four sites over the course of the project and also arranged for in-place testing to be conducted at specific times to measure the pavement response. The temperature data at the Warren Flats, Auburn, and Waterford sites was accessed remotely. Data loggers were installed at the Kancamagus sites during the fall and then collected and data downloaded in late spring/early summer.

Falling weight deflectometer testing was conducted on all of the sites at various times during the year to capture the range of pavement response under different temperature and moisture conditions. Testing on the Warren Flats and Kancamagus sites was conducted by WPI and CRREL staff; testing on the Auburn and Waterford sites was conducted by the ME DOT staff. Several baseline tests were conducted during the late summer and fall, at least one test was conducted in the winter, and regular testing was conducted during the spring thaw and recovery period each year. Timing of the spring thaw testing was determined by observing measured temperatures and projecting thawing times using available models and forecast air temperatures to calculate thawing indices. Rapid thawing occurred in the spring of 2014, limiting the amount of FWD data that could be collected during the thaw-weakening stage. Sufficient data was able to be collected during the 2015 spring thaw and recovery season.

Task 4: Data Analysis

The research team analyzed the FWD and temperature data collected during Task 3 to evaluate the seasonal variability of modulus values of the pavement layers containing recycled materials at each site. Two approaches were used: traditional backcalculation using available software programs and a forward calculation approach using layered elastic analysis. Based on the results of the analysis, the research team developed recommendations on the modulus values to be used for various materials in pavement design.

1.3. Report Organization

Detailed information on each instrumentation site is presented in Chapter 2, followed by the description of the analysis methods and results in Chapter 3. Chapter 4 provides recommendations based on the results of the testing and analysis. The appendices provide additional detailed information for reference purposes.

2. Site Descriptions

In this chapter, the details of the pavement structure and instrumentation for each site is described.

2.1. Auburn, ME

The Auburn, ME site is located on Rt 122 just east of the I-95 bridge, as shown in Figure 1. The instrumentation borehole is located in the eastbound lane and the data logger is located on a wooden post at the edge of the DOT maintenance shed area (Figure 2). Construction of this section was done in August of 2014 and consists of 3" of HMA over 6" of treated FDR and thermistors were installed to a depth of 80" (Figure 3); example data is shown in Figure 4.

Figure 1. Location of Auburn, ME Instrumentation Site

Figure 2. Auburn ME Data Logger Location

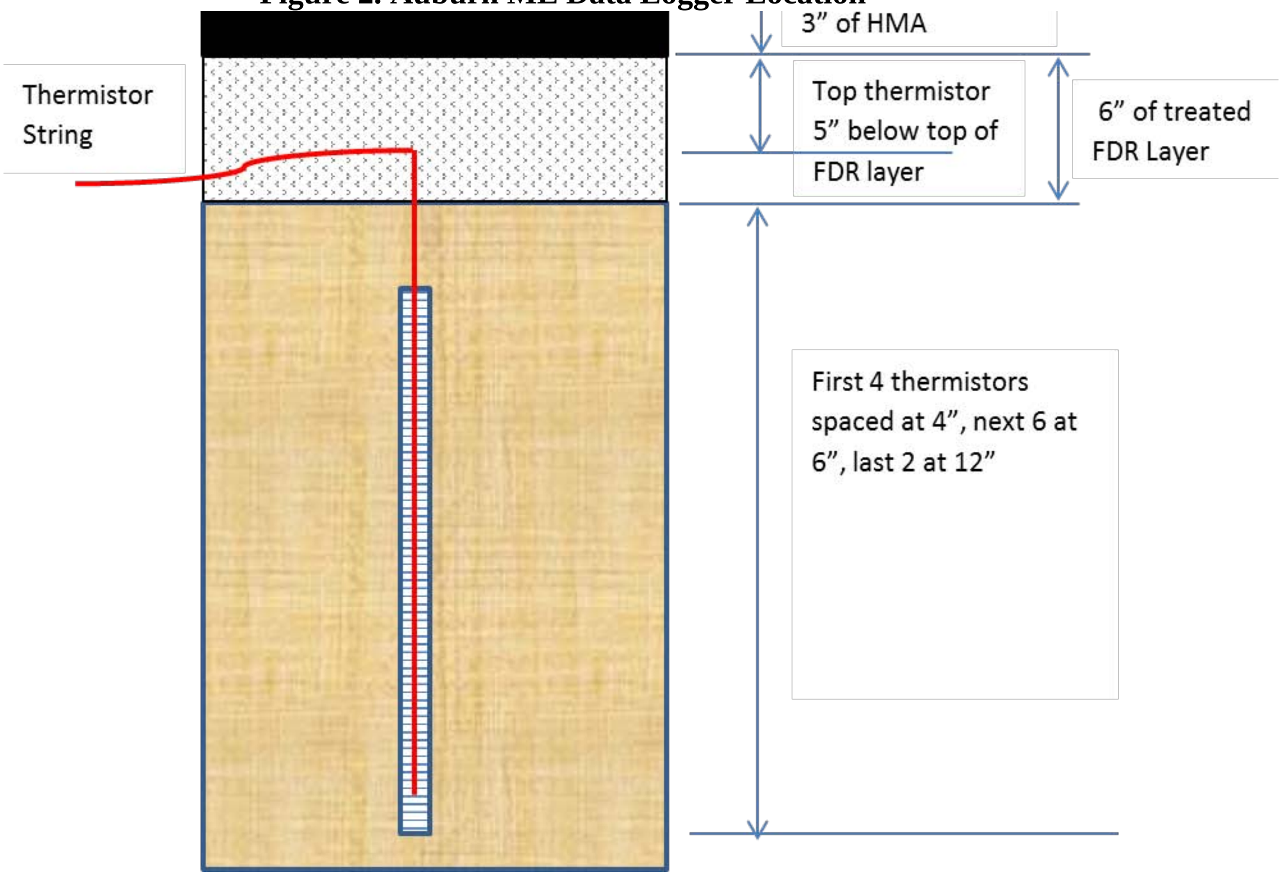


Figure 3. Auburn ME Instrumentation Cross-Section (not to scale)

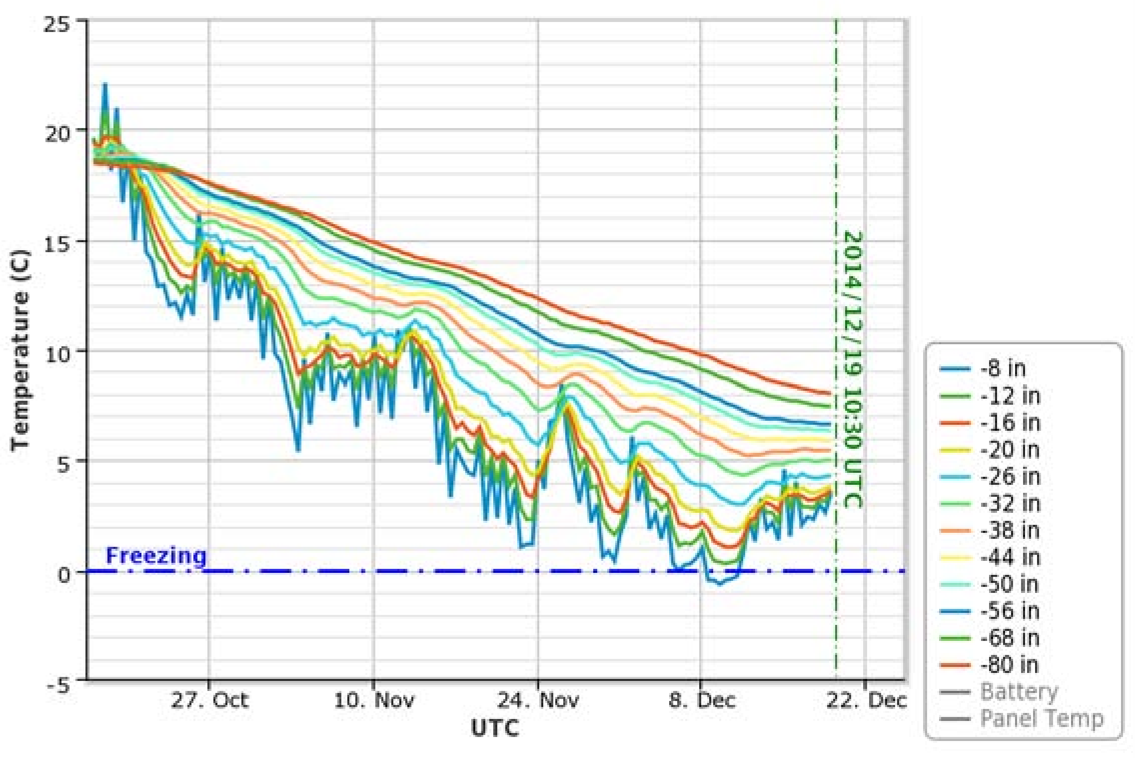


Figure 4. Temperature data collected from Auburn ME site in Fall 2014

During drilling operations for instrument installation, standard penetration testing (SPT) was conducted, and samples were obtained for laboratory testing. A summary of the SPT test results is presented in Table 1. In the lab, sieve analysis and moisture content determination were performed on each sample, and then each sample was classified according to the USCS and AASHTO classification systems. A summary of the laboratory test results is presented in Table 2.

Table 1. Auburn ME SPT results summary

Depth (ft.)	N-Value (Blows/ft.)
1.0-3.0	15
3.0-5.0	12
5.0-7.0	9

Table 2. Auburn ME Laboratory test results summary

Sample	Depth (ft.)	USCS	AASHTO	W%
1	1.0-3.0	SW	A-1-b	4.5
2	3.0-5.0	SP-SM	A-1-b	10.1
3	5.0-7.0	SW-SM	A-1-b	8.3

2.2. Waterford, ME

The Waterford, ME site is located on Rt 118 (Figure 5). The instrumentation borehole is located in the westbound lane and the data logger is located on a wooden post near the edge of the baseball field. Figure 6 below shows the data logger during the installation of the PM RAP layer and after final paving. The instrumentation of the lower layers in this section was done in May of 2014 and the thermistor for the PM RAP layer was installed in June 2014. A schematic (not to scale) of the cross section for this site is shown in Figure 7. The site consists of 5" of plant-mixed RAP over the existing 6" of HMA and then topped with 1.5" of new HMA. There are 12 thermistors installed in the pavement section; the first thermistor is located at the bottom of the PM RAP layer, approximately 6.5" below the final pavement surface. The lower thermistor string consists of 11 thermistors located 6" apart, with the top thermistor located approximately 15" below the pavement surface. A sample of data collected from the Waterford site is shown in Figure 8.

The PMRAP was processed to minus ¾" size and then added to a portable pugmill with cement and emulsion in a cold mixing process. The material was placed in one lift to grade and cross slope using a paver and compacted. As a minimum, a 10 ton dual drum vibratory or oscillatory roller, 16 ton pneumatic roller, and 10 ton final roller were required and the density met 96% of control strip TMD for acceptance.

Figure 5. Location of Waterford, ME Site

Figure 6. Waterford Instrumentation Site during PM RAP installation (left) and final (right)

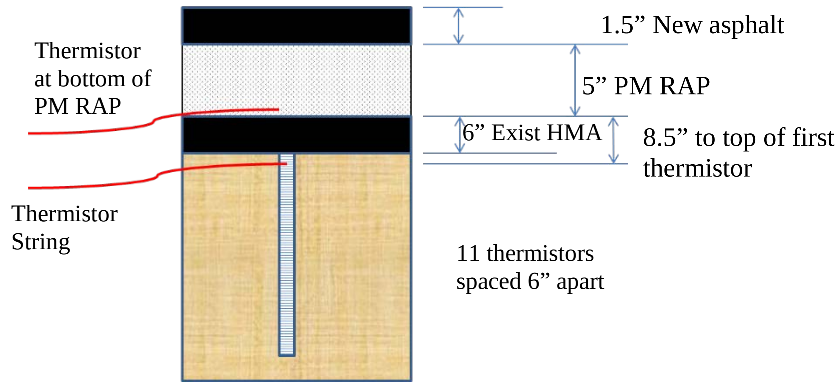


Figure 7. Waterford ME Instrumentation Cross-Section (not to scale)

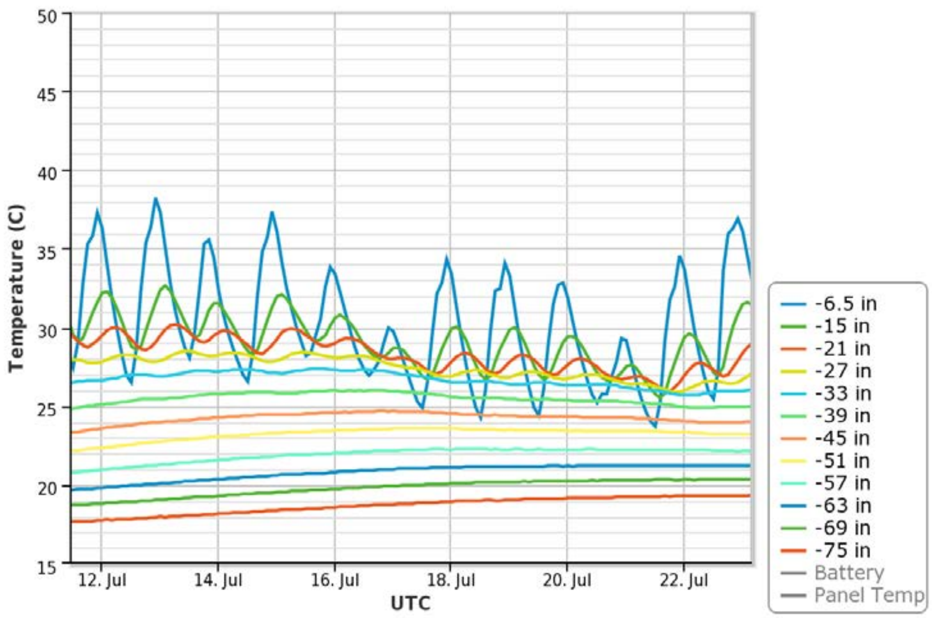


Figure 8. Temperature data collected from Waterford instrumentation site in July 2014

During drilling operations for instrument installation, standard penetration testing (SPT) was conducted, and samples were obtained for laboratory testing. A summary of the SPT test results is presented in Table 3. In the lab, sieve analysis and moisture content determination were performed on each sample, and then each sample was classified according to the USCS and AASHTO classification systems. A summary of the laboratory test results is presented in Table 4.

Table 3. Waterford ME SPT results summary

Depth (ft.)	N-Value (Blows/ft.)
1.0-3.0	29
3.0-5.0	22
5.0-7.0	30

Table 4. Waterford ME Laboratory test results summary

Sample	Depth (ft.)	USCS	AASHTO	W%
1	1.0-2.0	SW-SM	A-1-b	20.2
1a	2.0-3.0	SP	A-1-b	5.4
2	3.0-5.0	SP	A-1-b	5.8
3	5.0-5.6	SP	A-1-b	6.8
3a	5.6-7.0	SP	A-1-b	3.5

2.3. Warren Flats, NH

The Warren Flats, NH site was instrumented as part of a previous project; Figure 9 below shows the location of the site on Rt 25C. The roadway was reconstructed during the spring/summer of 2010; a 14 inch layer of RAP blended with gravel was placed on top of the old asphalt concrete pavement, and then that new base layer was topped with 4 inches of new asphalt pavement (Figure 10). The RAP/gravel blend was processed through a crusher and then laid at ambient temperatures. The material was placed in layers using a bulldozer and compacted with a vibratory roller.

A series of 12 thermistors (Yellow Springs Instrument, Inc. model 44007) are imbedded in the pavement; the deepest 4 sensors were placed at a spacing of 12 inches, and the remaining 5 were placed at a spacing of 6 inches. Additionally, thermistors are placed at the pavement surface, bottom of pavement, and within the granular base course. Example temperature data collected at this site is shown in Figure 11.

Figure 9. Location of Warren Flats, NH Site

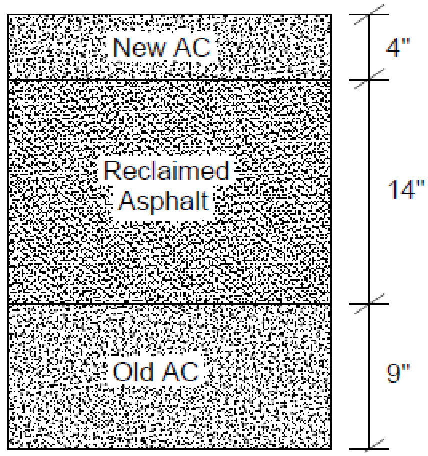


Figure 10. Cross-section of Warren Flats, NH site

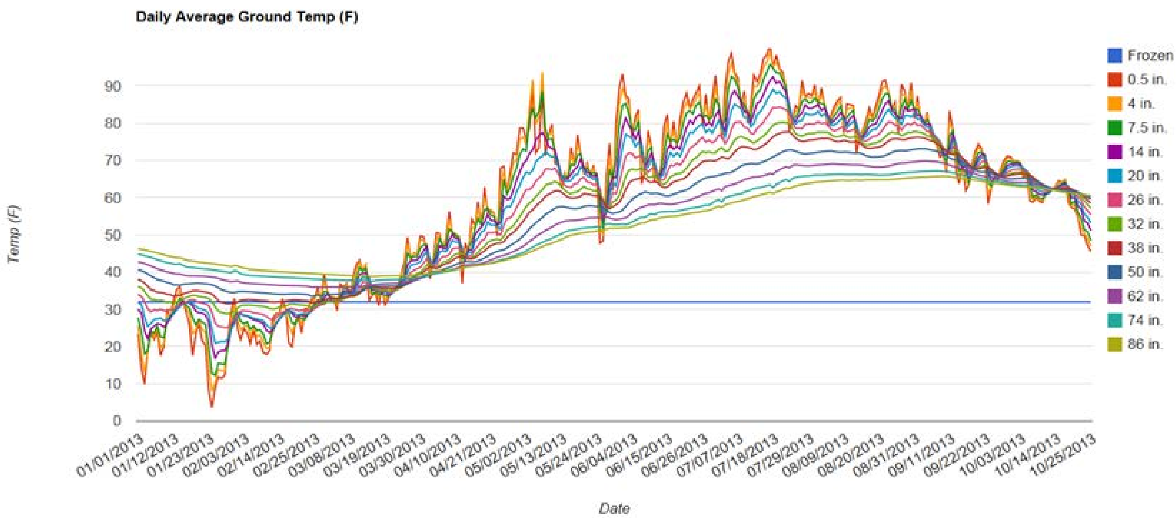


Figure 11. Temperature data collected from Warren Flats instrumentation site in 2013

A summary of the SPT and grain size distribution test results for the Warren Flats site are presented in Table 5 and Table 6, respectively.

Table 5. SPT N-Values at Warren Flats Site

Depth (ft)	N-Value (Blows/ft)
2.33-4.33	10
4.33-6.33	26
6.33-8.33	25

Table 6. Results of Grain Size Analyses and Moisture Content Determinations at Warren Flats Site

	USCS Particle Size Distribution								
Depth (feet)	% C. Gravel	% F. Gravel	% C. Sand	% M. Sand	% F. Sand	% Fines	Moisture Content (%)	AASHTO Symbol	USCS Symbol
2.25-2.42	0	12	11	18	40	20	14	A-2	SM
2.42-2.83	0	29	10	9	28	23	20	A-2	SM
3.00-3.50	0	1	5	23	59	12	9	A-2	SP-SM
5.29-5.63	4	25	12	25	29	5	13	A-1-b	SP-SM
5.63-6.00	0	0	2	27	63	7	13	A-3	SP-SM
6.00-6.33	0	0	8	32	53	7	14	A-3	SP-SM
7.21-7.46	0	0	6	23	52	18	17	A-2	SM
7.46-7.75	0	1	4	18	66	9	18	A-3	SP-SM
7.75-8.08	0	0	4	17	39	40	21	-	SM
8.08-8.33	0	0	0	3	52	45	23	-	SM
Reclaimed Base	9	22	14	31	21	3	-	A-1-b	SP

2.4. Kancamagus, NH

The Kancamagus site location is shown in Figure 12 below; this site was part of a research project funded through the Recycled Materials Research Center and contains three test sections within an approximately 1500-ft section of the highway about midway between its intersection with Route 16 on the east and Interstate 93 on the west. From west to east, the test sections consist of the following:

- K-1: Conventional reconstruction (station 45+37 to station 46+97)
- K-2: FDR with cement stabilization (station 50+00 to station 60+00)
- K-3: FDR without cement stabilization (station 60+00 to station 61+20)

The sections of roadway that underwent conventional reconstruction and FDR without cement stabilization extended for considerable distances to the west and east, respectively; however, testing for this research was confined to the limited sections as indicated above.

Initial work on the FDR test sections began in May 2005. The existing asphalt pavement, which was about 100 mm (4 in.) thick, was pulverized and blended with about 100 mm (4 in.) of the underlying base material. In June 2005, 200 mm (8 in.) of reclaimed material was reworked and mixed with water to increase its moisture content slightly. For the cement-stabilized section, 4 percent cement by weight of dry aggregate, determined from laboratory testing (6), was then mixed into the 200 mm (8-in.) thick reclaimed base material.

The "conventional reconstruction" consisted of excavating about 0.9 m (3 ft.) of existing asphalt, base, and subgrade soil and then replacing that material with virgin aggregate from a local borrow pit: 41 cm (16 in.) of sand followed by 25 cm (10 in.) of gravel and then 25 cm (10 in.) of crushed gravel base. The sand, gravel, and crushed gravel conformed to the requirements of item numbers 304.1, 304.2, and 304.3, respectively, of the NH DOT Standard Specifications for Base Materials. The conventional reconstruction between the stations noted above was conducted during early July 2005. All three test sections were paved with hot mix asphalt (HMA), consisting of a 50 mm (2-in.) binder layer placed in late July 2005 and a 38 to 51 mm (1.5- to 2-in.) wearing course placed in October 2005.

Based upon construction logs, borehole logs, and laboratory test data (sieve and hydrometer analyses), the cross-sections for the site are shown in Figure 13. In 2006, these three test sections were folded into a larger research project sponsored by the New Hampshire Department of Transportation (NH DOT) and the United States Department of Agriculture (USDA) Forest Service. For that project, additional instrumentation was installed, and falling-weight deflectometer (FWD) testing was conducted to investigate variations in pavement stiffness that result from seasonal changes in temperature and moisture content. The temperature instrumentation was used for this study, along with additional FWD testing.

Figure 12. Location of Kancamagus, NH Site

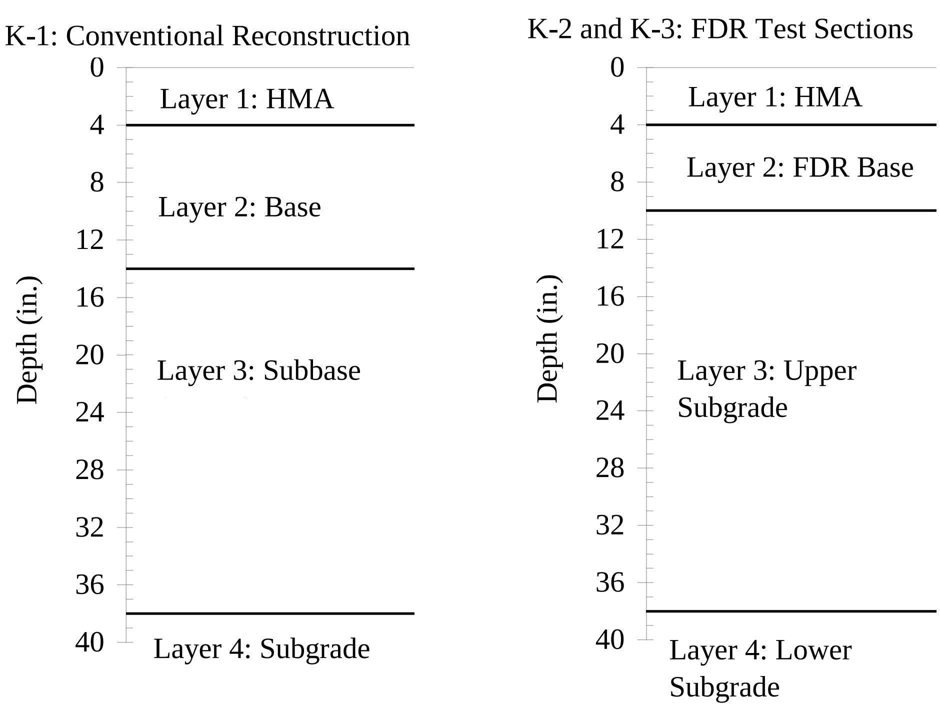


Figure 13. Cross-section of material layers assumed for mechanistic analyses.

Note: 1 in. = 2.54 cm K-2: FDR Base with Cement K-3: FDR without Cement

3. Results and Analysis

3.1. Falling Weight Deflectometer (FWD) Testing and Backcalculation

Falling Weight Deflectometer (FWD) has been extensively used for estimation of pavement layer moduli, and for determination of structural condition of pavements. The information obtained from FWD testing can be used in structural analysis to determine the capacity, estimate expected performance life, and design a rehabilitation plan for pavements. Deflections prior to and after pavement rehabilitations are done to evaluate the effectiveness of specific rehabilitation methods. FWD can also be used to test load transfer efficiency of joints within concrete pavements. American Society for Testing and Materials (ASTM) standards are available for use of FWD for pavement deflection based testing (*ASTM 4694*, *4695-96*). Standard calibration procedures for load cells and deflection sensors are also available.

In FWD testing, an impulse load is generated by dropping weight from different heights. Loads from 6.7 kN to 120 kN can be generated. The load is generated by a mass falling onto a base plate through a set of rubber buffers, as shown in Figure 14. The base plate is fitted with a load cell for measurement of applied force. The pavement deflection, in response to the applied load, is measured by processing the signals from geophones, placed at different places including at the center of the plate and pavement surface.

Using pavement layer thickness and Poisson's ratio (which should be known), and a set of "seed" moduli for the different layers, "back calculation" analysis is done to arrive at a set of estimated moduli. The backcalculation process involves adjustment of the moduli values until a set of moduli is found such that the predicted deflection basin is approximately identical to the measured deflection basin (within tolerances). An example of the backcalculation process is illustrated in Figure 15.

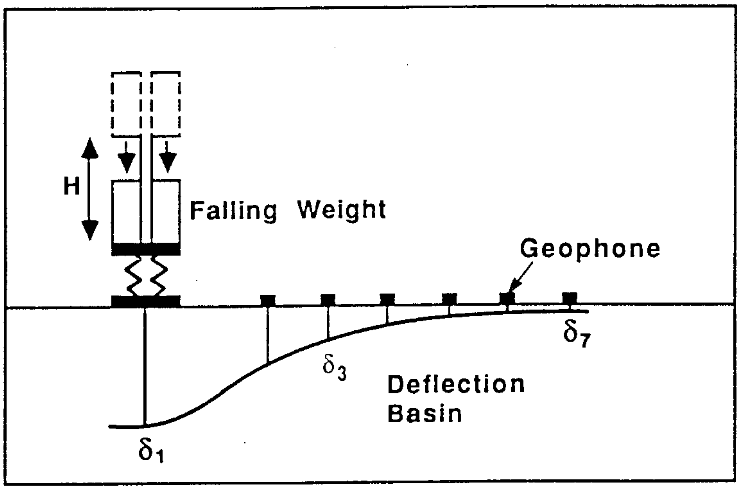


Figure 14. Schematic of Falling Weight Deflectometer

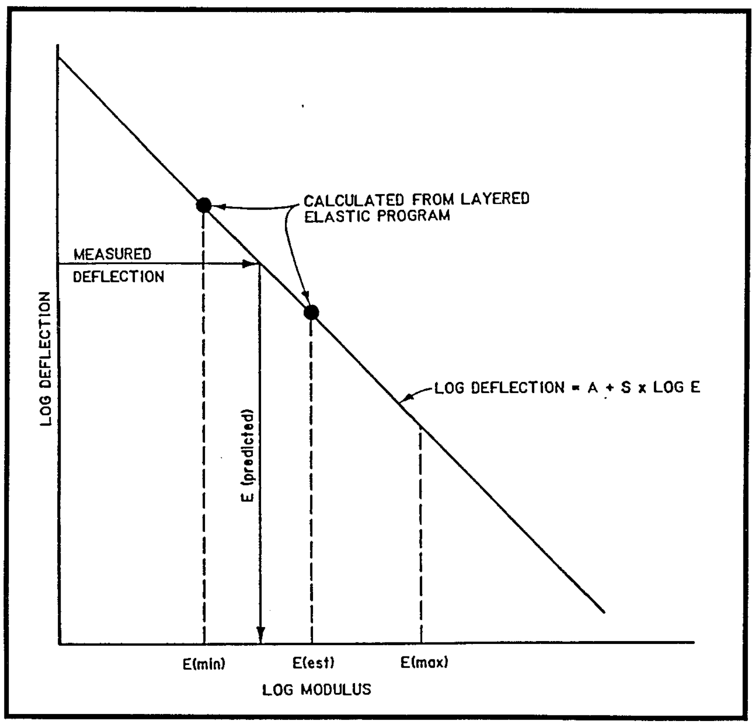


Figure 15. Backcalculation Process

An initial set of layer moduli with minimum and maximum values are assumed. The process starts by varying the modulus of each layer and computing the deflection (as shown in Figure 15 for one deflection point and one layer). For multiple deflections and layers, the process consist of solving a set of equations with slope and intercept for each deflection and each layer modulus:

$$\text{Log } D_j = A_{ji} + S_{ji}(\text{Log}E_i)$$

Where:
D = deflection at a point
A = intercept
S = slope
j = number of deflection
i = number of layer with unknown modulus

Examples of criteria for determination of modulus are: 1. Sum of absolute differences between computed and measured deflection to be less than a set percent (say 10 percent), and 2. The change in modulus for each layer is less than a set percent (say, 10 percent). These criteria can be written as follows:

$$\frac{E_i - E_c}{E_i} \leq 10\ \%$$

Where,
E_i = modulus from previous iteration
E_c = modulus from current iteration

And,

$$\sum \left| \frac{x_{mi} - x_{ci}}{x_{mi}} \right| \text{X } 100 \leq 10\ \%$$

Where,
x_{mi} = measured deflection
x_{ci} = computed deflection

Modulus of subgrade can also be determined from deflection at outer sensors. The most important advantage of a FWD is that information obtained from tests can be used for fundamental engineering analysis of pavements, using mechanistic methods (as opposed to empirical methods).

Numerous studies have been conducted on the accuracy of load and deflection measurements as well as on refinement of the backcalculation procedures, resulting in continuous improvement of both equipment as well as analysis procedures. As a result, FWD has become the principal non-destructive testing tool for pavement engineers. The use of backcalculated moduli using FWD has been recommended for rehabilitation of pavements by the newly developed AASHTO 2002 Pavement design guide (currently under development). Such use is absolutely necessary for determination of moduli of subsurface layers as well as for determination of moduli and consistency of new and innovative pavement materials. Examples of such use include the testing of full depth reclaimed pavements with different types of additives, such as foamed asphalt. Furthermore, the FWD is being used by numerous researchers in determination of pavement

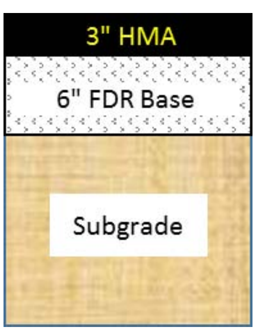
layer properties in full scale test sections and for evaluation of subgrades under unusual conditions as well as effect of environment and new materials on pavement properties.
One key requirement for the successful application of FWD is the use of accurate layer thickness and condition data. Without the use of any non-destructive tool, the only solution is to take cores, in sufficient numbers, such that accurate estimates of layer thickness and conditions can be made. However, taking cores defeats the whole idea of non-destructive testing and hence is not an attractive option. Non-destructive instrument such as Ground Penetrating Radar (GPR), with Infrared camera has now become a very valuable tool for the pavement engineers for providing the data necessary for using FWD.

Backcalculation of Layer Moduli
The BAKFAA software (from FAA) was utilized for backcalculation of layer moduli from (E) the different sections. The different sections were assumed as shown in Table 7 to Table 12. Freeze thaw data from moisture gages and temperature sensors were utilized to determine frozen and thawed parts of the different layers. If a layer was found to be partly frozen and partly thawed, the layer was divided up into two sub layers and different E values were assigned to the two layers. The seed E values are shown in Table 7 to Table 12. Note that the primary intent in these backcalculations was to estimate the moduli of the full depth reclaimed (FDR) layers.

The results of backcalculations for the different sections are shown in Table 13 through Table 18. Although low values of errors were obtained for all of the cases, a comparison of the predicted and actual deflections (Figure 16 to Figure 21) showed significant differences at one or more sensor locations in most of the sections. The problem was investigated and the research team concluded that the presence of a stiff layer was responsible for the difference – the existence of the stiff layer was not considered in the backcalculation, and neither was it predicted automatically from BAKFAA (existence of a stiff layer is automatically predicted by EVERCALC; however, this software does not work with current versions of Windows).

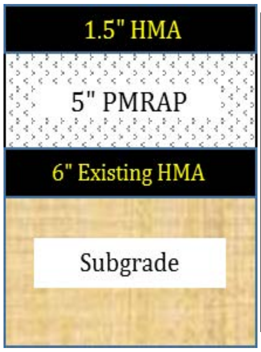
To resolve this issue, forward calculation was conducted with the layer moduli predicted from the backcalculations as the seed values, and with the consideration of a stiff layer, for those sections in which there was a significant difference between the predicted and measured deflections at one or more sensor locations. The details are provided in the following section.

Table 7. Structure and seed moduli for the different layers (Auburn, ME)



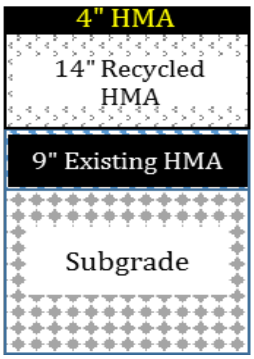
Layer	Moduli, Frozen	Moduli, Thawed
	PSI	PSI
HMA	750,000	500,000
FDR Base	500,000	145,000
Subgrade	100,000	7,000

Table 8. Structure and seed moduli for the different layers (Waterford, ME)



Layer	Moduli, Frozen	Moduli, Thawed
	PSI	PSI
HMA	750,000	500,000
PMRAP Base	500,000	145,000
Existing HMA	375,000	250,000
Subgrade	100,000	7,000

Table 9. Structure and seed moduli for the different layers (Warren Flats, NH)

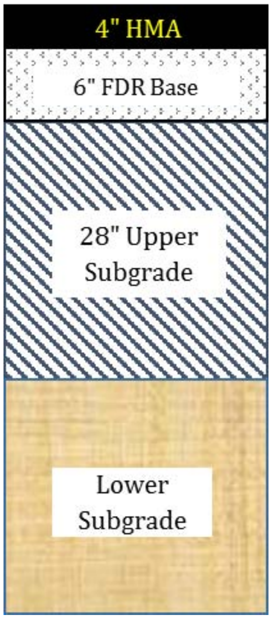


Layer	Moduli, Frozen	Moduli, Thawed
	PSI	PSI
HMA	750,000	500,000
Recycled HMA	500,000	145,000
Existing HMA	375,000	250,000
Subgrade	100,000	7,000

Table 10. Structure and seed moduli for the different layers (Kancamagus 1)

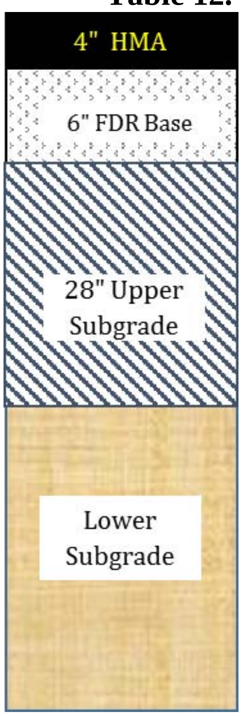
Layer	Moduli, Frozen	Moduli, Thawed
	PSI	PSI
HMA	750,000	500,000
Base	500,000	145,000
Subbase	300,000	75,000
Subgrade	100,000	7,000

Table 11. Structure and seed moduli for the different layers (Kancamagus 2)



Layer	Moduli, Frozen PSI	Moduli, Thawed PSI
HMA	750,000	500,000
FDR Base	500,000	145,000
Upper Subgrade	100,000	7,000
Lower Subgrade	100,000	7,000

Table 12. Structure and seed moduli for the different layers (Kancamagus 3)



Layer	Moduli, Frozen PSI	Moduli, Thawed PSI
HMA	750,000	500,000
FDR Base	500,000	145,000
Upper Subgrade	100,000	7,000
Lower Subgrade	100,000	7,000

Table 13. Results of backcalculations (Auburn, ME)

Date	Temperature (Deg F)	HMA		FDR Base		Subgrade									RMS
		Layer#1		Layer#2		Layer#3			Layer#4			Layer#5			
		F/UF	E1	F/UF	E2	F/UF	t	E3	F/UF	t	E4	F/UF	t	E5	
3/3/2015	37.85	F	7,560	F	36,189	F	1219	8,356	UF	-	330	-	-	-	0.0241
3/11/2015	56.66	UF	15,861	UF	2,485	UF	102	43	F	1118	4,498	UF	-	250	0.0641
3/16/2015	53.18	UF	14,081	UF	4,209	UF	330	84	F	889	1,266	UF	-	242	0.0467
3/20/2015	54.30	UF	7,182	UF	5,764	UF	584	111	F	610	3,001	UF	-	223	0.0414
3/27/2015	44.78	UF	6,210	UF	2,730	UF	762	109	F	330	2,621	UF	-	192	0.0689
3/31/2015	65.01	UF	4,828	UF	1,422	UF	-	145			-			-	0.3614
4/3/2015	70.53	UF	5,709	UF	1,539	UF	-	149			-			-	0.2047
4/10/2015	45.58	UF	7,108	UF	2,588	UF	-	165			-			-	0.1478
4/15/2015	78.13	UF	5,404	UF	1,302	UF	-	155			-			-	0.1532
4/17/2015	81.20	UF	1,402	UF	2,900	UF	-	165			-			-	0.1486
4/21/2015	60.98	UF	4,552	UF	2,144	UF	-	160			-			-	0.1846
6/5/2015	89.20	UF	2,608	UF	1,964	UF	-	175			-			-	0.1307

(Note: t = thickness in mm, of sub layers, assumed on the basis of freeze/thaw data)

Table 14. Results of backcalculations (Waterford, ME)

Date	Temperature (Deg F)	HMA		PMRAP		Existing HMA		Subgrade					RMS
		LAYER 1		LAYER 2		LAYER 3		LAYER 4			LAYER 5		
		F/UF	E1	F/UF	E2	F/UF	E3	F/UF	t	E4	F/UF	E5	
03/03/15	34.1	F	34,338	F	52,279	F	67,138	F	-	623			0.0151
03/11/15	62.11	F	10,635	F	11,585	F	9,164	F	-	707			0.0113
03/16/15	50.25	F	15,700	F	28,703	F	14,694	F	-	618			0.1698
03/20/15	41.17	UF	62,014	UF	38,196	UF	45,600	UF	-	578			0.0708
03/27/15	45.44	UF	95,833	UF	1,520	F	31,427	UF	-	446			0.1239
03/31/15	54.45	UF	8,630	UF	1,358	UF	16,363	UF	-	396			0.1069
04/03/15	70.74	UF	11,114	UF	1,124	UF	6,140	UF	-	307			0.0576
04/10/15	46.28	UF	31,915	UF	3,517	UF	284	F	-	195			0.0619
04/15/15	78.82	UF	2,414	UF	1,199	UF	1,240	UF	13.5	22	F	272	0.1871
04/17/15	63.34	UF	5,514	UF	1,718	UF	1,249	UF	21.5	27	F	324	0.157
04/21/15	55.1	UF	1,102	UF	3,939	UF	1,118	UF	37.5	64	F	185	0.1136
04/24/15	65.48	UF	767	UF	1,458	UF	2,080	UF	-	107			0.5626
04/30/15	74.9	UF	534	UF	841	UF	2,617	UF	-	102			0.691
05/07/15	103.06	UF	7,738	UF	1,681	UF	28	UF	-	141			0.1506
06/05/15	93.5	UF	4,929	UF	1,778	UF	49	UF	-	126			0.1837

(Note: t = thickness in mm, of sub layers, assumed on the basis of freeze/thaw data)

Table 15. Results of backcalculations (Warren Flats, NH)

Date	Temperature (Deg F)	HMA		Recycled HMA		Existing HMA						Subgrade						RMS
		LAYER 1		LAYER 2		LAYER 3			LAYER 4			LAYER 4/5			LAYER 5/6			
		F/UF	E1	F/UF	E2	F/UF	t	E3	F/UF	t	E4	F/UF	t	E4/5	F/UF	t	E5/6	
03/16/15	31.8	F	13,018	F	390	F		790	-	-	-	F	31	1,109	UF	-	434	0.09
03/27/15	40.65	UF	5,142	UF	101	UF	7	9,769	F	2	19,639	F	29	3,290	UF	-	239	0.3686
04/07/15	39.1	UF	6,107	UF	96	UF		7,016	-	-	-	UF	-	269	-	-	-	0.3613
04/16/15	49.53	UF	6,454	UF	88	UF		9,321	-	-	-	UF	-	186	-	-	-	0.3198
04/23/15	42.7	UF	5,485	UF	170	UF		2,128	-	-	-	UF	-	46	-	-	-	0.4412
05/13/15	60.24	UF	5,164	UF	105	UF		4,731	-	-	-	UF	-	201	-	-	-	0.2288
05/27/15	96.92	UF	1,804	UF	132	UF		5,722	-	-	-	UF	-	201	-	-	-	0.1413

(Note: t = thickness in mm, of sub layers, assumed on the basis of freeze/thaw data)

Table 16. Results of backcalculations (Kancamagus 1)

Date	Temperature (Deg F)	HMA		Base		Subbase						Subgrade					RMS
		LAYER 1		LAYER 2		LAYER 3			LAYER 4			LAYER 4/5			LAYER 5/6		
		F/UF	E1	F/UF	E2	F/UF	t	E3	F/UF	t	E4	F/UF	t	E4/5	F/UF	E5/6	
02/24/14	34.70	F	21,546	F	40	F	609.6	61,435				F	-	132			0.2188
03/21/14	35.00	F	29,361	F	85	F	609.6	6,725				F	-	215			0.1294
04/09/14	48.70	F	29,622	F	57	F	609.6	2,196				F	-	351			0.1551
03/31/15	36.31	F	7,060	F	1,487	F	609.6	76,012				F	-	794			0.0091
04/07/15	39.53	F	9,075	F	386	F	609.6	80,078				F	-	592			0.0449
04/16/15	58.68	UF	8,052	UF	98	UF	533.4	26,341	F	76.2	356,369	F	-	275			0.176
04/24/15	32.49	UF	9,885	UF	159	UF	609.6	615				UF	330.2	117	F	313	0.2613
05/07/15	75.65	UF	8,294	UF	122	UF	609.6	1,481				UF	965.2	159	F	212	0.154
05/14/15	65.96	UF	7,082	UF	114	UF	609.6	2,567				UF	-	179			0.095
05/28/15	81.60	UF	6,340	UF	142	UF	609.6	1,487				UF	-	187			0.0665
06/11/15	83.95	UF	6,149	UF	146	UF	609.6	1,179				UF	-	194			0.0789
07/14/15	78.27	UF	4,878	UF	142	UF	609.6	1,402				UF	-	194			0.0599

(Note: t = thickness in mm, of sub layers, assumed on the basis of freeze/thaw data)

Table 17. Results of backcalculations (Kancamagus 2)

Date	Temperature (Deg F)	HMA		Base		Upper Subgrade						Lower Subgrade					RMS
		LAYER 1		LAYER 2		LAYER 3			LAYER 4			LAYER 4/5			LAYER 5/6		
		F/UF	E1	F/UF	E2	F/UF	t	E3	F/UF	t	E4	F/UF	t	E4/5	F/UF	E5/6	
04/09/14	50.7	F	30,145	F	2,024	F	711.2	20				F	-	3,034			**0.217**
03/31/15	47.09	F	2,671	F	1,439	F	711.2	4,567				F	965.2	4,741	**UF**	244	0.285
04/07/15	40.77	UF	5,576	UF	1,752	UF	177.8	81	F	533.4	1,689	F	914.4	5,904	UF	312	0.1905
04/16/15	68.08	UF	875	UF	2,289	UF	558.8	66	F	152.4	1,221	F	736.6	2,750	UF	229	0.6807
04/24/15	32.62	UF	5,020	UF	1,558	UF	711.2	134				F	609.6	1,635	UF	71	1.1101
05/07/15	81.15	UF	14,425	UF	38	UF	711.2	229				UF	-	173			0.3642
05/14/15	71.96	UF	13,377	UF	110	UF	711.2	129				UF	-	201			0.3755
05/28/15	88.76	UF	709	UF	1,513	UF	711.2	197				UF	-	122			1.0285
06/11/15	89.81	UF	1,242	UF	1,092	UF	711.2	136				UF	-	159			0.7589
07/14/15	78.38	UF	13,361	UF	29	UF	711.2	1,060				UF	-	172			0.249

(Note: t = thickness in mm, of sub layers, assumed on the basis of freeze/thaw data)

Table 18. Results of backcalculations (Kancamagus 3)

Date	Temperature (Deg F)	HMA		FDR Base						Upper Subgrade					
		LAYER 1		LAYER 2			LAYER 3			LAYER 4/5			LAYER 5/6		
		F/UF	E1	F/UF	t	E2	F/UF	t	E3	F/UF	t	E4/5	F/UF	t	E5/6
04/09/14	52.7	F	0	F	0	0				F	0	0			
03/31/15	48.21	UF	0	UF	0	0	F	0	0	F	0	0			
04/07/15	41.85	UF	0	UF	0	0	-	-		UF	0	0	F	0	0
04/16/15	69.53	UF	0	UF	0	0	-	-		UF	0	0	F	0	0
04/24/15	34.27	UF	0	UF	0	0	-	-		UF	0	0			
05/07/15	84.04	UF	0	UF	0	0	-	-		UF	0	0			
05/14/15	73.65	UF	0	UF	0	0	-	-		UF	0	0			
05/28/15	89.76	UF	0	UF	0	0	-	-		UF	0	0			
06/11/15	93.21	UF	0	UF	0	0	-	-		UF	0	0			
07/14/15	77.41	UF	0	UF	0	0	-	-		UF	0	0			

Date	Lower Subgrade									RMS
	LAYER 6/7			LAYER 7/8			LAYER 8/9			
	F/UF	t	E6/7	F/UF	t	E7/8	F/UF	t	E8/9	
04/09/14	F	-	0							0
03/31/15	F	0	0	**UF**	**-**	0				0.5398
04/07/15	F	0	0	UF	-	0				0.238
04/16/15	F	0	0	UF	-	0				0.5565
04/24/15	UF	0	0	F	16	0	UF	-	0	0.627
05/07/15	UF	0	0	F	5	0	UF	-	0	0.4914
05/14/15	UF	-	0							0.9479
05/28/15	UF	-	0							0.2933
06/11/15	UF	-	0							0.3903
07/14/15	UF	-	0							0.2863

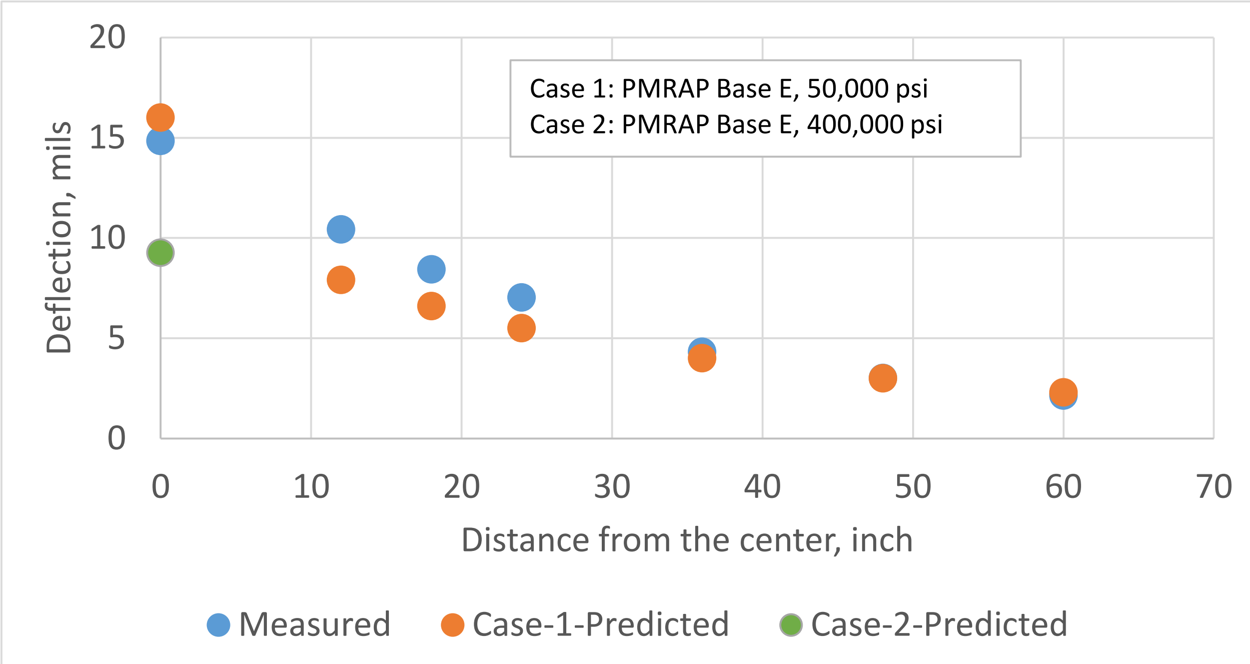


Figure 16. Comparison of predicted and actual deflections at different sensor locations for backcalcul values of the base layer (Auburn, ME)

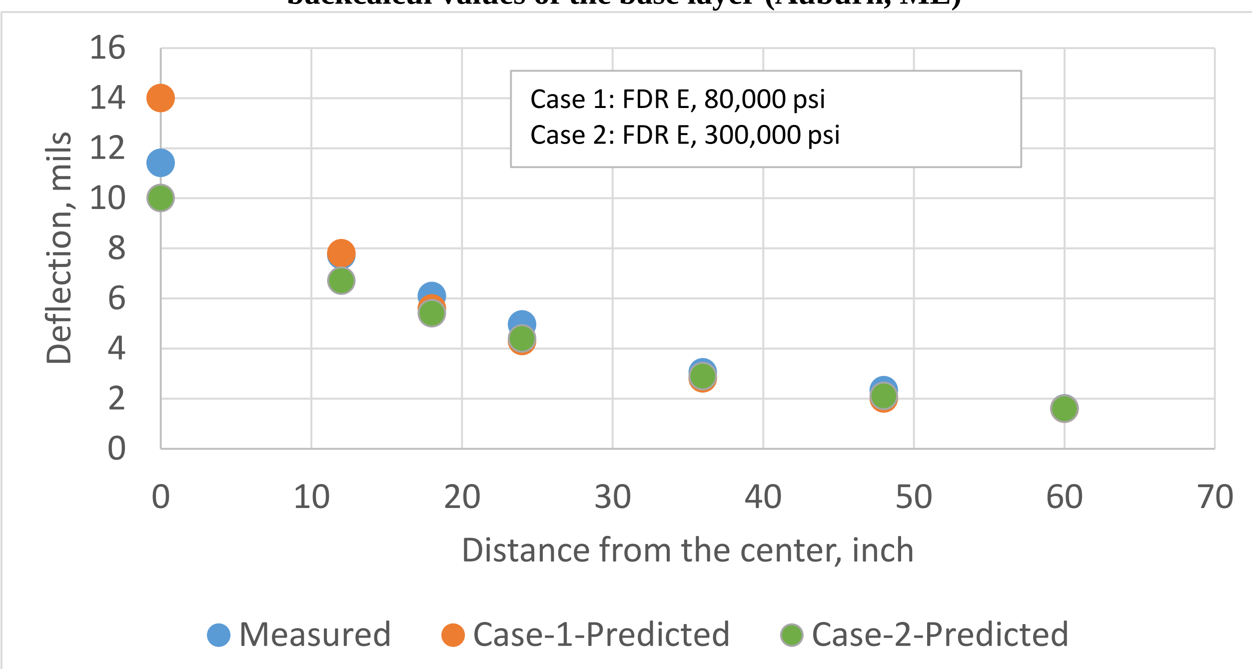


Figure 17. Comparison of predicted and actual deflections at different sensor locations for backcalculated values of the base layer (Waterford, ME)

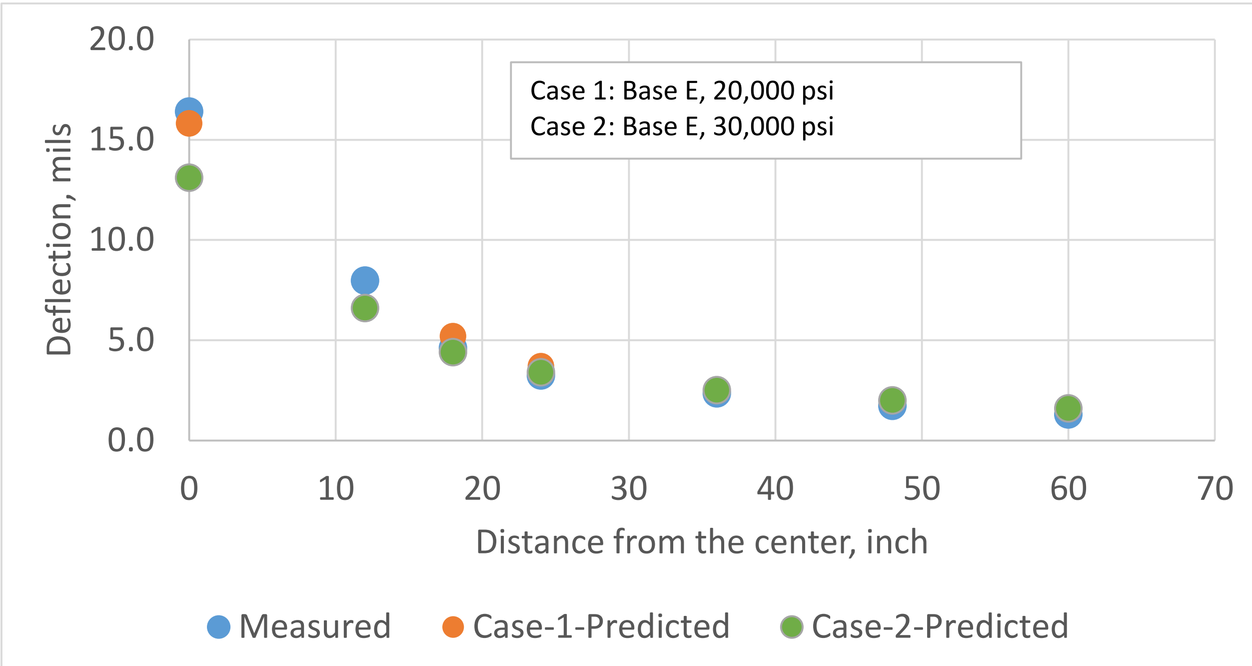


Figure 18. Comparison of predicted and actual deflections at different sensor locations for backcalculated values of the base layer (Warren Flats, NH)

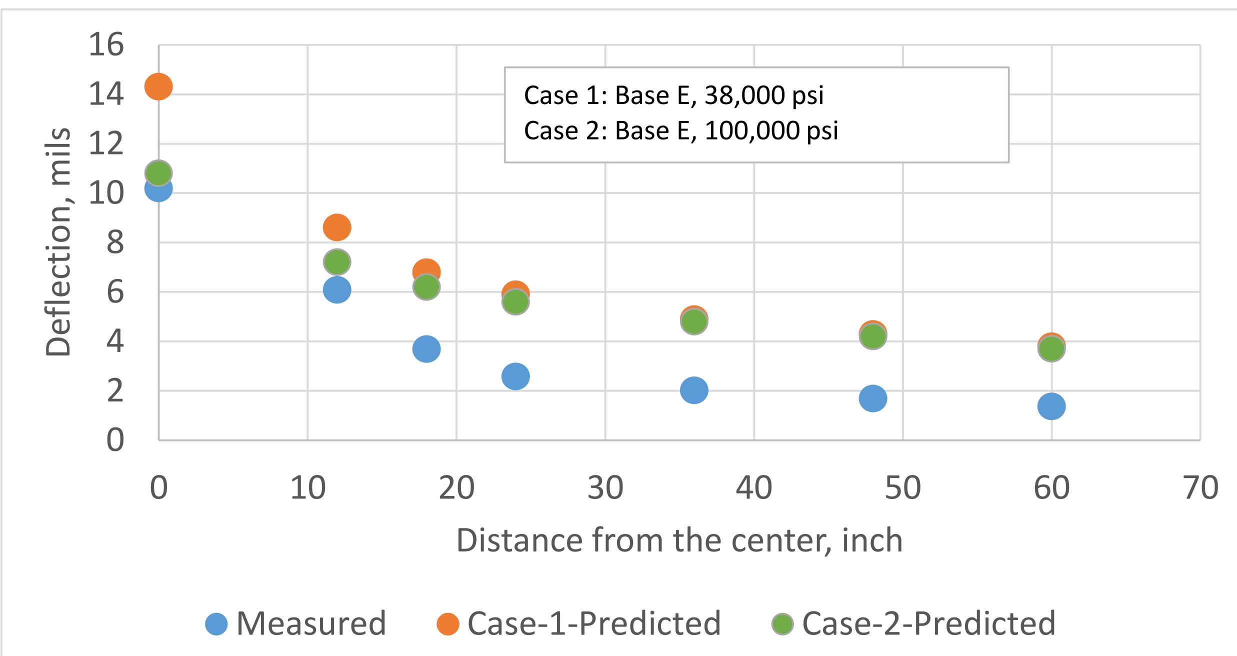


Figure 19. Comparison of predicted and actual deflections at different sensor locations for backcalculated values of the base layer (Kancamagus 1)

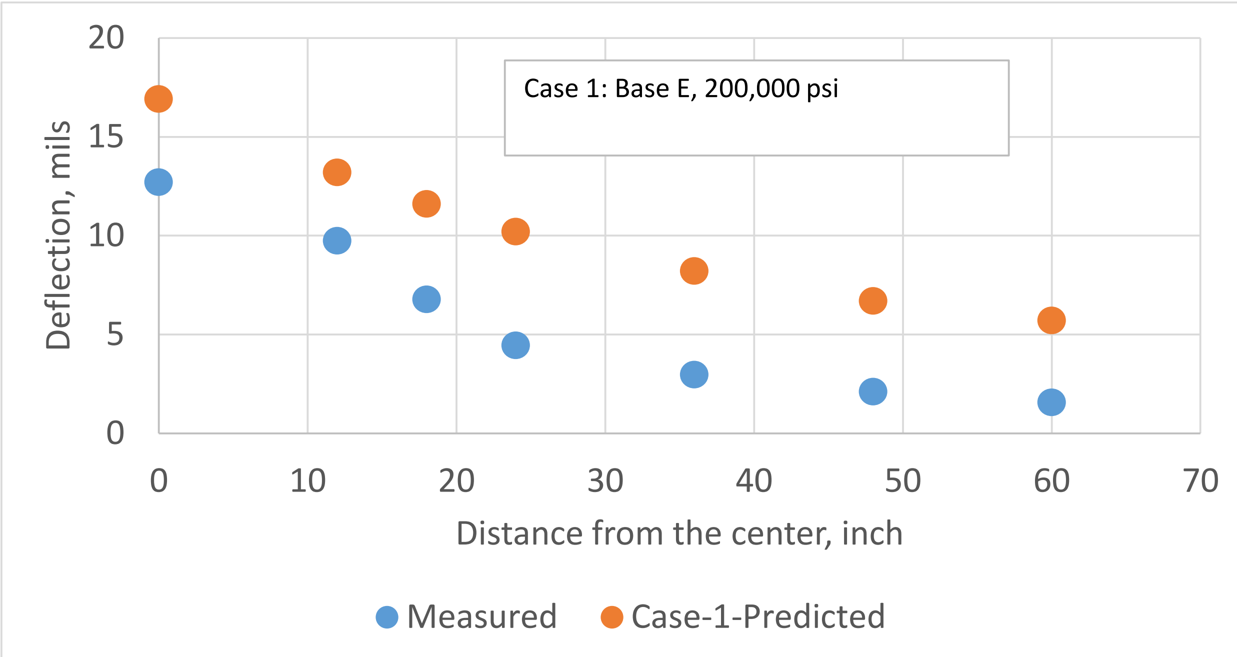


Figure 20. Comparison of predicted and actual deflections at different sensor locations for backcalculated values of the base layer (Kancamagus 2)

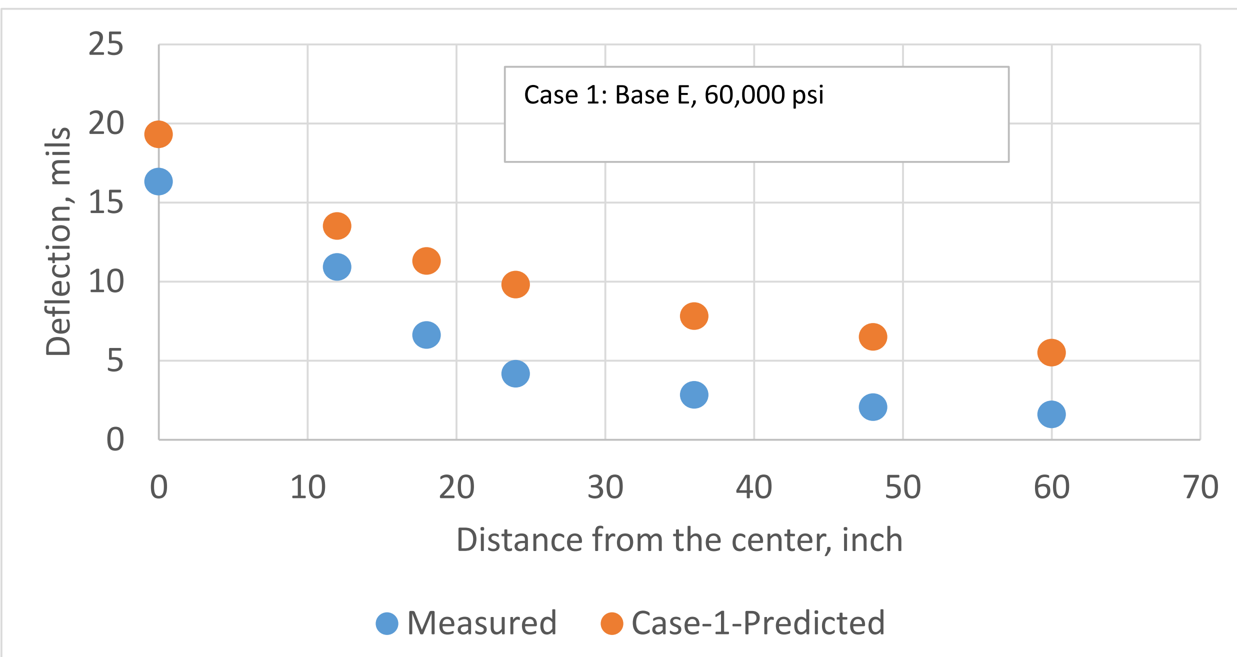


Figure 21. Comparison of predicted and actual deflections at different sensor locations for backcalculated values of the base layer (Kancamagus 3)

3.2. Forward Calculation Procedures to Confirm Modulus Values

Forward calculation procedures were conducted to confirm and/or adjust modulus values obtained via backcalculations and empirical equations. The WinJULEA software was used for this task. To utilize that software, required input for each material layer in the pavement structure includes layer thickness, Poisson's ratio and modulus of elasticity. For any given circular loading configuration, the software will perform a linear elastic analysis and provide output which includes predicted deflections at any distance and depth away from the center of the circular load plate. The goal of this task was to model the loading applied in the FWD tests, using assumed input parameters as described below, and to compare deflections measured at the pavement surface at each sensor location in the FWD test with deflections predicted by the WinJULEA software at comparable locations. If the measured and predicted deflection values were not in close agreement, then the assumed modulus values were adjusted and the WinJULEA analyses repeated until a reasonable match was obtained.

When conducting FWD testing, multiple tests were performed at different load levels, and then the deflections were normalized to a 9,000-lb load as follows (3):

$$Normalized\ Deflection\,(mils) = \frac{Measured\ Deflection\,(mils)\ x\ 9{,}000\ lb}{Applied\ Load\ (lb)}$$

The deflection measured by the FWD sensor directly at the center of the load, D_0, is also usually adjusted to account for changes in asphalt stiffness that result from changes in temperature. Therefore, the raw center deflection readings were first normalized to a 9,000-lb load, and were then adjusted to a standard temperature of 77 ^{o}F using the following equation:

$$\text{Adjusted Center Deflection} = D_o\left(1.5788 - 0.0071439\,T^{1.01}\right)$$

For analysis using the WinJULEA software, the thickness of each material layer was assumed based upon field logs and laboratory testing of samples collected during drilling of boreholes for instrument installation at each test site. Assumed layer thicknesses at each test site (when no frost was present) are shown in Figure 22 through Figure 26. When a frozen layer was present, layer thicknesses were adjusted slightly and/or additional layers were assumed to account for material layers that may have been partially frozen and partly thawed. Values of Poisson's ratio for each layer were assumed based upon empirical recommendations presented in in the "*EVERSERIES User's Guide*" (4). Initial modulus values used in the WinJULEA analyses were obtained via backcalculation procedures and/or empirical equations, as described in the previous of this report. As noted previously, if the deflection values predicted with WinJULEA were not in close agreement with those measured in FWD tests, then the assumed modulus values were adjusted and the WinJULEA analyses repeated until a reasonable match was obtained.

As shown in Figure 22 through Figure 26, a "stiff layer" was assumed at all sites except for Auburn, Maine. As discussed in the "*EVERSERIES User's Guide*" (4), backcalculation procedures can often result in erroneously high modulus values for base and subgrade layers when a stiff layer is not assumed as the lower (infinite thickness) layer. In that guide, they recommend using a stiff layer modulus value of about 100,000 psi when the stiff layer is due to a dense glacial till or bedrock, and a value of about 50,000 psi when the stiff layer is due to a groundwater table. At the NH sites, periodic measurements of groundwater levels had been taken during 2008-2010, and those historical measurements, along with borehole logs, were used to establish the assumed stiff layer location and modulus values shown in Figure 24 through Figure 26. At the Waterford, Maine site, neither groundwater nor a dense soil or bedrock layer was encountered when drilling the borehole for thermistor installation. Maine DOT personnel present at the site during drilling operations had pointed out drainage basins that had been excavated just off the edge of the roadway in numerous locations and said that those had been created to help drain water during the spring thaw period. Based upon that information, and some experimentation with trial depths for a stiff layer using the WinJULEA software, a "stiff layer" at a depth of about 8.7 feet with a modulus value of 50,000 psi was assumed at the Waterford site. The Auburn, Maine site was located at the top of a fairly substantial fill. Because of that, and since no groundwater or stiff layer was encountered during drilling operations at that site, a stiff layer was not assumed for forward calculations at that site.

For all of the test sites except the two test sections along the Kancamagus Highway in NH, forward calculations were conducted for each FWD test date. For the two test sections along the Kancamagus Highway, forward calculations were only conducted for selected FWD test dates. Because the modulus values obtained for those selected test dates agreed well with modulus values obtained in previous studies at those sites (5), additional WinJULEA analyses were not conducted. For each FWD test, a plot showing the measured FWD deflections at each sensor location along with the deflections predicted using the WinJULEA software at those same locations are included in Appendix B. In that Appendix, it can be seen that in most cases (with the exception of data collected during frozen conditions), there was a very good match between measured and predicted deflections. During frozen conditions, deflections were so small that the accuracy of the measured deflection itself becomes questionable. Summary tables of modulus values during frozen, thaw-weakened and recovered conditions at each test site are included in Table 19 through Table 23.

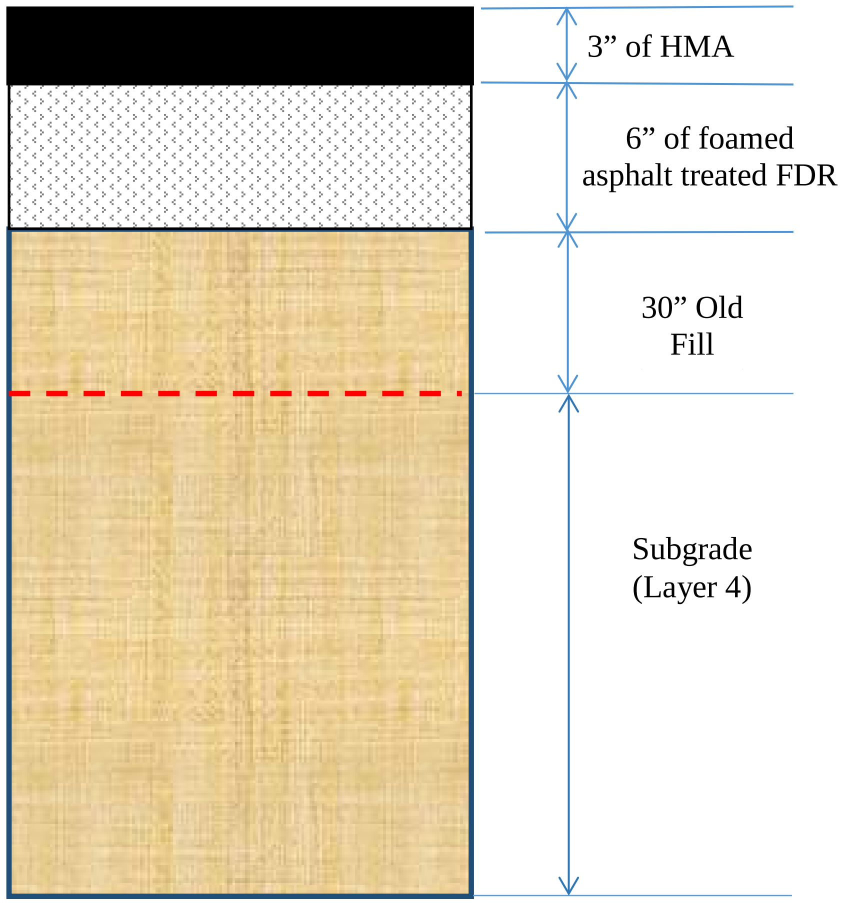


Figure 22. Assumed Cross-Section for Site at Auburn, ME

Stiff Layer Not Assumed in This Analysis

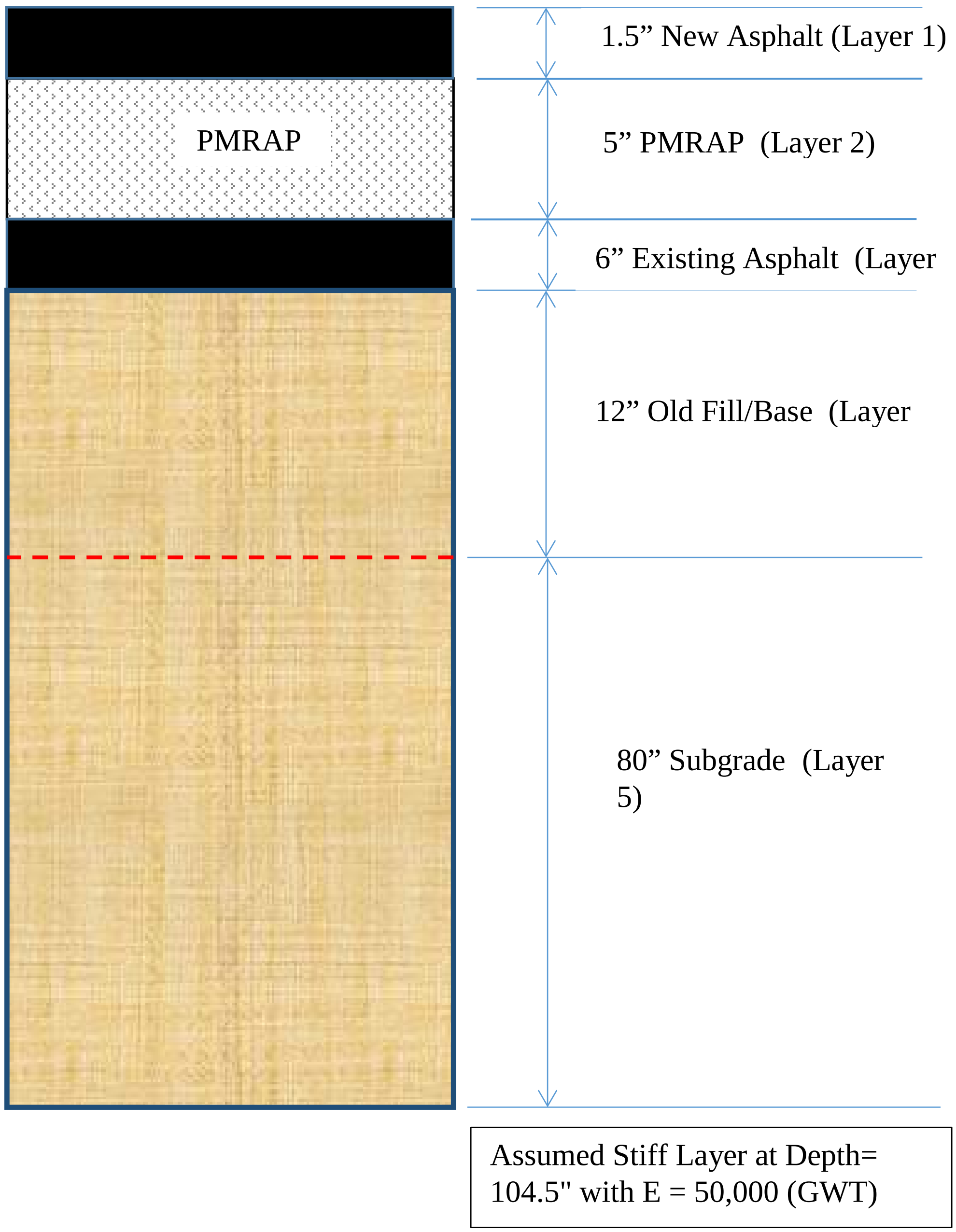


Figure 23. Assumed Cross-Section for Site at Waterford, Maine

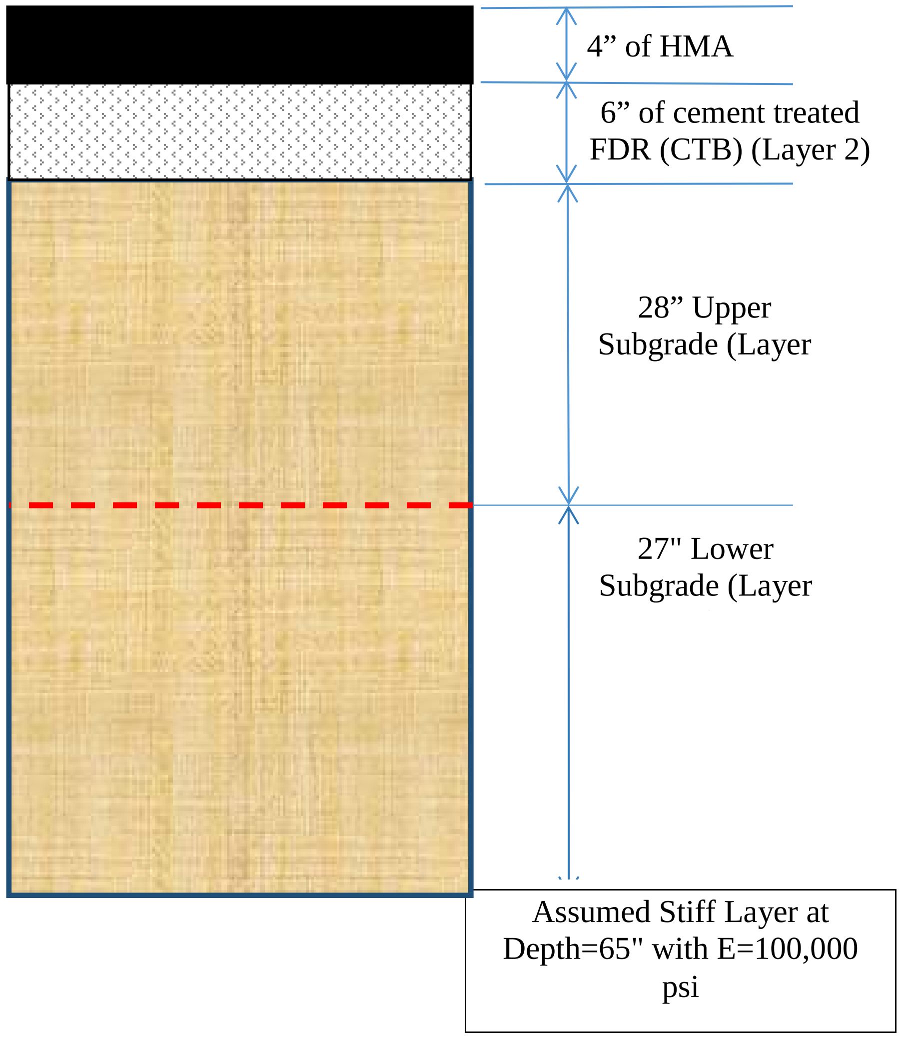


Figure 24. Assumed Cross-Section for Site at Kanc 2, NH

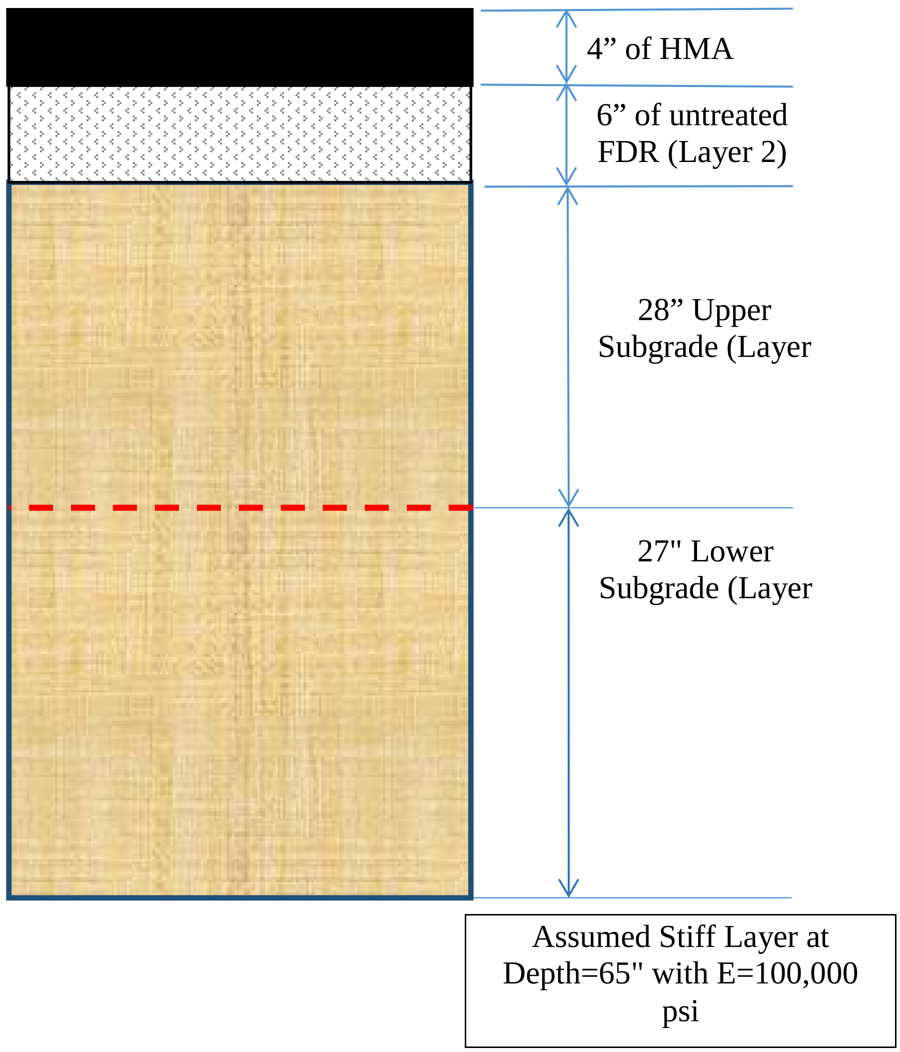


Figure 25. Assumed Cross-Section for Site at Kanc 3, NH

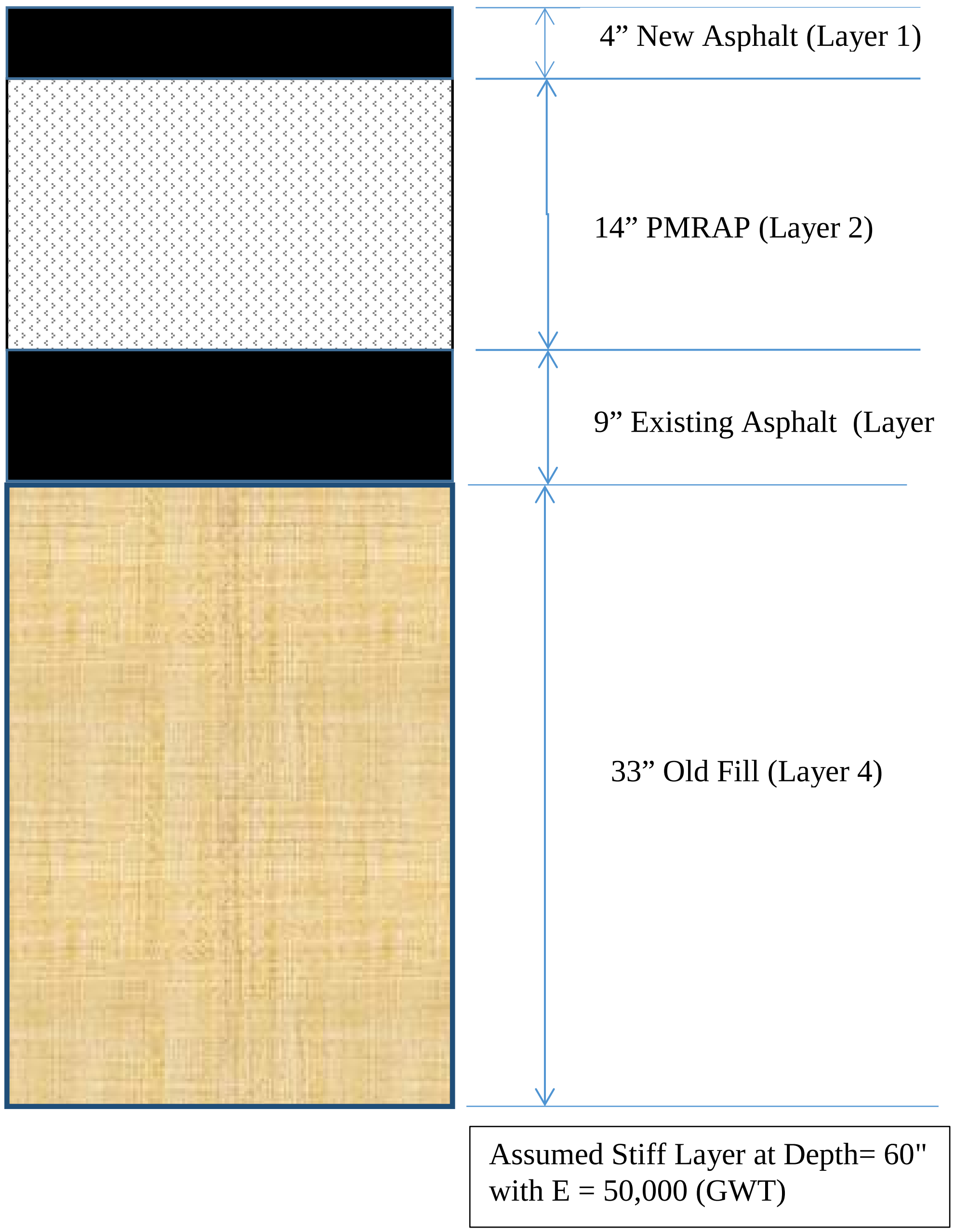


Figure 26. Assumed Cross-Section for Site at Warren Flats, NH

Table 19. Layer Modulus Values at Auburn, ME site

	Modulus (psi)					
Date	Layer 2 (FDR)	Layer 3 (Old Fill) Thawed	Layer 3 (Old Fill) Frozen	Layer 4 (Subgrade) Thawed	Layer 4 (Subgrade) Frozen	Comments
10/15/14	300,000	25,000	na	na	25,000	Baseline
03/03/15	300,000	169,500	169,500	169,500	169,500	Frozen
03/11/15	300,000	32,000	100,000	50,000	50,000	14.6" Thawed
03/16/15	300,000	28,000	100,000	50,000	33,000	21" Thawed
03/20/15	300,000	35,000	100,000	50,000	32,000	29" Thawed
03/27/15	200,000	25,000	na	50,000	24,000	39" Thawed
03/31/15	230,000	20,000	na	na	23,000	End of Thaw
04/03/15	260,000	21,000	na	na	23,000	
04/10/15	260,000	25,000	na	na	25,000	
04/15/15	240,000	21,000	na	na	25,000	
04/17/15	260,000	23,000	na	na	25,000	
04/21/15	270,000	22,000	na	na	24,000	
06/05/15	300,000	25,000	na	na	25,000	

NOTE: Color Legend (Tables 19 through 23)

Thawed
Frozen

Table 20. Layer Modulus Values at Waterford, ME site

Date	Modulus (psi)						Comment
	Layer 2 (PMRAP)	Layer 3 (Old Asphalt)	Layer 3 (Old Fill) Thawed	Layer 3 (Old Fill) Frozen	Layer 4 (Subgrade) Thawed	Layer 4 (Subgrade) Frozen	
10/15/2014	160,000	300,000	13,000	na	11,000	na	Baseline
03/03/15	350,000	300,000	na	100,000	na	100,000	Frozen
03/11/15	350,000	300,000	na	100,000	na	100,000	7" Thawed
03/16/15	350,000	300,000	na	100,000	na	100,000	Frozen
03/20/15	350,000	300,000	na	100,000	na	100,000	Frozen
03/27/15	350,000	300,000	na	100,000	na	100,000	10.3" Thawed
03/31/15	300,000	300,000	na	80,000	na	65,000	13.2" Thawed
04/03/15	300,000	300,000	na	50,000	na	50,000	11.7" Thawed
04/10/15	180,000	300,000	15,000	28,000	na	22,000	15.7" Thawed
04/15/15	120,000	300,000	5,000	na	na	18,000	26" Thawed
04/17/15	120,000	300,000	5,500	na	13,000	16,000	34" Thawed
04/21/15	120,000	300,000	6,000	na	12,000	16,000	50" Thawed
04/24/15	120,000	300,000	9,000	na	11,000	na	End of Thaw
04/30/15	95,000	300,000	11,000	na	10,000	na	
06/05/15	90,000	300,000	11,000	na	10,000	na	

Assumed Stiff Layer at Depth= 104.5" with E=50,000 psi

Results of the forward calculations for layer modulus values at the NH test sites are included in Tables 21, 22, and 23 below.

Table 21. Layer Modulus Values at Kanc 2, NH site

Date	Modulus (psi)					Comments
	Layer 2 (FDR-CTB)	Layer 3 (Upper Subgrade) Thawed	Layer 3 (Upper subgrade) Frozen	Layer 4 (Lower Subgrade) Thawed	Layer 4 (Lower Subgrade) Frozen	
03/31/15	200,000	na	100,000	na	100,000	Frozen
04/24/15	80,000	12,000	na	2,000	100,000	38" Thawed
05/07/15	100,000	24,000	na	5,500	na	End of Thaw
05/14/15	100,000	24,000	na	5,500	na	
06/11/15	100,000	25,000	na	7,000	na	
07/14/15	100,000	25,000	na	7,000	na	Baseline

Assumed Stiff Layer at Depth=65" with E=100,000 psi

Table 22. Layer Modulus Values at Kanc 3, NH site

Date	Modulus (psi)					Comments
	Layer 2 (FDR)	Layer 3 (Upper Subgrade) Thawed	Layer 3 (Upper subgrade) Frozen	Layer 4 (Lower Subgrade) Thawed	Layer 4 (Lower Subgrade) Frozen	
03/31/15	60,000	na	100,000	na	100,000	Frozen
04/24/15	12,000	16,000	na	5,000	100,000	46.2" Thawed
05/14/15	45,000	22,000	na	5,000	na	
07/14/15	55,000	25,000	na	7,000	na	Baseline

Assumed Stiff Layer at Depth=65" with E=100,000 psi

Table 23. Layer Modulus Values at Warren Flats, NH site

	Modulus (psi)				
Date	Layer 2 (PMRAP)	Layer 3 (Old Asphalt)	Layer 4 (Old Fill) Thawed	Layer 4 (Old Fill) Frozen	Comments
03/16/15	80,000	250,000	na	50,000	Frozen
03/27/15	15,000	250,000	na	50,000	25.2" Thawed
04/07/15	15,000	250,000	25,000	na	End of Thaw
04/16/15	16,000	250,000	9,000	na	
04/23/15	17,000	250,000	7,000	na	
05/13/15	18,000	250,000	13,000	na	
05/27/15	20,000	250,000	21,000	na	Baseline

Assumed Stiff Layer at Depth= 60" with E=50,000 psi

4. Summary and Recommendations

The primary objective of this research project was to determine the in-place properties of recycled materials common to the New England region and document how the properties change with variations in temperature and moisture; particularly during the spring thaw period. Five instrumented pavement sections with base layers that contained recycled materials were evaluated over the course of the study. Falling weight deflectometer testing was conducted throughout the year and at frequent intervals during the spring to capture thaw weakening and recovery behavior of the materials. Modulus values for the layers were initially backcalculated from the FWD data using the BAKFAA software program; seed values used in the analysis were estimated using empirical equations and typical values. The modulus values obtained from backcalculation were further refined using a forward calculation procedure and the final recommended values for the sites evaluated in this study are presented below.

Table 24 presents the modulus values determined from the forward calculation procedure for each of the sites and Table 25 shows the ratios of the frozen and thaw weakened modulus to the baseline modulus. The treated full-depth reclamation layers have modulus values significantly higher than the untreated layer and also only lose 20-30% of their strength due to spring thaw conditions whereas the untreated material lost 80% of its strength. The two plant-mixed RAP layers have very different modulus values as determined from the in-place material property analysis. This can be explained by the fact that the Waterford material was 100% RAP material with added cement and emulsion whereas that Warren Flats material was RAP blended with gravel with no stabilizing materials. The strength loss during spring thaw for these materials ranged from 20-40%.

Table 24. Recommended Modulus Values for Recycled Layers

Condition	Modulus Value (psi)				
	Full Depth Reclamation			Plant-Mixed RAP	
	Cement Treated	Untreated	Foamed asphalt treated		
	Kanc 2	Kanc 3	Auburn	Waterford	Warren Flats
Baseline	100,000	55,000	300,000	160,000	20,000
Frozen	200,000	60,000	300,000	350,000	80,000
End of thaw weakest	80,000	12,000	200,000	90,000	15,000

Table 25. Ratio of Modulus Values Compared to Baseline Modulus

Condition	Modulus Ratio				
	Full Depth Reclamation			Plant-Mixed RAP	
	Cement Treated	Untreated	Foamed asphalt treated		
	Kanc 2	Kanc 3	Auburn	Waterford	Warren Flats
Frozen/Baseline	2.0	1.1	1.0	2.2	4.0
End of thaw weakest/Baseline	0.8	0.2	0.7	0.6	0.8

The testing and analysis conducted through this study shows that the in-place modulus values of recycled materials can vary significantly depending upon the material type, and even within classifications of material type (e.g. plant-mixed RAP). It is important to have more detailed information on the processes used to produce and construct the recycled layers. Treated FDR materials have modulus values several times greater than untreated FDR materials and are also less sensitive to changes in temperature and moisture. Continued monitoring of the instrumented sections would be valuable to evaluate the magnitude in changes from year to year and also to evaluate changes in modulus over the life of the pavement structure. The addition of FWD testing on additional sections (even without instrumentation) would also be valuable to establish mean and range of in-place modulus values for recycled materials.

5. References

1. Federal Aviation Administration (FAA). BAKFAA Version 2.0
2. Federal Highway Administration (FHWA). Pavement Deflection Analysis. NHI Course 13127, FHWA-HI-94-021.

3. Washington State Department of Transportation (WSDOT). *Development of a Computer Program for the Determination of the Area Value and Subgrade Modulus using the Dynatest FWD*, Olympia, WA, 1999.

4. *EVERSERIES User's Guide*: Pavement Analysis Computer Software and Case Studies. Washington State Department of Transportation, Olympia, WA, 2005.

5. Miller, H. J., M. Amatrudo, M. A. Kestler and W.S. Guthrie. Mechanistic Analysis of Reconstructed Roadways Incorporating Recycled Base Layers. Paper No. 11-2612. Proceedings of the Transportation Research Board 90th Annual Meeting. CD-ROM. Washington, D.C., January 2011.

Appendix A

Survey for recycled asphalt pavement layers
survey background:

This survey is part of work being conducted under New England Transportation Consortium project NETC 07-1: In-Place Response Mechanisms of Recycled Layers Due to Temperature and Moisture Variations. The objectives of this survey are to:

1. Obtain a better understanding of current uses and needs of the New England States with regard to recycled materials in unbound pavement layers
2. Determine locations of suitable recycled asphalt pavement sites in which instrumentation could be (or might already be) installed for monitoring performance

The research team for this project includes Dr. Jo Daniel, University of NH; Dr. Heather Miller, University of Massachusetts at Dartmouth; Dr. Rajib Mallick, Worcester Polytechnic Institute; and Ms. Maureen Kestler, USDA Forest Service.

Would you please take a few minutes to answer the following questions to further this project.
Thank you for your time and willingness to participate!
If you have any questions, please call or email Dr. Jo Daniel: 603-862-3277

INSTRUCTIONS:

This survey should be completed using Microsoft Word or equivalent word processing software. When you have completed the survey, please save the file with "name_DOT" as a prefix in the filename and e-mail it, by September 30, 2013, to Dr.Jo Daniel, jo.daniel@unh.edu .

PARTICIPANT Contact Information

Please complete the following fields so that we may contact you in the future.

Name:
Title:
State Department of Transportation:
Responsibility area or Geographic Region:
Phone number:
e-mail address:

DESIGN AND CONSTRUCTION:

1. Are recycled materials used in construction or reconstruction of pavements in your jurisdiction? If so, what pavement construction approaches do you use?
(Please check all that apply.)

☐ Full depth reclamation (FDR), with or without stabilizing additives incl. foamed asphalt

☐ Plant mix cold recycled asphalt pavement (RAP)/Plant Mixed RAP (PMRAP)

☐ Blending RAP with unbound subbase layers

☐ Substitution of unbound subbase layers with RAP

☐ Other:

2. When stabilization is selected for FDR, which types of stabilizers and fillers do you most commonly use? (Please check all that apply.)

☐ Portland cement

☐ Lime

☐ Fly ash

☐ Slag

☐ Asphalt emulsion -Types:

☐ Foamed asphalt –Type of asphalt

☐ Calcium chloride

3. How do you determine the optimum amount of chemical stabilizer to add to a given base or subgrade material? (Please check all that apply.)

☐ Specified mix design procedure (please attach document or provide a link)

☐ Supplier or manufacturer recommendations

☐ Other guidelines - Describe/Provide link to document

☐ Field experience – Describe/Provide link to document

☐ Soil classification - Describe/Provide link to document

4. What would be a typical mix design method used by your state / jurisdiction?

5. For full-depth recycling of asphalt pavements, what is the typical weight ratio of reclaimed asphalt pavement that you use in the mixture with the underlying base material? For example, a blend of 40 percent RAP and 60 percent base would be a ratio of 40:60. (Full-depth recycling is the process in which an aged asphalt surface is pulverized and blended with some amount of the underlying base material to create a new base layer.) How do you determine the depth of recycling?

6. For construction pavements with recycled layers, what other materials specifications or processing specifications do you utilize? Please list and describe the equipment and the construction sequences.

7. Overall, what are your observations regarding the performance of pavements constructed using unbound recycled layers in your jurisdiction? Have you noticed any changes in the stiffness of the recycled layers over different seasons, as determined with a Falling Weight Deflectometer (FWD) for example? Have you collected any temperature and/or moisture data from recycled layers at different times of the year?

8. Overall, what are your observations regarding the performance of pavements constructed using chemically and/or mechanically stabilized recycled layers in your jurisdiction? Please provide details for each type of stabilizer with which you have experience.

9. Do you have any existing recycled sites? Are any of these sites instrumented for temperature and/or moisture (&/or other)?

10. Do you have any pavement construction projects scheduled for the end of this year or for next year that will utilize recycled materials?

If yes, please briefly describe the projects:

Please list the contact person for these projects.

Name:
Title:
Responsibility area or Geographic Region:
Phone number:
e-mail address:

11. Would you be willing to send some sample(s) of recycled base material(s) to the University of NH, WPI, or the University of Massachusetts at Dartmouth for testing as part of this project? If yes, please briefly describe the material:

Thank you!!

Summary of New England States' responses to 2013 Survey for NETC/UNH Recycled Pavement Project

	ME	NH	MA	CT	RI	Comments
1-Recycled techniques used						
FDR	X	Infrequently	X	X	X	All use FDR
RAP, PMRAP	X	First in many yrs is scheduled for this yr.		X		
Blending RAP w/unbound subbase			X	X		
Substitution of unbound Subbase layers w/RAP	X					
Other				X PCC rubblization		
2-Commonly used stabilizers used w/FDR		None		No response		Not a lot of stabilization
Portland cement	X		X			
Lyme						
Fly Ash						
Slag						
Asphalt emulsion–Types	MS-2, SS-1		X (no types provided)		MS-2, HFMS-2	
Foamed asphalt–Types	PG 58-28 PG 64-28		X "			
Calcium chloride			X		X	
3-Determining optimal amount stabilizer		N/A		No response		

	ME	NH	MA	CT	RI	Comments
Specified mix design	X		X		X	
Supplier or manufacturer						
Other guidelines			X			
Field experience						
Soil classification						
4-Typical mix design used by state/jurisdiction	-FDR w/foamed asphalt: Wirtgen design -FDR w/cement: PCA soil cement design meth -FDR w/emulsified asph: Maine DOT method -Cold central plant recycl: Maine DOT method	N/A	NO PM RAP used	FDR is not stabilized. There is no mix design beyond 100% passing the 5-in sieve & 90-100% passing the 3.5 in sieve.	Attachment	
5-For FDR, typical weight ratio of reclaimed asphalt pavement. How is depth of recycling determined?	f(thickness of existing asph layer). Pulverization incl 1-2" of underlying layer, so ratio varies. 6" stabilizn typical. 75:25 ratio typical. FDR encompasses entire existing pavement depth, stabilizers in	25:75 min.; minimum requirement is 15% AC in the final product.	50:50 = rule of thumb, but ratio may be adjusted based on gradation of underlying subbase/subgrade. Since they like to achieve their gravel spec, the cut depth	50:50 is the max RAP/unbound ratio by wt. -Typical ratio varies since typical recycling depth is 10". -Depth of recycling is constrained on the low end by the depth of suitable base (i.e.,	Ranges from 1:1 to 2:1 RAP to soil	

	ME	NH	MA	CT	RI	Comments
	upper 5-6”.		varies based on the layer composition & the amount of “crushed stone/RAP” for blending.	low silt or clay content) – many reclaimed roads that were built decades ago have about 6” of suitable base, plus about 2.5” (or more) of a bound material. This makes 10” achievable in most instances. But if there were less suitable base (or bound material), the recycling depth may be as little as 8 or 9”. On the high end, the recycling depth is constrained by the machine capability (in one pass) – 15” or so. Recycling depth would increase from 10” when the depth of bound layers is greater than 5” – so if there are 6” of bound material, 12” may be recycled; beyond 7” typically milling of some material at the surface is called for		

	ME	NH	MA	CT	RI	Comments
				prior to reclaiming. (This is not very common).		
6-Other material specs. Equipment & construction sequence.	Attachment (all materials sized to 10% passing 2" sieve. Pulverizing & grading precedes stabilizing.)	Glass cullet must meet AASHTO M 318 before blending w/other aggregates. No special equipment. Recycled concrete must meet AASHTO M 319, except for gradation. No special equipment. -Free-draining material must exist below the layer -Material must come from a homogenous stockpile meeting the gradation of the material being substituted -Transitions between recycled material &	Attachment	No response	Attachment	

	ME	NH	MA	CT	RI	Comments
		substituted material must be made using a 50-ft. taper. -Material must be placed directly below the pavement. Recycled shingles & rubber are allowed in HMA. No special equipment for roadway constr'n, just at the HMA plant.				
7-Performance observations - ***unbound*** recycled? Seasonal observations? Temp & moisture collected?	Monitored stiffness on several. 1 project showed stiffness increased after initial construction.	In general, no. Heather Miller, et al. research project on Kanc provides only known observations of this type.	Done mostly on federal aid municipal projects, so no FWD or stiffness analysis conducted. There's been no research on moisture data.	No data collection beyond normal network-level distress eval's. General observations on unbound-recycled-layer pavements: 1- They have been typically capped with a standard bituminous-concrete	No data collected	

	ME	NH	MA	CT	RI	Comments
				overlay of 3” (typically, LVRs). 2- Initial performance is greatly improved over previous treatments (2” resurfacing not sufficient to eliminate reflection of underlying cracks for long). 3- First distress observed has been longitudinal cracking, not transverse cracking. In other cases edge cracking is the first form of distress observed. This is particularly prevalent on narrow old roads. 4- In cases, the oldest roads reclaimed have developed rutting and alligator cracking. 5- These observations indicate that the structure could be strengthened for a better long-term result, & more		

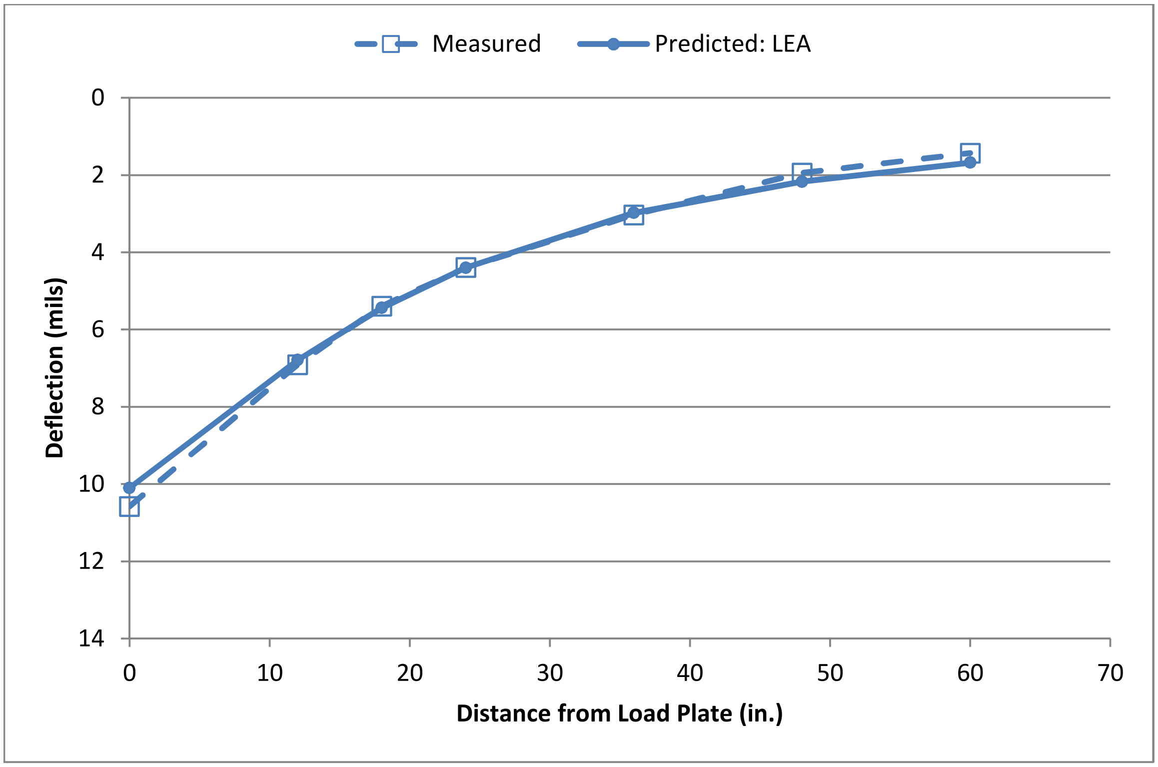
	ME	NH	MA	CT	RI	Comments
				provisions could be taken to strengthen the road base.		
8- Performance observations – ***stabilized*** layers?	Good. -Projects using cold central plant recycled layers exhibit reduced bottom-up cracking. -On a project completed in 2000, treated out-performed untreated control section. -ME has used emulsified asphalt w/cement, foamed asphalt, cement, & cold central plant recycling (numerous projects w/each treatment). -Constructed one research test section using emulsified asphalt with lime. -Calcium chloride has fallen out of favor. Asphalt,	Denis reported that the HMA pavement over the cement stabilized base on the Kanc Hwy. tented, while the non-stabilized section did not. This area has a relatively flat grade, which Denis stated is not a typical condition for tenting.	Good performance w/ reclamation, reclamation stabilized w/calcium & cement stabilization. There's not a lot of data on the emulsion/foam stabilized reclamation. One negative observation is that overly deep stabilization (18-21") can have compaction issues.	N/A	Too soon to determine performance, but FWD testing on reclaimed layer indicates they should see increased pavement life for little added cost.	

	ME	NH	MA	CT	RI	Comments
	emulsion, & Portland cement are the most popular. -Untreated FDR is used in limited applications, w/low traffic, or limited project scope.					
9-Existing recycled sites?	Hundreds of recycled sites (began FDR - late 80s, began wide stabilization - early 2000s.)	Every paving site has RAP. NH completes about $1M of FDR annually.		There are some recycled pavements (FDR) (without subsequent rehabilitation).	Yes	
Any instrumented?	None instrumented.	Only the Miller sites are instrumented.	No	No	Not yet, but scheduled to be instrumented	Only Kanc. Some scheduled in RI.
10-Any Planned sites for this yr or next?	Construction planned for several in 2014. -Caratunk: Foaming -Waterford: PM-RAP -Presque Isle: PM-RAP -Poland: Cement Stabilized	Remaining paving projects.	FDR w/calc. next yr. Likely foamed asphalt & cement stabilized FDR in 2 yrs.	No	No	

	ME	NH	MA	CT	RI	Comments
	-Others					
10-contact person & contact info	Scott Bickford Asst. Program Manager – Highway Program 207-215-3817 Scott.Bickford@Maine.Gov	Denis Boisvert Chief of Materials Technology 603-271-1545 dboisvert@dot.state.nh.us	Kevin Fitzgerald Pavement Rehab Engr, 857 368-8990 Kevin.Fitzgerald@dot.state.ma.us	No contact provided	Michael Byrne Principal Civ Engr 401-222-2524 x4135 mpbyrne@dot.ri.gov	
11-Willing to send samples?	Yes, during the constr'n season	No	Don't have samples, but would be happy to collect during a project & provide to the local univ.	N/A	Yes	
Survey completed by:	Derek Nener-Plante Assistant Engineer, Pavement Design/Quality ME DOT 207-215-0849 derek.nener-plante@maine.gov	Denis Boisvert (Same as #10)	Edmund Naras Pavement Mgmt Engr Mass DOT 857 368-8989 Edmund.Naras@state.ma.us	Ed Block P.E. Supervising Engineer CT DOT (860) 594-2495 Edgardo.block@ct.gov	Michael Byrne (Same as #10)	

Appendix B

The figures in this appendix show the measured FWD deflections at each sensor location along with the deflections predicted using the WinJULEA software with the given layer properties. These figures support the forward calculation summary presented in section 3.2.



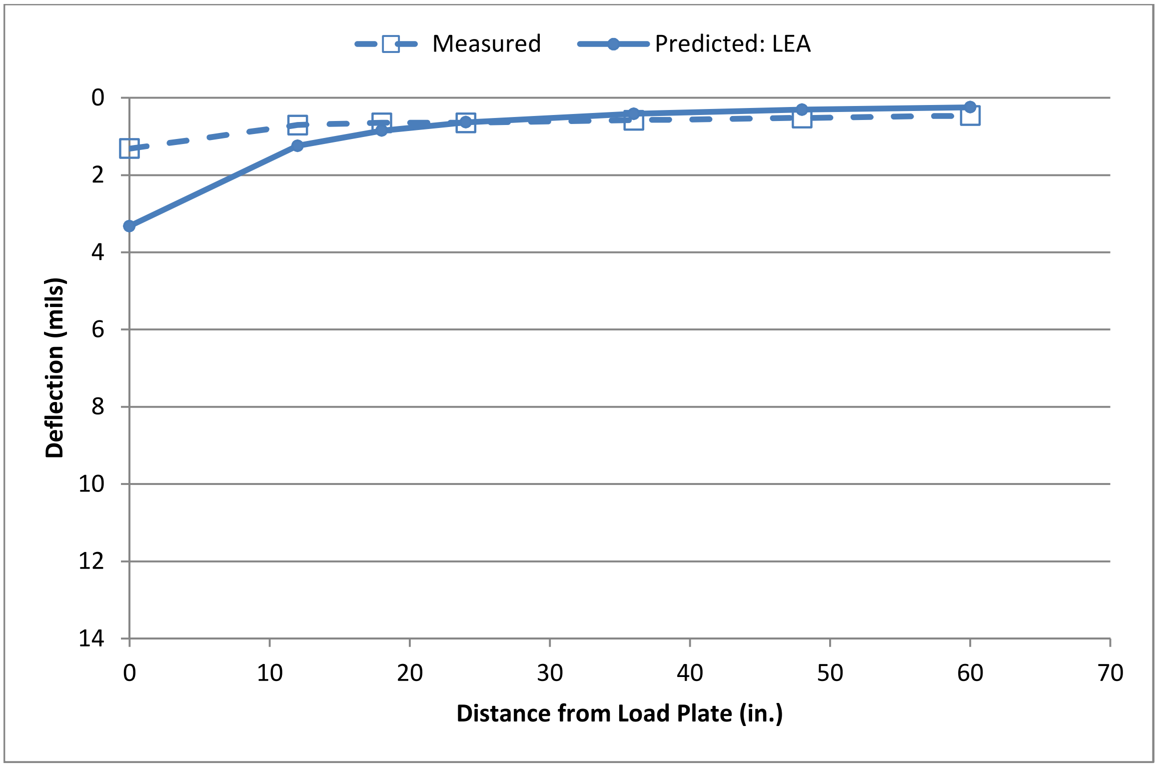
Auburn, ME 10/15/14 Baseline (after Re-construction)

3" HMA E = 500,000 psi

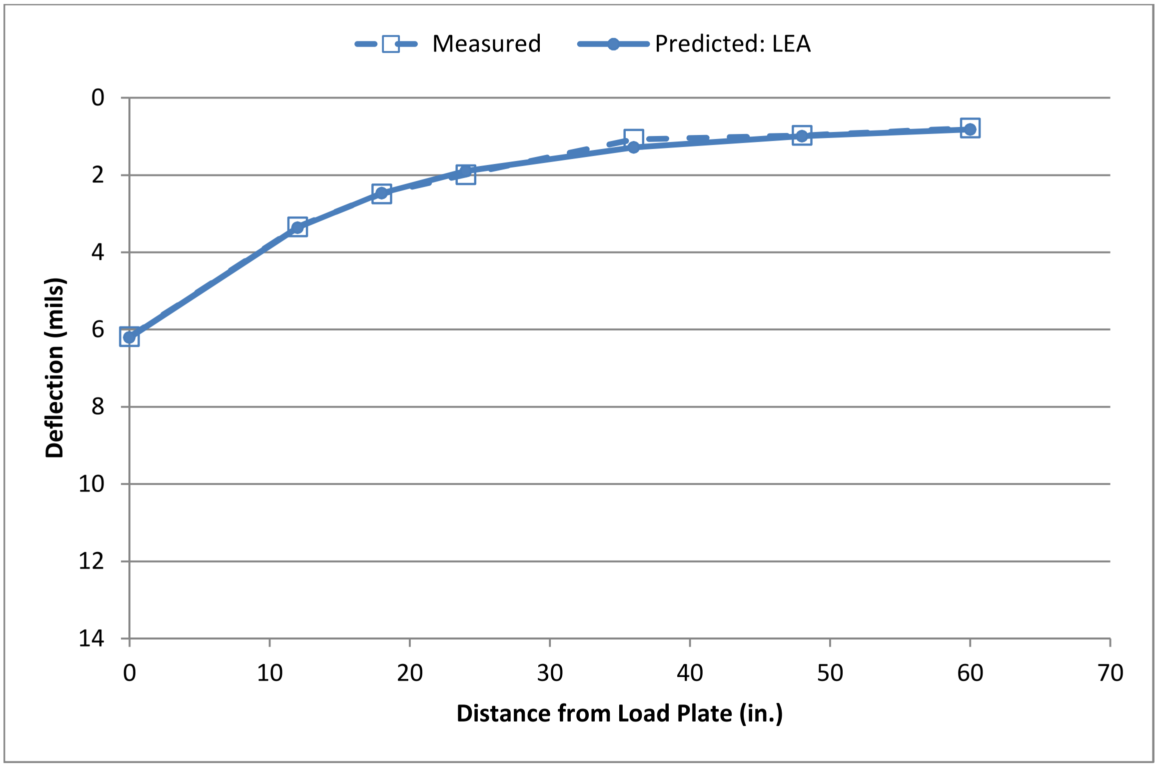
6" FDR (Foamed Asphalt) E = 300,000 psi

30" Old Fill (Base) E = 25,000 psi

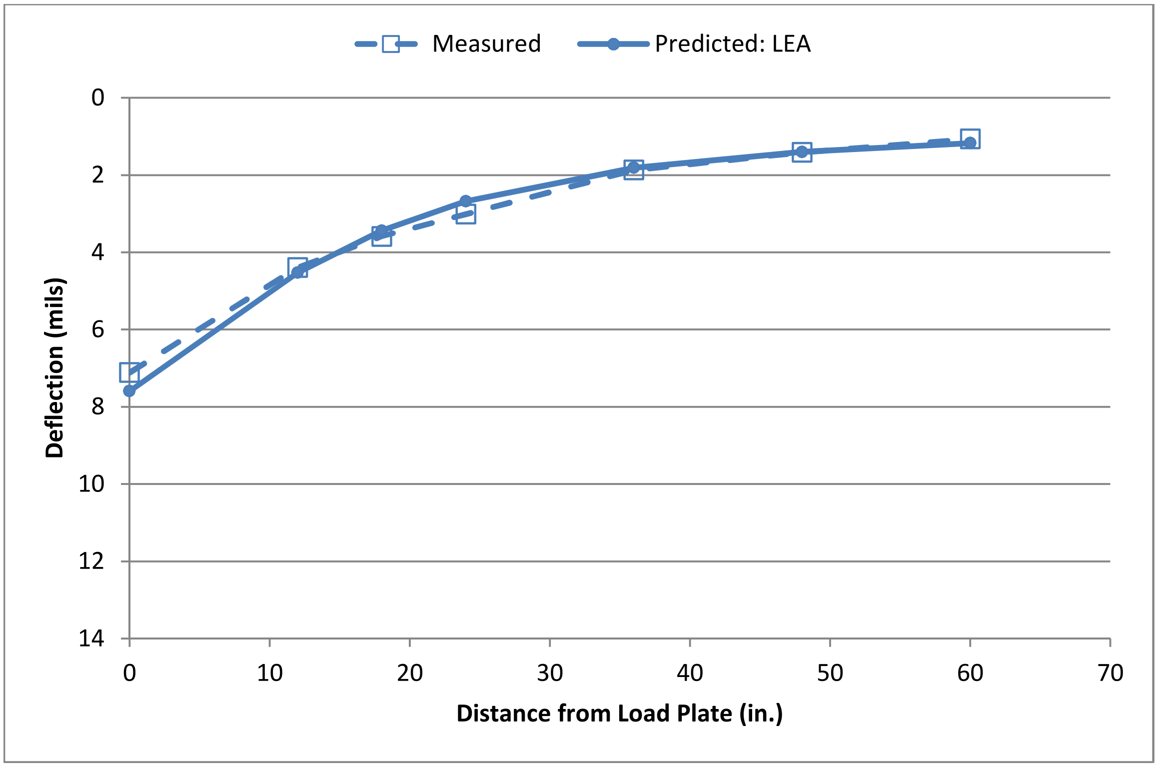
Subgrade E = 25,000 psi



Auburn, ME	03/03/15 Frozen
3" HMA	E = 500,000 psi
6" FDR (Foamed Asphalt)	E =300,000 psi
30" Old Fill (Base)	E = 169,500 psi
Subgrade	E = 169,500 psi

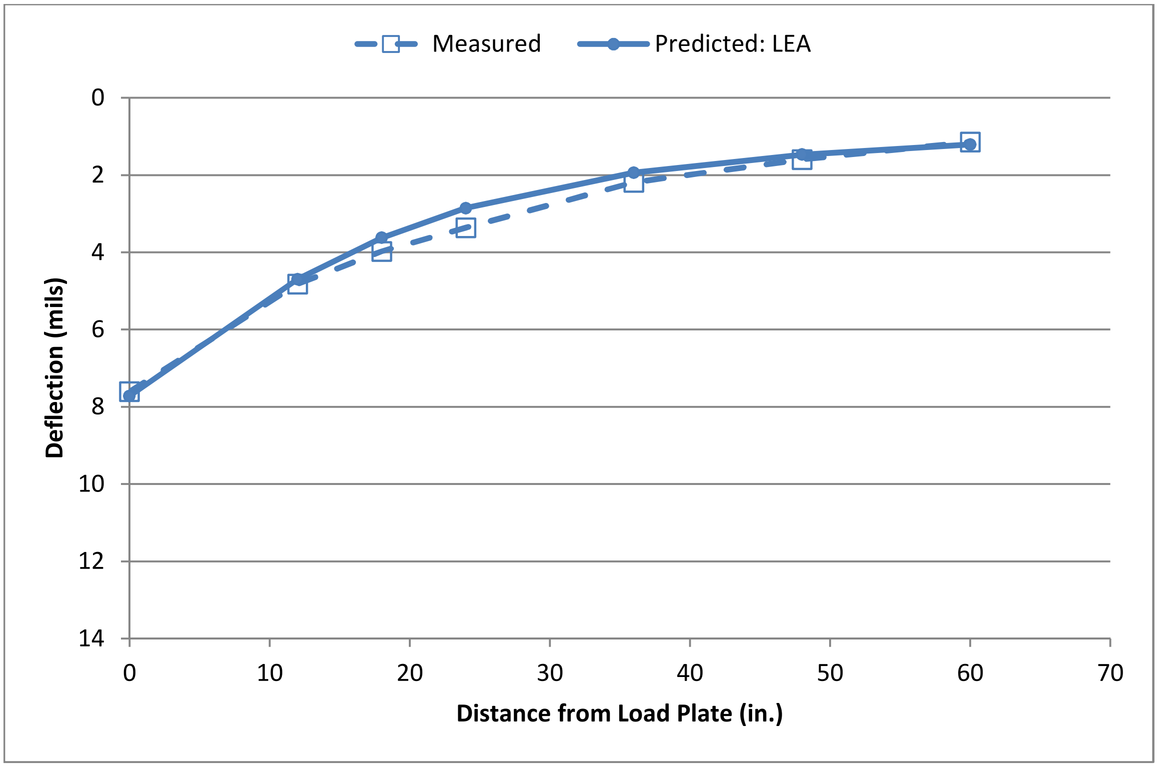


Auburn, ME	03/11/15 Thawed to about 13"	
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E =300,000 psi	
30" Old Fill (Base)	6" E = 32,000 psi	24" E = 100,000 psi
Subgrade	E = 50,000 psi	

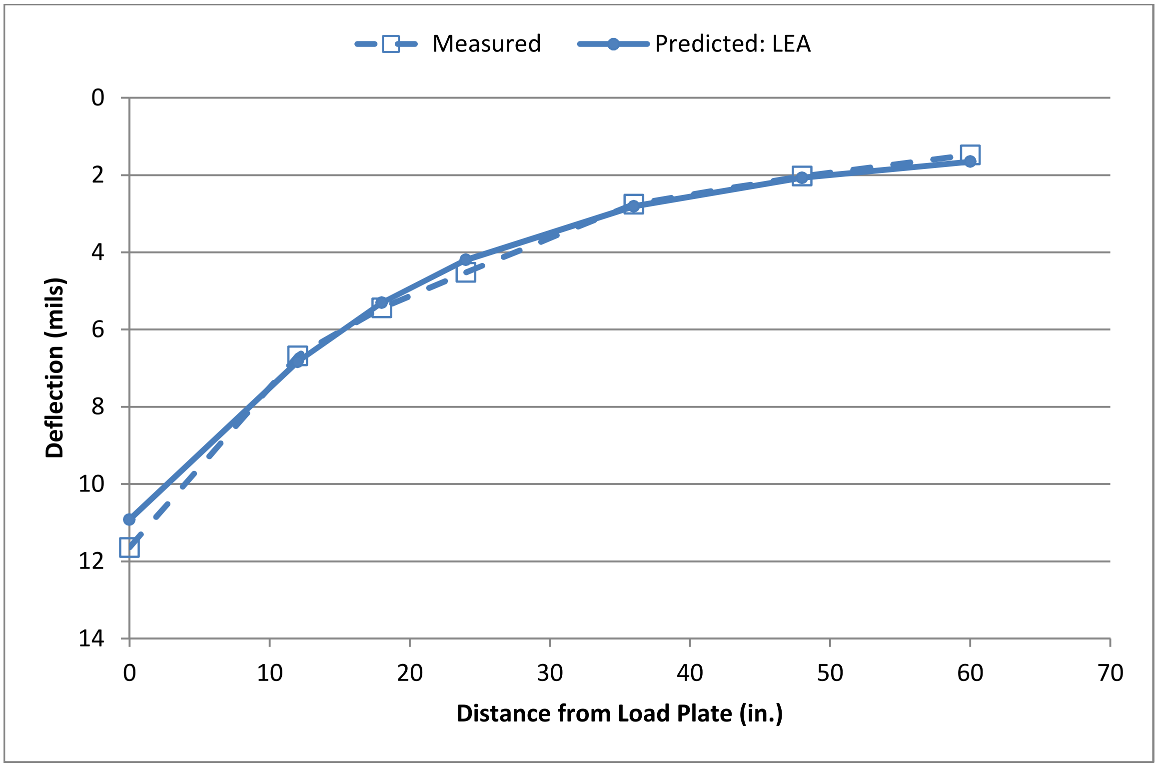


Auburn, ME	03/16/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E =300,000 psi	
30" Old Fill (Base)	12" E = 28,000 psi	18" E = 100,000 psi
Subgrade	18" E = 50,000 psi	E = 33,000 psi

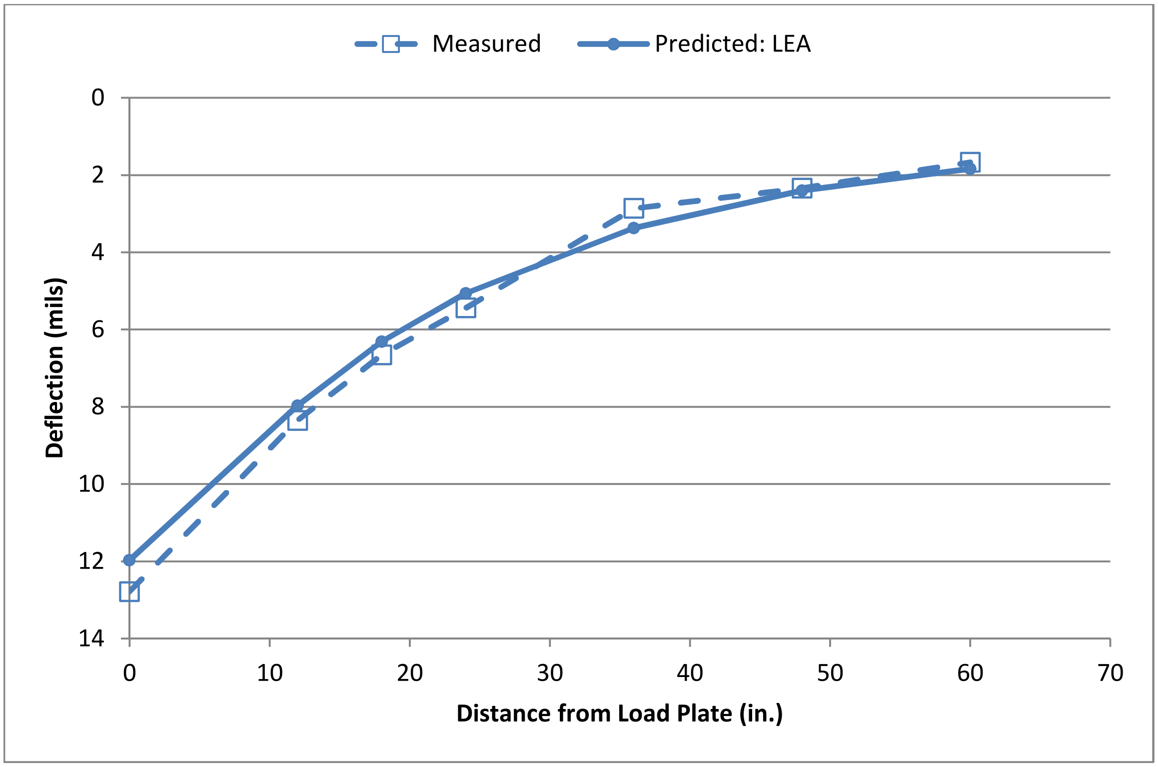
Auburn_SUMMARY_Forward Calculation-Modulus Values.xlsx



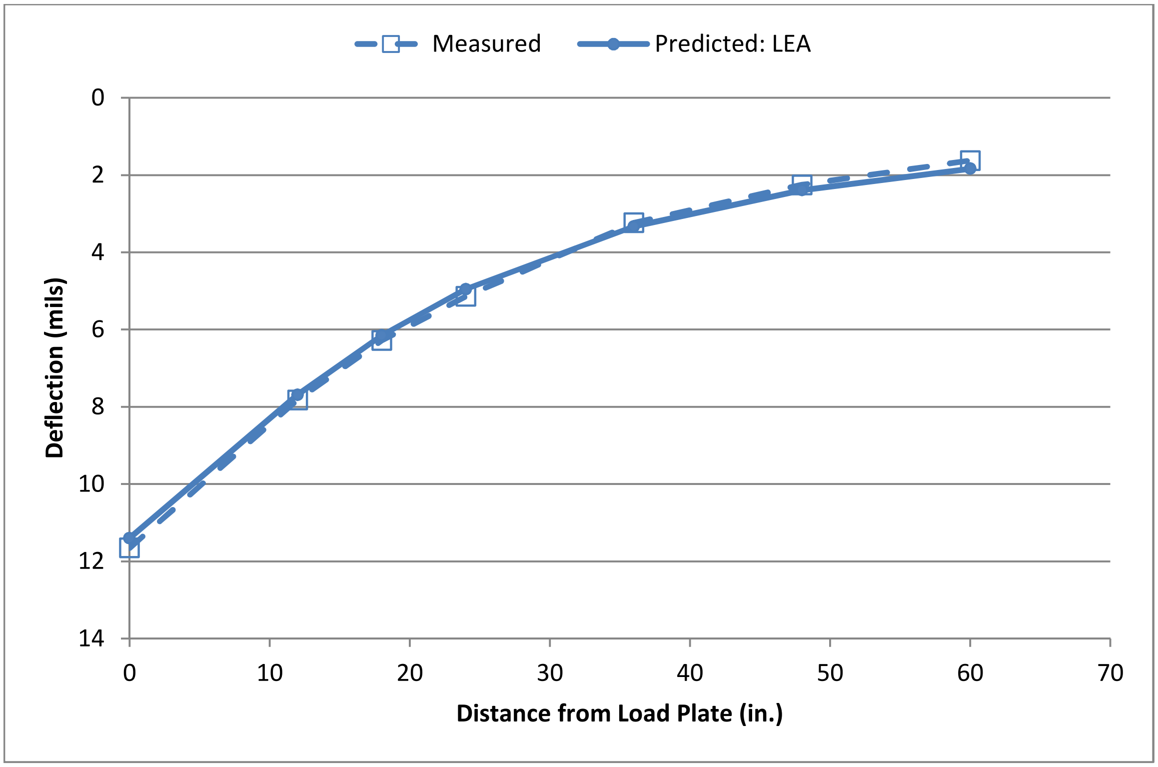
Auburn, ME	03/20/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E =300,000 psi	
30" Old Fill (Base)	20" E = 35,000 psi	10" E = 100,000 psi
Subgrade	17" E = 50,000 psi	E = 32,000 psi



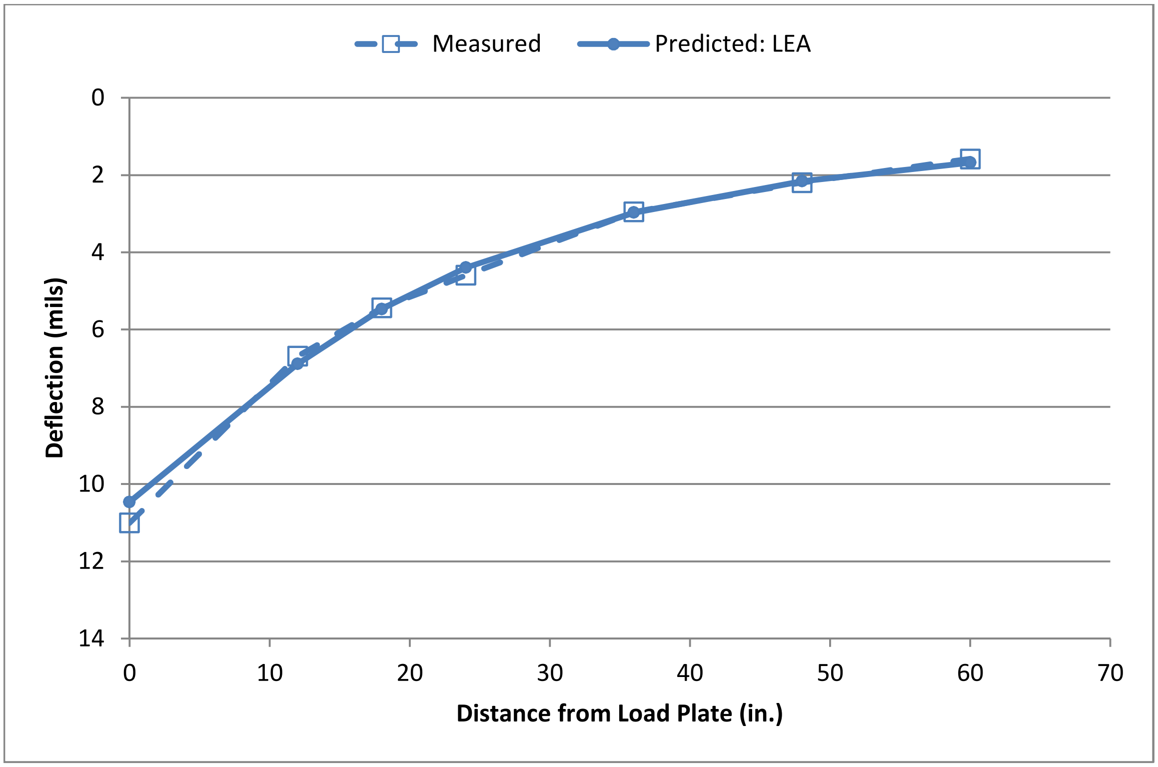
Auburn, ME	03/27/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E =200,000 psi	
30" Old Fill (Base)	E = 25,000 psi	
Subgrade	13" E = 50,000 psi	E = 24,000 psi



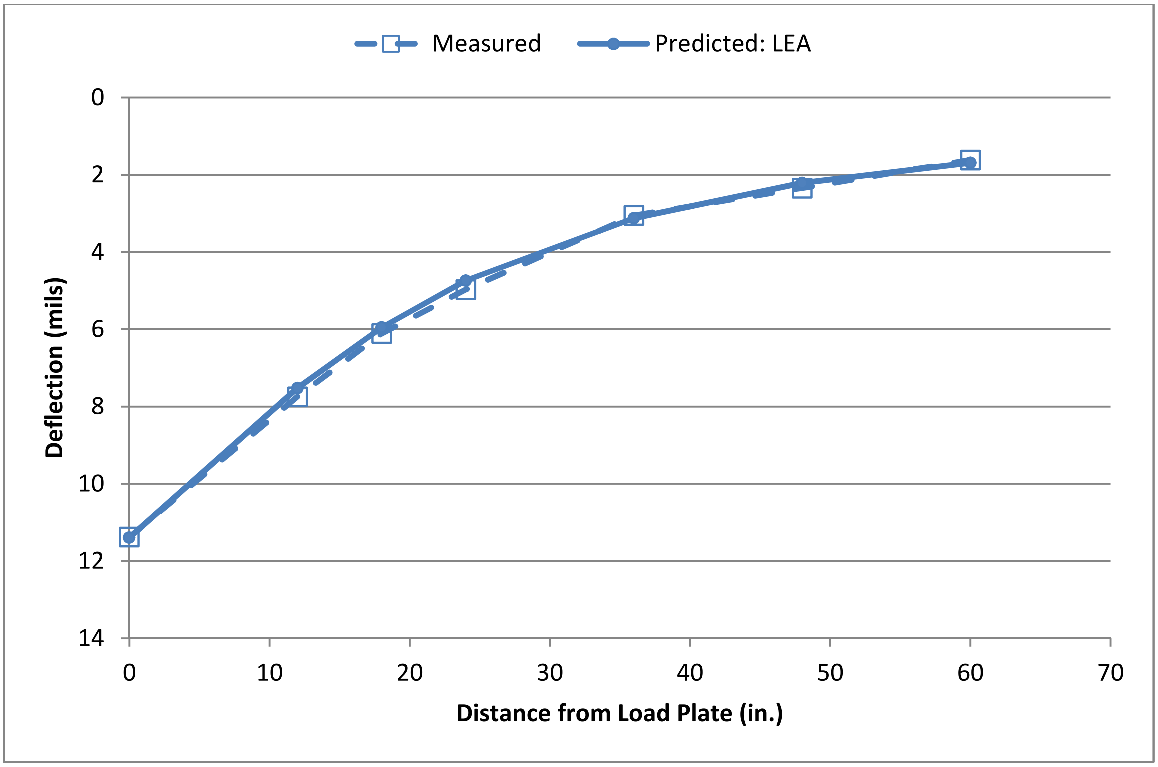
Auburn, ME	03/31/15 All layers just Thawed
3" HMA	E = 500,000 psi
6" FDR (Foamed Asphalt)	E = 230,000 psi
30" Old Fill (Base)	E = 20,000 psi
Subgrade	E = 23,000 psi



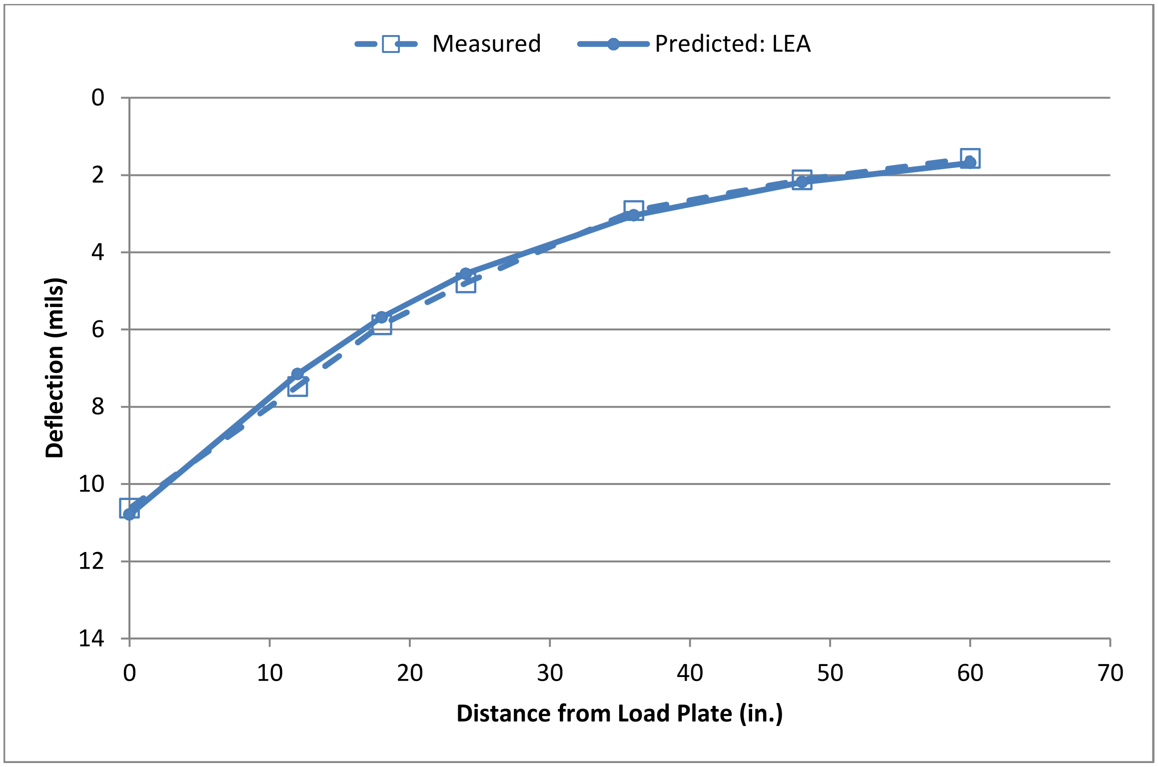
Auburn, ME	04/03/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 260,000 psi	
30" Old Fill (Base)	E = 21,000 psi	
Subgrade	E = 23,000 psi	



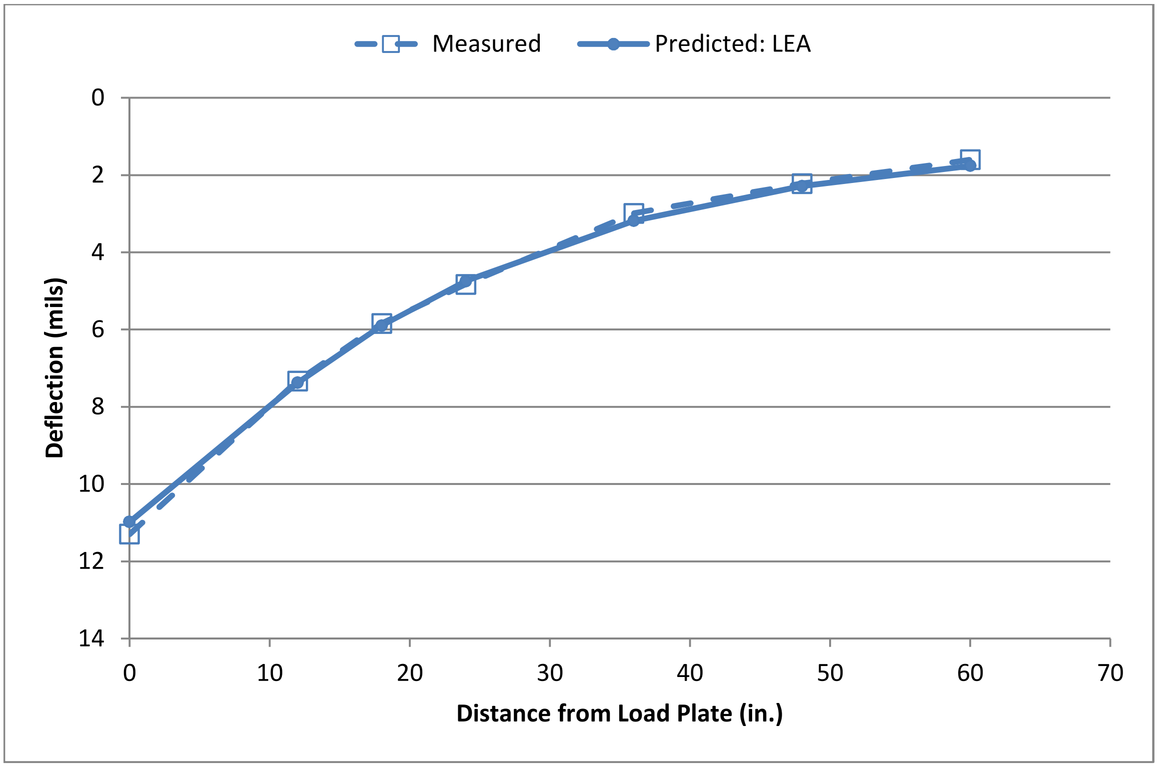
Auburn, ME	04/10/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 270,000 psi	
30" Old Fill (Base)	E = 25,000 psi	
Subgrade	E = 25,000 psi	



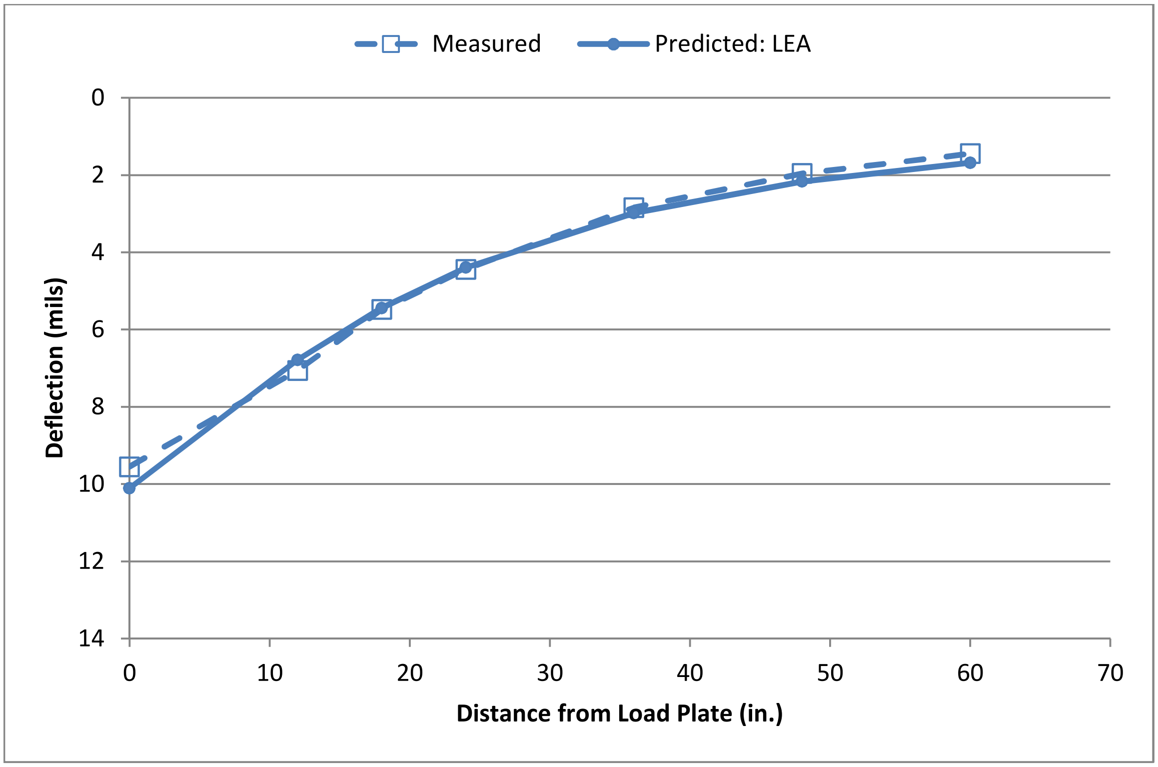
Auburn, ME	04/15/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 240,000 psi	
30" Old Fill (Base)	E = 21,000 psi	
Subgrade	E = 25,000 psi	



Auburn, ME	04/17/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 260,000 psi	
30" Old Fill (Base)	E = 23,000 psi	
Subgrade	E = 25,000 psi	

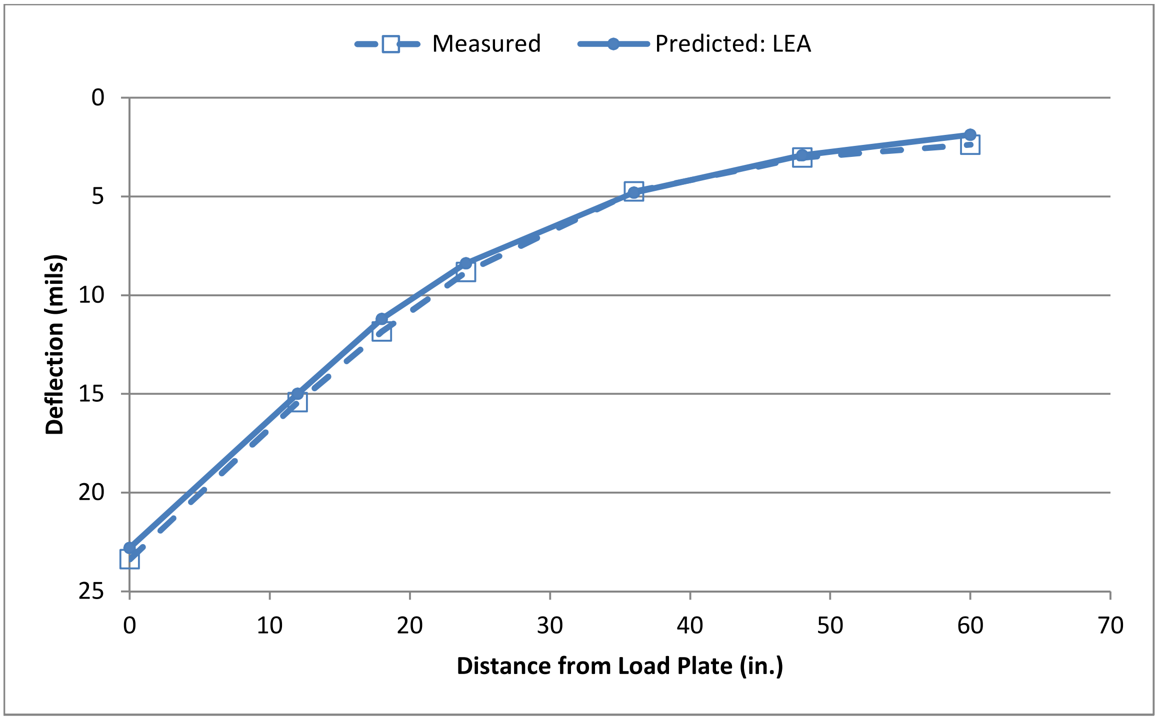


Auburn, ME	04/21/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 270,000 psi	
30" Old Fill (Base)	E = 22,000 psi	
Subgrade	E = 24,000 psi	



Auburn, ME	06/05/15	0
3" HMA	E = 500,000 psi	
6" FDR (Foamed Asphalt)	E = 300,000 psi	
30" Old Fill (Base)	E = 25,000 psi	
Subgrade	E = 25,000 psi	

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME 05/14/14 Prior to Re-Construction

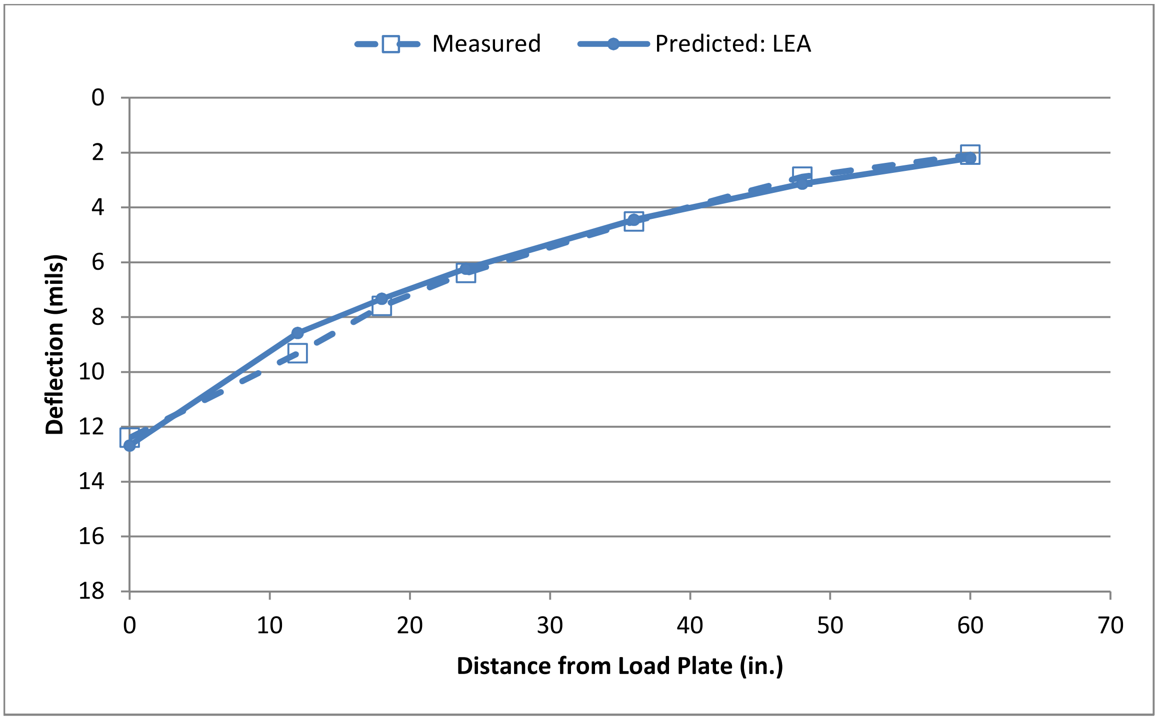
6" Old AC E = 300,000 psi

12" Old Fill/Base E = 13,000 psi

80" Subgrade E = 10,000 psi

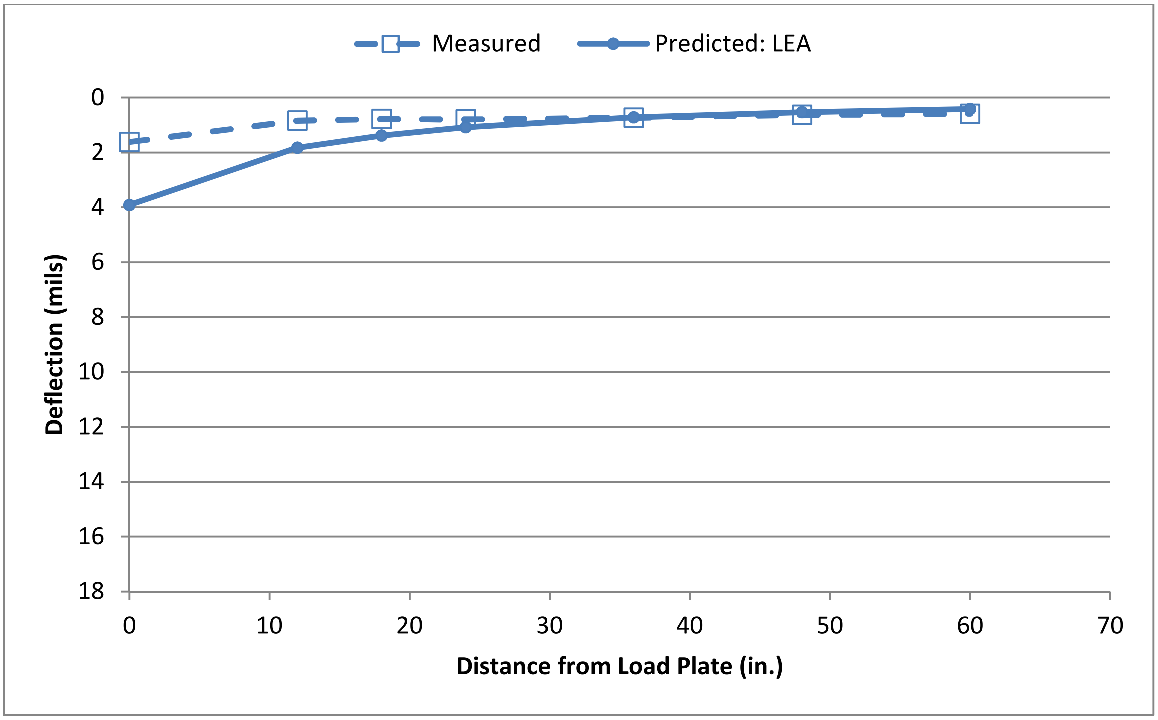
Stiff Layer E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



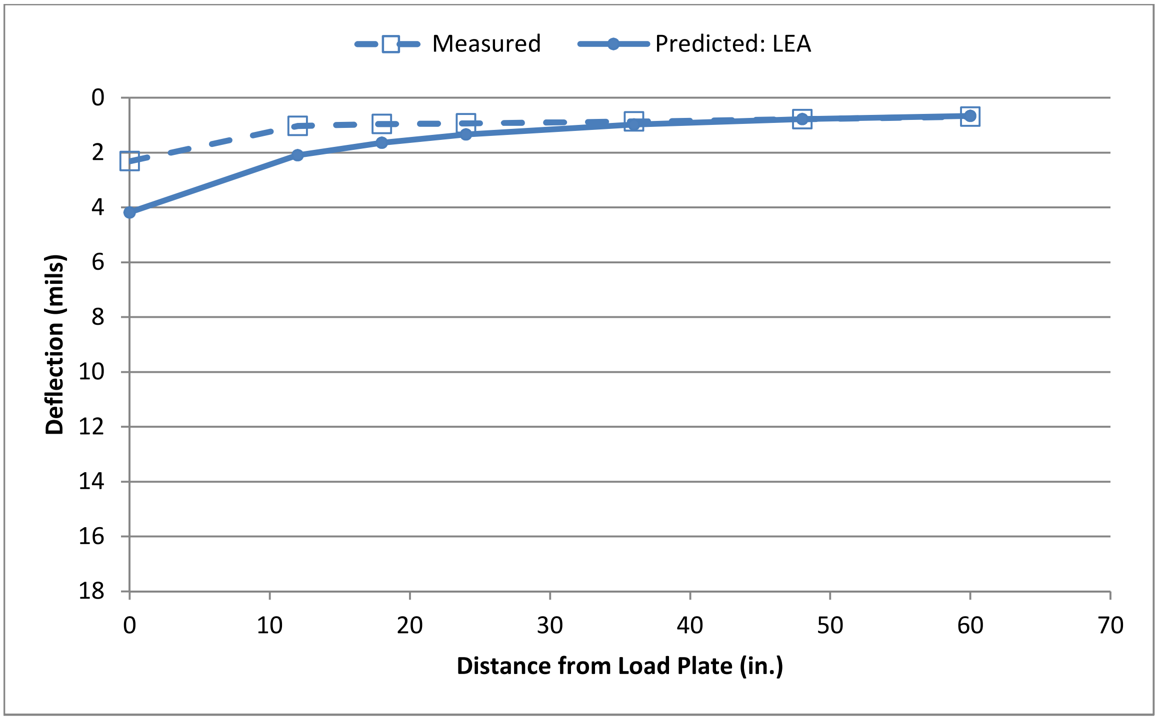
Waterford, ME	10/15/14 Baseline (after Re-construction)
1.5" HMA	E = 500,000 psi
5" PMRAP	E = 160,000
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E = 13,000
80" Subgrade	E = 11,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



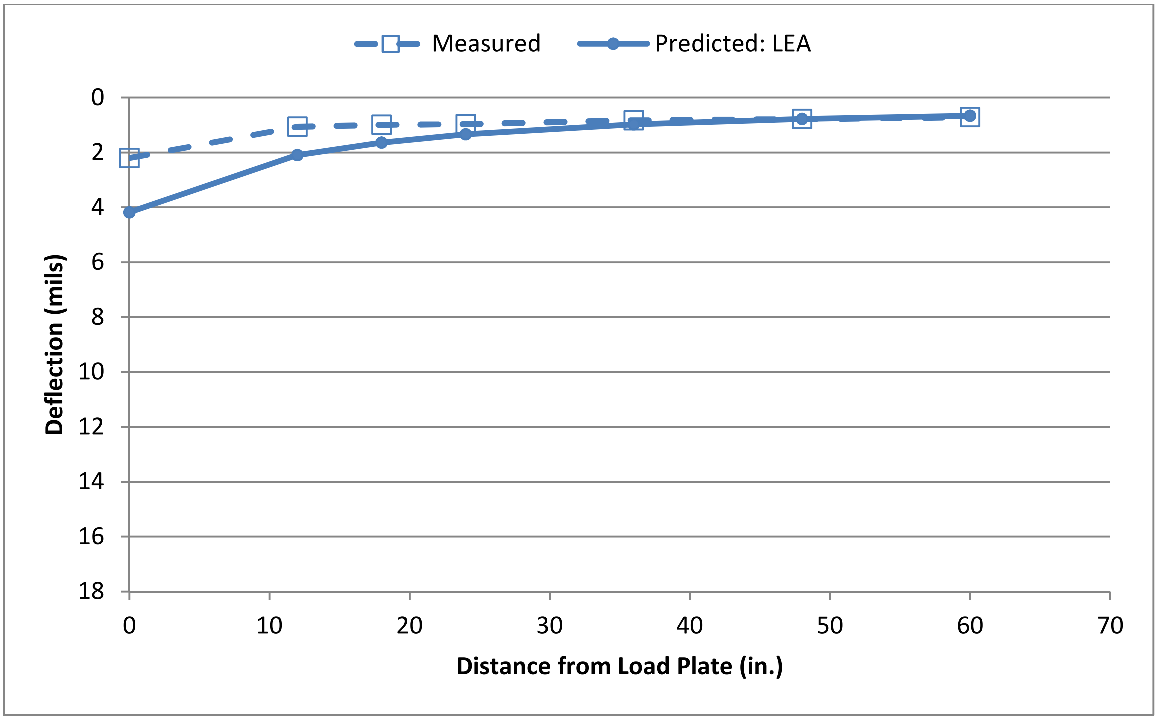
Waterford, ME	03/03/15	All layers Frozen
1.5" HMA	E = 500,000 psi	
5" PMRAP	E = 350,000	
6" Old AC	E = 300,000 psi	
12" Old Fill/Base	E = 100,000	
80" Subgrade	E = 100,000 psi	
Stiff Layer	E = 100,000 psi	

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME	03/11/15
1.5" HMA	E = 500,000 psi
5" PMRAP	E =350,000 psi
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =100,000 psi
80" Subgrade	E =100,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME 03/16/15 Refrozen

1.5" HMA E = 500,000 psi

5" PMRAP E =350,000 psi

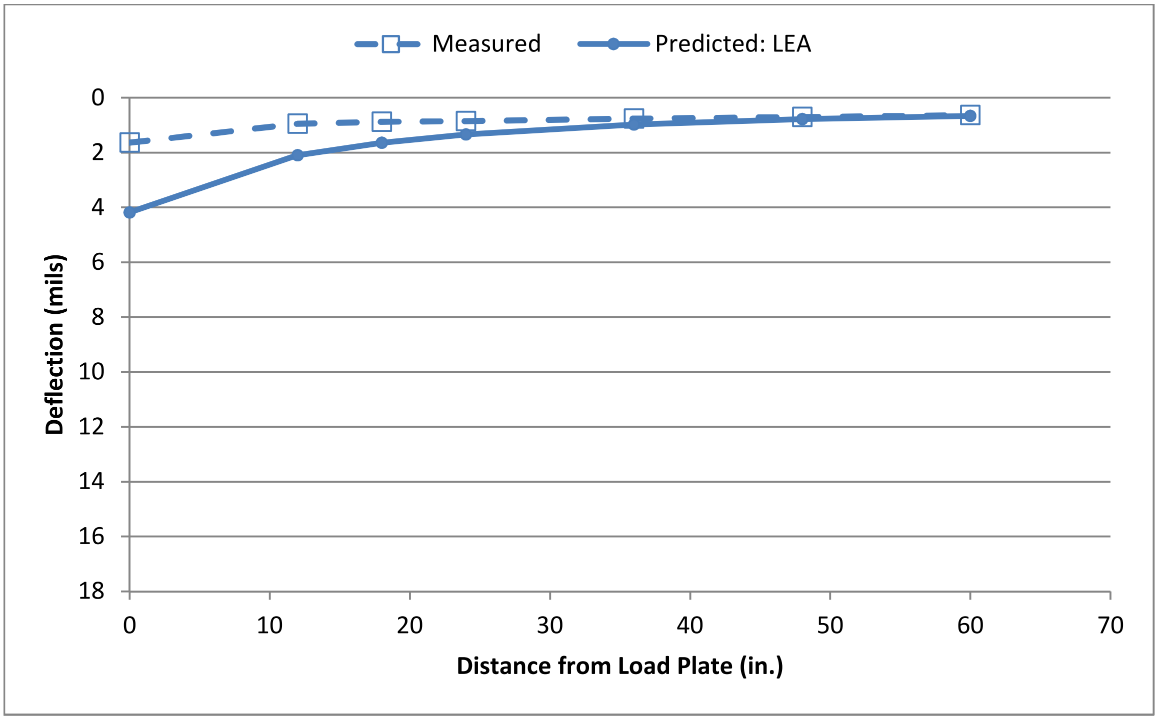
6" Old AC E = 300,000 psi

12" Old Fill/Base E =100,000 psi

80" Subgrade E =100,000 psi

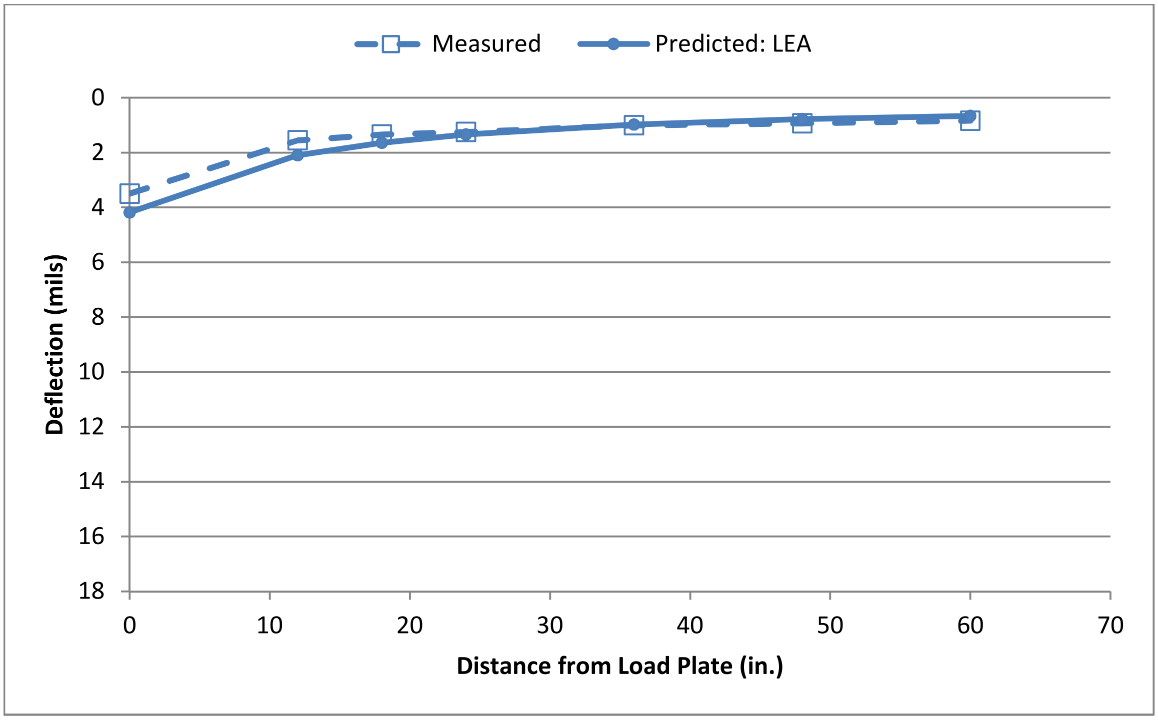
Stiff Layer E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



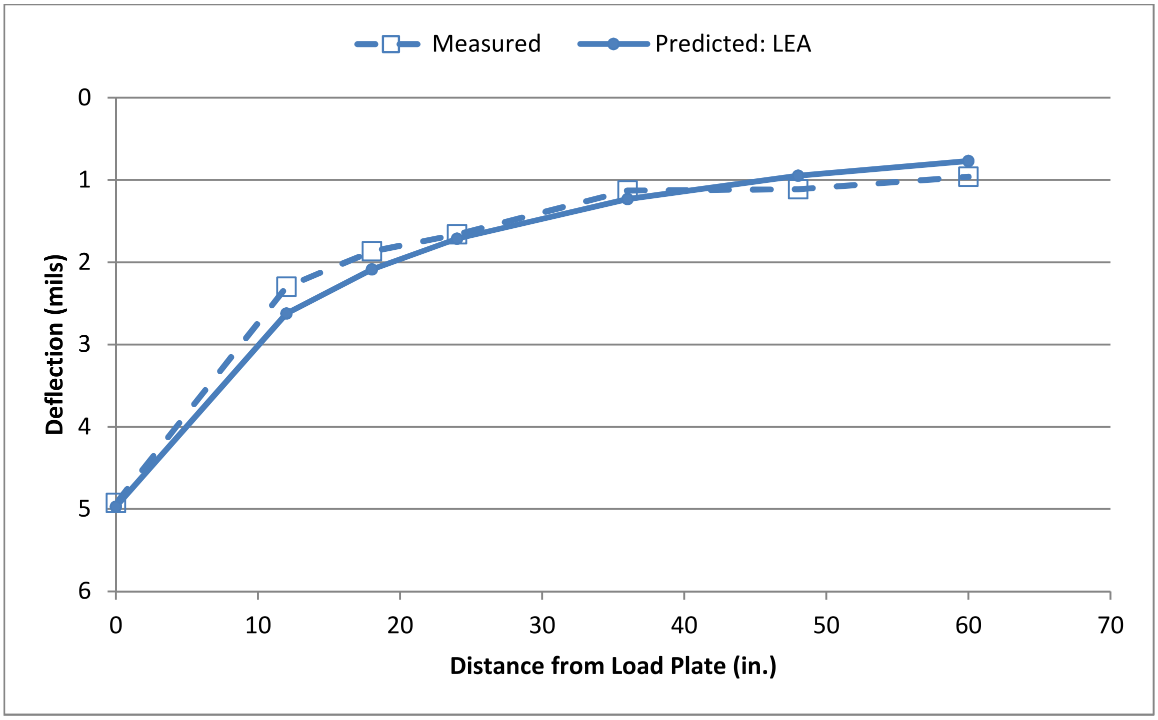
Waterford, ME	03/20/15 Refrozen
1.5" HMA	E = 500,000 psi
5" PMRAP	E =350,000 psi
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =100,000 psi
80" Subgrade	E =100,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



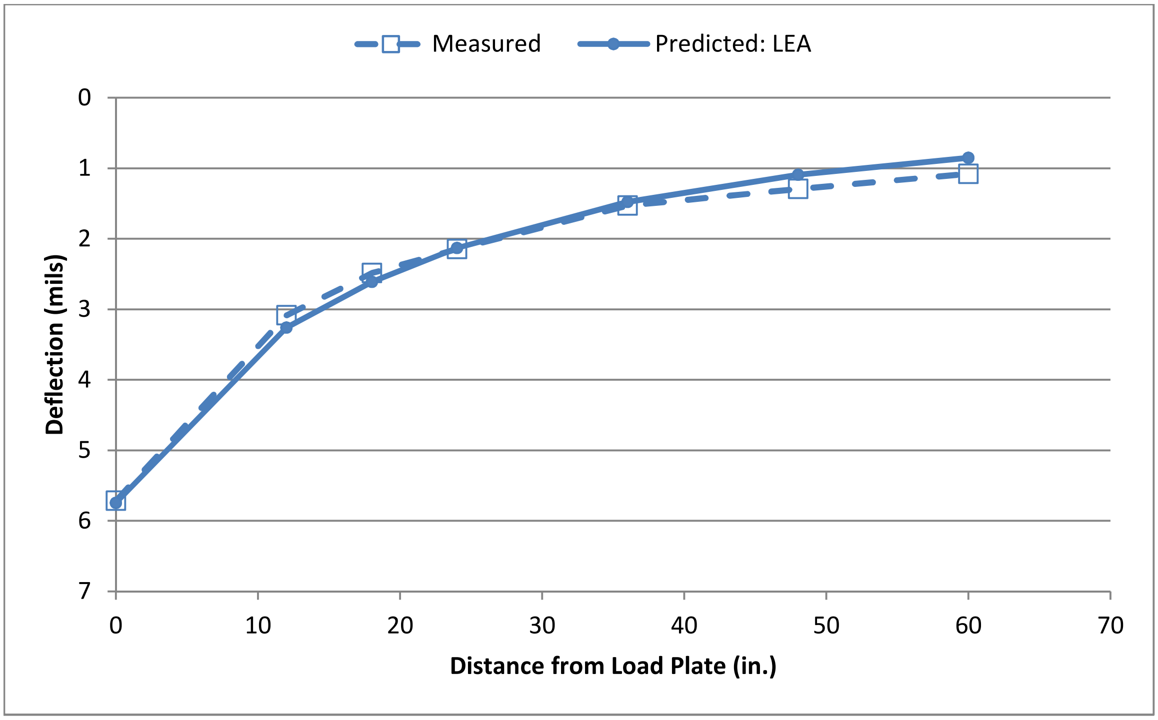
Waterford, ME	03/27/15 10.3" thawed
1.5" HMA	E = 500,000 psi
5" PMRAP	E =350,000 psi
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =100,000 psi
80" Subgrade	E =100,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME	03/31/15 13.2" thawed
1.5" HMA	E = 500,000 psi
5" PMRAP	E =300,000 psi
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =80,000 psi
80" Subgrade	E =65,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME 04/03/15 11.7" Thawed

1.5" HMA E = 500,000 psi

5" PMRAP E =300,000

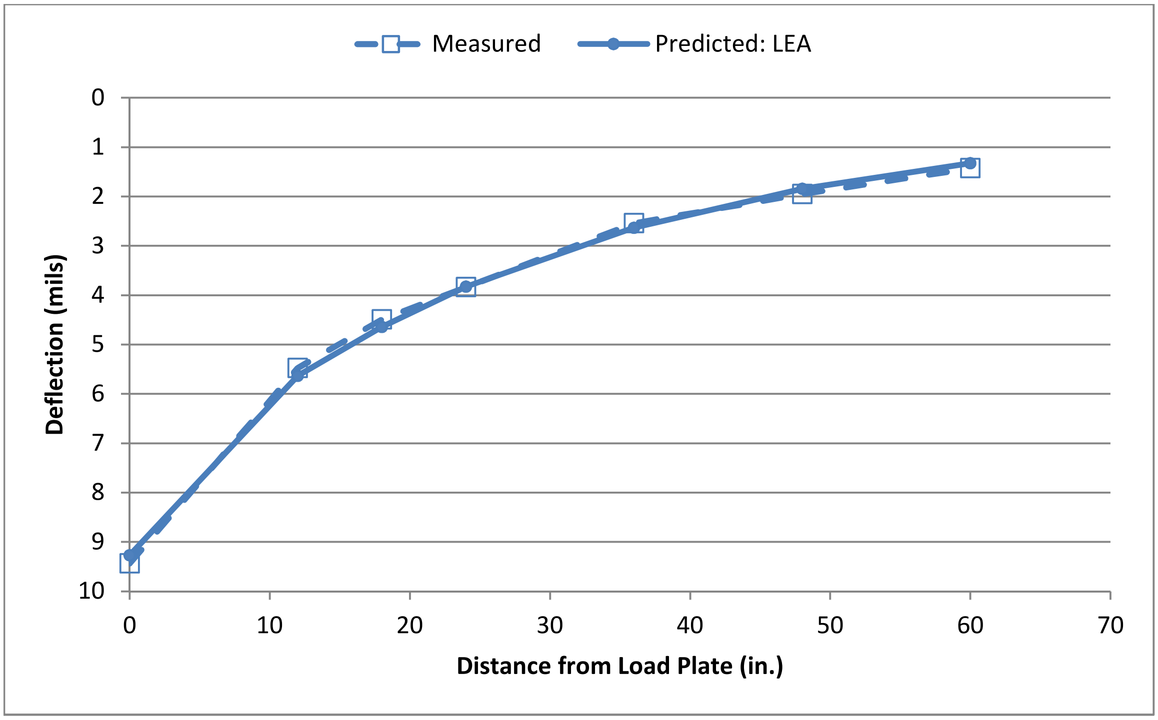
6" Old AC E = 300,000 psi

12" Old Fill/Base E = 50,000

80" Subgrade E = 50,000 psi

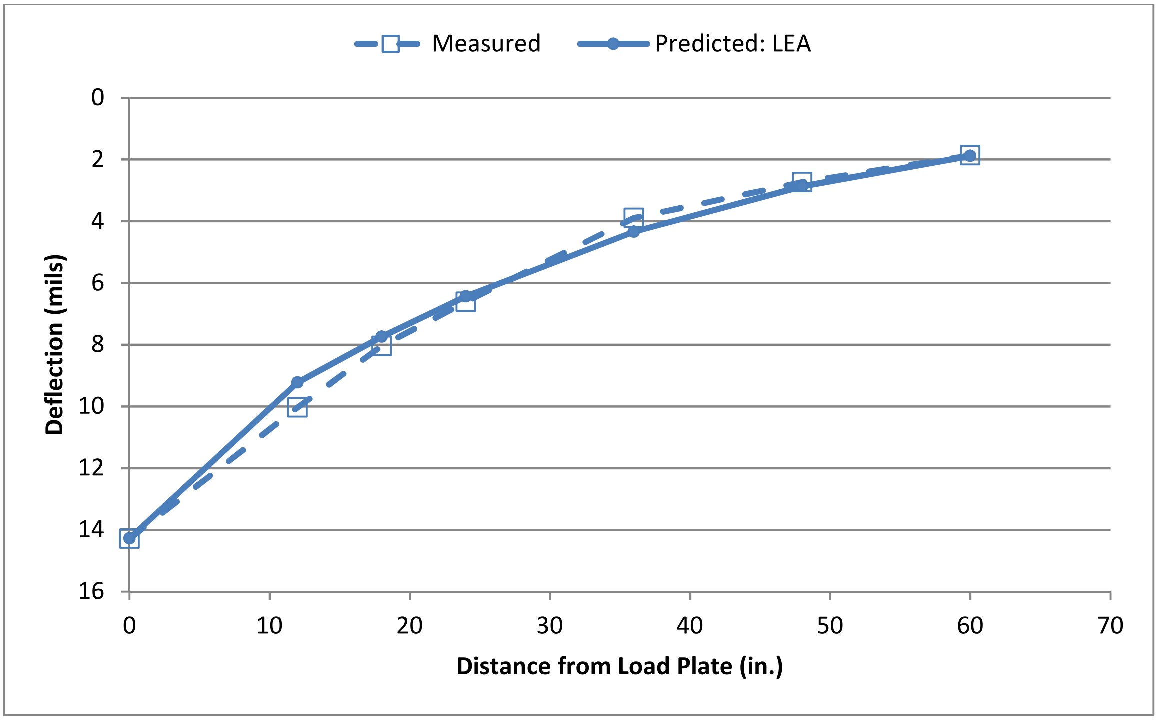
Stiff Layer E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



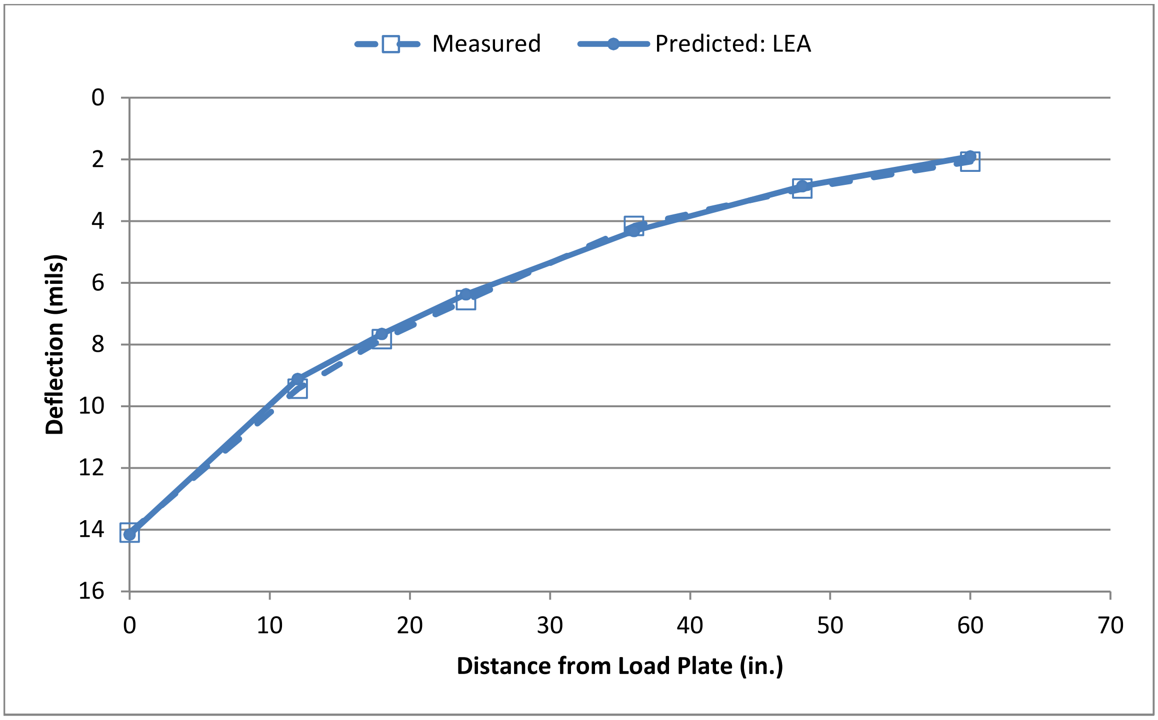
Waterford, ME	04/10/15 15.7" Thawed	
1.5" HMA	E = 500,000 psi	
5" PMRAP	E =180,000	
6" Old AC	E = 300,000 psi	
12" Old Fill/Base	3.2":E = 15,000	8.8": E = 28,000
80" Subgrade	E = 22,000 psi	
Stiff Layer	E = 50,000 psi	

Waterford_SUMMARY_Forward Calculation-Modulus Values



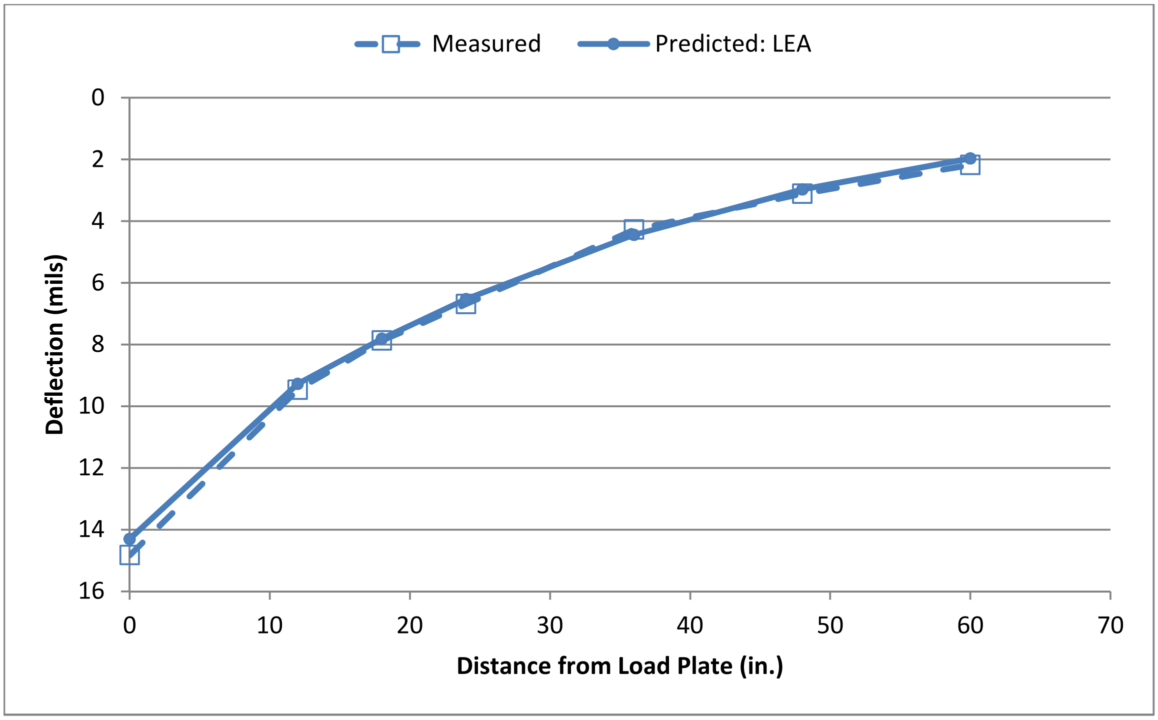
Waterford, ME	04/15/15 26" Thawed
1.5" HMA	E = 500,000 psi
5" PMRAP	E =120,000
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =5,000
80" Subgrade	E = 18,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME	04/17/15 34" Thawed	
1.5" HMA	E = 500,000 psi	
5" PMRAP	E =120,000	
6" Old AC	E = 300,000 psi	
12" Old Fill/Base	E =5,500	
80" Subgrade	10": E = 13,000 psi	70": E = 16,000 psi
Stiff Layer	E = 50,000 psi	

Waterford_SUMMARY_Forward Calculation-Modulus Values



Waterford, ME 04/21/15 50" Thawed

1.5" HMA E = 500,000 psi

5" PMRAP E =120,000

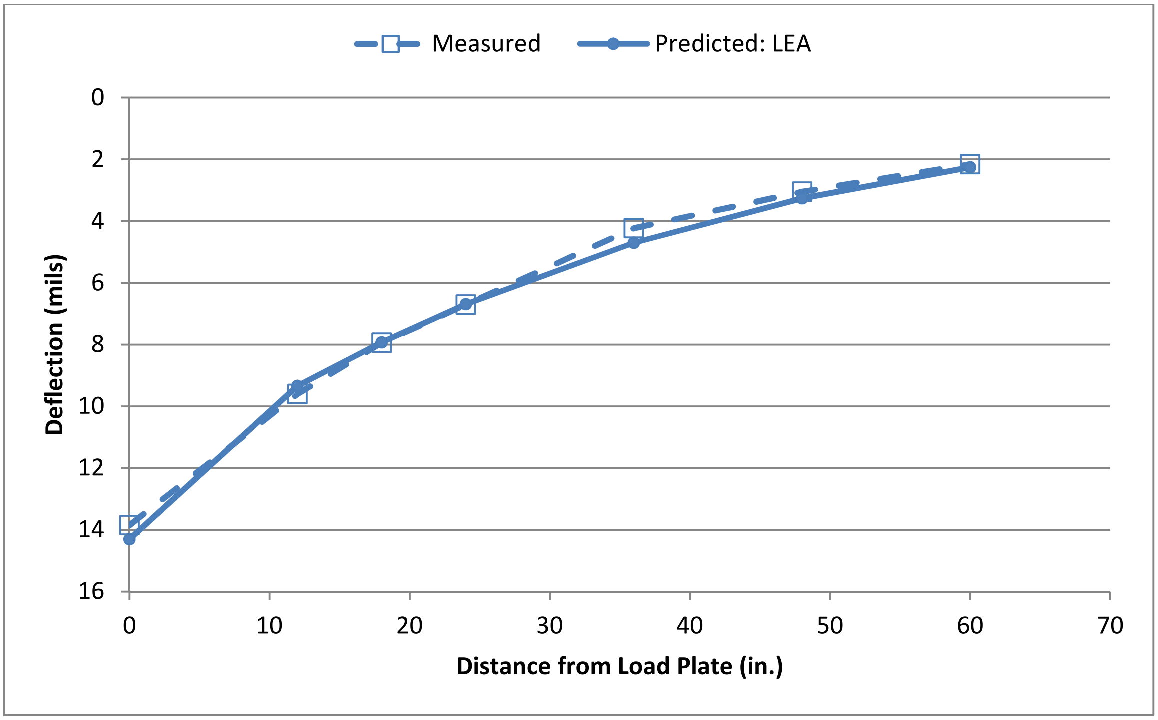
6" Old AC E = 300,000 psi

12" Old Fill/Base E =6,000

80" Subgrade 26": E = 12,000 psi 54": E = 16,000 psi

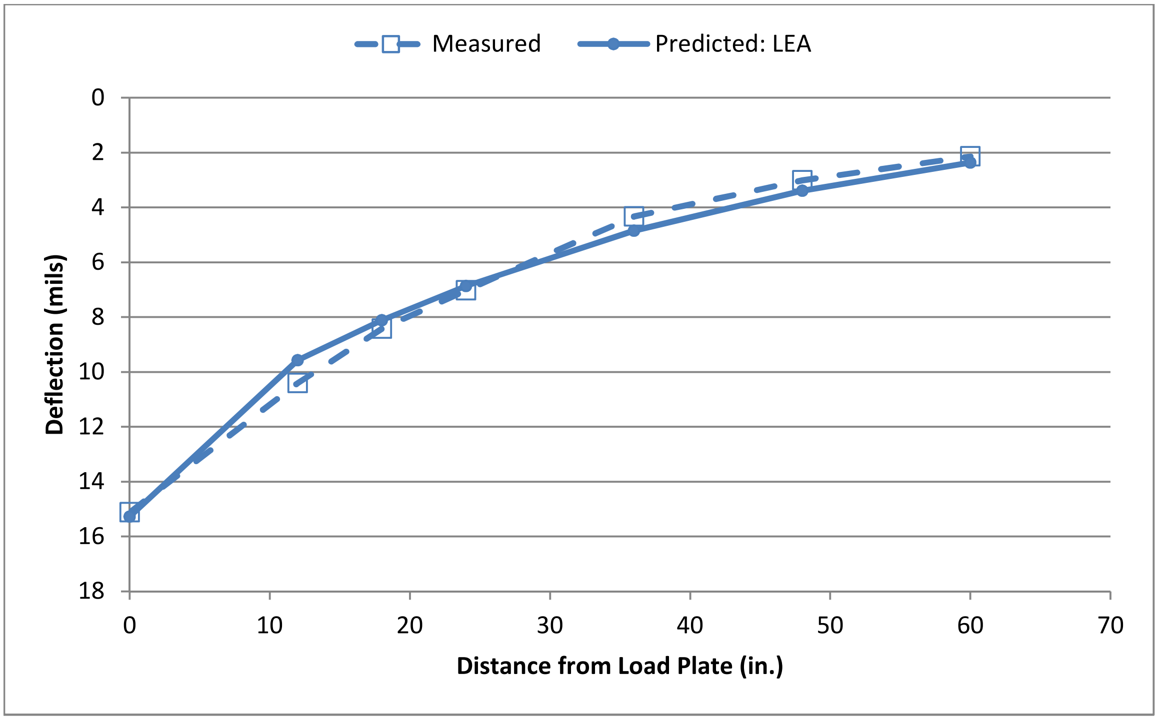
Stiff Layer E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



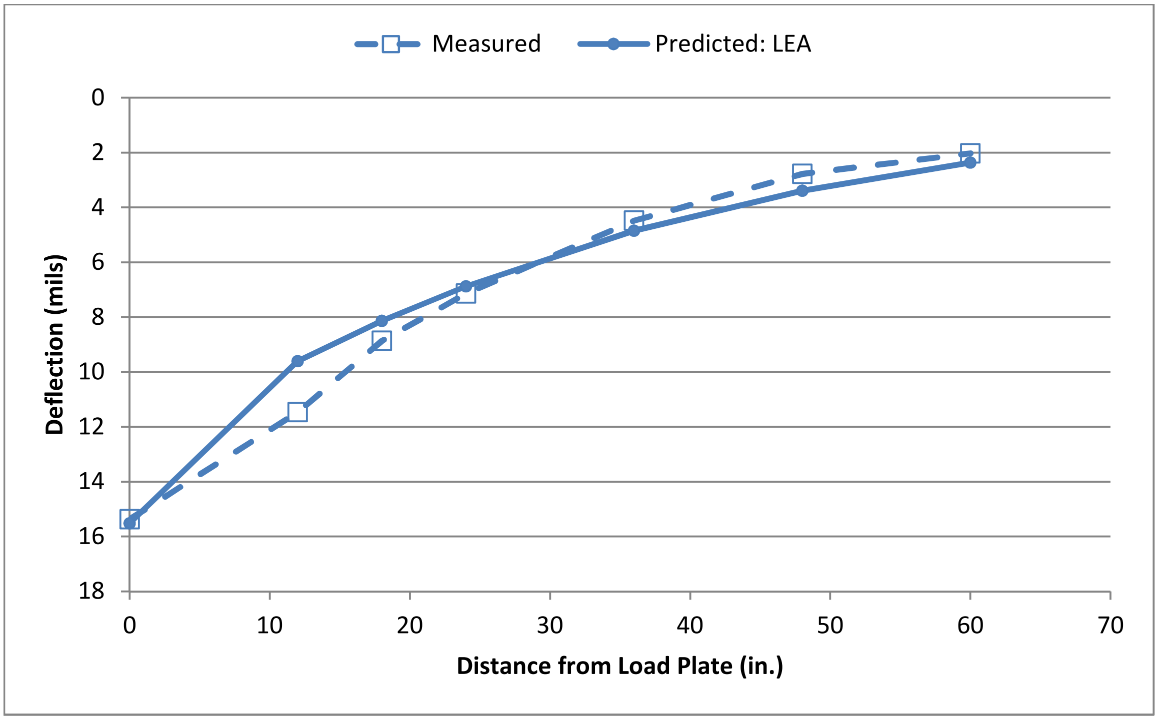
Waterford, ME	04/24/15 End of Thaw
1.5" HMA	E = 500,000 psi
5" PMRAP	E =120,000 psi
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =9,000 psi
80" Subgrade	E =11,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



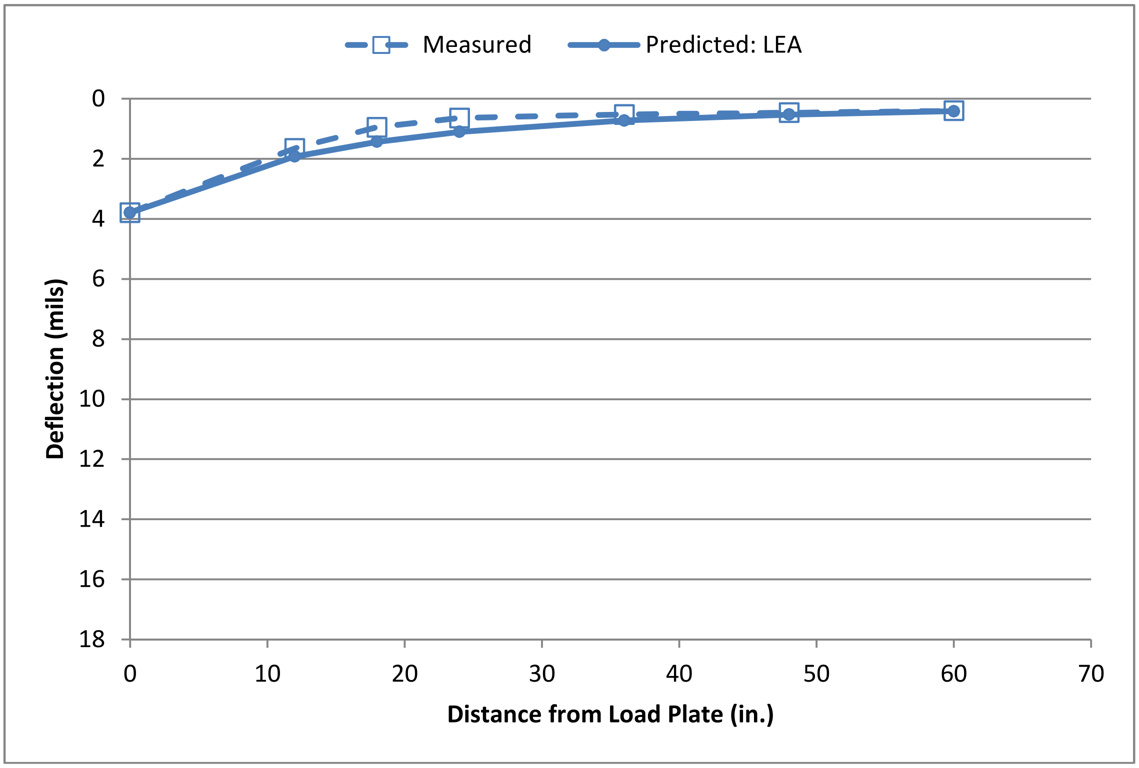
Waterford, ME	04/30/15
1.5" HMA	E = 500,000 psi
5" PMRAP	E =95,000
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =11,000
80" Subgrade	E = 10,000 psi
Stiff Layer	E = 50,000 psi

Waterford_SUMMARY_Forward Calculation-Modulus Values



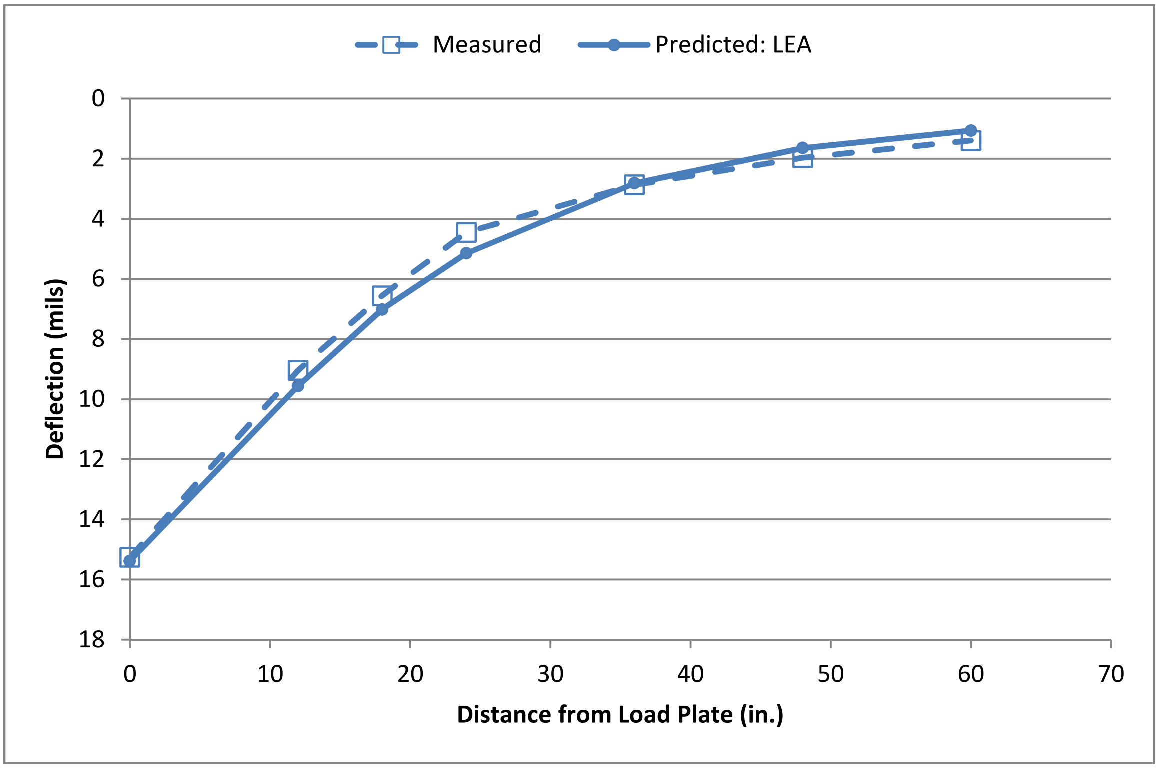
Waterford, ME	06/05/15 Partially (but not fully) Recovered?
1.5" HMA	E = 500,000 psi
5" PMRAP	E =90,000
6" Old AC	E = 300,000 psi
12" Old Fill/Base	E =11,000
80" Subgrade	E = 10,000 psi
Stiff Layer	E = 50,000 psi

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



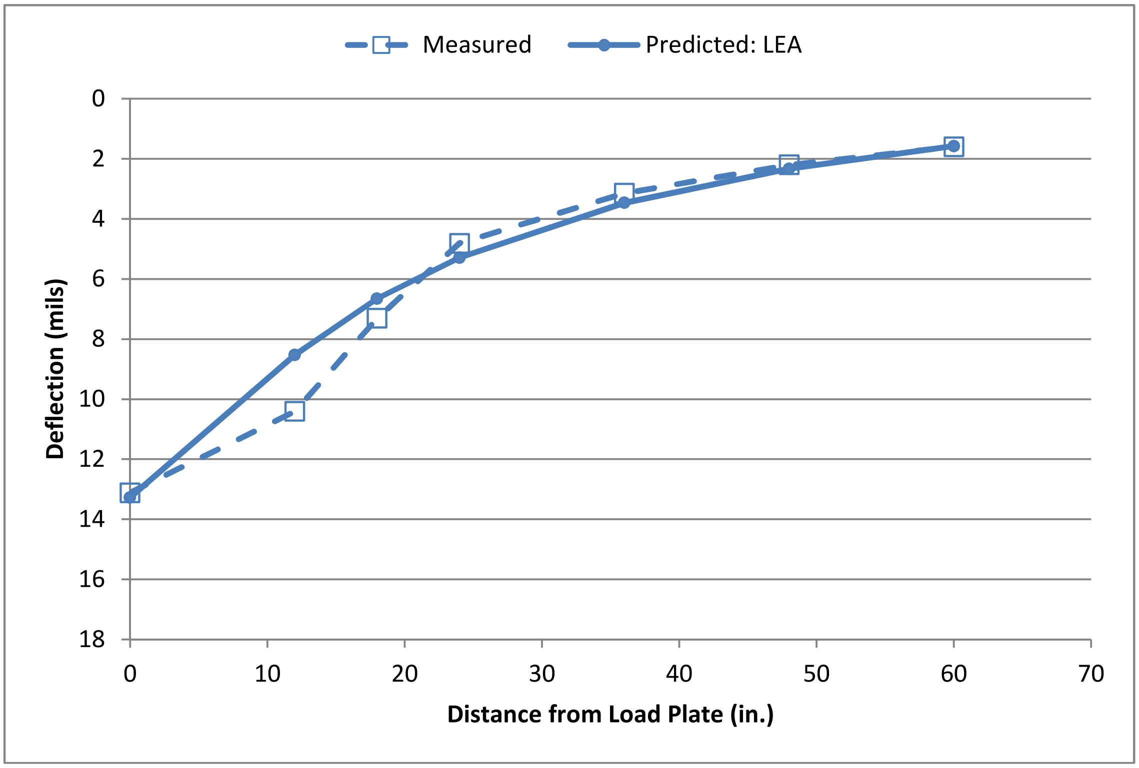
	K-2 (Kanc, NH)	03/31/15	Frozen (after thaw/re-freeze in CTB Base Layer)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - CTB**	E = 200,000	
3	28" Upper Subgrade	E = 100,000	
4	27" Lower Subgrade	E = 100,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



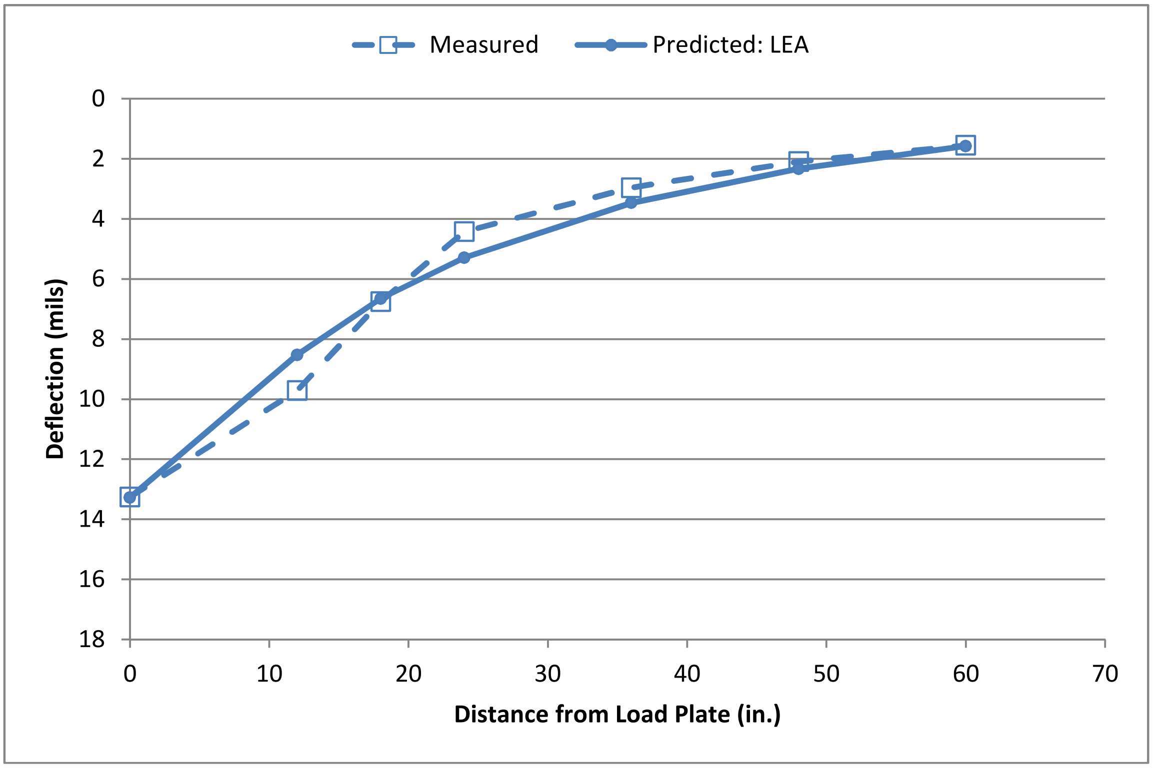
	K-2 (Kanc, NH)	04/24/15	Partly Frozen-Weak		
1	4" HMA	E = 500,000 psi	(Fixed)		
2	6" **FDR - CTB**	E = 80,000			
3	28" Upper Subgrade	E = 12,000			
4	23"+8" Lower Subgrade	E = 100000(	Frozen protic	E = 2000	Thawed Portion
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)		

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



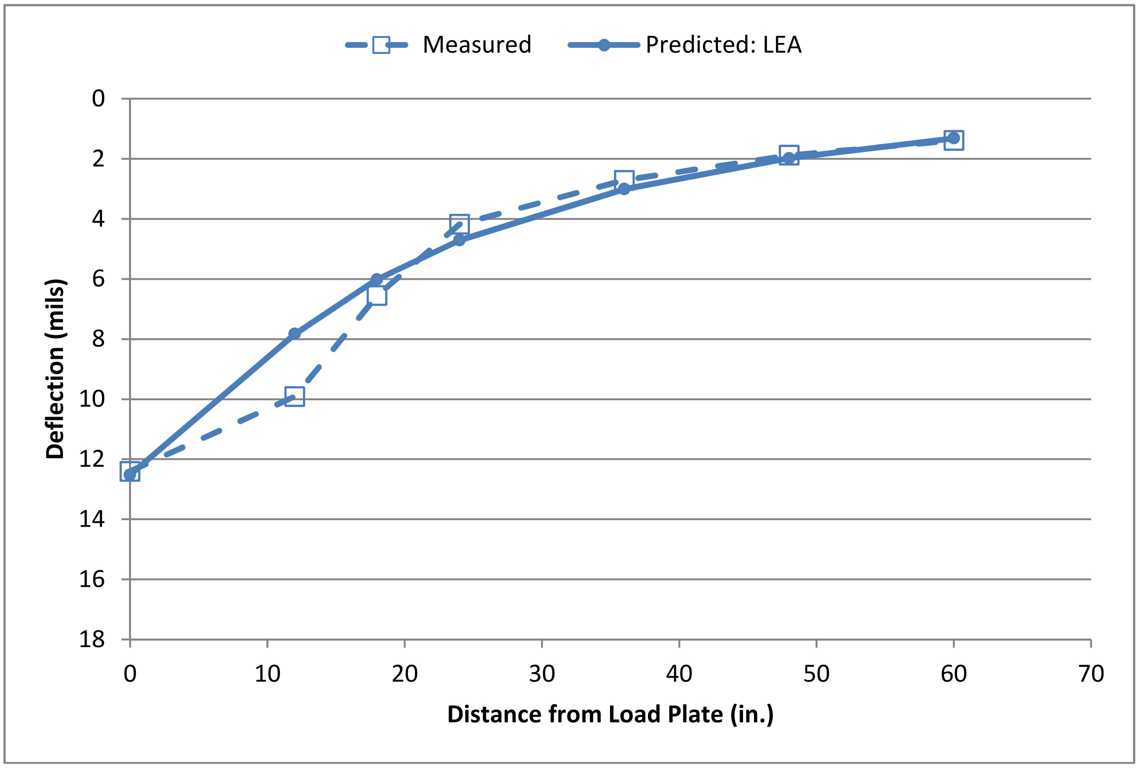
K-2 (Kanc, NH)	05/07/15	Thawed-Weak
1 4" HMA	E = 500,000 psi	(Fixed)
2 6" **FDR - CTB**	E = 100,000	
3 28" Upper Subgrade	E = 24,000	
4 27" Lower Subgrade	E = 5500	
5 Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



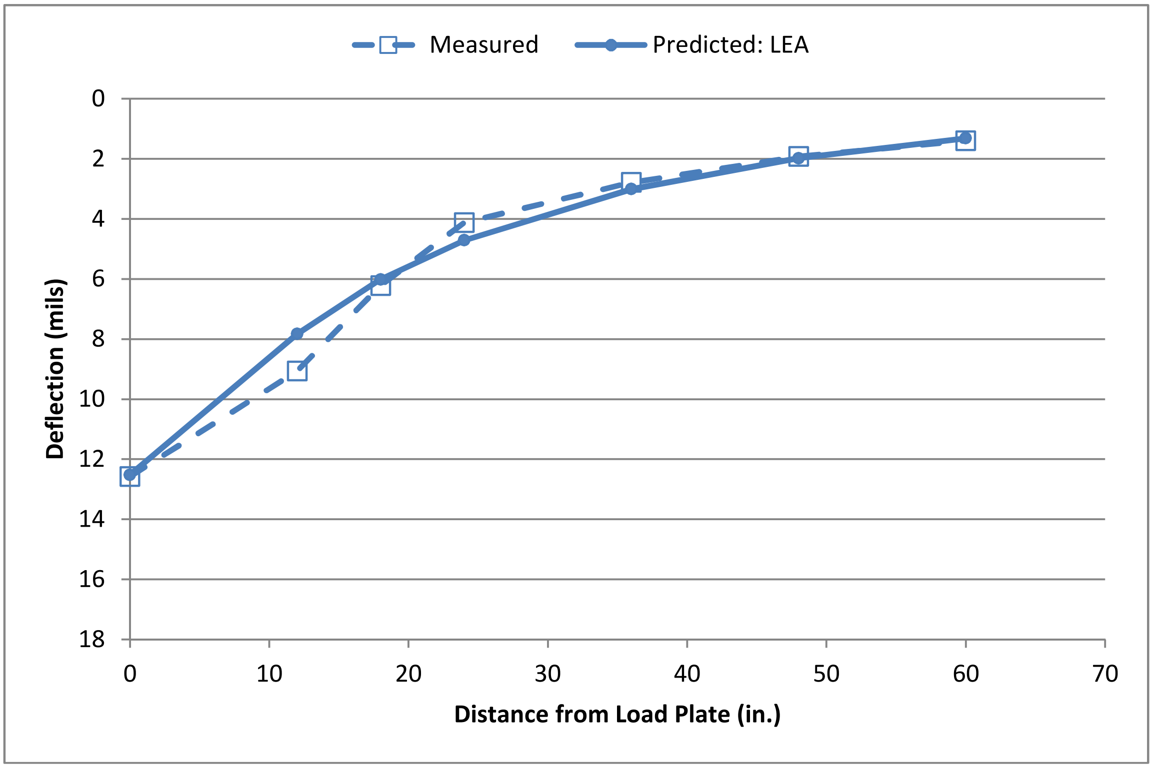
	K-2 (Kanc, NH)	05/07/15	Thawed-Weak
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - CTB**	E = 100,000	
3	28" Upper Subgrade	E = 24,000	
4	27" Lower Subgrade	E = 5,500	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



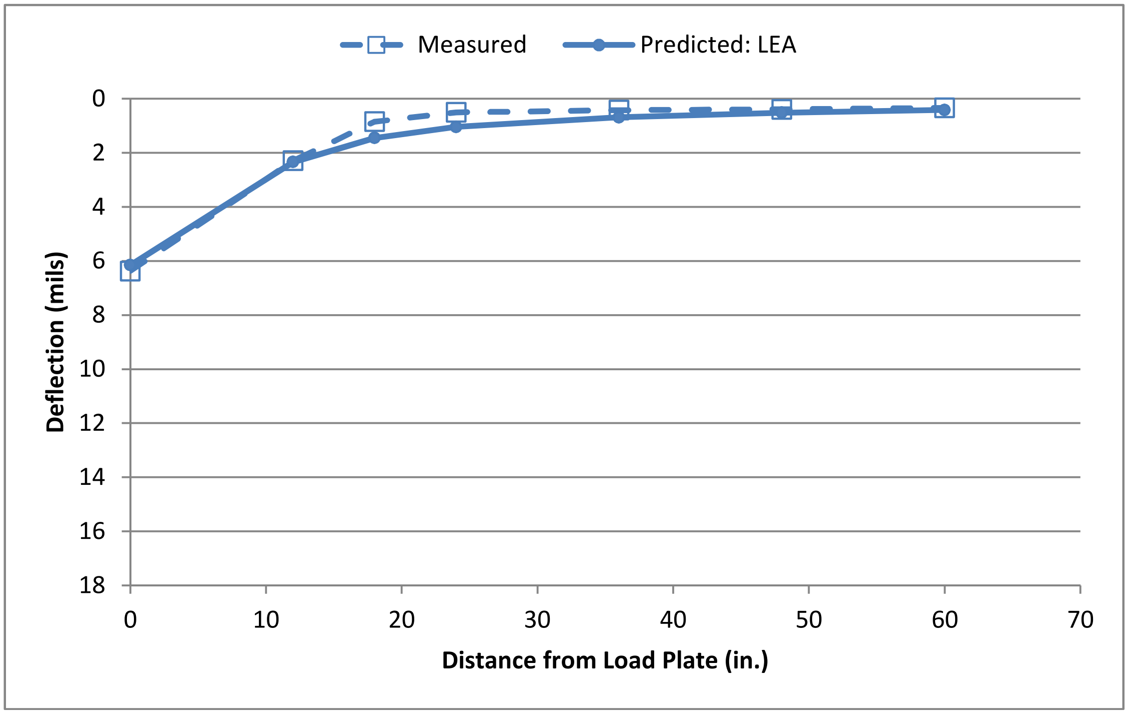
	K-2 (Kanc, NH)	06/11/15	Thawed (Recovered)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - CTB**	E = 100,000	
3	28" Upper Subgrade	E = 25,000	
4	27" Lower Subgrade	E = 7,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



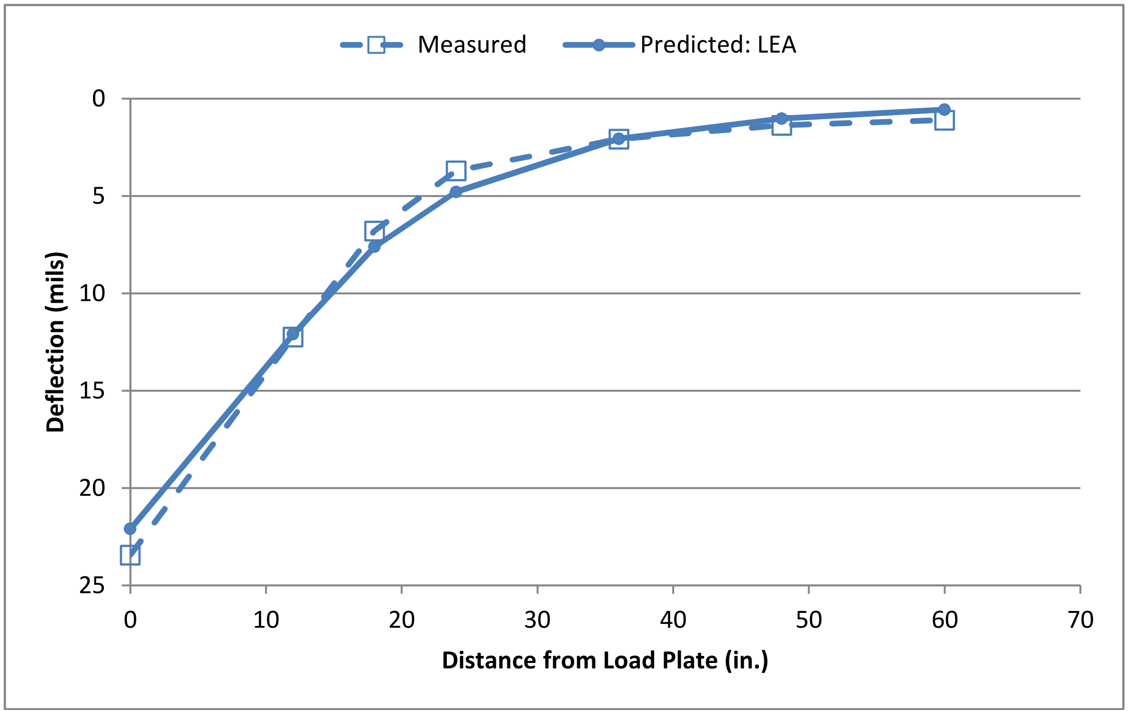
	K-2 (Kanc, NH)	07/14/15	Thawed (Recovered)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - CTB**	E = 100,000	
3	28" Upper Subgrade	E = 25,000	
4	27" Lower Subgrade	E = 7,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



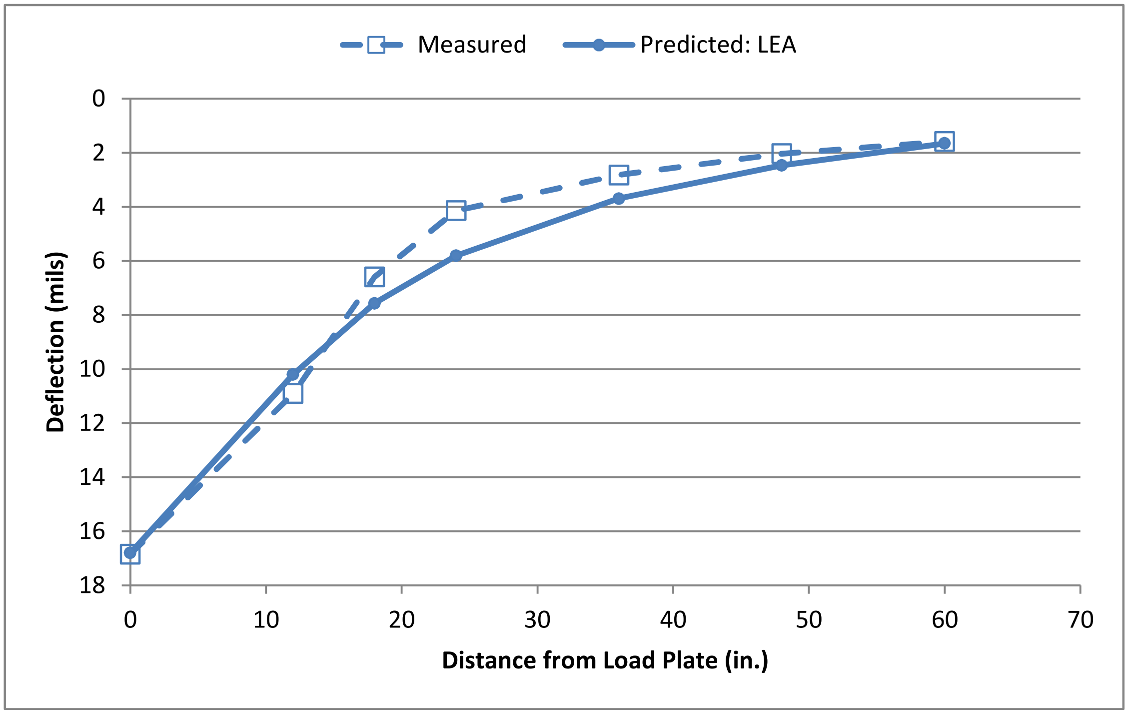
	K-3 (Kanc, NH)	03/31/15	FDR Layer partly Thawed (all other layers Frozen)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - unstabilized**	E = 60,000	
3	28" Upper Subgrade	E = 100,000	
4	27" Lower Subgrade	E = 100,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



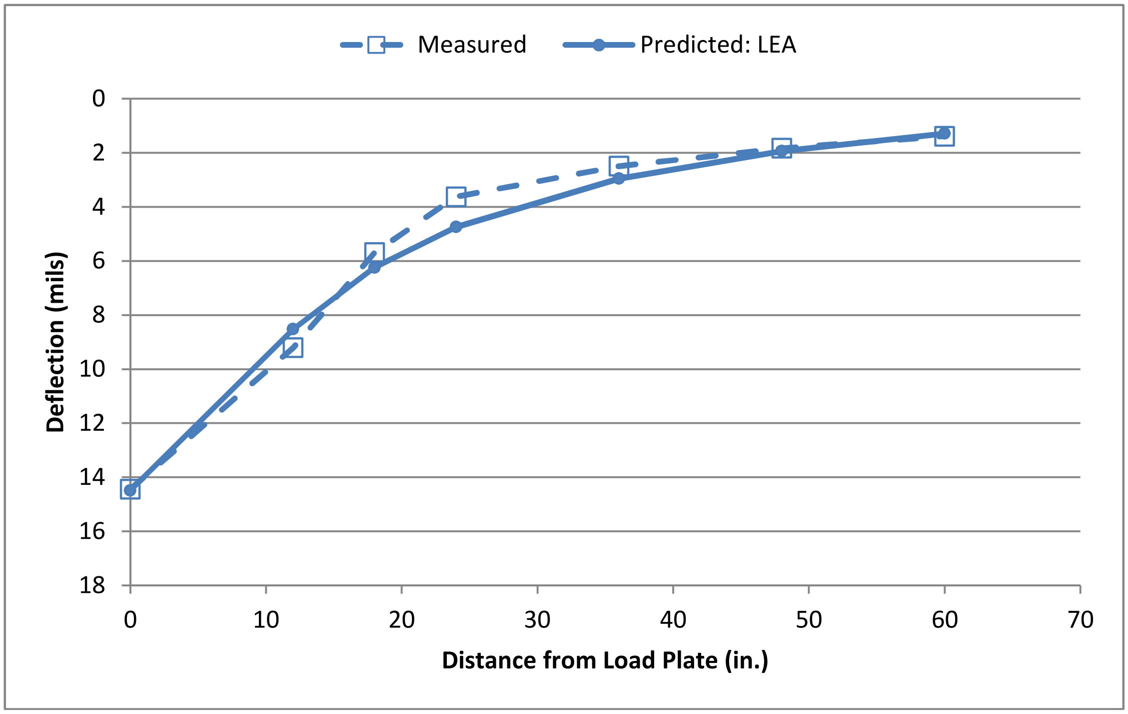
	K-3 (Kanc, NH)	04/24/15	Partly Frozen-Weak
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - unstabilized**	E = 12,000	Thawed
3	28" Upper Subgrade	E = 16,000	Thawed
4	8" Lower Subgrade	E = 5,000	Thawed
5	Frozen Lower Subgrade Combined with Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



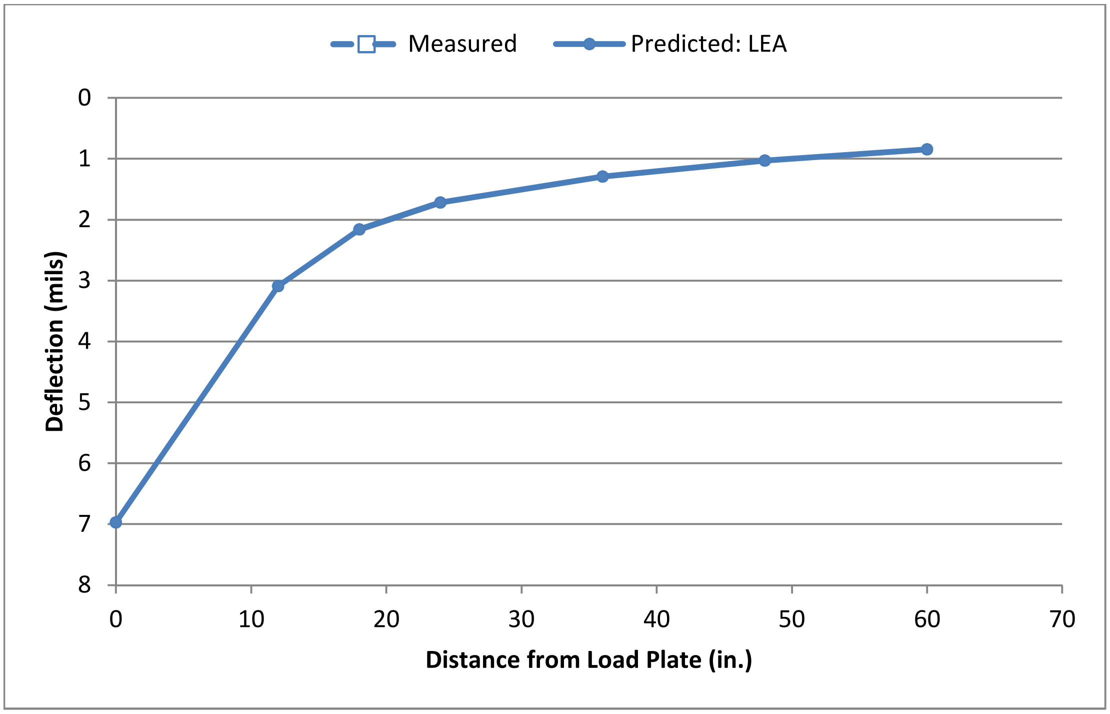
	K-3 (Kanc, NH)	05/14/15	Thawed (During Recovery)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - unstabilized**	E = 45,000	
3	28" Upper Subgrade	E = 22,000	
4	27" Lower Subgrade	E = 5,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

Kancamagus_SUMMARY_Foward Calculation-Modulus Values



	K-3 (Kanc, NH)	07/14/15	Thawed (Recovered)
1	4" HMA	E = 500,000 psi	(Fixed)
2	6" **FDR - unstabilized**	E = 55,000	
3	28" Upper Subgrade	E = 25,000	
4	27" Lower Subgrade	E = 7,000	
5	Subgrade (Stiff Layer)	E = 100,000 psi	(Fixed)

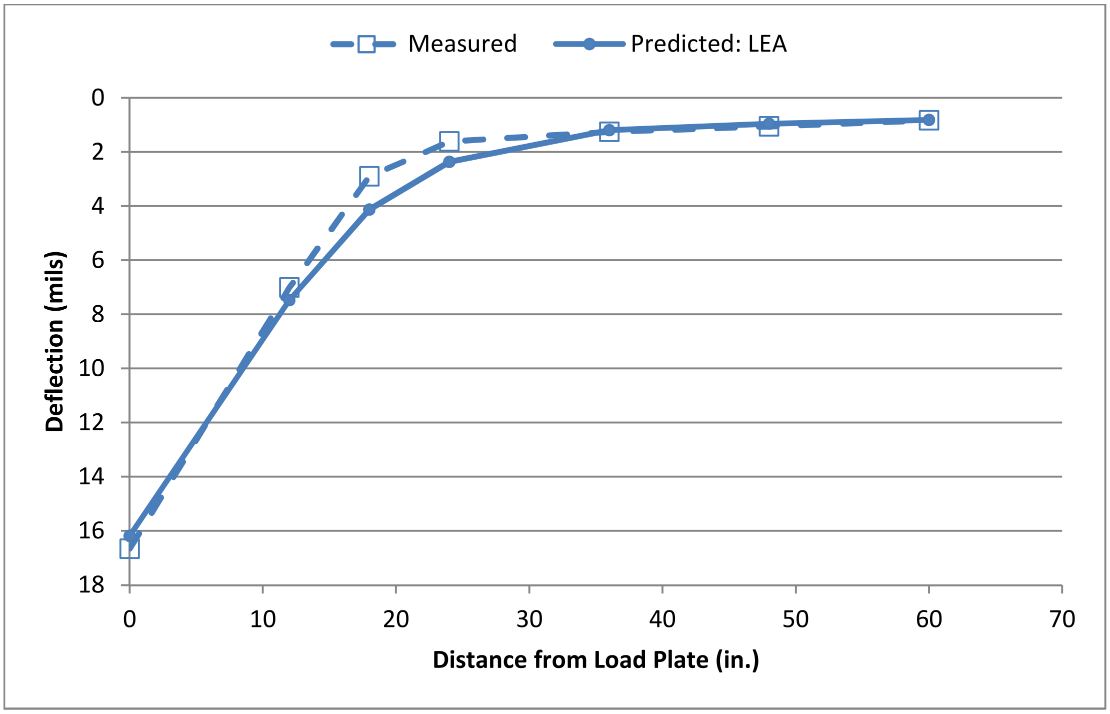
Warren Flats_SUMMARY_Foward Calculation-Modulus Values



Warren Flats, NH 03/16/15 Frozen (all layers) ***after*** thaw & then re-freeze in PMRAP layer

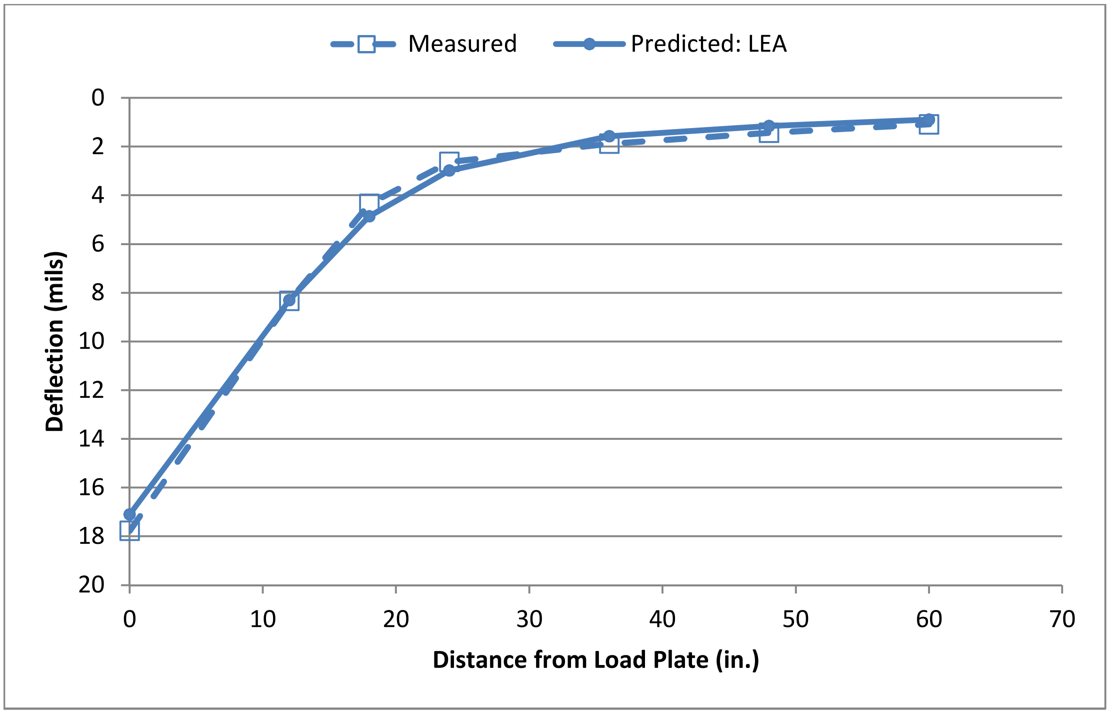
4" HMA	E = 500,000 psi
14" PMRAP	E = 80,000
9" Old AC	E = 250,000 psi
33" Subgrade (Old Fill)	E = 50,000
Subgrade (Stiff Layer)	E = 50,000 psi

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



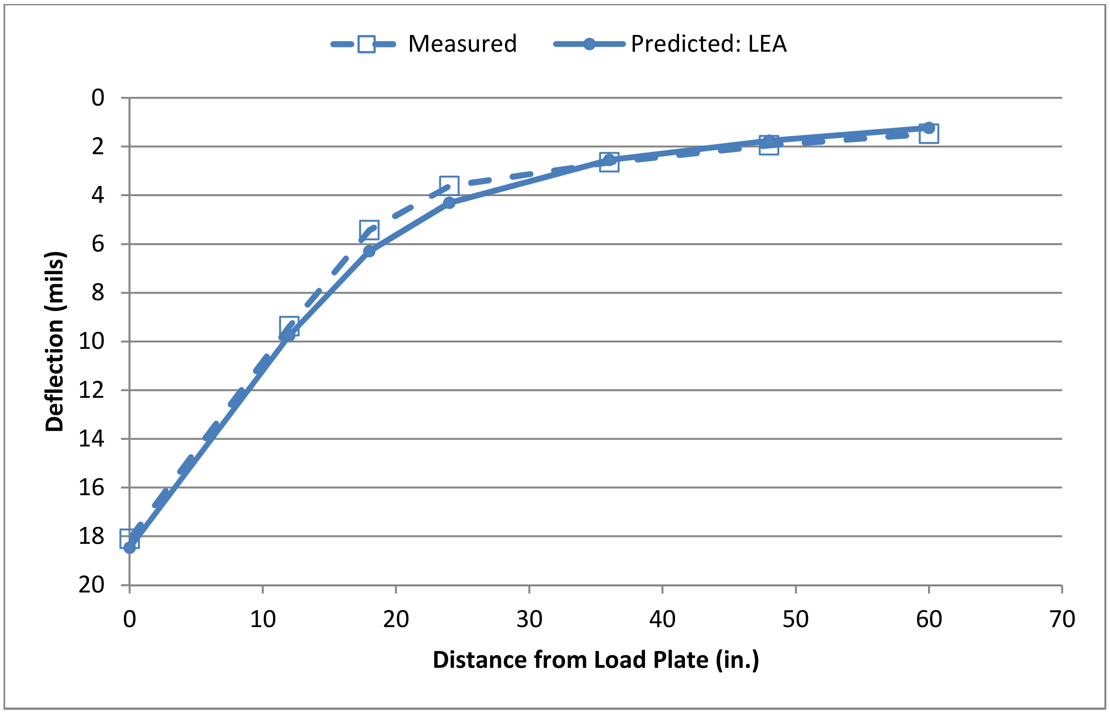
Warren Flats, NH	03/27/15 Layer 2 Thawed; Layer 4 mostly frozen
4" HMA	E = 500,000 psi
14" PMRAP	E = 15000
9" Old AC	E = 250,000 psi
33" Subgrade (Old Fill)	E = 50,000
Subgrade (Stiff Layer)	E = 50,000 psi

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



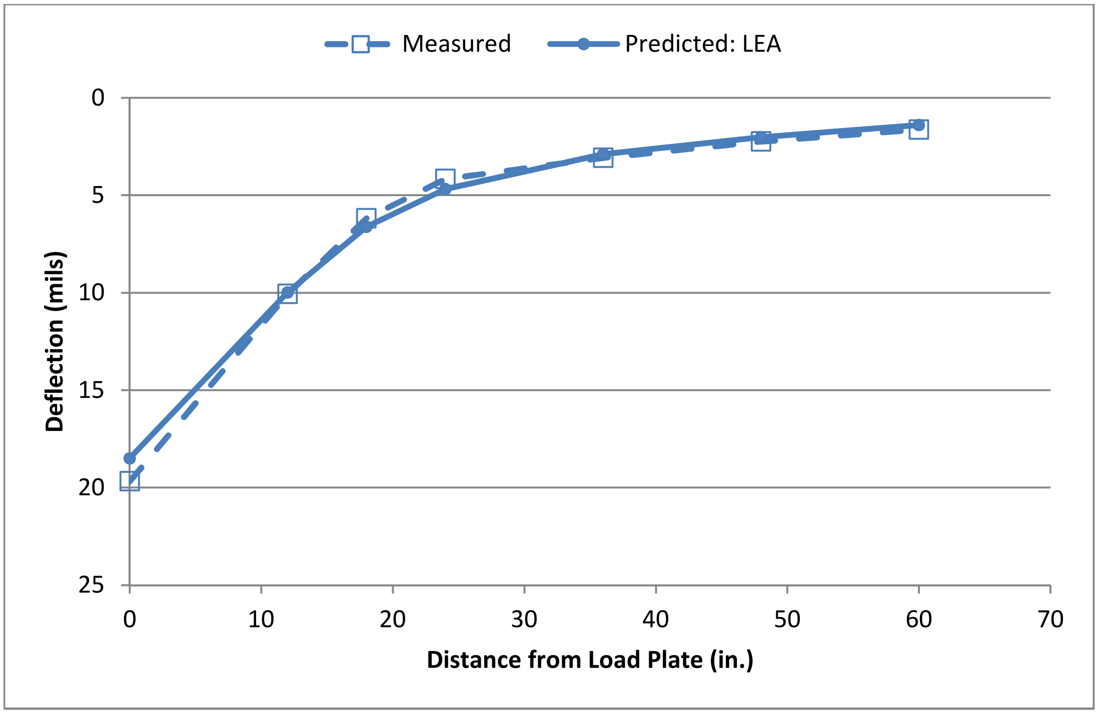
Warren Flats, NH	04/07/15 All layers just thawed
4" HMA	E = 500,000 psi
14" PMRAP	E = 15000
9" Old AC	E = 250,000 psi
33" Subgrade (Old Fill)	E = 25,000
Subgrade (Stiff Layer)	E = 50,000 psi

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



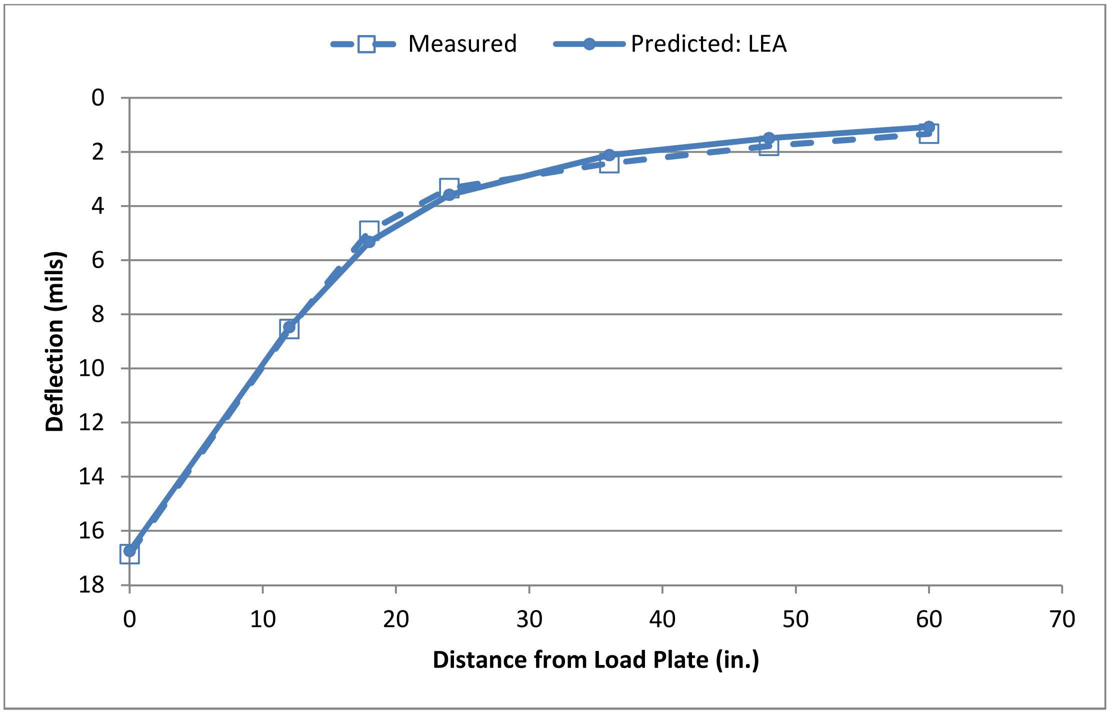
Warren Flats, NH	04/16/15 All layers thawed
4" HMA	E = 500,000 psi
14" PMRAP	E = 16000
9" Old AC	E = 250,000 psi
33" Subgrade (Old Fill)	E = 9,000
Subgrade (Stiff Layer)	E = 50,000 psi

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



Warren Flats, NH	04/23/15 All layers thawed (weakest condition)	
4" HMA	E = 500,000 psi	
14" PMRAP	E = 17,000	
9" Old AC	E = 250,000 psi	
33" Subgrade (Old Fill)	E = 7,000	
Subgrade (Stiff Layer)	E = 50,000 psi	

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



Warren Flats, NH 05/13/15 All layers thawed; during recovery

4" HMA E = 500,000 psi

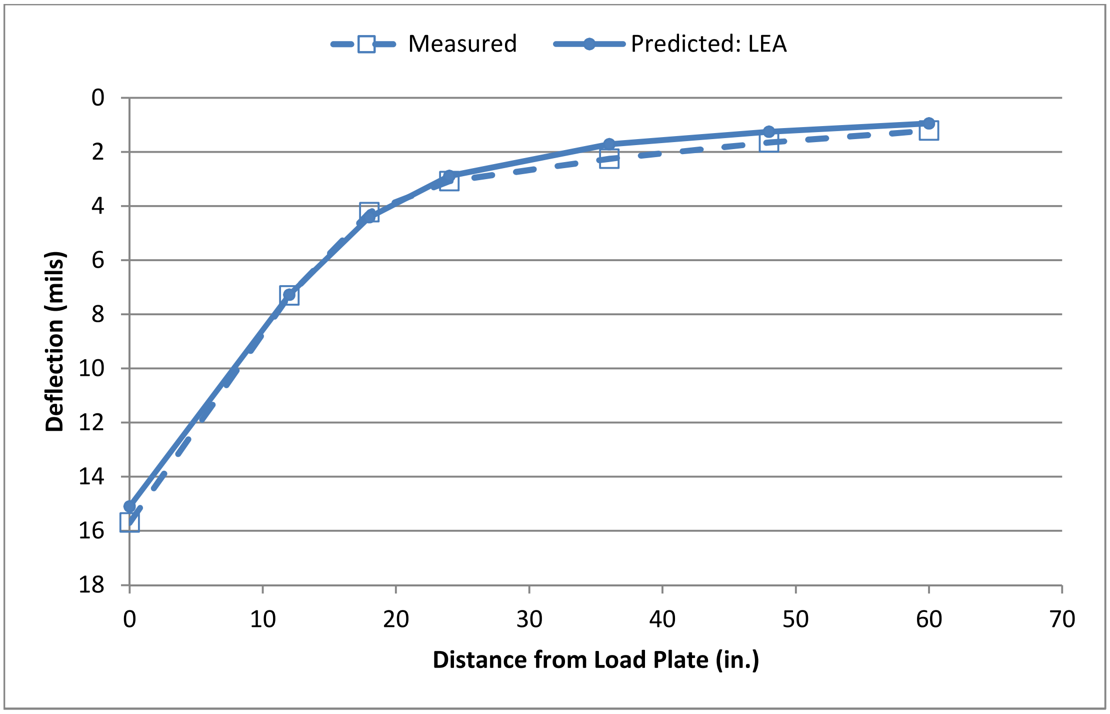
14" PMRAP E = 18000

9" Old AC E = 250,000 psi

33" Subgrade (Old Fill) E = 13,000

Subgrade (Stiff Layer) E = 50,000 psi

Warren Flats_SUMMARY_Foward Calculation-Modulus Values



Warren Flats, NH	05/27/15 Baseline (Last Test Date-Recovered +/-)
4" HMA	E = 500,000 psi
14" PMRAP	E = 20,000
9" Old AC	E = 250,000 psi
33" Subgrade (Old Fill)	E = 21,000
Subgrade (Stiff Layer)	E = 50,000 psi