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16. Abstract

Current roadway quality control and quality acceptance (QC/QA) procedures for the Louisiana Department of Transportation and Development (LADOTD) include coring for thickness, density, and air voids in hot mix asphalt (HMA) pavements and thickness and compressive strength for Portland cement concrete (PCC) pavements. Non-destructive testing (NDT) devices, such as the light weight deflectometer (LWD) and the portable seismic pavement analyzer (PSPA), provide a non-destructive and portable means of quick in-place determination of pavement properties, resulting in an increase in sampling frequency to supplement coring. Many researchers have shown good trends between measurements of the NDTs and other pavement properties, though variability has shown to differ from report to report. The PSPA exhibited seismic modulus values of the surface layer with an average coefficient of variation (CoV) of 2 to 15 percent for repeat collections without moving the apparatus. The PSPA variability increased to a range of 6 to 28 percent if the apparatus changed orientation or moved within a close proximity. The LWD exhibited deflections values of the pavement structure with an average CoV of 4 to 12 percent for repeat collections without moving the apparatus. The PSPA exhibited project wide seismic modulus values with a CoV between 1 and 32 percent. The LWD exhibited project wide deflection values with a CoV between 18 and 55 percent. Factors that increased variability include: deterioration of the feet pads, presence of vibrations, placement of a foot into a groove, testing close to joints, and temperature. Changing the orientation of the sensors showed to increase the variability of the PSPA measurements; however, the variability increase is no different than moving the apparatus within a close proximity. Orientation of the sensors did not show to have a bias to measuring parallel or perpendicular to the paving direction. The strength gain measured by the PSPA correlated well with the strength gain of laboratory testing for only one of the PCC data sets for this study. The LWD deflections correlated well with the FWD deflections, but the back-calculated moduli of the surface layer did not correlate well. No trends were observed between the PSPA and LWD. A preliminary sampling procedure was developed for the PSPA as a quality control tool in Louisiana.

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ABSTRACT

Current roadway quality control and quality acceptance (QC/QA) procedures for the Louisiana Department of Transportation and Development (LADOTD) include coring for thickness, density, and air voids in hot mix asphalt (HMA) pavements and thickness and compressive strength for Portland cement concrete (PCC) pavements. Non-destructive testing (NDT) devices, such as the light weight deflectometer (LWD) and the portable seismic pavement analyzer (PSPA), provide a non-destructive and portable means of quick in-place determination of pavement properties, resulting in an increase in sampling frequency to supplement coring. Many researchers have shown good trends between measurements of the NDTs and other pavement properties, though variability has shown to differ from report to report.

The PSPA exhibited seismic modulus values of the surface layer with an average coefficient of variation (CoV) of 2 to 15 percent for repeat collections without moving the apparatus. The PSPA variability increased to a range of 6 to 28 percent if the apparatus changed orientation or moved within a close proximity. The LWD exhibited deflections values of the pavement structure with an average CoV of 4 to 12 percent for repeat collections without moving the apparatus. The PSPA exhibited project wide seismic modulus values with a CoV between 1 and 32 percent. The LWD exhibited project wide deflection values with a CoV between 18 and 55 percent.

Factors that increased variability include: deterioration of the feet pads, presence of vibrations, placement of a foot into a groove, testing close to joints, and temperature. Changing the orientation of the sensors showed to increase the variability of the PSPA measurements; however, the variability increase is no different than moving the apparatus within a close proximity. Orientation of the sensors did not show to have a bias to measuring parallel or perpendicular to the paving direction.

The strength gain measured by the PSPA correlated well with the strength gain of laboratory testing for only one of the PCC data sets for this study. The LWD deflections correlated well with the FWD deflections, but the back-calculated moduli of the surface layer did not correlate well. No trends were observed between the PSPA and LWD. A preliminary sampling procedure was developed for the PSPA as a quality control tool in Louisiana.

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IMPLEMENTATION STATEMENT

The authors recommend using the portable seismic pavement analyzer for a trial evaluation as a quality control and assurance tool for Louisiana. The device will only supplement coring at the present time. Proper implementation of the PSPA into current quality control and assurance will require additional laboratory testing during the design phase to establish mixture specific target values. Such testing will be required as Louisiana pushes toward performance-based specifications, and the need for field moduli measurements will increase as well. Full implementation of the portable seismic pavement analyzer should be reconsidered when performance-based specifications are implemented.

At present, a database should be setup to warehouse PSPA collections using the sampling procedure described in this report. The database can later be used to determine limits for quality control by pavement type or function and to update the cost/benefit analysis.

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INTRODUCTION

Current roadway QC/QA procedures for LADOTD include coring for thickness, density, and air voids in HMA pavements and thickness and compressive strength for PCC pavements. NDT devices, such as the LWD and the PSPA, provide a non-destructive and portable means of quick in-place determination of pavement properties, resulting in an increase in sampling frequency to supplement coring. The ability to measure pavement design parameters directly in the field would be another step toward performance-based specifications in Louisiana. The measurements of these devices can either be used as a stand-alone measure or, in most cases, be correlated to other pavement properties. Many researchers have shown good trends between measurements of the NDTs and other pavement properties, though variability has shown to differ from report to report.

Current practices of only measuring volumetric properties in the field do not capture the requirements of mechanistic design. As LADOTD pushes towards a mechanistic design and performance-based specifications, new parameters of the pavement must be considered. Mechanistic design is based on the modulus value of pavement layers. The modulus can be measured from gyratory specimens in the laboratory; however, the recommended test requires a specimen thickness that is not typical for an HMA layer. Also, field properties tend to vary from lab properties, due to compaction efforts and coring damage. The PSPA and LWD are capable of measuring the in-situ modulus of a pavement layer.

This report details an evaluation of the PSPA and LWD. Data collected from multiple projects is used to determine if the devices show adequate repeatability for use as QC/QA tools in Louisiana. Various factors are tested to determine which ones potentially impact measurements collected by these devices. Also, measurements from the devices are compared to laboratory measurements to confirm trends developed in other studies.

Literature Review

Non-destructive Testing Equipment

The PSPA, shown in Figure 1, measures the modulus of the pavement surface layer through the use of seismic/ultrasonic technologies. The device contains a source foot that “taps” the pavement surface, creating vibrations in the form of stress waves. Two receiver feet measure the amplitude and wavelength of the stress waves. The wavelength corresponds to depth within the pavement, while the time between receivers can be used to develop a phase difference, which corresponds to seismic modulus *[1]*.

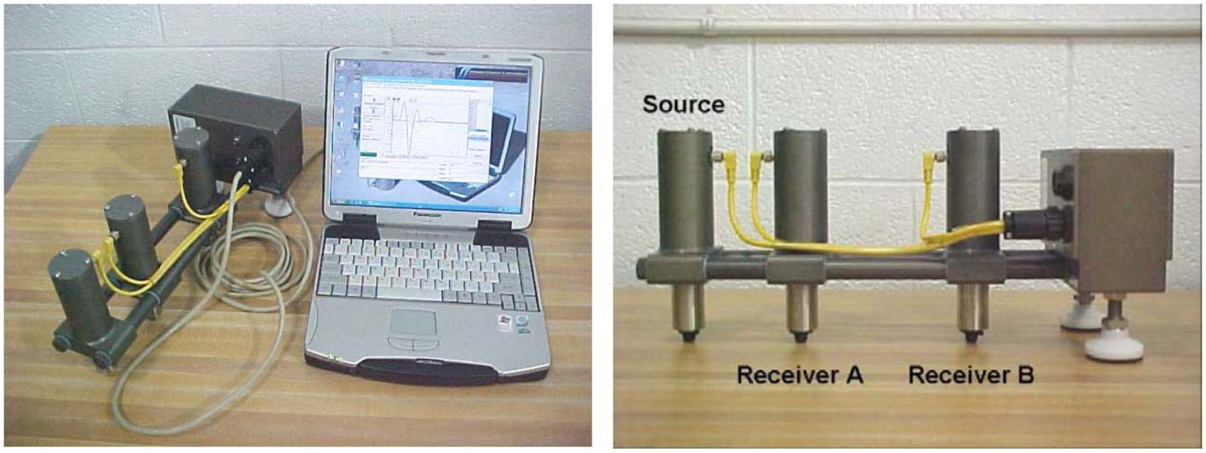

Figure 1
PSPA

The LWD, shown in Figure 2, is a smaller version of the trailer pulled falling weight deflectometer (FWD). This process involves a load impacting a plate on the surface of the pavement and a response deflection is measured using a geophone located underneath the plate. The addition of two radial geophones allow for a deflection basin to be measured. The measured deflections paired with assumed thicknesses are used to iteratively back calculate the pavement modulus of individual layers using theories of pavement design *[2]*.

Figure 2
LWD with additional geophones

Research by Others

LWD was originally designed for unbound materials; however, it is now being studied for pavement applications *[2]*, *[3]*, *[4]*. The device has been tested for application on flexible pavements; however, results have been varied. LWD deflections usually correlate well with the FWD deflections; however, the back calculations show differently *[4]*. The relationship between LWD and FWD varies with thickness *[3]*. The variations could be due to the lower contact stress, fewer geophones to capture the deflection basin, and shallower depth of influence of the LWD *[3]*, *[5]*. Back-calculation algorithms assume the pavement layers decrease in modulus values from the surface down, which causes erroneous estimations if the layers are not ordered as such or the pavement structure contains a very thin layer *[2]*, *[6]*. The modulus measurement of the LWD relies on back calculation, so bad estimations of inputs result in erroneous layer moduli. Also, the surface layer can be influenced by the supporting layers *[7]*.

NCHRP 626 was setup to identify NDT devices that have immediate application for routine and practical QC/QA. The project compared variability between the devices as well as each devices ability to identify artificially created abnormalities. None of the devices measured exactly to laboratory results, however some showed similar trends. The PSPA and FWD were selected for HMA pavement. The PSPA showed good trends to laboratory results and was able to identify 93 percent of the abnormalities, while the FWD showed trends different from laboratory results and was able to identify only 50 percent of the abnormalities. The PSPA was recommended as the best suited device for QC/QA applications. The LWD was used for unbound layers only and showed poor success for quality control of layers; however, the devices show potential for acceptance of the whole pavement structure *[7]*.

Multiple studies on the PSPA and seismic pavement analysis methods have been published by Dr. Soheil Nazarian and associates. Many of his studies conclude that the PSPA is a self-contained NTD that can be readily incorporated into a QC/QA program. Much of his research has shown a coefficient of variation (CoV) ranging from 1 to 10 percent, depending on testing conditions *[7]*, *[8]*, *[9]*, *[10]*, *[11]*, *[12]*, *[13]*, *[14]*, *[15]*, *[16]*. Other researchers have shown higher ranges, but the average is usually less than 10 percent. Steyn and Sadzik conducted triplicate repeatability tests with the PSPA showing only 14 percent of the 272 comparison tests as significantly different ($\alpha = 0.05$) *[17]*. Table 1 and Table 2 summarize CoV averages and ranges from various sources. Much of the literature containing CoV for the LWD state that the device was used on unbound and cement treated soil layers and report CoV up to 80 percent. Nazzal et al. states the variability of the LWD is reduced as the modulus of the layer being tested increases *[5]*. Therefore, the CoV for asphalt layers is expected to be lower; Fleming et al. reports a CoV of 17 percent for the LWD on asphalt pavement *[3]*.

Table 1
PSPA coefficient of variation in percentage from literature, average (range)

Literature	Same Location	Close Proximity	Material
Yuan et al. *[8]*	0.5 (0.4-0.5)	0.8 (0.1 to 3.5)	PCC
Rue *[18]*		(3.8-5.9)	PCC
Bell *[19]*	11 (1-25)		PCC
Von Quintus et al. *[7]*	(1-31)*		HMA
Celaya et al. *[9]*	4.6 (0-53)*		HMA
Velivelli et al. *[11]*		8.6	HMA
Abdallah et al. *[12]*	4		HMA
Mallick et al. *[15]*	5.3 (0.8-14.1)		HMA
Nazarian et al. *[16]*	3.7		HMA
Oh and Fernando *[17]*	9.8 (1.4-25.4)		HMA

* = computed from data in the report

Table 2
LWD coefficient of variation in percentage from literature, average (range)

Literature	Same Location	Close Proximity	Material
Fleming et al. *[3]*	17		HMA
Nazzal et al. *[5]*	(2.1-28)		Unbound Cement Treated
Von Quintus et al. *[7]*	(5-80)		Unbound
Hossain and Apeagyei *[20]*		(22-77)	Gravel

Yuan et al. and Nazarian et al. have shown good correlations of laboratory-measured, seismic moduli to compressive strengths and maturity of PCC cylinders cast in the field, shown in Figure 3 *[8]*, *[16]*. The PSPA uses similar principles to those used in the lab to measure seismic moduli and is expected to give similar results in the field; however, multiple sources show values measured by PSPA are generally 15 to 25 percent lower than values measured in the laboratory as shown in Figure 4. The lower values are believed to be caused by the differences in the compaction effort and curing between the laboratory and field, differences in the sensor placement between test methods, and NDT measurements not directly aligned with locations of cores *[8]*, *[13]*, *[14]*, *[16]*. The Arizona Department of Transportation and Celaya and Nazarian have shown good correlations between the laboratory seismic modulus of HMA cores and the PSPA, Figure 5 *[13]*, *[14]*.

Comparison of 180 collection points across six HMA sites from Celaya et al. shows an absolute difference between longitudinal and transverse orientation of 0 to 1570 ksi. The average absolute difference between the orientations for each site ranges from 8 to 25 percent of the site mean. The results do not show bias to one orientation always being higher than the other *[9]*.

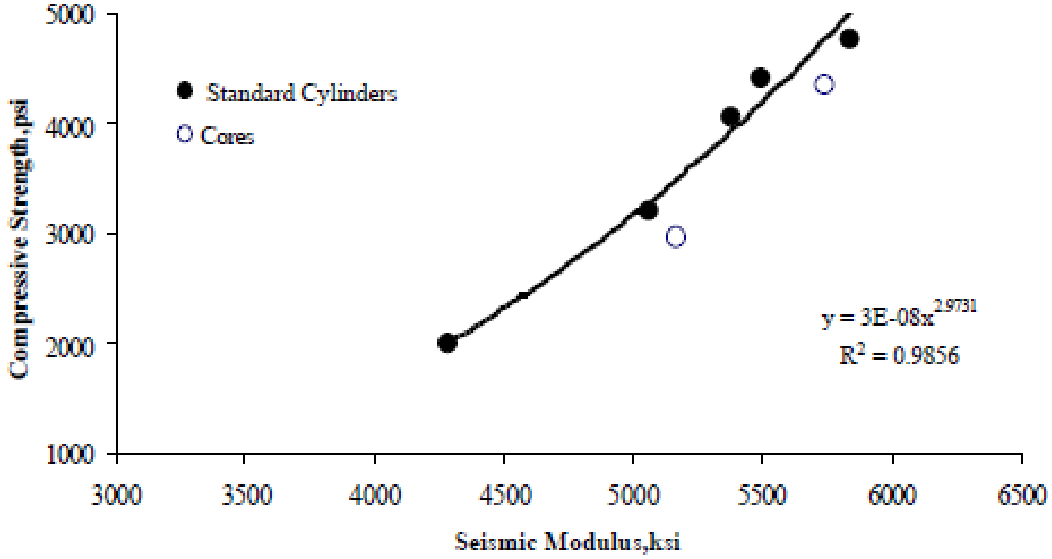

Figure 3
Correlation of compressive strength of PCC cylinders to laboratory seismic modulus *[8]*

Yuan et al. performed PSPA testing to compare ungrooved slabs to slabs with various groove spacing, depths, and widths at parallel and perpendicular orientations *[8]*. The width and depth of the smallest groove exceeds the values specified for tine texturing in Louisiana. Testing parallel to the grooves showed only a slight difference in seismic moduli, while testing perpendicular to the grooves showed a six to twenty percent reduction in seismic moduli. Using an inline PSPA further reduced the impact of grooves *[8]*.

The majority of the sources recommend the PSPA as an analysis tool and a few also recommend incorporating it into quality control programs *[4]*, *[7]*, *[8]*, *[9]*, *[10]*, *[11]*, *[12]*, *[13]*, *[14]*, *[15]*, *[16]*, *[17]*, *[19]*. Most recommend it for HMA pavements and require additional laboratory testing to determine target values during design. Texas is the only state with a draft specification to incorporate the PSPA into quality control *[21]*. The LWD has shown results correlating to FWD; however, it has not been recommended for routine pavement quality control purposes at this time *[3]*, *[7]*.

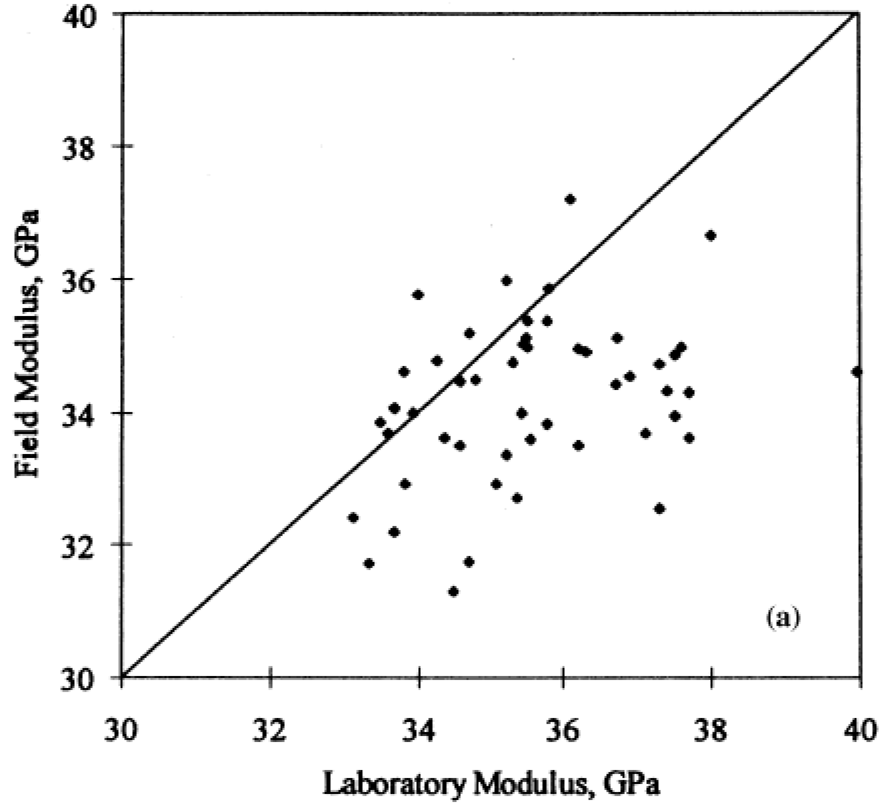

Figure 4
Correlation of field PSPA seismic modulus to laboratory seismic modulus of PCC *[16]*

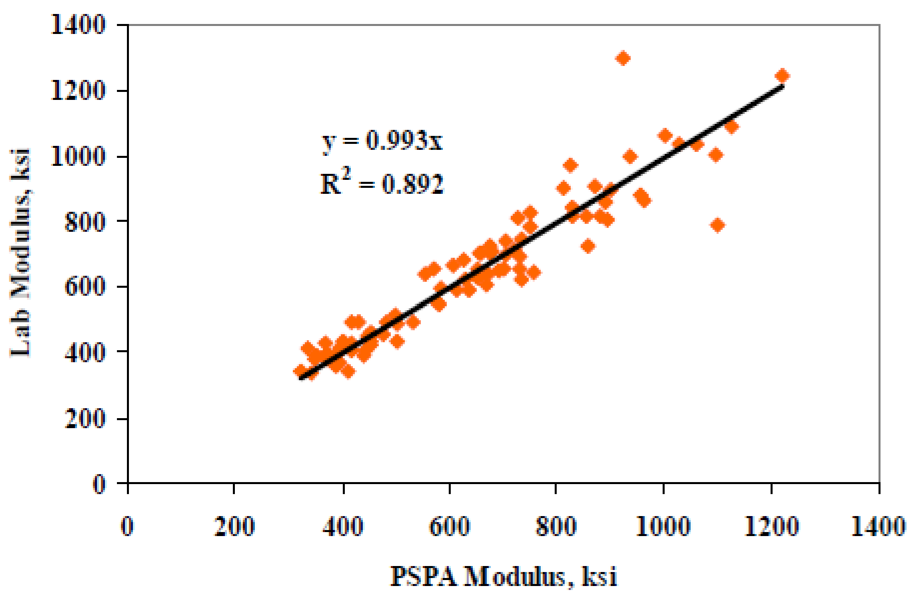

Figure 5
Correlation of field PSPA seismic modulus to laboratory seismic modulus of HMA *[13]*

Limitations

The PSPA should not be used on high temperature HMA; results of NCHRP 626 recommend at least one day of cooling after placement. The rubber pads on the feet of the PSPA can melt if the pavement surface is too hot *[7]*. The pads must be checked frequently for deterioration, because the rubber can tear from repeated placement or shifting of the device *[7]*, *[19]*. The PSPA should not be used near joints or pavement edges *[19]*. Shallow and narrow grooves on the pavement surface have shown minimal impact on the measurements of the device; however, the feet must be in good contact with the surface *[8]*. The recommended collection procedure from the U.S. Army Corps of Engineers suggests avoiding testing over cracks, testing grooved surfaces parallel to the grooves, and testing at least one PSPA length from a joint or pavement edge *[19]*. Areas containing open-graded surface or visible cracks should be avoided *[22]*, *[22]*. The PSPA software requires an individual trained to inspect the load pulse and response data to recognize erroneous measurements *[7]*.

The LWD requires a flat level surface to function properly. Due to the lighter weight of the LWD, the contact stress is lower than that of the FWD allowing the apparatus to sometimes bounce and move immediately after impact of the weight *[7]*. The LWD is not ideal for thicker pavements due to the low contact stress and a limited depth of influence *[2]*, *[5]*. The additional geophones are tethered to the apparatus by short cables; some researchers found these cumbersome *[7]*.

While the testing is quick and non-destructive, the PSPA and LWD are still limited to point measurements only. However, the area for isolated deficient sections can be lessened with increased non-destructive sampling *[7]*. Both devices are influenced by the temperature of HMA and frequency of the testing device; therefore, measurements are mixture specific. The latest research suggests developing a mixture-specific relationship during the design process between the seismic modulus and other parameters such as air voids, asphalt content, and temperature. Temperature and a seismic modulus can be correlated through the use of a laboratory dynamic modulus master curve, which defines a mixture specific relationship between modulus, frequency, and temperature *[4]*, *[7]*, *[13]*, *[14]*. Through these relations, a mixture-specific target seismic modulus value can be determined for field quality control. Seismic moduli from the field are generally 15 to 25 percent lower than the target developed in the laboratory; Celaya et al. recommend using 75 percent of the target modulus developed in the laboratory for a field quality control limit *[13]*.

OBJECTIVE

The objectives of this research were to:

1. Evaluate the repeatability of LWD with additional geophones and PSPA for pavement quality assurance applications.
2. Determine factors of influence for LWD and PSPA through ruggedness testing.
3. Develop procedures for operating the LWD and PSPA for pavement quality assurance applications in Louisiana.
4. Compare laboratory properties obtained from cores and cylinders to field properties obtained from LWD and PSPA.

SCOPE

To meet the objectives of this project, the portable seismic pavement analyzer and light weight deflectometer were used to collect measurements on multiple field sites of different mix designs and pavement structures. A section sampling plan was established for collections. Also, minor modifications and additional data points were included to represent various "ruggedness" scenarios. Due to the abundance of literature showing good correlations between the laboratory and field for the portable seismic pavement analyzer on hot mix asphalt pavement, this objective was only performed for PCC pavements.

The project sample set consisted of seven asphalt pavements and four concrete pavements in different districts of Louisiana. The PSPA was used on all pavements and the LWD was used on five of the asphalt pavements. All sections were included for repeatability analysis; however, only nine of the pavements were selected for the additional testing included in the ruggedness analysis. Three of the concrete pavements were also used to observe measurements over time and to compare laboratory measurements to field measurements.

METHODOLOGY

Field Testing

Field testing consisted of data collection with the PSPA and LWD of on-going LADOTD projects, including test lanes at the accelerated loading facility (ALF). Most projects used a structured sampling factorial; however, on a few projects the collection was limited to a partial factorial. Additional points were collected over abnormalities and ruggedness scenarios to compare with typical results. The LWD would bounce and move when used on a PCC pavement and was not recommended for thick pavements; therefore, the LWD was only used on thin HMA surfaces for this study.

Field Projects

Data from four concrete projects and eight asphalt projects were used to evaluate the NDT devices. Projects varied in mixture design, pavement layer type, and surface layer thickness. Table 3 and Table 4 show which device was used on each project and the thickness of the surface layer.

Table 3
Concrete projects

Project	PSPA	LWD	Thickness in.
LA3073	yes	no	10
US61	yes	no	8
I-49	yes	no	11
ALF	yes	yes	8

Table 4
Asphalt projects

Project	PSPA	LWD	Thickness in.
I-55	yes	no	8
I-55 (2)	yes	no	8
LA3191	yes	yes	2
LA3121	yes	yes	2
LA116	yes	yes	3.5
US171	yes	yes	2
ALF	no	yes	3

Data Collection

The typical sampling pattern was similar from project to project; however, the frequency and spacing were dependent upon the available pavement and timing of traffic control. The typical pattern consisted of nine to fifteen points, three to five stations respectively, spaced evenly apart with one point in each wheel path and in the center of the lane, as shown in Figure 6. Spacing ranged from 20- to 100-ft. increments. A point consisted of the average of repeat collections, including different orientations and shifting small distances, about 6 in., along the longitudinal direction of the pavement.

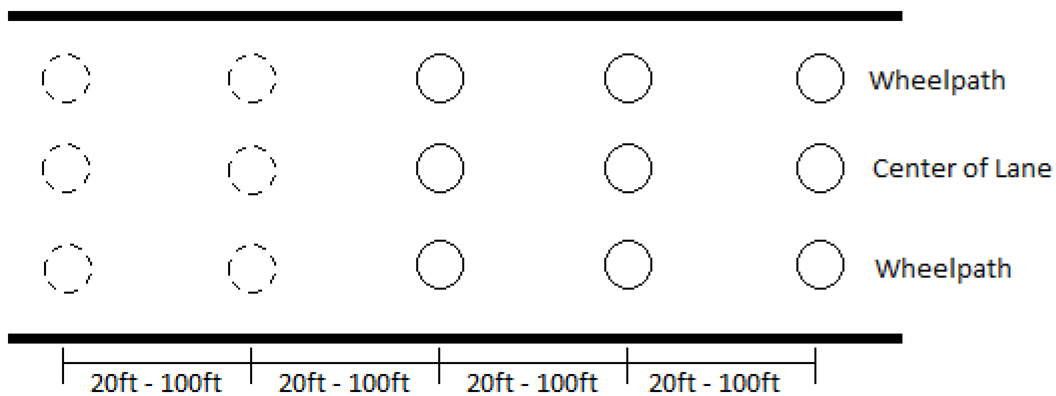

Figure 6
Typical NDT collection pattern for single section

LWD

A Dynatest 3031 LWD was used in this study. Measurements were collected using the 6-in. loading plate, the 44-lb. drop weight, and the maximum drop distance of 30 in. A few projects included a collection with two additional geophones to develop a deflection basin for back calculation of moduli. The additional geophones were placed at 12 in. and 24 in. from the center geophone. Measurements were collected and stored using a personal digital assistant (PDA) linked to the LWD apparatus via a wireless Bluetooth connection *[2]*.

The center deflection (d_0) is produced in real time by the LWD collection software. The center deflection and the load generated by the drop weight are measured directly by the apparatus. The back-calculated modulus of individual layers requires data analysis by LWDmod software *[2]*.

PSPA

An inline PSPA was used in this study. The apparatus consists of a source foot that generates vibrations by tapping the pavement at high frequencies and two receiver feet that measure the amplitude and wavelength of the vibrations. The PSPA includes a built-in temperature sensor to measure the surface temperature of the pavement *[1]*. Research reports state that temperature normalization of measurements on HMA is still needed after processing *[7]*, *[19]*. The distance between the feet can impact the depth of influence of the PSPA, and the spacers between the feet are interchangeable. There are different recommendations between the manual and research reports about spacer configuration for certain depths. Typically shorter spacers are used between the receivers for less than 6 in. and longer spacers are used for more than 6 in. [1], [19].

The PSPA uses the Ultrasonic Surface Wave (USW) method, which relates the velocity of surface waves to the modulus of the pavement surface layer. Seismic waves exist as compression waves, shear waves, and surface (Rayleigh) waves. If the surface layer is assumed uniform and wavelengths are less than the thickness of the surface layer, then the elastic modulus of the surface layer can be defined empirically in terms of shear wave velocity using equation (1). Surface waves are easiest to measure because these waves carry the majority of the energy; equation (2) gives a relationship between shear and surface waves [9]. The velocity of surface waves is measured using the time difference between the PSPA receivers [1].

$$E = 2\rho \, V_S^2 \, (1 + v) \tag{1}$$

$$V_S = V_R(1.13 - 0.16v) \tag{2}$$

where,
E = seismic modulus, ksi;
ρ = mass density, pcf;
V_S = velocity of shear waves, fps;
V_R = velocity of surface (Rayleigh) waves, fps; and
ν = Poisson's ratio.

The PSPA software, SPA Manager, performs the data analysis automatically. The analysis method breaks the recorded signal into multiple components of different frequencies. Each component represents a different frequency or wavelength, which are related to depth. Longer wavelengths represent deeper material. The velocity of surface waves is represented as a phase difference. A phase difference is computed for each frequency component to develop a dispersion curve relationship between seismic modulus and depth. Moduli values within the surface layer thickness are averaged to yield a seismic modulus measurement [1].

The PSPA is also capable of estimating the thickness of the surface layer using the impact echo method. When the PSPA taps, stress waves are propagated through the layer. Part of the wave is reflected when it reaches the underlying layer. The wave continues to reflect between the surface and next layer creating an echo effect. The SPA Manager software breaks the signal into multiple wavelength components, which are related to depth, using the

Fourier analysis. The resonant frequency peak observed occurs at the bottom of the surface layer [1].

Repeatability

An objective of the study was to evaluate the repeatability of the PSPA seismic modulus, LWD center deflection, and LWD back-calculated modulus. The American Society for Testing and Materials (ASTM) defines repeatability as the variation measured by one operator under the same test conditions. In order to justify use as quality control tools, the variation of the non-destructive devices should be similar or lower than variability of similar test methods. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens specifies a coefficient of variation of 2.4 percent to 3.2 percent for single operators, depending on test conditions *[23]*. ASTM C469: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression specifies a coefficient of variation of 4.25 percent for single operators *[24]*. AASHTO PP 62: Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt specifies a coefficient of variability of 7.5 percent for a properly conducted test with three specimens *[25]*. As shown in the introduction, many researchers document the PSPA averaging from 1 to 10 percent CoV and the LWD averaging around 17 percent CoV for pavement.

Ruggedness Testing

Another objective of the study was to perform a ruggedness test on the LWD and PSPA as per ASTM E1169: Standard Practice for Conducting Ruggedness Tests. ASTM E1169 defines a ruggedness test as a test plan in which test conditions are purposely varied in order to evaluate the effects of such variation. The ruggedness test method requires each variable to have two levels for each factor. A factorial is setup to obtain results of all possible combinations of the factors and levels *[26]*.

Controlling the factors to meet the requirements of the ruggedness factorial was found to be difficult; some were pavement-type specific. Instead of a ruggedness test, each factor had to be evaluated individually using analysis of variance (ANOVA), f-test, and t-test statistical methods to compare measurements including the factor to typical results. A few of the factors are computational adjustments and the impact of these factors can be understood by comparing the differences in the computation methods. The factors selected for the study include:

Orientation of Receivers. The receivers of the PSPA and the additional geophones of the LWD were tested either parallel or perpendicular to the paving and rolling direction. The PSPA was also tested at a 45 degree angle for a few of the projects.

Presence of Vibrations. Some projects are constructed with traffic in the adjacent lane or other construction equipment running nearby. The vibrations caused by large vehicles could be picked up by the NDT sensors and create false readings.

Presence of Small Surface Cracks. The NDT devices measure surface waves and deflections. The presence of small cracks could cause a reduction in the wave energy, resulting in changes to the reported modulus values.

Distance from Joints. A joint or pavement edge represents a change in medium. When stress waves encounter a change in medium, some of the energy is reflected. The NDT sensors could pick up the reflections as false readings.

Assumptions in Input Parameters. The PSPA requires the thickness of the surface layer as an input to estimate an average modulus for the surface layer. The LWD back calculation software requires a thickness and an initial modulus value to iterate for each layer. Incorrectly estimating the actual thickness could result in influence on modulus values from the supporting layer.

Temperature Normalization Methods. The moduli measured by NDT devices are impacted by temperature on HMA pavements. Multiple methods exist to normalize temperature such as equation (3) using either surface temperature or mid-depth temperature from BELLS3 model (4) *[4]*, *[10]*. For analysis, all HMA measurements were normalized using the BELLS3 mid-depth temperature in the temperature normalization equation. Also, AASHTO has temperature adjustment charts for pavement deflections, shown in Figure 7 *[27]*.

$$E_{25} = \frac{E_T}{1.35 - 0.014\,T} \quad (3)$$

$$T_m = 0.95 + 0.892 * IR + \{ \log(d) - 1.25 \} \{ -0.448 * IR + 0.621 * D_1 + 1.83 * \sin(Hr_{18} - 15.5)\} + 0.42 * IR * \sin(Hr_{18} - 13.5) \quad (4)$$

where,
E_{25} = modulus at 25°C, MPa;
E_T = modulus at test temperature, MPa;
T = pavement temperature, °C;
T_m = pavement mid-depth temperature, °C;
IR = Infrared surface temperature, °C;
d = depth in pavement to predict temperature, mm;
D_1 = average air temperature the day before testing, °C; and
Hr_{18} = Time of day, in 24-hr system, but calculated using an 18-hr asphalt concrete.

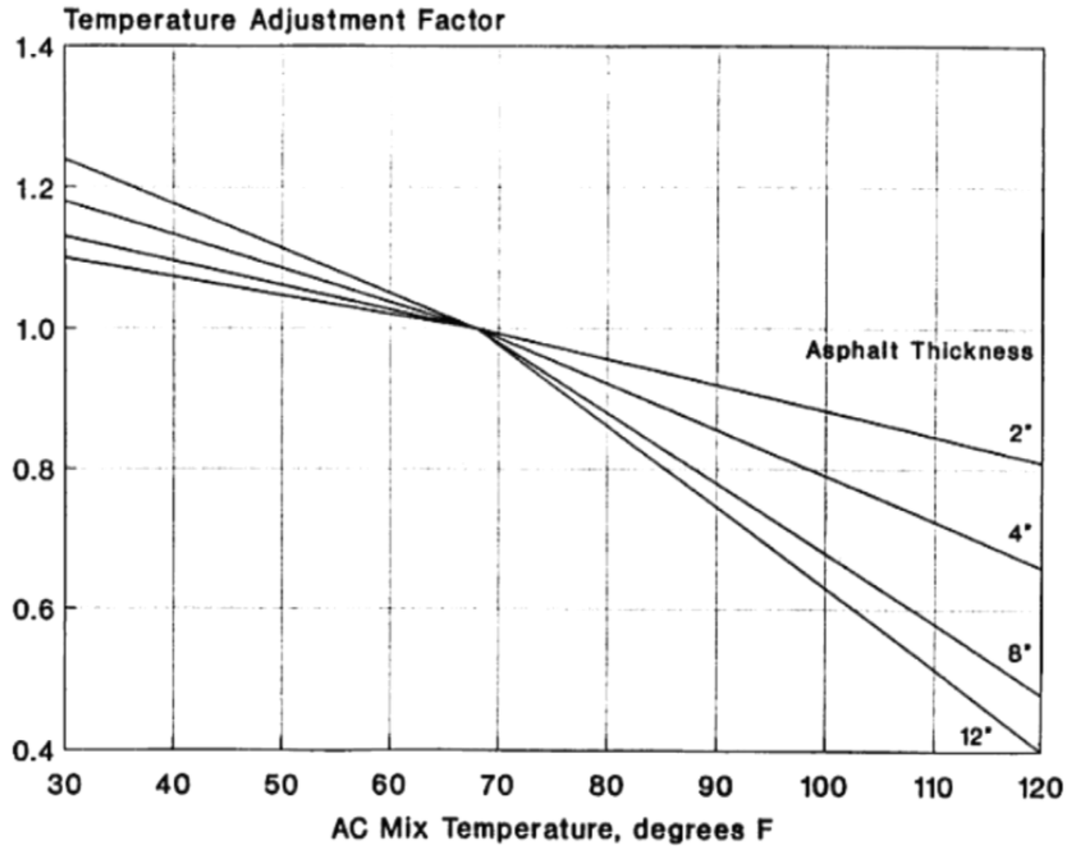

Figure 7
AASHTO deflection adjustment factor for temperature *[27]*

Grooves in Pavement. Current LADOTD practices require surface tines for PCC pavement. A grooved surface could cause a reduction in the energy of surface wave generated by the NDT devices.

Laboratory Testing

Due to the large amount of published material relating PSPA results from the field to the laboratory for HMA pavements, this study focused more on the field to laboratory relationship for PCC pavements *[4]*, *[7]*, *[9]*, *[11]*, *[12]*, *[13]*, *[14]*, *[15]*, *[17]*. Compressive strength and elastic modulus tests were performed on specimens cast in the field from the same sections PSPA measurements were collected.

Compressive Strength

ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens was used to determine the compression strength of cylinders and cores *[23]*.

Compressive strengths were compared to NDT measurements on the same pavement at similar ages.

Elastic Modulus

ASTM C469: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression was used to determine the modulus of elasticity of cylinders and cores. Modulus of elasticity is calculated by comparing the rate of loading to the rate of vertical deflection in the elastic range, up to 40 percent of the maximum load to failure, of a specimen *[23]*. The moduli of samples were compared to NDT measurements on the same pavement at similar ages.

DISCUSSION OF RESULTS

LTRC Experience Operating the Devices

LWD

The LWD test can be performed by a single person; however, the operation and mobility of the apparatus are very cumbersome with only a single person. When using the full drop weight, the apparatus should be transported using the supplied dolly, even for short distances. The additional geophones must be carried separately, but close because the cords tethering the additional geophones to the apparatus are very short. The authors recommend two people to efficiently perform the LWD test, one person to move and operate the apparatus and one person to manage the software. The data collection and operation of the apparatus are straight forward and fairly quick, usually less than five minutes to seat the apparatus, correctly position additional geophones, and collect six repeat measurements as one point. The LWD does not record pavement temperature; therefore, a separate means of recording temperature is needed.

The LWD apparatus interfaces with the LWD software on a PDA via a wireless Bluetooth link; any design with fewer cords is easier to manage. However, the PDA must remain within 15 ft. of the apparatus to maintain the link, and even then the link can randomly drop. The LWD software shows the measured deflection and combined surface modulus immediately after each reading. To obtain layer moduli, the data must be transferred to a computer to perform back calculations with LWDmod. In addition, LWDmod is limited in the layer analysis options and often randomly crashes.

The LWD apparatus requires assembly prior to use and requires breaking down into manageable parts for even short distance vehicle transport. LTRC experienced many complications with the LWD throughout the project. The center geophone tip would unscrew during transport; this should be checked frequently. The whole apparatus would bounce and move after the weight impact if not level or if the surface layer is too rigid; erroneous measurements caused by this were obvious. The battery must be removed to charge; the battery connector was damaged due to repeated charging and battery swapping. The connectors for the additional geophones were damaged, probably due to moving the apparatus during testing while the additional geophones were attached with such short cords. The additional geophones were held in place by small springs, which were easily damaged during transport.

PSPA

The PSPA consists of a small hand carried apparatus tethered to a laptop. The PSPA test can be performed by a single person; however, the process is slightly cumbersome for a single person to carry the laptop and move the apparatus. Recently a transport cart with a laptop holder was developed specifically for the PSPA test, making the device easier to transport with a single person *[7]*. The authors recommend two people to efficiently perform the PSPA test, one person to move the apparatus and one person to manage the software. Data collection is simple and quick, usually less than a couple of minutes to seat the apparatus and collect six repeat measurements at one point.

The study was started with an older model of the PSPA and completed with a newer model. The older model used a serial cable to connect the laptop to the apparatus and had a self-contained power supply that needed charging separate of the laptop. Shortly into the project, the internal wiring of the serial cable connector was damaged with a commonly known issue to the manufacturer. The damaged wiring would cause the PSPA to stop reading while on site and would start reading after an extended period of time. Eventually the PSPA stopped reading altogether and the wiring had to be replaced. The older PSPA would report erroneous or blank measurements if the battery was low. The newer model transfers data and power using a USB connection.

The PSPA software is easy to setup and manage. The recommended laptop screen is sometimes difficult to see on a bright day or on a dusty jobsite. The PSPA apparatus is metallic and becomes hot to the touch after extended use on sunny summer days. The rubber pads on the feet need to be checked frequently as these are prone to melting and quick deterioration. The feet need to be checked with each placement to ensure good contact with surface. Poor surface contact can cause erroneous values; however, a well-trained user can identify poor surface contact from the real-time graphs produced during collection.

Data Analysis

Repeatability

Each roadway point consists of repeat collections. The LWD back calculation software computes one average modulus value of the repeat measurements at each point, so the variability of the deflection is considered for the stationary apparatus. Table 5 shows the CoV average and range of the PSPA seismic moduli and LWD center deflections without moving the apparatus. The HMA overlays of 2-in. thickness (LA3121 and LA3191) showed higher variability with the PSPA than thicker HMA pavements. The authors believe this is due to the PSPA foot configuration used during collection and that part of the base was included in the measurement. The majority of the projects exhibited an average CoV less than 10 percent with ranges similar to those observed in the literature. The cause of the high variability observed on both collections of I-49 is unknown.

Table 5
PSPA and LWD coefficient of variation average in percentage (range), stationary apparatus

Project	Material	Layer	Number of Test Points	PSPA	LWD Deflection
LA116 (base)	Soil Cement	Base	- / 60		10 (0-37)
LA116 (binder)	Asphalt	Binder	20 / 60	6 (0-26)	9 (0-45)
LA116 (wearing)	Asphalt	Wearing	60 / 60	5 (0-22)	9 (0-62)
I-55 (1)	Asphalt	Wearing	27 / -	3 (0-16)	
I-55 (2)	Asphalt	Wearing	27 / -	8 (1-24)	
US171	Asphalt	Wearing	6 / 54	5 (1-8)	7 (0-49)
LA3121 (base)	Soil Cement	Base	- / 60		9 (0-66)
LA3121 (wearing)	Asphalt	Wearing	60 / 60	9 (0-32)	5 (0-27)
LA3191	Asphalt	Wearing	27 / 27	11 (0-41)	4 (0-13)
ALF (soil cement)	Soil Cement	Base	- / 105		12 (1-68)
ALF (asphalt)	Asphalt	Wearing	- / 50		4 (0-14)
US61 (shoulder)	Concrete	Shoulder	5 / -	6 (0-29)	
US61	Concrete	Mainline	60 / -	2 (0-9)	
LA3073 (1 day)	Concrete	Mainline	24 / -	3 (0-28)	
LA3073 (7 day)	Concrete	Mainline	24 / -	2 (0-9)	
LA3073 (14 day)	Concrete	Mainline	24 / -	3 (0-12)	
LA3073 (28 day)	Concrete	Mainline	24 / -	2 (0-11)	
LA3073 (56 day)	Concrete	Mainline	12 / -	2 (0-9)	
I-49 (7 day)	Concrete	Mainline	27 / -	14 (4-56)	
I-49 (28 day)	Concrete	Mainline	27 / -	15 (1-62)	
ALF (concrete)	Concrete	Mainline	5 / -	3 (0-20)	

For most projects, the measurements were collected on the same point at multiple orientations. The PSPA was rotated about the center point of the apparatus. The main apparatus of the LWD was not moved; only the additional geophones were repositioned in orientation. The variability of the center deflection does not change with orientation; however, the modulus of each orientation was back calculated separately. The LWD radial geophones require 2 ft. of distance from the main apparatus. The geophones could not always be placed on the same side of the main apparatus for measurements of the transverse orientation. Table 6 shows the CoV average and range of PSPA seismic moduli and LWD back calculations if all values from each point are grouped regardless of orientation. The CoV averages show an increase of 3 to 14 percent, suggesting that orientation has an impact on the measurements.

On some projects the apparatuses were moved a small distance in the longitudinal direction of the pavement, about six inches. Minimal influence from material and construction variability was assumed for such a close proximity. Table 7 shows the CoV average and range of PSPA seismic moduli, LWD deflections, and LWD back calculations. The PSPA results show similar increases in average CoV as the results of changing orientation, about 3 to 12 percent. The LWD results show increases of 6 to 10 percent.

Table 6
PSPA and LWD coefficient of variation average in percentage (range), changing orientation

Project	Material	Layer	Number of Test Points	PSPA	LWD Back-calculation
LA116 (binder)	Asphalt	Binder	20 / -	14 (6-25)	
LA116 (wearing)	Asphalt	Wearing	60 / -	10 (2-31)	
I-55 (1)	Asphalt	Wearing	27 / -	9 (4-14)	
I-55 (2)	Asphalt	Wearing	27 / -	12 (3-26)	
LA3121	Asphalt	Wearing	60 / -	16 (1-36)	
LA3191	Asphalt	Wearing	27 / 27	21 (3-56)	7 (0-28)
US61 (shoulder)	Concrete	Shoulder	5 / -	18 (2-50)	
US61	Concrete	Mainline	60 / -	7 (1-20)	
LA3073 (1 day)	Concrete	Mainline	24 / -	8 (0-37)	
LA3073 (7 day)	Concrete	Mainline	24 / -	7 (1-26)	
LA3073 (14 day)	Concrete	Mainline	24 / -	9 (1-28)	
LA3073 (28 day)	Concrete	Mainline	24 / -	10 (1-27)	
LA3073 (56 day)	Concrete	Mainline	12 / -	6 (1-21)	
I-49 (7 day)	Concrete	Mainline	27 / -	28 (8-74)	
I-49 (28 day)	Concrete	Mainline	27 / -	28 (10-59)	
ALF (concrete)	Concrete	Mainline	5 / -	7 (1-34)	

The overall project averages and CoVs of the PSPA measurements using the typical collection pattern are shown in Table 8. On some projects, the sections were spaced only 200 ft. apart while other projects were spaced several thousand feet apart because one section was collected at the start, middle, and end of the project. The variability across an entire project includes variability of construction and materials across a significant range, which better represents variability across a lot or sublot. On the second I-55 collection, variability increased drastically about half-way through, as shown in Figure 8. An inspection of the equipment after the collections showed that the rubber pads on the PSPA feet tore during collection; the technicians were unaware at the time. The authors believe the increase in variability is a result of the continued collection with damaged pads. Averages and CoVs for individual stations and sections within each project as well as contours of each section can be found in the Appendix.

Table 7
PSPA and LWD coefficient of variation average in percentage (range), close proximity

Project	Material	Layer	Number of Test Points	PSPA	LWD Deflection	LWD Back-calculation
LA116 (base)	Soil Cement	Base	- / 60		20 (3-75)	
LA116 (binder)	Asphalt	Binder	- / 60		15 (0-39)	
LA116 (wearing)	Asphalt	Wearing	- / 60		13 (0-38)	
LA3191	Asphalt	Wearing	27 / 27	23 (4-61)	10 (2-22)	20 (0-68)
LA3073 (1 day)	Concrete	Mainline	24 / -	8 (0-31)		
LA3073 (7 day)	Concrete	Mainline	24 / -	6 (1-24)		
LA3073 (14 day)	Concrete	Mainline	24 / -	9 (2-30)		
LA3073 (28 day)	Concrete	Mainline	24 / -	10 (1-30)		
LA3073 (56 day)	Concrete	Mainline	12 / -	8 (1-21)		
ALF (concrete)	Concrete	Mainline	5 / -	7 (1-26)		

Table 8
PSPA average modulus and coefficient of variation across entire project

Project	Number of Test Points	Average	Stdev	CoV
		ksi	ksi	%
LA116 (binder)	20	1586	227	14
LA116 (wearing)	60	1770	256	15
I-55 (1)	27	1310	149	11
I-55 (2)*	12	1856	181	10
LA3121	60	1824	326	18
LA3191	27	1834	413	23
US61	60	5818	399	7
LA3073 (1 day)	24	4104	605	15
LA3073 (7 day)	24	4704	268	6
LA3073 (14 day)	24	4460	323	7
LA3073 (28 day)	24	3946	364	9
LA3073 (56 day)	12	5273	243	5
I-49 (7 day)	27	4737	1491	32
I-49 (28 day)	27	4672	1069	23

* average prior to pads on PSPA feet tearing

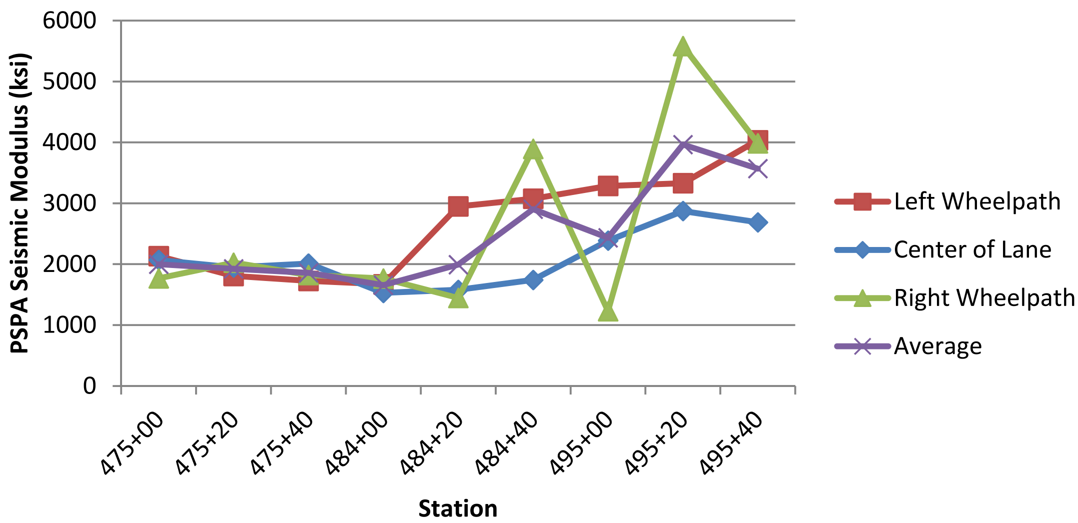

Figure 8
PSPA variability increase from damaged pads on feet

The overall project averages and CoVs of the LWD deflections and back-calculated moduli of the layer using the typical collection pattern are shown in Table 9. Similar to the PSPA collections, some project sections were spaced only 200 ft. apart while other projects were spaced several thousand feet apart because one section was collected at the start, middle, and end of the project. The variability across an entire project includes variability of construction and materials across a significant range which better represents variability across a lot or sublot. LA3191 back calculations produced very low values due to the inclusion of the concrete layer underneath. The back-calculated moduli for all projects showed higher variability than the deflections. Averages and CoVs for individual stations and sections within each project as well as contours of each section can be found in the Appendix.

Table 9
LWD average and coefficient of variation across entire project

Project	Number of Test Points	Deflection			Moduli		
		Average	Stdev	CoV	Average	Stdev	CoV
		mil	mil	%	ksi	ksi	%
LA116 - SC	60	2.2	0.6	26			
LA116 - Binder	60	1.5	0.3	20			
LA116 - Wearing	60	1.6	0.3	18			
US171	54	2.0	0.4	19			
LA3121 (base)	60	3.2	1.6	49	415	291	70
LA3121 (wearing)	60	3.2	1.8	55	719	443	62
LA3191	27	3.8	1.2	31	156	69	44

Orientation

Measurements with the PSPA were collected in the longitudinal direction, parallel to paving and rolling, and in the transverse direction, perpendicular to paving and rolling. The PSPA apparatus was simply picked up and turned 90 degrees about its center to collect over the same point. A t-test, assuming equal variance and $\alpha = 0.05$, was performed for each point. The percentage of points determined statistically different for each project is shown in Table 10. These values are misleading due to the wide variability range of the device; if either orientation exhibited a very high standard deviation, the t-test would show it was statistically similar. Therefore, the differences between the averages for each orientation were compared. As shown in Table 10, regardless of the surface material, the longitudinal values were higher for about half of the collections.

Table 10
PSPA comparison between longitudinal and transverse orientation

Project	Percent Statistically Different ($\alpha = 0.05$)	Percent Longitudinal Greater than Transverse	Average Absolute Difference as Percentage of Project Average
LA116 (binder)	60	70	21
LA116 (wear)	18	54	13
I-55 (1)	33	30	13
I-55 (2)	76	48	21
LA3121	21	45	21
LA3191	53	46	18
US61 (shoulder)	73	42	27
US61	57	47	12
LA3073 (1)	25	66	12
LA3073 (2)	25	50	11
LA3073 (3)	13	40	13
LA3073 (4)	29	67	17
LA3073 (5)	17	57	10
I-49 (1)	33	40	38
I-49 (2)	48	40	44
ALF (concrete)	43	59	12

Presence of Vibrations

Measurements were collected within 10 ft. of active coring and within 5 ft. of large vehicles passing in the adjacent lane. In only a couple of instances when a large vehicle was passing near the PSPA, the operator noticed a significant drop in the measured moduli. These values were ruled out on site as erroneous and recollected.

Presence of Small Cracks

All projects were new construction; therefore, locating suitable sections containing small cracks was difficult. The only small cracks found were located in the soil cement base layer of LA116. Comparative collections were performed with the LWD. Measurements over the cracks would yield deflections two or three times higher than the average for the project.

Distance from Joints

The PSPA was placed within 6 in. of the edges and corners of a concrete slab. Measurements were collected in both longitudinal and transverse orientations and averaged. Figure 9 shows the values near the center of the slab are similar and exhibited low standard deviations while the values along the joints differed significantly, many with higher standard deviations. Unfortunately, the internal wiring complications occurred after this collection, and only the one slab was tested.

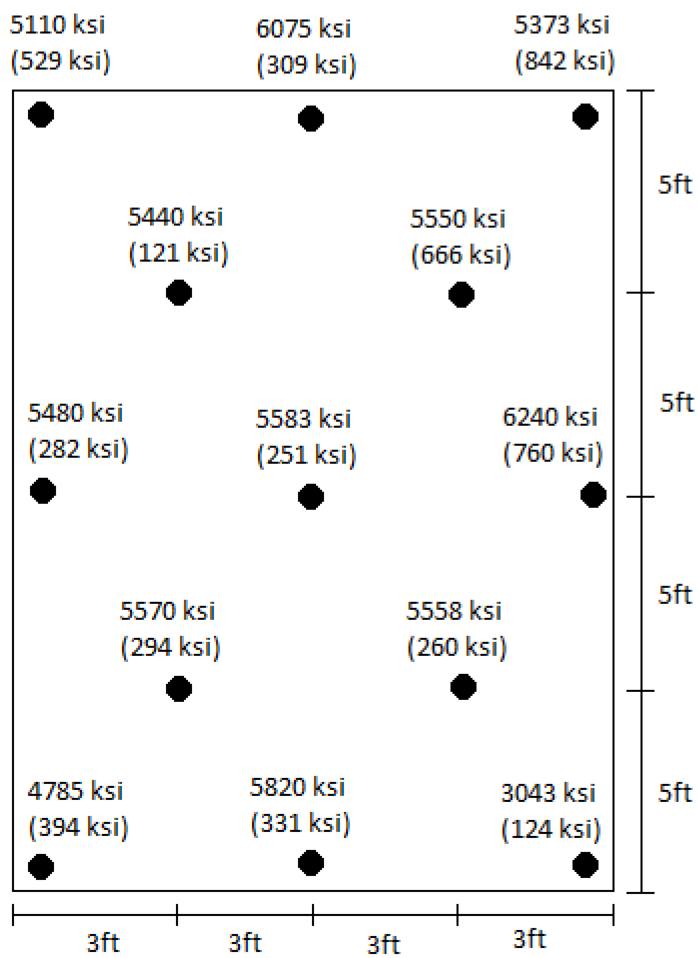

Figure 9
Layout of PSPA seismic modulus on concrete slab, average (standard deviation)

Assumptions in Input Parameters

Both devices require the thickness of the surface layer to compute the modulus of the surface layer. The PSPA averages the moduli computed for different depths (wavelengths) from the surface to the input thickness. The plot of moduli versus depth produced by the SPA Manager shows the moduli are usually similar through the surface layer. Therefore, underestimating the thickness should result in little change. However, overestimating the thickness could result in a change as the moduli below the surface layer will begin to shift depending on the stiffness of the supporting layer, as shown in Figure 10.

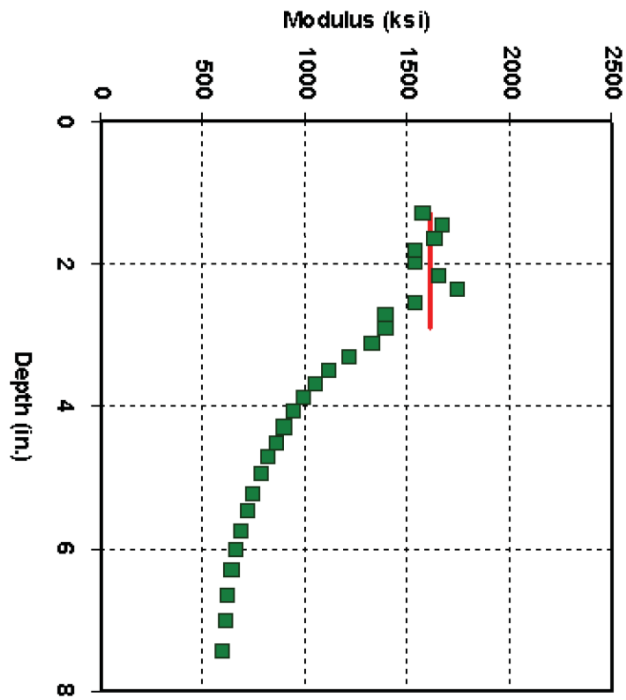

Figure 10
Typical PSPA dispersion curve *[9]*

The LWDmod software back calculates the modulus of the surface layer based on the thickness and modulus input entered for each pavement layer. LWDmod is limited in the analysis inputs; only three layers can be evaluated at one time. The modulus of the center layer will not change in the iterations unless using a constant ratio between the surface layer and underlying layer. With only two radial geophones to compute the deflection basin, the back-calculation results change significantly with different inputs. An example is shown in Table 11.

Table 11
Example of LWD variability in back calculation assumptions, LA3121

Surface Thickness (in.)	2			2		
Surface Initial Modulus (ksi)	300			300		
Base Thickness (in.)	12			12		
Base Initial Modulus (ksi)	200			*		
Subgrade Modulus (ksi)	20			20		
Station	Surface Modulus (ksi)	Soil Cement Modulus (ksi)	Subgrade Modulus (ksi)	Surface Modulus (ksi)	Soil Cement Modulus (ksi)	Subgrade Modulus (ksi)
183+00 south outer	226.3	150.9	29.8	108.4	210	28.9
183+00 south center	223.3	148.9	42.7	60.2	404	37.4
183+00 south inner	317.8	211.9	55.7	103	441	51.2
183+00 north outer	111.4	74.3	20.4	37.4	165	19
183+00 north center	371.1	247.4	34.8	155.3	367	33.3
183+00 north inner	287.1	191.4	45.7	101.4	367	42.6

* back-calculated modulus of each point of soil cement layer from prior testing

Temperature Normalization Methods

Measurements of both NDT need to be corrected for temperature. The PSPA software records the surface temperature of the pavement with each point, but does not apply a correction. The LWD software contains a field for entry of the temperature, but does not automatically record the temperature or apply a correction. Neither of the collection software is setup to easily apply the correction during use.

As temperature increases, the modulus of asphalt will decrease. The factors of three accepted normalization methods were compared. Table 12 shows an example with the range of factors for each method on a 2-in. HMA pavement across a wide range of temperatures normalized to 77°F. The farther the measured temperature is from 77°F, the greater the difference between the methods. For this example, the values differ up to 16 percent. These values will increase as the thickness of the pavement increases as well. An alternative and more accurate method is to develop the specific relationship between modulus and temperature for each mixture. However, this method requires additional laboratory testing prior to construction and is subject to change if the mixture is modified afterward.

Table 12
Comparison of temperature normalization methods for 2 in. HMA

Surface Temp.	Correction Factor to 77°F			Measured Modulus	Normalized Modulus to 77°F		
	BELLS3*	Nazarian **	AASHTO ***		BELLS3 *	Nazarian **	AASHTO ***
°F				ksi	ksi	ksi	ksi
40	1.26	1.29	1.12	1200	956	932	1072
50	1.19	1.21	1.09	1200	1007	992	1097
60	1.13	1.13	1.06	1200	1063	1060	1135
70	1.07	1.05	1.02	1200	1127	1138	1176
80	1.00	0.98	0.99	1200	1198	1229	1213
90	0.94	0.90	0.95	1200	1279	1335	1259
100	0.87	0.82	0.91	1200	1372	1461	1317
110	0.81	0.74	0.88	1200	1479	1614	1371

* Equation (3) with mid depth from equation (4) using 1:00 PM and previous day temperature of 77°F

** Equation (3) only

*** Figure 7

Grooves in the Pavement

Based on the experiment of Yuan et al., grooves can have a slight impact on PSPA measurements *[8]*. However, the tine texture requirements of Louisiana are narrower and shallower than those tested by Yuan. The results shown previously in Table 10 show instances where transverse and longitudinal orientations were statistically different on tined pavements (US61, LA3073, I-49). However, only 50 percent of the time the longitudinal collection was higher than the transverse suggesting that the tines were not the cause of the difference.

The larger impact of tines observed during PSPA collections was the difficulty of seating the PSPA perpendicular to the tines. Louisiana specifies randomly spaced tines; in many instances one of the PSPA feet would be centered over a groove. The operator would have to move the apparatus and retest.

Comparison of Field to Laboratory

The PSPA was used to monitor the strength gain of concrete pavements and to compare to laboratory results. Various sections of LA3073 were tested for strength gain and cylinders were cast during the construction. Figure 11 shows a plot of the averages of the PSPA seismic moduli for each section versus the laboratory elastic modulus and laboratory compressive strength. The results show the field seismic moduli decreasing from the age of 7 days to 28 days, and increasing to 56 days, while the laboratory elastic modulus and compressive strength increase only with age. No trend was observed between PSPA seismic moduli and laboratory values for this data set; however, all PSPA data sets exhibited similar behavior. The difference in curing methods between field and laboratory could be the cause. Note, a few sections are missing; the PSPA was exhibiting the internal wiring complications during the later collections and would stop reading while on site.

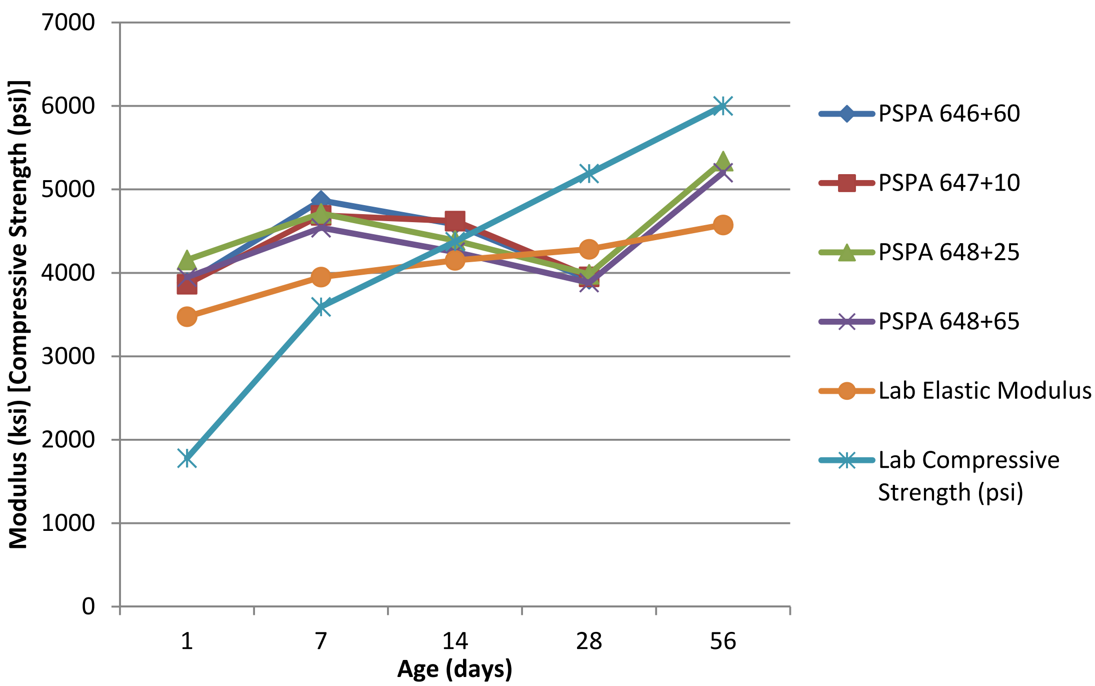

Figure 11
LA3073 PSPA seismic modulus compared to laboratory elastic modulus and compression strength

A PCC layer was placed at the ALF. The PSPA was used to test the strength gain of the slab and cylinders were cast during construction to compare the results. The PSPA seismic modulus, laboratory modulus, and laboratory compressive strength show a steady increase in the first 10 days, shown in Figure 12. Unfortunately, measurements after 10 days were not collected due to the internal wiring issue. Figure 13 shows the PSPA seismic moduli correlate well with laboratory compressive strengths for the early age of the ALF PCC mixture.

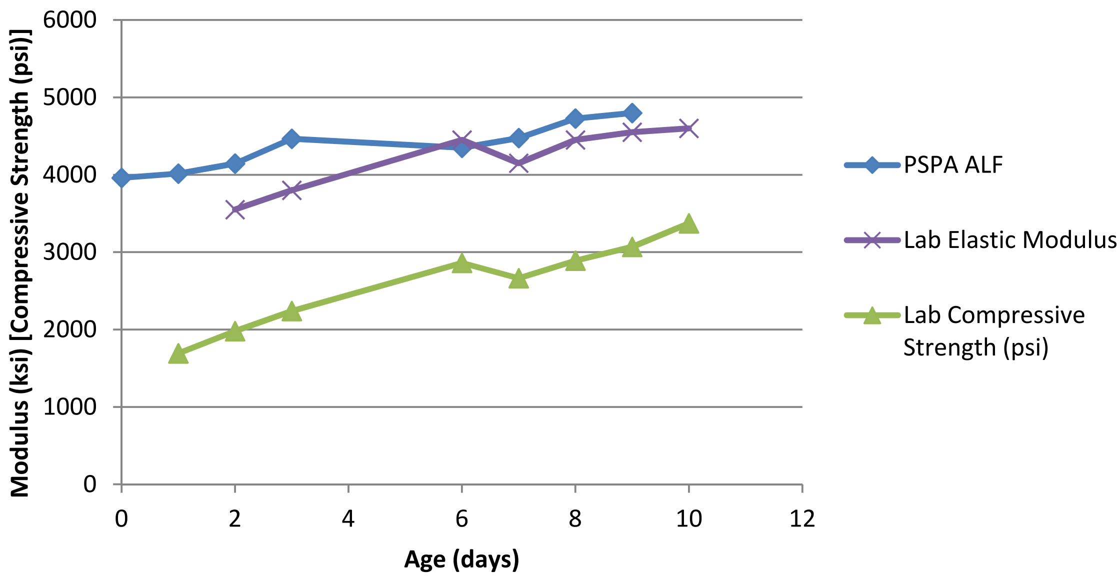

Figure 12
ALF PCC PSPA seismic modulus compared to laboratory elastic modulus and compressive strength

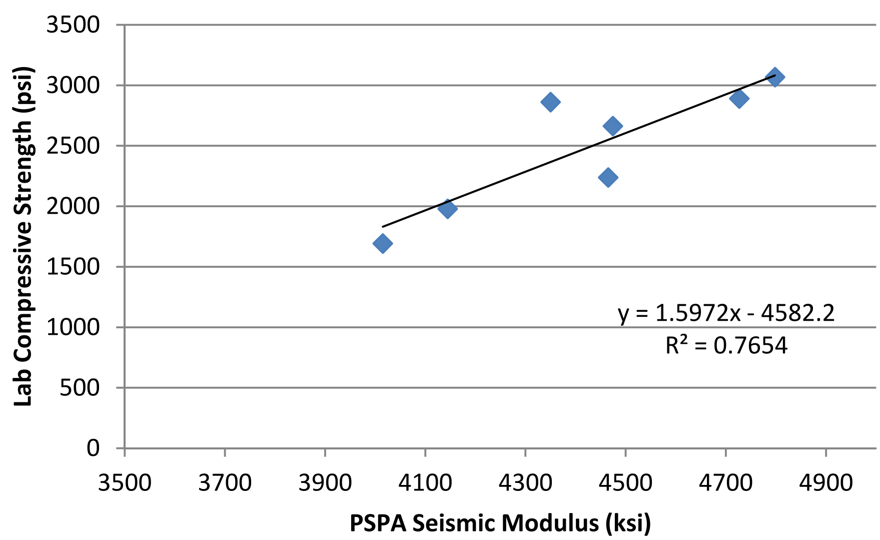

Figure 13
ALF PCC PSPA seismic modulus correlation to laboratory compressive strength

Three PCC sections of I-49 were tested with the PSPA at 7 and 28 days of age and compared to cylinders cast during construction. The I-49 data sets showed the PSPA seismic modulus decreasing with age for a few of the sections; this could be a result of the high variability observed in the repeatability section. Figure 14 shows one section of the data set as an example; the remaining figures can be found in the Appendix. No trends were observed for the overall data set.

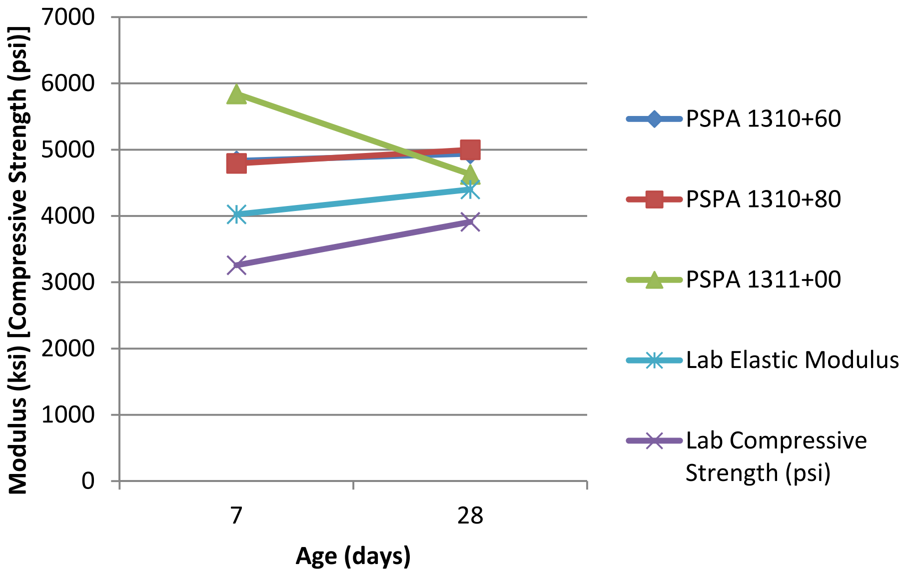

Figure 14
I-49 PSPA seismic modulus compared to laboratory elastic modulus and compressive strength

Comparison between LWD and FWD

An HMA lane at the LADOTD ALF was tested on 27 points with both LWD and FWD for comparison. The deflections were corrected for temperature and normalized to a stress of 80 psi. Both technologies use the same principle; the LWD is simply a portable, smaller-scale version of the FWD. The center deflections measured correlate well between the LWD and FWD, though the LWD deflections were about 60 percent lower, shown in Figure 15. The moduli of the surface layer were back-calculated using the same input parameters for thickness and initial iteration moduli. The back-calculated moduli do not correlate as well as the deflections, shown in Figure 16. The authors believe this is due to fewer points in the LWD deflection basin and limitations of the LWDmod back-calculation software.

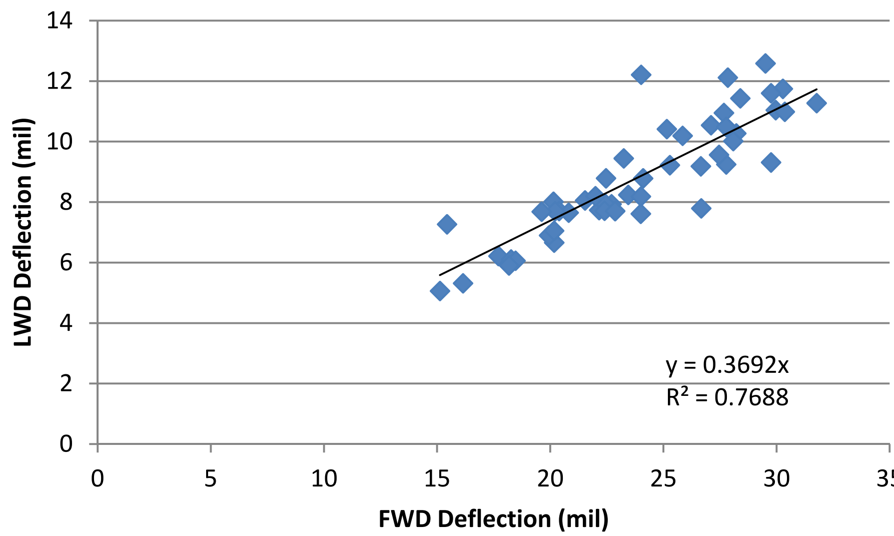

Figure 15
LWD deflection correlation to FWD deflection

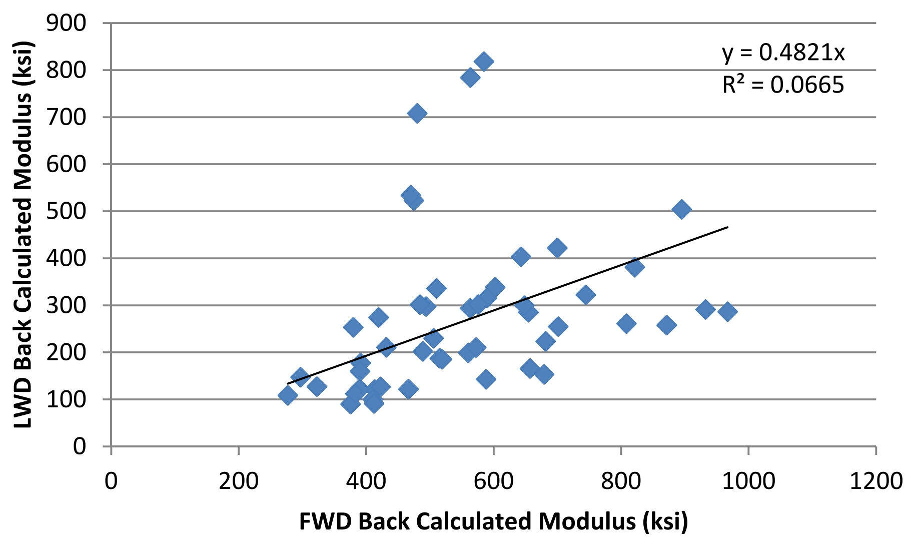

Figure 16
LWD back-calculated modulus correlation to FWD back-calculated modulus

Comparison between PSPA and LWD

The PSPA measures the modulus of the surface layer, which is back calculated by the LWDmod software. The frequency at which each device operates is different and is expected to cause a shift in the values. A similar trend is expected to occur between the moduli measurement of each device. However, no such trend was observed.

Sampling Procedure and Operation

The variability of the PSPA observed on most projects in the study exhibited similar results to those of the literature. A recommended sampling procedure has been developed for the PSPA based on conclusions and recommendations of the literature. Celaya et al. picked an arbitrary value of 30 samples per half shift lot, approximately 1500 tons, to begin quality control *[13]*. Velivelli et al. computed the sample size for various test methods based on multiple variables, independent of lot size, such as: buyer risk, seller risk, and cost of sampling and testing. Using a PSPA CoV range of 5.2 to 8.6 percent, the report concluded a minimum sample size at 75 percent probability in which the standard deviation of the population is less than or equal to the standard deviation of the sample for the PSPA that is 6 to 12 per lot; at 95 percent the sample size is 13 to 24 per lot *[11]*.

The authors recommend starting with a random sampling at 20 stations per HMA sublot (1000 tons or 5000 lane feet) or PCC lot (4000 square yards) at a distance randomly selected on or between the wheel paths of the lane. A minimum of two seismic moduli will be collected for both parallel and perpendicular orientation to the pavement. The temperature shall be recorded with each collection. For HMA pavements, the pavement must be allowed to cool for at least one full day. For PCC pavements, seismic moduli should be collected on 7 and 28 days of age. Operators must be trained to inspect the waveform display in order to determine if the collection is acceptable or if a retest is required. If the PSPA continues to show unacceptable readings, the apparatus should be moved no more than 6 in. to retest.

The pads on the PSPA feet must be checked at the beginning of collection at each station, if any deterioration is observed, the feet must be replaced before collection. The PSPA feet must be checked during each placement that good contact is made. On PCC pavements, the feet should be situated such that no single foot is placed directly into a groove. On PCC pavements, the PSPA must be at least 1 ft., one apparatus length, from any joints or cracks.

During analysis, the seismic moduli of HMA pavements shall be normalized to 77°F using the surface temperature and equation (4). The values of each station shall be averaged together to represent a single seismic modulus for each station.

Benefit/Cost Analysis

At present, NDT will only supplement coring, not replace, resulting in additional costs. The benefits of NDT are the increased frequency of testing and the non-destructive nature allowing for monitoring throughout the life of the pavement. As Louisiana moves towards performance-based specifications, non-destructive technologies will become more widely accepted and needed as quality control tools. Devices such as the PSPA could one day replace coring.

CONCLUSIONS

The results of this study yield the following conclusions:

The PSPA exhibited seismic modulus values of the surface layer with an average CoV of 2 to 15 percent for repeat collections without moving the apparatus. The majority of the data sets fall within the specified limits of variability of the laboratory tests currently used for quality control. The PSPA variability increased to a range of 6 to 28 percent if the apparatus changed orientation or moved within a close proximity.

The LWD exhibited deflections values of the pavement structure with an average CoV of 4 to 12 percent for repeat collections without moving the apparatus. The majority of the data sets fell within the specified limits of variability of the laboratory tests currently used for quality control. Variability increased when the surface layer moduli were back calculated.

The PSPA exhibited project-wide seismic modulus values with a CoV between 1 and 32 percent. The LWD exhibited project-wide deflection values with a CoV between 18 and 55 percent. Using the measured deflection basin to back calculate the modulus of the surface layer would increase the variability for the project.

NDT operators need to be trained to identify when a device is reading incorrectly. Deterioration of the feet pads, the presence of vibrations, or placement of a foot into a groove can cause incorrect measurements. Such measurements should be identified and recollected.

Changing the orientation of the sensors showed to increase the variability of the PSPA measurements; however, the variability increase is no different than moving the apparatus within a close proximity. Orientation of the sensors did not show a bias when measuring parallel or perpendicular to paving. Testing close to joints showed impact on measurements of the PSPA.

Temperature will impact the NDT measurements on HMA pavements. Different normalization methods produce up to a 16 percent difference in corrected values. The best method to normalize NDT measurements on temperature is to develop a mixture specific relationship between temperature and NDT measurements in the laboratory.

Incorrect input parameters can change the outcome of analysis, such as overestimating the surface layer thickness when testing with the PSPA or using incorrect values of moduli for supporting layers when back calculating with LWD software.

The literature has shown the PSPA measurements correlate very well with laboratory testing of HMA samples. The relationship does not hold as well for PCC samples. The strength gain measured by the PSPA correlated well with the strength gain of laboratory testing for only one of the PCC data sets for this study.

The LWD deflections correlate well with FWD deflections, but the back-calculated moduli of the surface layer do not correlate well. This is due to the difference in the number of geophones representing the deflection basin and difference in back-calculation software.

A preliminary sampling procedure was developed for the PSPA as a quality control tool in Louisiana.

RECOMMENDATIONS

The authors recommend the PSPA for a trial evaluation as a quality control and assurance tool for Louisiana. As described in the literature, proper implementation of the PSPA into current quality control and assurance will require additional laboratory testing during the design phase to determine mixture specific target values. Such testing is currently being evaluated in LTRC project 10-4B as requirements for performance-based specifications. This research will serve as a pilot project for 10-4B.

At present, a database will be setup to warehouse NDT collections using the sampling procedure described in this report. The database can later be used to determine to set limits for quality control by pavement type or function and to update the cost/benefit analysis.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ALF	Accelerated Loading Facility
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
cm	centimeter(s)
FHWA	Federal Highway Administration
ft.	foot (feet)
FWD	Falling Weight Deflectometer
HMA	Hot Mix Asphalt
in.	inch(es)
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
LWD	Light Weight Deflectometer
lb.	pound(s)
m	meter(s)
mm	millimeter(s)
NDT	Non-Destructive Testing (or Technology)
PCC	Portland Cement Concrete
PDA	Personal Digital Assistant
PSPA	Portable Seismic Pavement Analyzer
QC/QA	Quality Control and Quality Assurance (or Acceptance)
USB	Universal Serial Bus
USW	Ultrasonic Surface Wave

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APPENDIX

Station and section average, standard deviation, and CoV for PSPA on I-55

I-55									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
371+00	1125	111	9.9	1259	120	9.5	1310	149	11.4
371+20	1329	49	3.7						
371+40	1324	45	3.4						
365+20	1205	37	3.1	1238	102	8.2			
365+00	1164	25	2.2						
364+80	1346	111	8.2						
303+80	1422	285	20	1433	149	10.4			
304+00	1396	40	2.9						
304+20	1480	27	1.8						

Station and section average, standard deviation, and CoV for PSPA on I-55 (2)

I-55 (2)									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
475+00	1999	196	9.8	1923	146	7.6	2458	1028	41.8
475+20	1924	110	5.7						
475+40	1857	144	7.8						
484+00	1655	119	7.2	2183	886	40.6			
484+20*	1991	832	41.8						
484+40*	2904	1087	37.4						
495+00*	2434	1031	42.4	3266	1219	37.3			
495+20*	3964	1451	36.6						
495+40*	3570	764	21.4						

* stations where PSPA feet pads became damaged

Station and section average, standard deviation, and CoV for PSPA on LA116 (binder)

LA116 (binder)									
Station	Station (2 pt)			Section (4-6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
58+00 eb	1597	206	12.9	1532	227	14.8	1586	227	14.3
59+00 eb	1673	279	16.6						
60+00 eb	1327	77	5.8						
64+00 eb	1661	253	15.2	1423	333	23.4			
65+00 eb	1184	204	17.2						
58+00 wb	1925	988	51.3	1822	536	29.4			
59+00 wb	2076	137	6.6						
60+00 wb	1465	191	13.0						
64+00 wb	1289	297	23.1	1477	339	22.9			
65+00 wb	1665	338	20.3						

eb = east bound, wb = west bound

2" pavement, believed variation from base

Station and section average, standard deviation, and CoV for PSPA on LA116 (wearing)

LA116 (wearing)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
58+00 eb	1739	278	16.0	1773	194	11.0	1770	256	14.5
58+50 eb	1790	95	5.3						
59+00 eb	1793	145	8.1						
59+50 eb	1888	191	10.1						
60+00 eb	1658	279	16.8						
64+00 eb	1930	624	32.3	1834	304	16.6			
64+50 eb	1758	75	4.3						
65+00 eb	1821	136	7.5						
65+50 eb	1970	363	18.5						
66+00 eb	1691	147	8.7						
58+00 wb	1857	115	6.2	1792	284	15.8			
58+50 wb	1740	172	9.9						
59+00 wb	1805	164	9.1						
59+50 wb	1699	188	11.0						
60+00 wb	1859	654	35.2						
64+00 wb	1828	261	14.3	1682	230	13.7			
64+50 wb	1526	313	20.5						
65+00 wb	1665	209	12.6						
65+50 wb	1666	246	14.8						
66+00 wb	1722	163	9.5						

eb = east bound, wb = west bound

Station and section average, standard deviation, and CoV for PSPA on LA3212

LA3121									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
94+00 nb	1637	223	13.6	1721	333	19.3	1824	326	17.9
96+00 nb	2179	387	17.8						
98+00 nb	1739	282	16.2						
100+00 nb	1515	180	11.9						
102+00 nb	1533	141	9.2						
175+00 nb	1568	164	10.4	1772	405	22.8			
177+00 nb	1845	382	20.7						
179+00 nb	1459	339	23.2						
181+00 nb	1696	286	16.8						
183+00 nb	2293	380	16.6						
183+00 sb	1620	201	12.4	1852	340	18.3			
181+00 sb	1874	151	8.0						
179+00 sb	1591	192	12.1						
177+00 sb	2111	507	24.0						
175+00 sb	2065	316	15.3						
312+00 sb	2064	158	7.7	1952	156	8.0			
310+00 sb	1815	181	10.0						
308+00 sb	1975	88	4.4						
306+00 sb	1938	227	11.7						
304+00 sb	1967	72	3.7						

nb = north bound, sb = south bound

Station and section average, standard deviation, and CoV for PSPA on LA3191

LA3191									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
10+50*							1834	413	22.5
10+70*									
10+90*									
20+00	1637	381	23.3	1944	350	18.0			
20+20	2069	157	7.6						
20+40	2127	322	15.1						
21+20	1774	773	43.6	1724	461	26.8			
21+40	1863	405	21.7						
21+60	1534	56	3.6						

* wiring issue caused erroneous values and device to stop

Station and section average, standard deviation, and CoV for PSPA on US61

US61									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
356+60 i	5741	318	5.5	5876	306	5.2	5818	399	6.9
356+70 i	6153	447	7.3						
356+80 i	5994	225	3.7						
356+90 i	5753	185	3.2						
357+00 i	5736	236	4.1						
362+73 i	5853	435	7.4	5800	310	5.4			
362+83 i	5743	264	4.6						
362+93 i	5842	141	2.4						
363+03 i	5619	394	7.0						
363+13 i	5943	386	6.5						
356+60 o	6011	973	16.2	5887	602	10.2			
356+70 o	5923	394	6.7						
356+80 o	5880	776	13.2						
356+90 o	5932	561	9.5						
357+00 o	5689	657	11.5						
362+73 o	5979	449	7.5	5711	314	5.5			
362+83 o	5831	132	2.3						
362+93 o	5638	311	5.5						
363+03 o	5370	106	2.0						
363+13 o	5737	219	3.8						

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on LA3073 day 1

LA3073 (day 1)									
Station	Station (3 pt)			Section (6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
646+60 i 1day	3930	311	7.9	3958	206	5.2	4104	605	14.7
647+10 i 1day	3986	82	2.1						
648+25 i 1day	4185	385	9.2	4006	510	12.7			
648+65 i 1day	3827	637	16.7						
646+60 o 1day	3811	441	11.6	3776	290	7.7			
647+10 o 1day	3742	110	3.0						
648+25 o 1day	4125	482	11.7	4675	861	18.4			
648+65 o 1day	5224	846	16.2						

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on LA3073 day 7

LA3073 (day 7)									
Station	Station (3 pt)			Section (6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
646+60 i 7day	4918	30	0.6	4765	350	7.3	4704	268	5.7
647+10 i 7day	4613	486	10.5						
648+25 i 7day	4813	91	1.9	4694	171	3.6			
648+65 i 7day	4575	150	3.3						
646+60 o 7day	4818	479	9.9	4798	345	7.2			
647+10 o 7day	4777	260	5.4						
648+25 o 7day	4613	78	1.7	4559	141	3.1			
648+65 o 7day	4506	187	4.2						

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on LA3073 day 14

LA3073 (day 14)									
Station	Station (3 pt)			Section (6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
646+60 i 14day	4470	307	6.9	4627	271	5.9	4460	323	7.3
647+10 i 14day	4784	125	2.6						
648+25 i 14day	4411	501	11.4	4395	325	7.4			
648+65 i 14day	4378	108	2.5						
646+60 o 14day	4693	326	7.0	4576	298	6.5			
647+10 o 14day	4459	273	6.1						
648+25 o 14day	4366	413	9.5	4243	320	7.5			
648+65 o 14day	4120	198	4.8						

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on LA3073 day 28

LA3073 (day 28)									
Station	Station (3 pt)			Section (6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
646+60 i 28day	4218	273	6.5	4084	353	8.6	3946	364	9.2
647+10 i 28day	3950	427	10.8						
648+25 i 28day	4154	715	17.2	4063	465	11.5			
648+65 i 28day	3972	78	2.0						
646+60 o 28day	3630	240	6.6	3794	320	8.4			
647+10 o 28day	3957	343	8.7						
648+25 o 28day	3894	404	10.4	3845	297	7.7			
648+65 o 28day	3795	223	5.9						

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on LA3073 day 56

LA3073 (day 56)									
Station	Station (3 pt)			Section (6 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
646+60 i 56day*							5273	243	4.6
647+10 i 56day*									
648+25 i 56day	5309	176	3.3	5270	140	2.6			
648+65 i 56day	5231	115	2.2						
646+60 o 56day*									
647+10 o 56day*									
648+25 o 56day	5371	365	6.8	5277	331	6.3			
648+65 o 56day	5183	339	6.5						

* wiring issue causing device to stop completely

i = inside lane, o = outside lane

Station and section average, standard deviation, and CoV for PSPA on I-49 day 7

I-49 (day 7)									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
1310+60 7day	4830	1312	27.2						
1310+80 7day	4793	1237	25.8	5155	1890	36.7			
1311+00 7day	5842	3158	54.0						
1315+60 7day	4264	549	12.9						
1315+80 7day	3996	1176	29.4	4289	1156	27.0	4737	1491	31.5
1316+00 7day	4606	1839	39.9						
1320+60 7day	4640	1942	41.9						
1320+80 7day	4157	1282	30.8	4768	1377	28.9			
1321+00 7day	5507	872	15.8						

Station and section average, standard deviation, and CoV for PSPA on I-49 day 28

I-49 (day 28)									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
1310+60 28day	4939	1058	21.4						
1310+80 28day	4999	1437	28.7	4855	1205	24.8			
1311+00 28day	4628	1583	34.2						
1315+60 28day	5523	1261	22.8						
1315+80 28day	4212	1075	25.5	4837	1217	25.2	4672	1069	22.9
1316+00 28day	4776	1372	28.7						
1320+60 28day	4047	929	22.9						
1320+80 28day	4298	781	18.2	4324	761	17.6			
1321+00 28day	4627	767	16.6						

Station and section average, standard deviation, and CoV for LWD deflections on LA116 (base)

LA116 (base)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
58+00 eb	2.8	0.8	28.4	2.3	0.8	33.0	2.2	0.6	26.0
58+50 eb	2.6	0.5	17.7						
59+00 eb	2.0	0.2	12.2						
59+50 eb	1.6	0.3	16.8						
60+00 eb	2.6	1.2	47.8						
64+00 eb	2.2	0.5	21.9	2.1	0.3	16.3			
64+50 eb	1.8	0.2	13.1						
65+00 eb	2.1	0.1	5.0						
65+50 eb	2.3	0.5	22.6						
66+00 eb	2.1	0.3	13.4						
58+00 wb	2.0	0.3	14.6	2.1	0.5	24.0			
58+50 wb	2.3	0.0	1.3						
59+00 wb	1.9	0.1	6.7						
59+50 wb	2.7	0.7	25.4						
60+00 wb	1.9	0.8	41.1						
64+00 wb	2.5	0.7	26.3	2.2	0.6	27.6			
64+50 wb	1.9	0.6	33.5						
65+00 wb	1.7	0.1	6.8						
65+50 wb	2.5	0.9	36.9						
66+00 wb	2.4	0.1	4.8						

eb = east bound, wb = west bound

Station and section average, standard deviation, and CoV for LWD deflections on LA116 (binder)

LA116 (binder)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
58+00 eb	1.5	0.3	18.6	1.6	0.3	16.5	1.5	0.3	19.6
58+50 eb	1.6	0.1	6.9						
59+00 eb	1.5	0.3	19.6						
59+50 eb	1.7	0.3	19.6						
60+00 eb	1.7	0.4	22.4						
64+00 eb	1.5	0.1	5.6	1.5	0.3	20.6			
64+50 eb	1.1	0.2	15.4						
65+00 eb	1.7	0.4	23.2						
65+50 eb	1.6	0.2	11.0						
66+00 eb	1.7	0.1	5.6						
58+00 wb	1.3	0.0	3.6	1.3	0.2	15.4			
58+50 wb	1.1	0.1	7.7						
59+00 wb	1.4	0.2	17.2						
59+50 wb	1.6	0.1	4.6						
60+00 wb	1.2	0.2	13.6						
64+00 wb	1.6	0.3	20.3	1.6	0.3	18.6			
64+50 wb	1.4	0.2	17.0						
65+00 wb	1.5	0.2	15.7						
65+50 wb	1.5	0.2	10.0						
66+00 wb	2.1	0.2	7.5						

eb = east bound, wb = west bound

Station and section average, standard deviation, and CoV LWD deflections on LA116 (wearing)

LA116 (wearing)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
58+00 eb	1.7	0.5	27.2	1.5	0.3	17.6	1.6	0.3	17.7
58+50 eb	1.4	0.4	27.0						
59+00 eb	1.4	0.1	8.6						
59+50 eb	1.5	0.2	12.0						
60+00 eb	1.6	0.1	3.4						
64+00 eb	1.5	0.2	15.3	1.6	0.3	17.3			
64+50 eb	1.3	0.1	9.7						
65+00 eb	1.7	0.4	21.3						
65+50 eb	1.8	0.0	2.2						
66+00 eb	1.5	0.2	15.7						
58+00 wb	1.4	0.0	0.0	1.5	0.2	15.7			
58+50 wb	1.4	0.1	9.4						
59+00 wb	1.5	0.1	3.3						
59+50 wb	1.4	0.5	33.1						
60+00 wb	1.7	0.2	11.4						
64+00 wb	1.8	0.1	6.5	1.8	0.3	15.7			
64+50 wb	1.5	0.1	9.1						
65+00 wb	1.7	0.2	10.9						
65+50 wb	1.7	0.2	12.8						
66+00 wb	2.2	0.2	9.4						

eb = east bound, wb = west bound

Station and section average, standard deviation, and CoV for LWD deflections on US61

US171									
	Station (3 pt)			Section (9 pt)			Project		
Station	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
23+00 REDISET	2.1	0.2	9.3	2.1	0.3	14.9	2.0	0.4	18.8
23+20 REDISET	2.2	0.2	10.1						
23+40 REDISET	1.9	0.4	23.4						
27+00 REDISET	1.8	0.2	9.2	2.0	0.5	25.3			
27+20 REDISET	1.6	0.2	13.1						
27+40 REDISET	2.6	0.4	14.5						
39+00 REDISET	1.9	0.1	4.6	2.0	0.2	10.0			
39+20 REDISET	2.2	0.2	9.0						
39+40 REDISET	1.9	0.1	6.0						
53+00 REDISET	1.8	0.2	9.8	1.9	0.2	9.0			
53+20 REDISET	2.0	0.1	7.4						
53+40 REDISET	2.0	0.2	9.9						
66+00 30% WM	1.7	0.1	3.3	2.0	0.5	26.7			
66+20 30% WM	1.8	0.1	7.2						
66+40 30% WM	2.6	0.7	28.4						
78+00 30% WM	2.1	0.4	17.3	2.0	0.5	23.2			
78+20 30% WM	2.1	0.8	36.4						
78+40 30% WM	1.8	0.2	8.8						

Station and section average, standard deviation, and CoV for LWD deflections on LA3121 (base)

LA3121 (base)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
94+00 nb	2.6	1.0	39.0	3.2	1.4	45.1	3.2	1.6	48.9
96+00 nb	3.7	2.6	71.5						
98+00 nb	3.4	1.9	55.6						
100+00 nb	3.5	1.2	33.6						
102+00 nb	2.8	0.5	16.3						
175+00 nb	4.2	1.0	24.3	3.6	1.3	35.3			
177+00 nb	2.3	1.2	54.8						
179+00 nb	4.4	0.8	18.4						
181+00 nb	3.5	1.5	44.3						
183+00 nb	3.6	1.2	33.1						
175+00 sb	2.5	0.7	29.8	3.5	2.3	67.2			
177+00 sb	2.4	0.6	25.9						
179+00 sb	7.3	2.5	34.6						
181+00 sb	2.6	1.5	56.7						
183+00 sb	2.6	1.1	41.9						
304+00 sb	3.5	1.6	44.4	2.7	0.9	33.9			
306+00 sb	2.0	0.1	3.9						
308+00 sb	2.1	0.2	7.2						
310+00 sb	2.4	0.3	11.8						
312+00 sb	3.3	0.6	18.3						

nb = north bound, sb = south bound

Station and section average, standard deviation, and CoV for LWD moduli on LA3121 (base)

LA3121 (base)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
94+00 nb	507.0	339.7	67.0	400.3	241.3	60.3	415.4	291.0	70.0
96+00 nb	378.4	242.0	64.0						
98+00 nb	434.5	398.8	91.8						
100+00 nb	341.7	169.3	49.6						
102+00 nb	339.6	124.7	36.7						
175+00 nb	190.0	81.2	42.8	421.2	419.5	99.6			
177+00 nb	977.5	658.5	67.4						
179+00 nb	215.4	32.3	15.0						
181+00 nb	482.4	341.1	70.7						
183+00 nb	240.7	109.7	45.6						
175+00 sb	294.2	99.5	33.8	372.3	257.9	69.3			
177+00 sb	634.4	315.2	49.7						
179+00 sb	90.9	54.9	60.4						
181+00 sb	490.4	292.4	59.6						
183+00 sb	351.5	124.1	35.3						
304+00 sb	318.9	205.9	64.6	467.9	225.5	48.2			
306+00 sb	568.3	17.1	3.0						
308+00 sb	720.2	322.9	44.8						
310+00 sb	441.6	64.4	14.6						
312+00 sb	290.4	112.4	38.7						

nb = north bound, sb = south bound

Station and section average, standard deviation, and CoV for LWD deflections on LA3121 (wearing)

LA3121 (wearing)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
94+00 nb	1.4	0.2	14.2	3.2	1.9	60.5	3.2	1.8	55.2
96+00 nb	1.8	0.4	19.9						
98+00 nb	2.9	1.2	42.3						
100+00 nb	5.5	1.6	30.0						
102+00 nb	4.3	2.0	45.3						
175+00 nb	6.3	1.1	17.6	4.0	1.9	48.7			
177+00 nb	2.5	0.6	24.9						
179+00 nb	4.5	1.4	32.0						
181+00 nb	2.3	0.7	30.6						
183+00 nb	4.4	2.5	56.6						
175+00 sb	2.2	0.8	35.4	3.4	2.0	58.5			
177+00 sb	1.8	0.3	16.0						
179+00 sb	6.7	1.7	25.0						
181+00 sb	2.7	0.1	3.9						
183+00 sb	3.5	0.7	20.3						
304+00 sb	3.1	0.6	19.4	2.4	0.7	30.2			
306+00 sb	4.0	2.0	51.4						
308+00 sb	2.0	0.3	17.0						
310+00 sb	2.0	0.6	30.8						
312+00 sb	2.1	0.2	9.3						

nb = north bound, sb = south bound

Station and section average, standard deviation, and CoV for LWD moduli on LA3121 (wearing)

LA3121 (wearing)									
Station	Station (3 pt)			Section (15 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
94+00 nb	1189.1	416.2	35.0	766.7	391.2	51.0	719.2	442.8	61.6
96+00 nb	874.7	230.0	26.3						
98+00 nb	639.2	361.4	56.5						
100+00 nb	463.2	185.4	40.0						
102+00 nb	667.2	466.5	69.9						
175+00 nb	190.1	37.3	19.6	572.4	409.8	71.6			
177+00 nb	422.0	219.1	51.9						
179+00 nb	350.5	150.7	43.0						
181+00 nb	894.3	236.1	26.4						
183+00 nb	1005.0	533.4	53.1						
175+00 sb	800.2	447.5	55.9	756.3	619.9	82.0			
177+00 sb	1748.6	544.2	31.1						
179+00 sb	184.0	77.9	42.3						
181+00 sb	629.8	118.2	18.8						
183+00 sb	419.1	87.6	20.9						
304+00 sb	506.4	346.9	68.5	781.4	299.6	38.3			
306+00 sb	827.1	450.7	54.5						
308+00 sb	978.2	222.2	22.7						
310+00 sb	892.1	208.5	23.4						
312+00 sb	703.0	98.3	14.0						

nb = north bound, sb = south bound

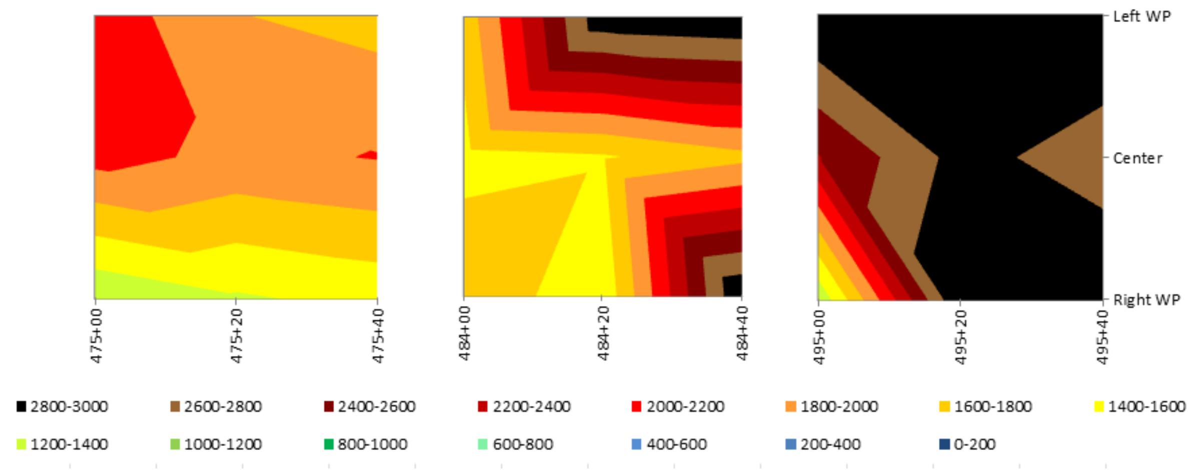
Station and section average, standard deviation, and CoV for LWD deflections on LA3191

LA3191									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	mil	mil	%	mil	mil	%	mil	mil	%
10+50	2.3	0.1	5.4	2.9	0.7	22.3	3.8	1.2	31.4
10+70	3.0	0.2	6.5						
10+90	3.5	0.7	19.4						
20+00	4.8	1.1	22.1	4.7	1.0	21.2			
20+20	4.5	0.8	18.6						
20+40	4.8	1.4	29.8						
21+20	3.4	1.4	41.9	3.7	1.2	31.8			
21+40	3.7	1.2	31.6						
21+60	4.0	1.4	34.0						

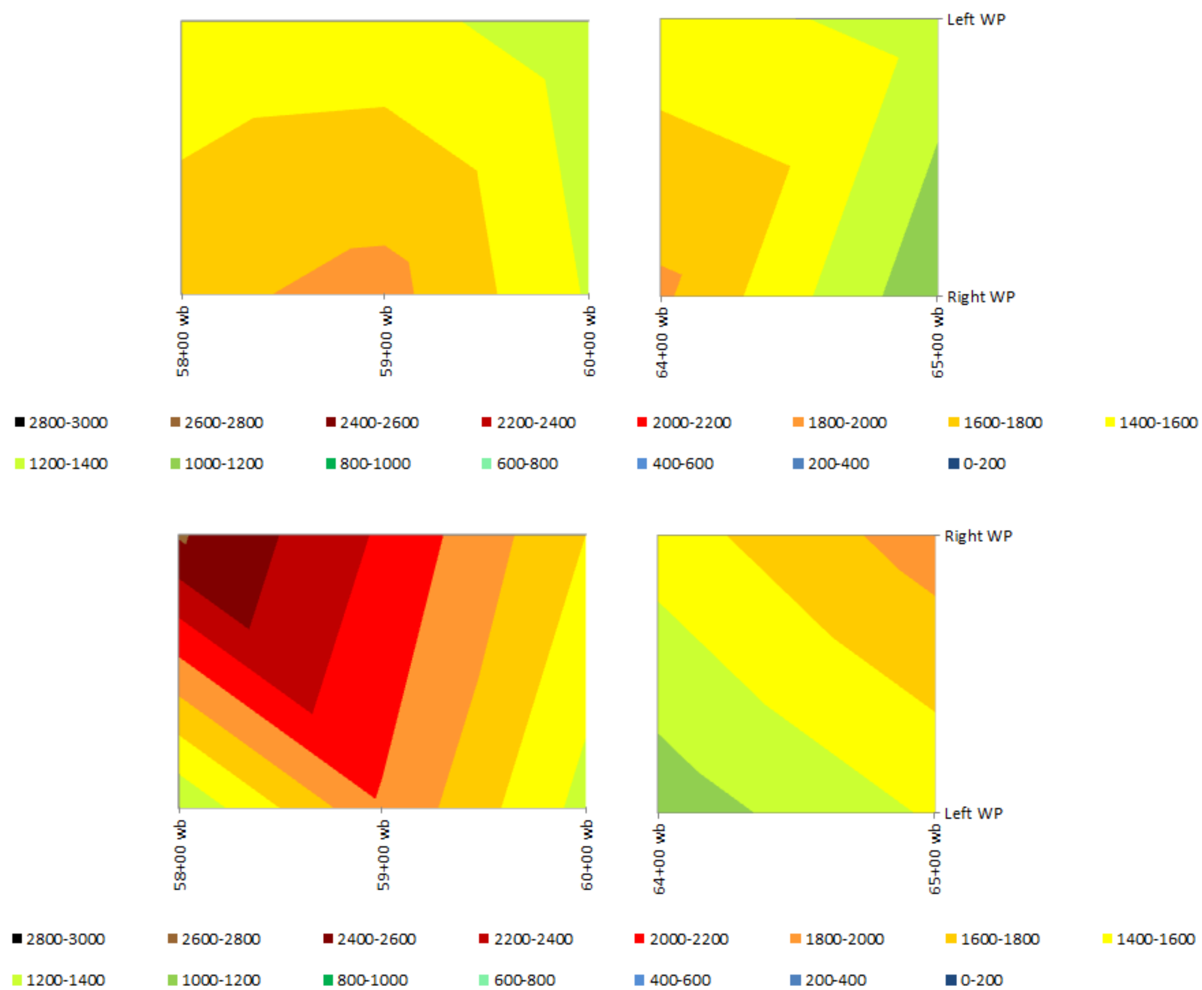
Station and section average, standard deviation, and CoV for LWD moduli on LA3191

LA3191									
Station	Station (3 pt)			Section (9 pt)			Project		
	Average	Stdev	CoV	Average	Stdev	CoV	Average	Stdev	CoV
	ksi	ksi	%	ksi	ksi	%	ksi	ksi	%
10+50	275.2	37.7	13.7	216.9	55.1	25.4	155.9	69.2	44.4
10+70	191.6	37.5	19.6						
10+90	183.8	40.3	21.9						
20+00	100.5	21.8	21.7	119.6	41.1	34.4			
20+20	117.6	36.6	31.1						
20+40	140.6	61.1	43.4						
21+20	143.1	68.5	47.9	131.3	67.0	51.1			
21+40	116.7	49.5	42.4						
21+60	133.9	101.5	75.8						

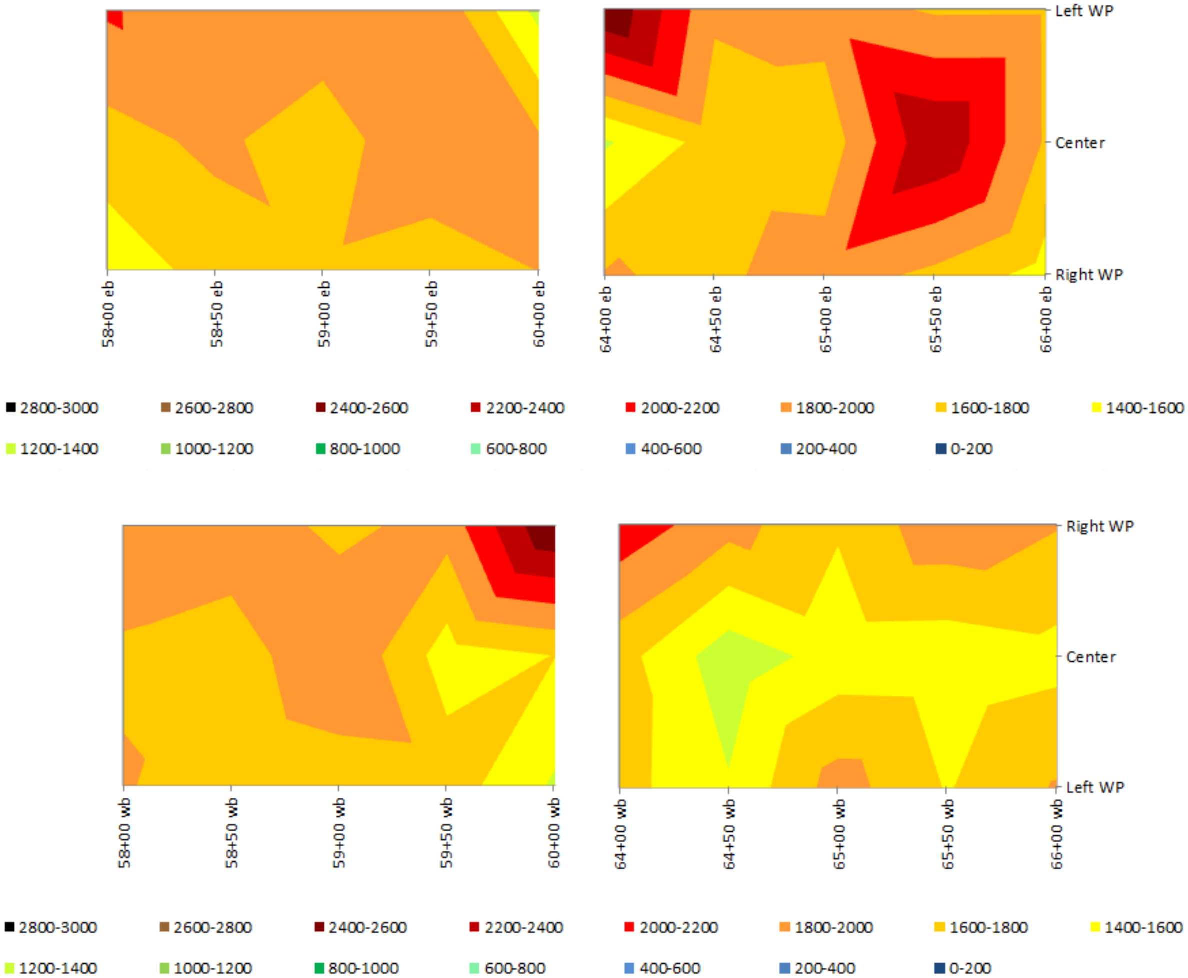
I-55 PSPA contour (ksi)



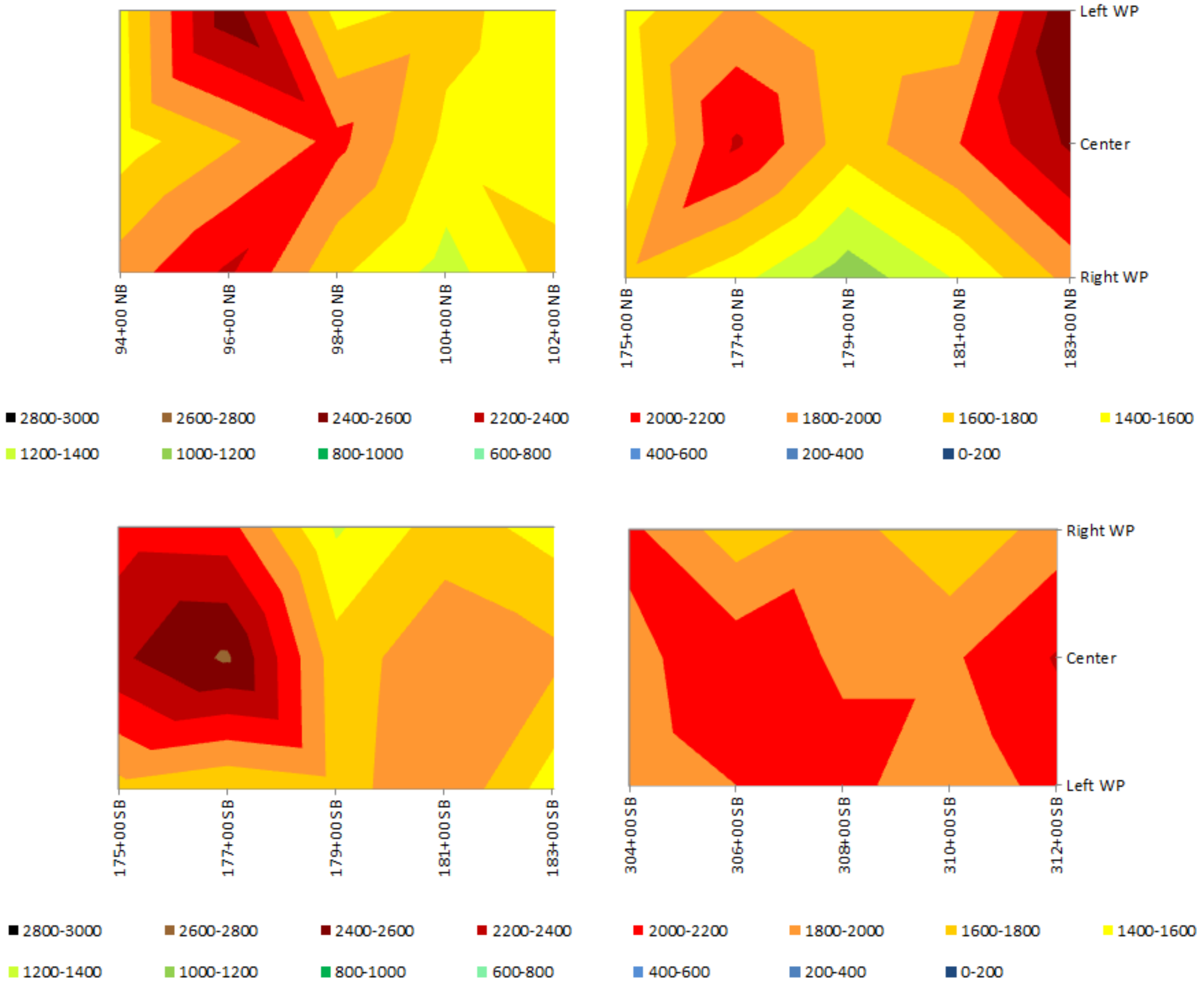
I-55 (2) PSPA contour (ksi)



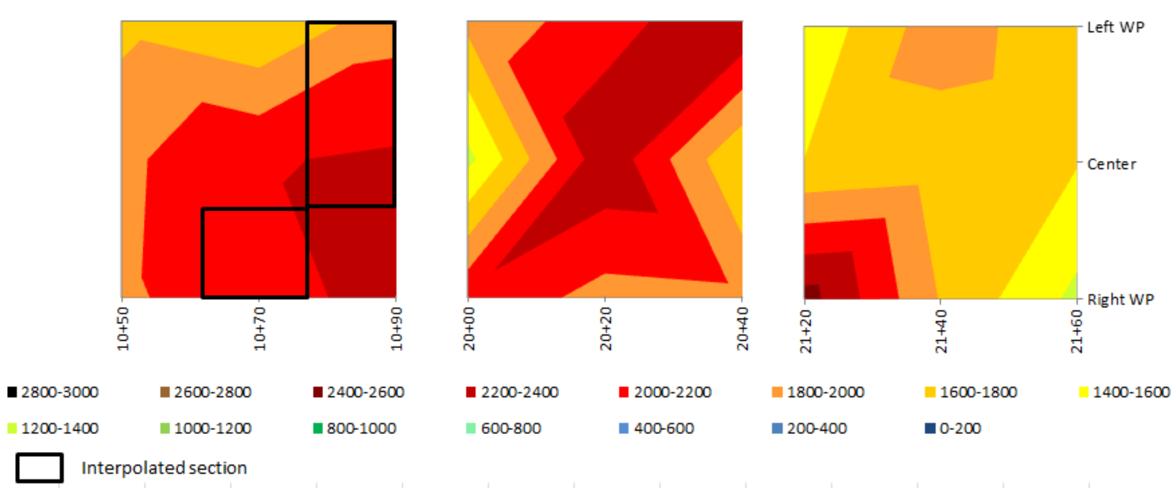
LA116 (binder) PSPA contour (ksi)



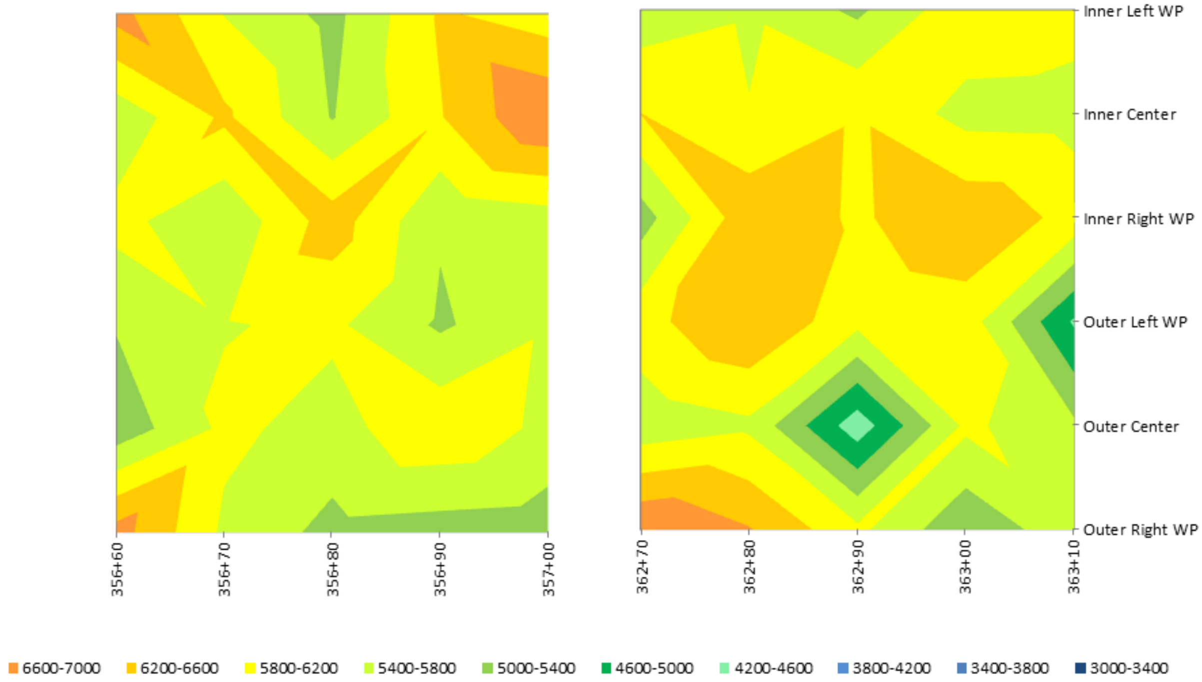
LA116 (wearing) PSPA contour (ksi)



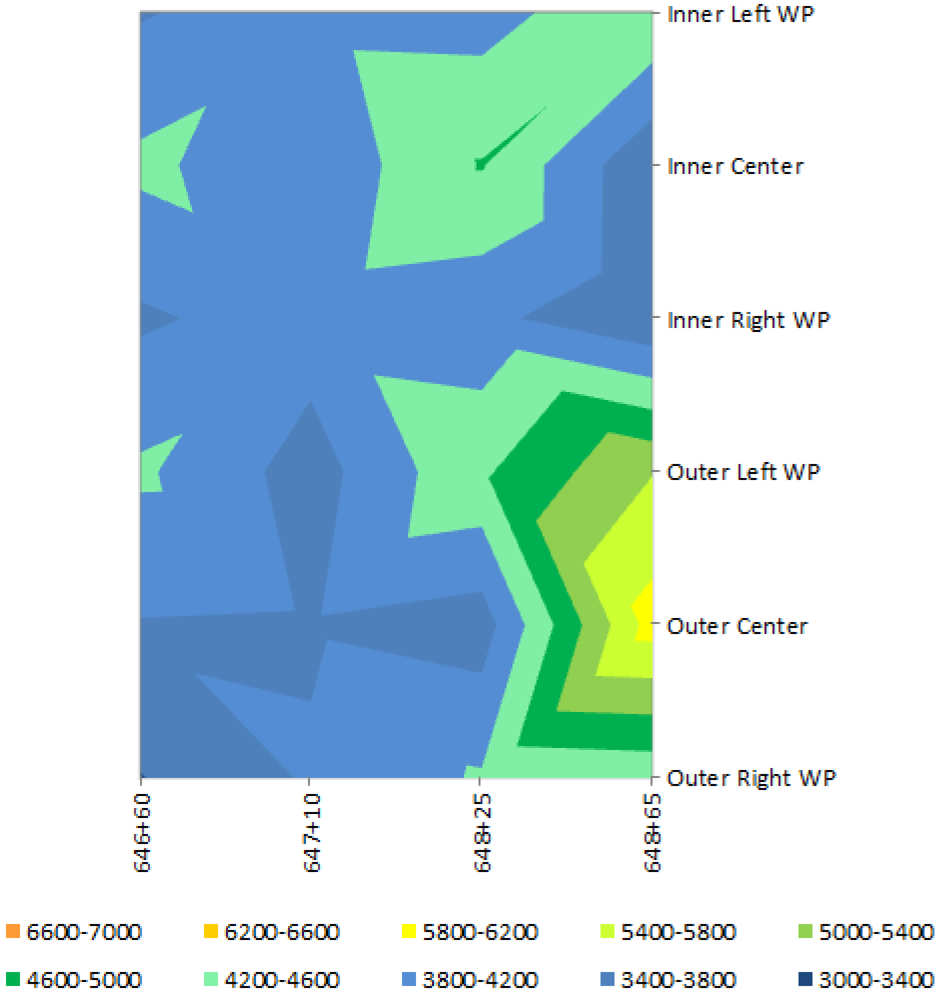
LA3121 (wearing) PSPA contour (ksi)



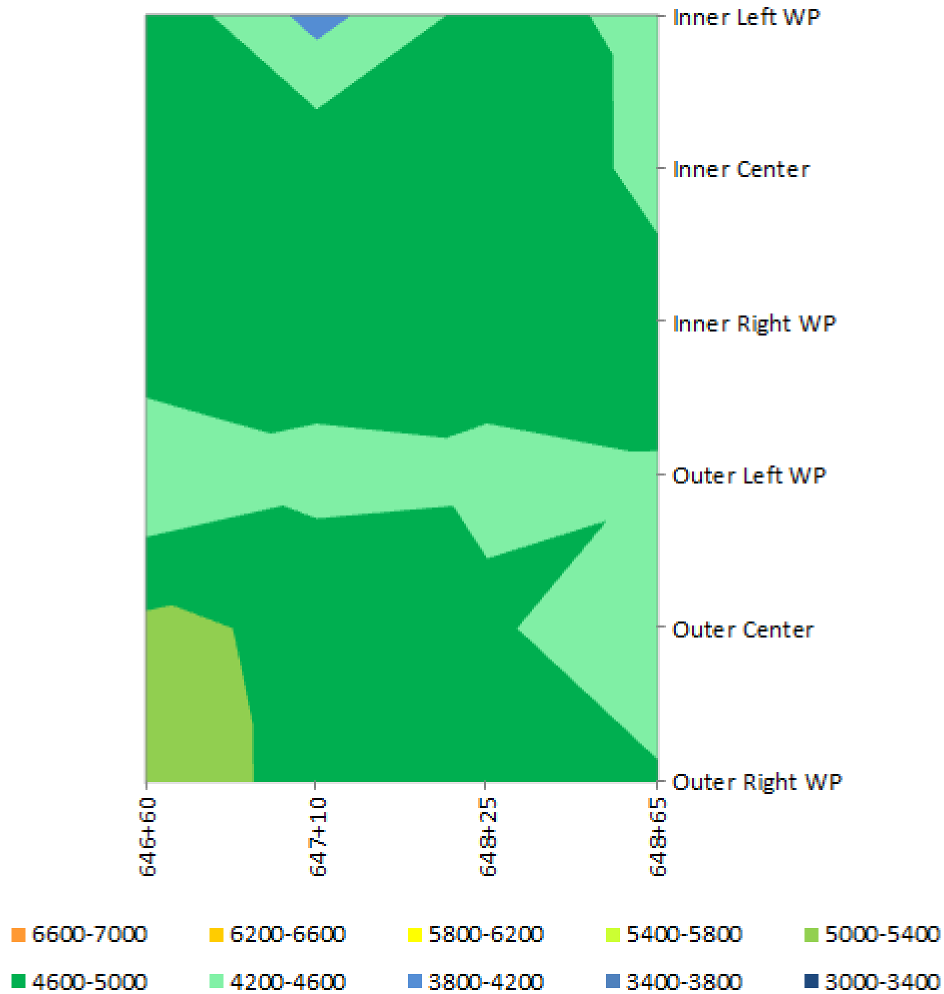
LA3191 PSPA contour (ksi)



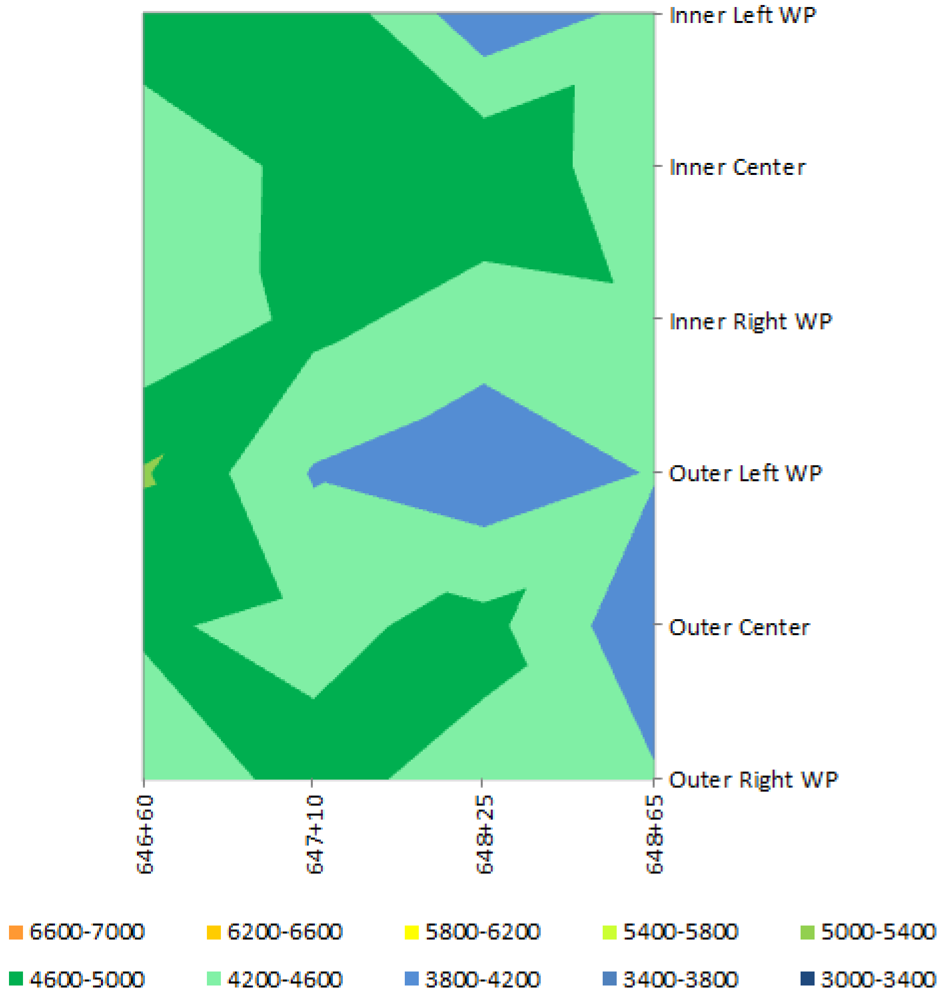
US61 PSPA contour (ksi)



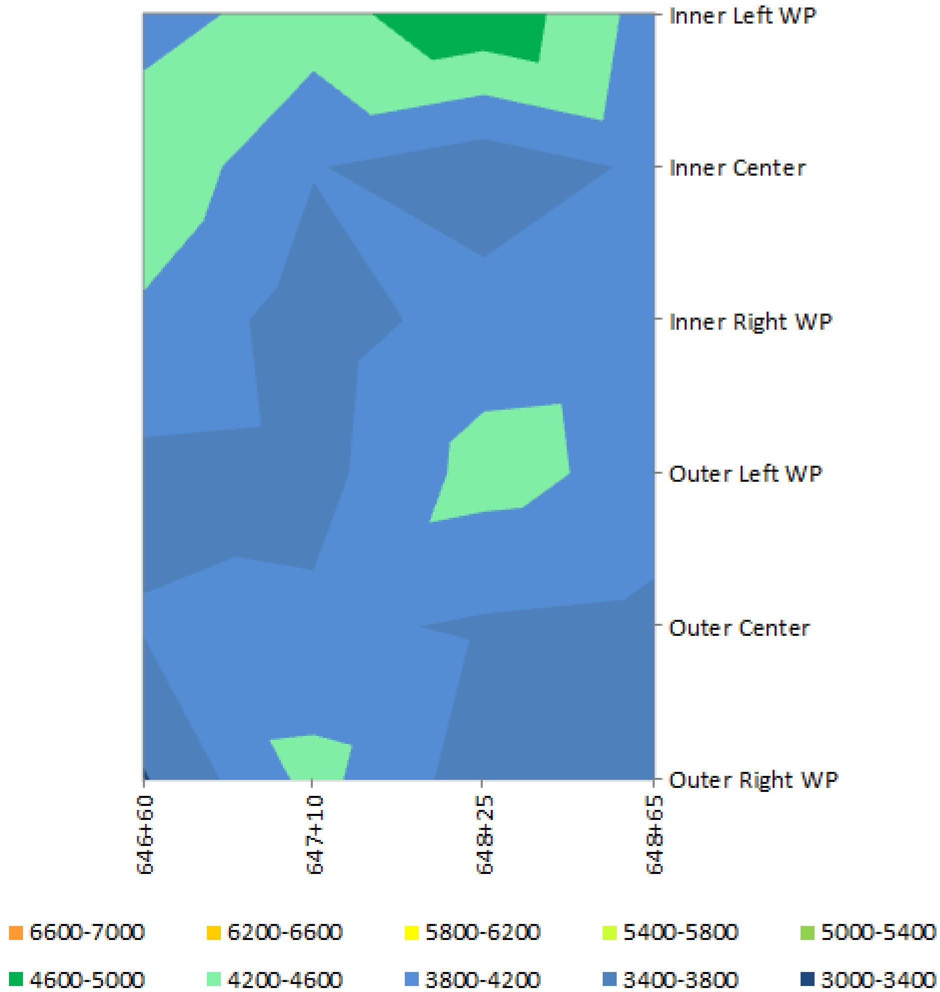
LA3073 (day 1) PSPA contour (ksi)



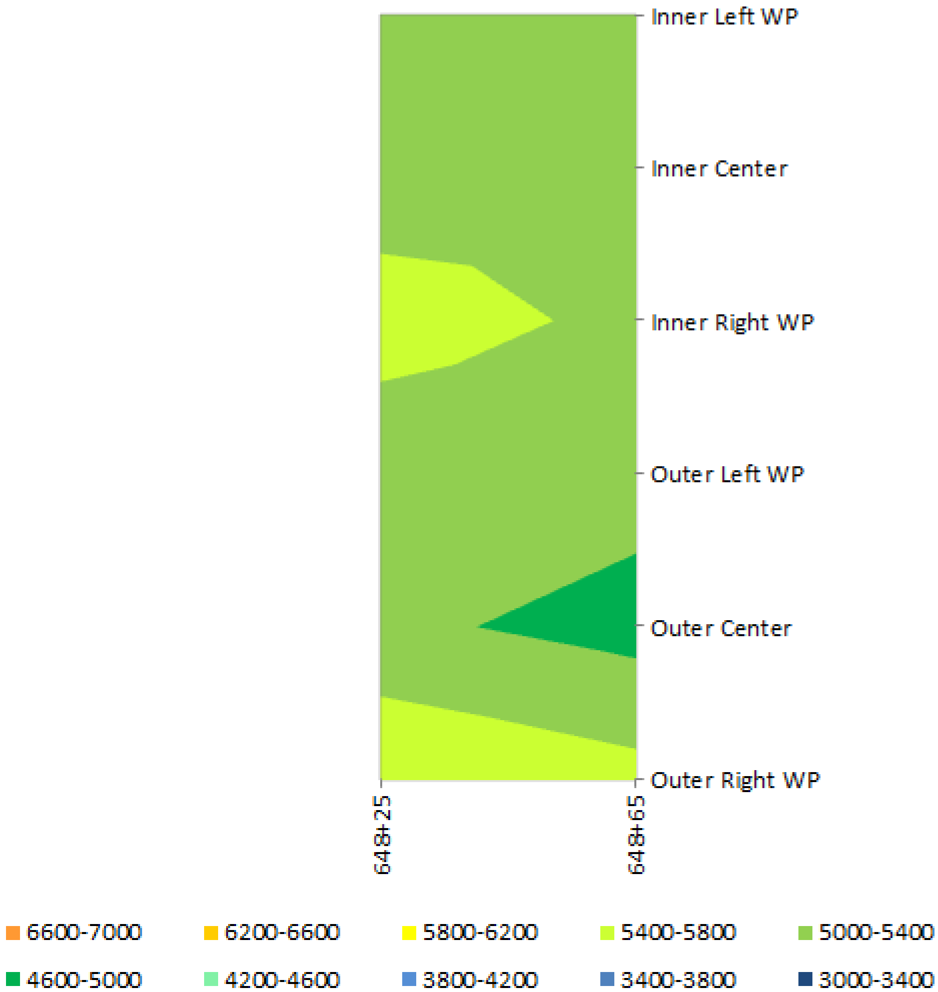
LA3073 (day 7) PSPA contour (ksi)



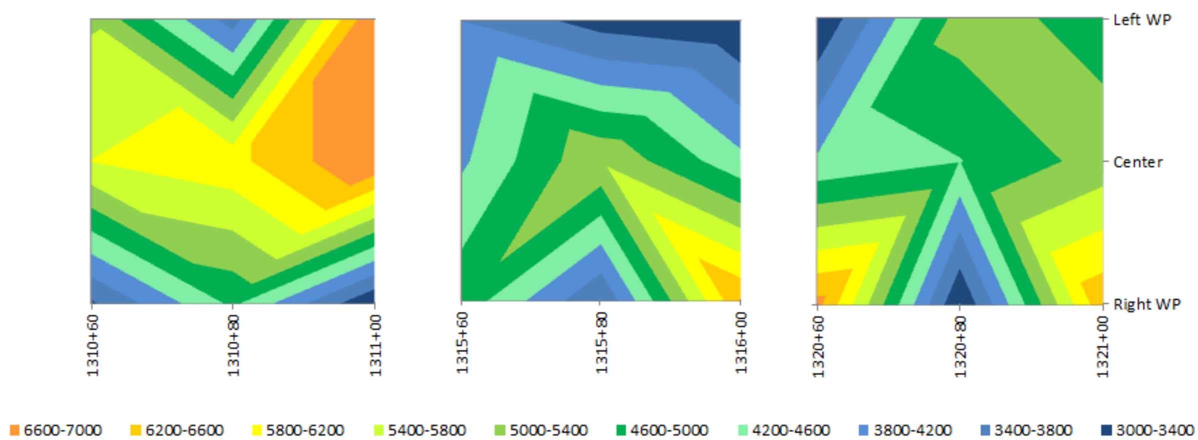
LA3073 (day 14) PSPA contour (ksi)



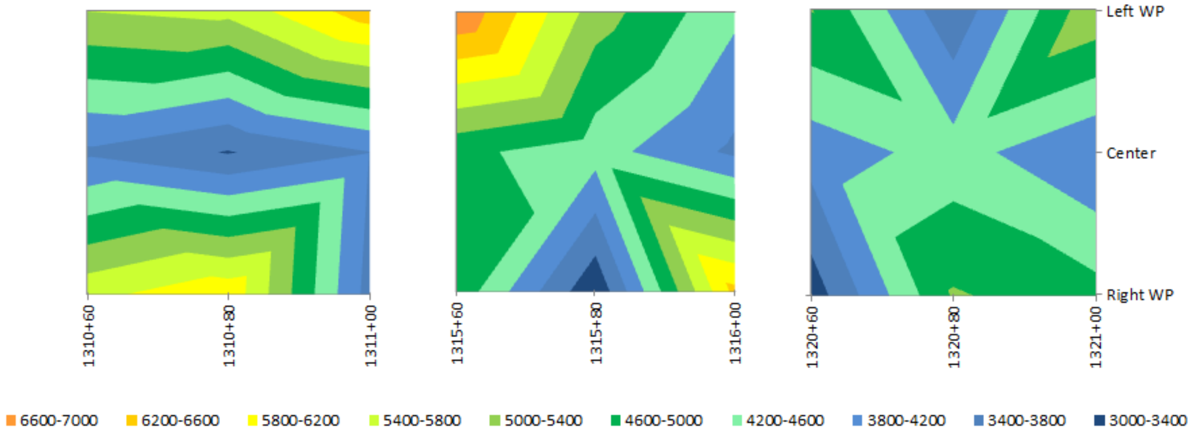
LA3073 (day 28) PSPA contour (ksi)



LA3073 (day 56) PSPA contour (ksi)

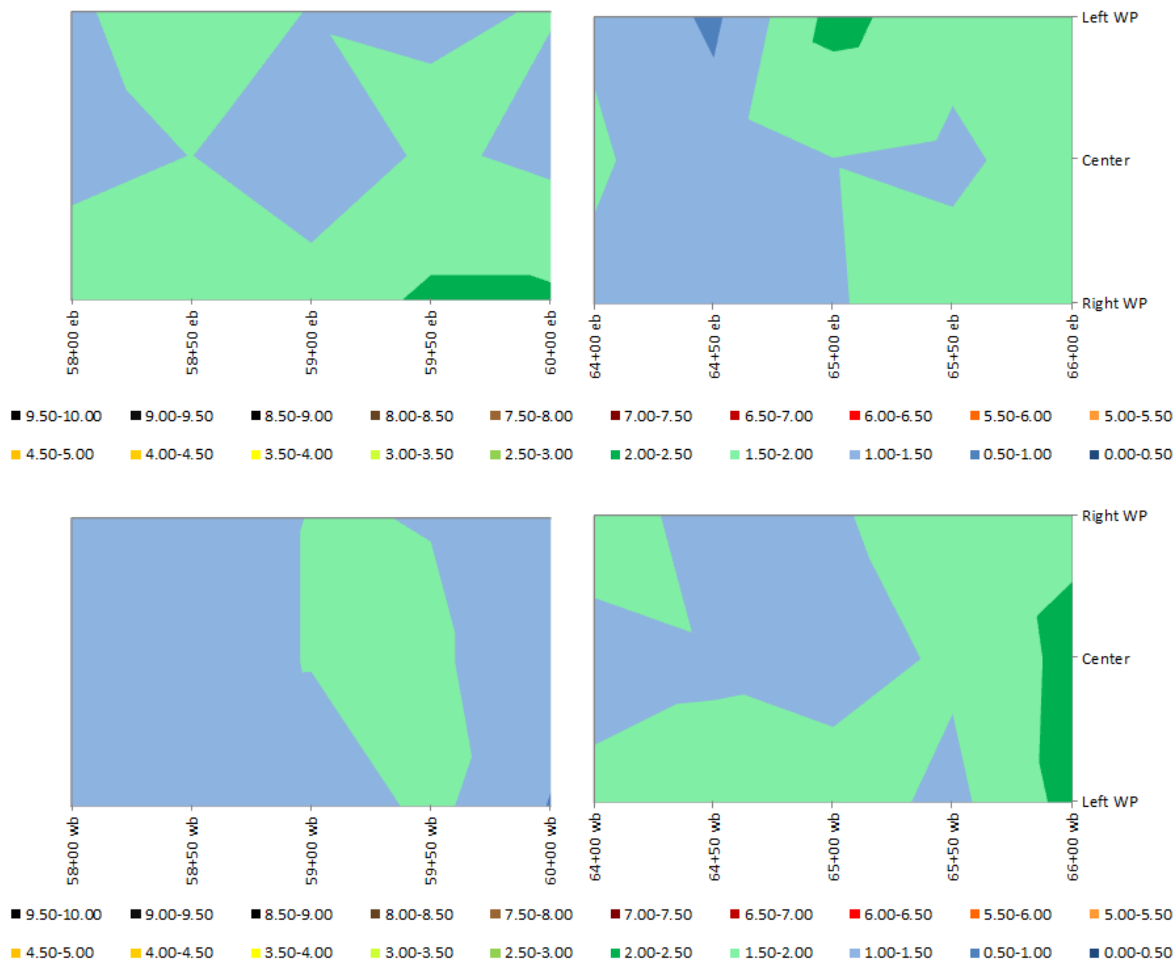


I-49 (day 7) PSPA contour (ksi)



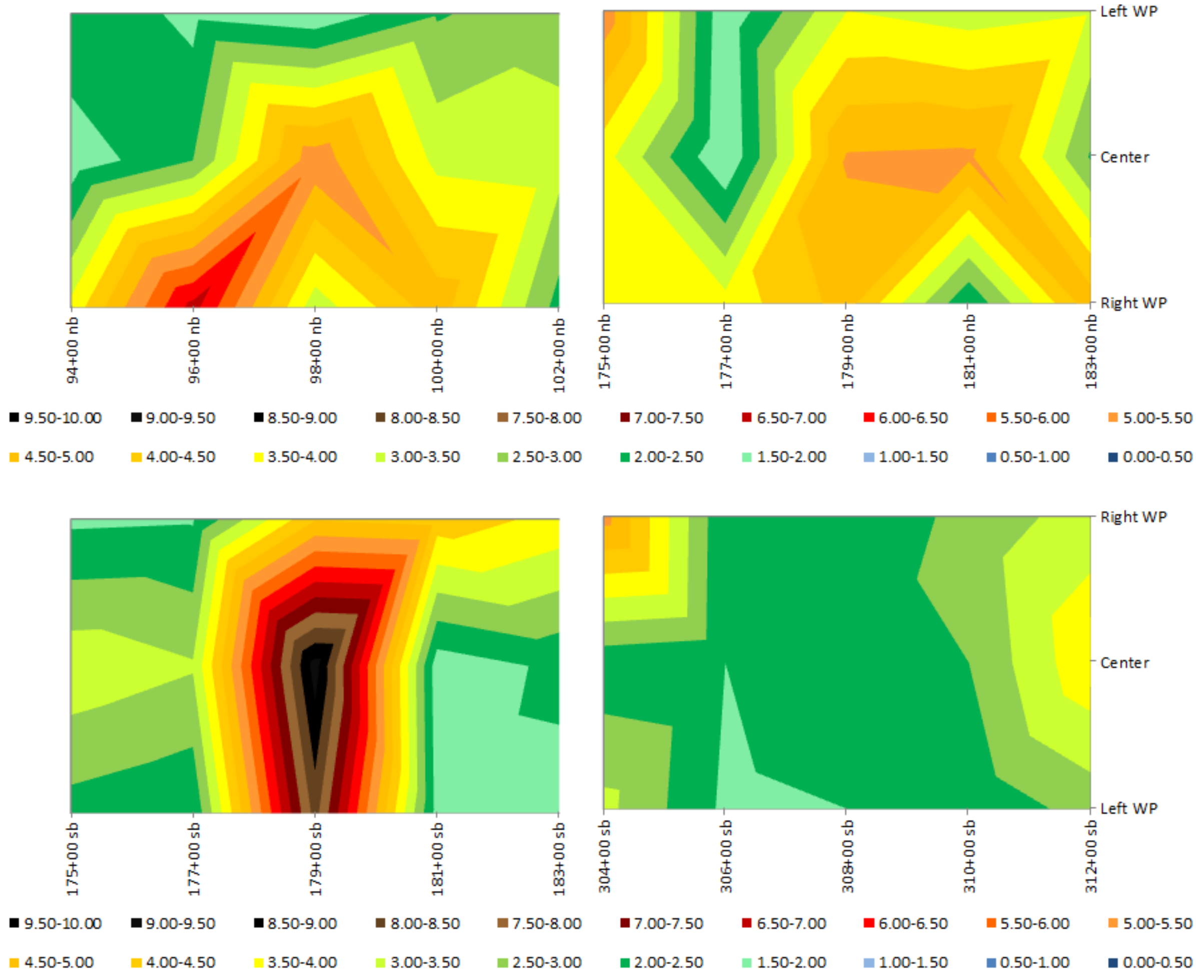
I-49 (day 28) PSPA contour (ksi)

LA116 (base) LWD deflection contour (mils)

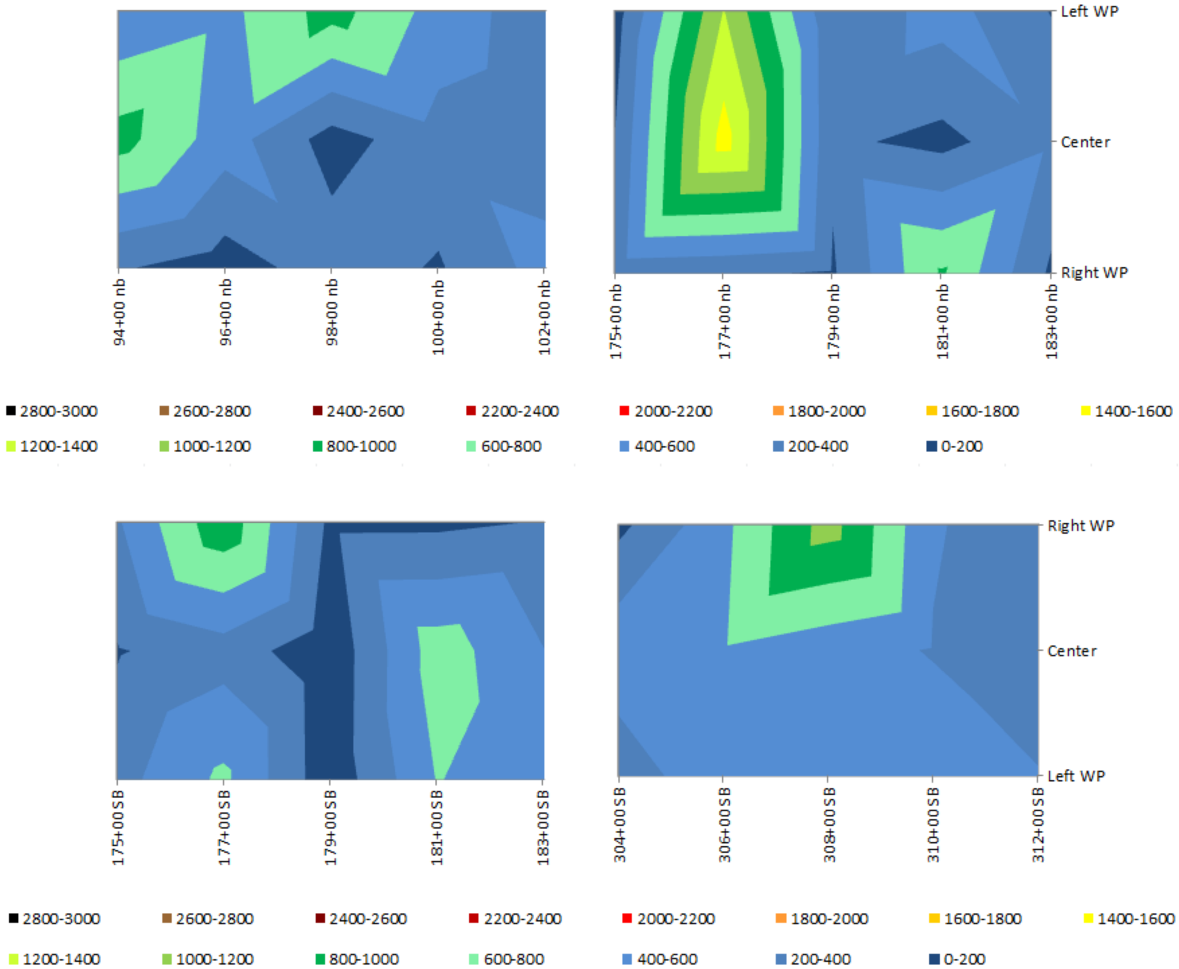


LA116 (binder) LWD deflection contour (mils)

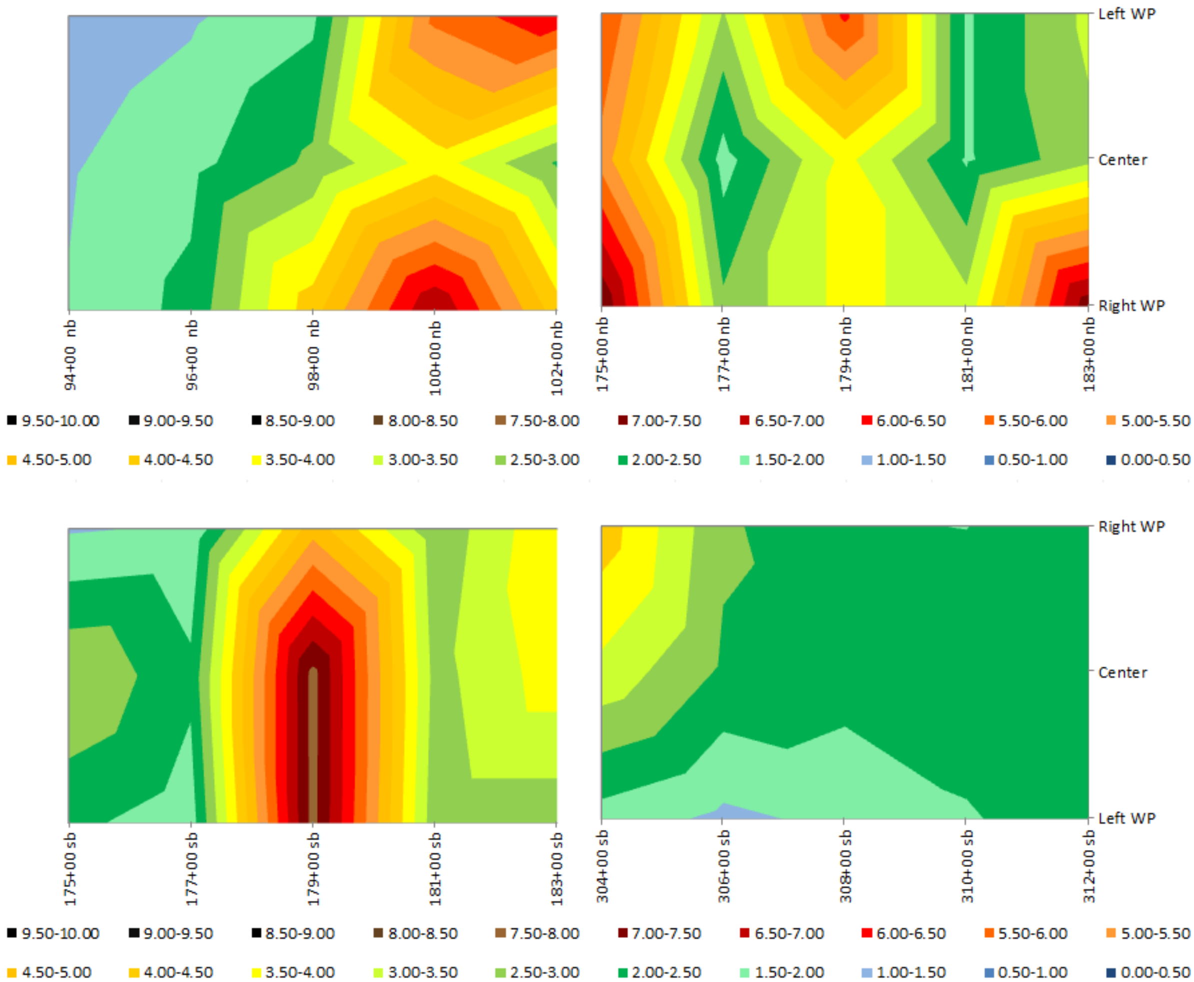
LA116 (wearing) LWD deflection contour (mils)



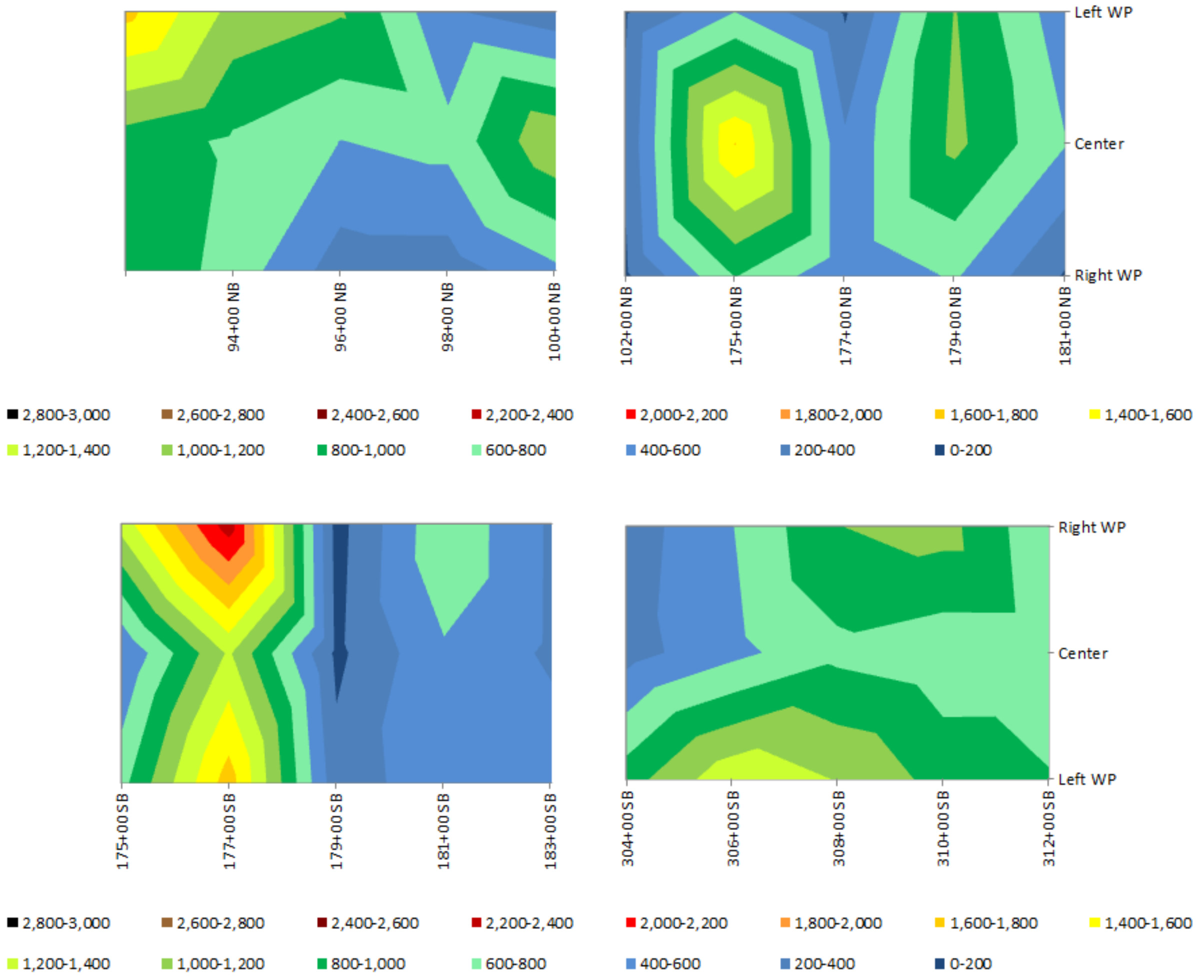
LA3121 (base) LWD deflection contour (mils)



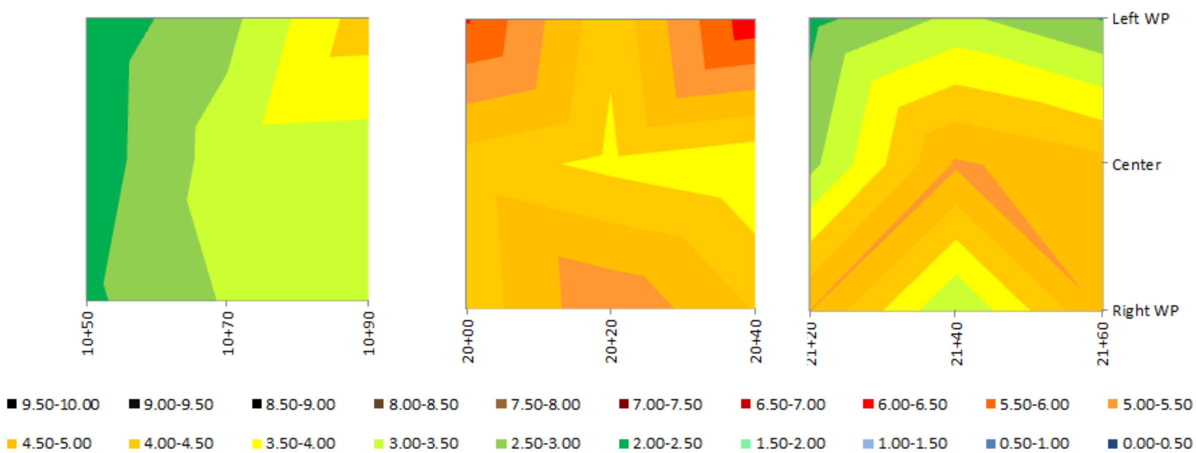
LA3121 (base) LWD back-calculated layer moduli contour (ksi)



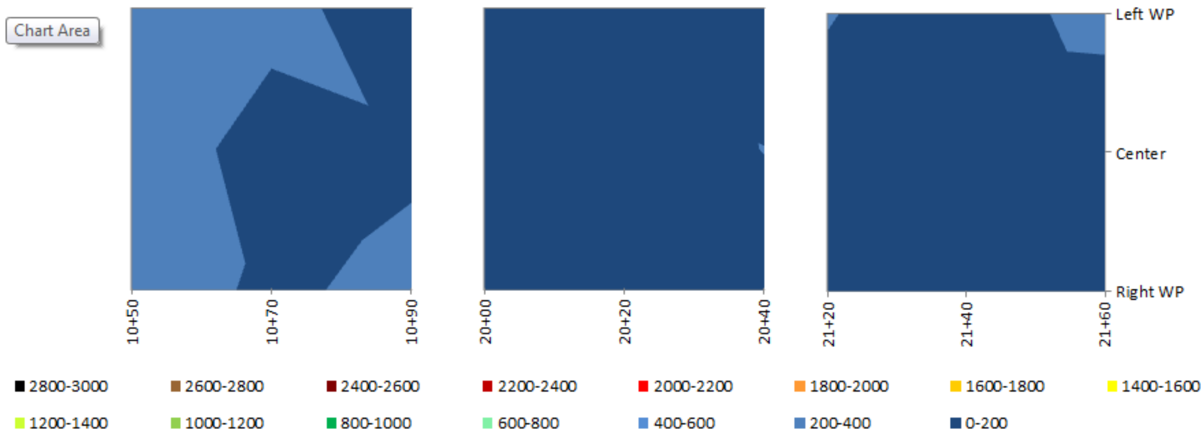
LA3121 (wearing) LWD deflection contour (mils)



LA3121 (wearing) LWD back-calculated layer moduli contour (ksi)

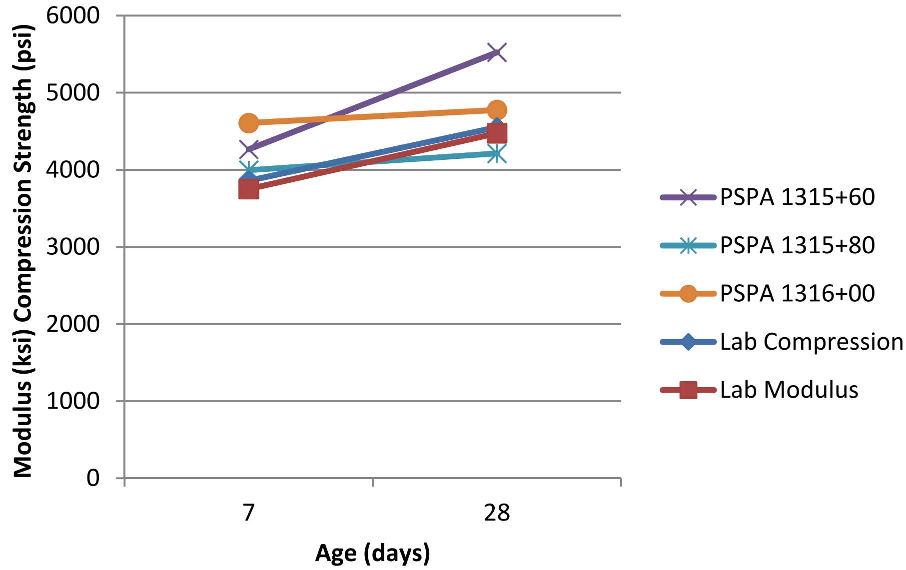


LA3191 LWD deflection contour (mils)

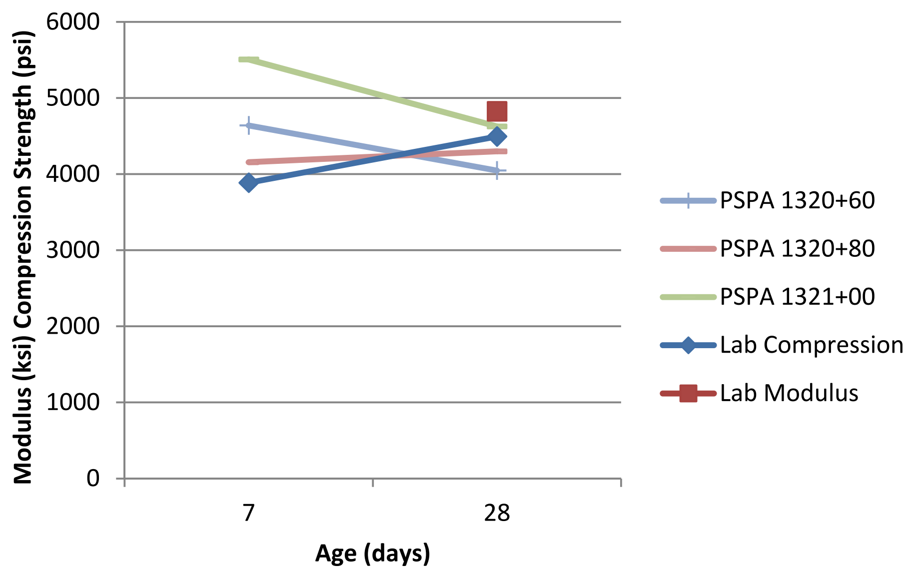


LA3191 LWD back-calculated layer moduli contour (ksi)

US171 LWD deflection contour (mils)



I-49 section 2 PSPA seismic modulus compared to laboratory modulus and compression strength



I-49 section 3 PSPA seismic modulus compared to laboratory modulus and compression strength