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Measuring Foundation Course Modulus Using Falling Weight Deflectometer, Light Weight Deflectometer, and Dynamic Cone Penetration

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Background

There have been attempts in the past to forensically evaluate subgrade and foundation course strength that underly concrete pavement by Falling Weight Deflectometer (FWD) testing on top of doweled concrete. The accuracy of these data is unknown.

Figure 1 - Falling Weight Deflectometer (FWD) measures modulus via deflection with 7 sensors and machine-dropped weights.

The Falling Weight Deflectometer is a trailer mounted, non-destructive testing device that drops a weight onto the pavement and has sensors that measure the amount of resulting deflection, Figure 1. The slope of the load and resulting deflection is referred to as the modulus.

NDOT has years of experience testing strata beneath asphalt surfaces but because FWD testing of subgrades beneath rigid pavement are not well established, NDOT has not adopted testing of rigid pavements and underlying bases by FWD.

Purpose of the Investigation

The purpose of this investigation was to determine the feasibility of measuring bituminous foundation course modulus under concrete roadways by comparing testing results derived before and after paving using FWD, Light Weight Deflectometer (LWD) Figure 2, and Dynamic Cone Penetrometer (DCP) Figure 3.

Figure 2 - Light Weight Deflectometer (LWD) measures deflection by dropping a weight by hand.

Figure 3 - Dynamic Cone Penetrometer (DCP) measures stiffness using inches per blow.

Field Investigation

The strength characteristics of bituminous foundation course were measured before and after construction of doweled concrete pavement. The study location was a construction project with new doweled concrete pavement located in Nebraska on US Hwy 30 from Rogers to North Bend, NE. Researchers employed Falling Weight Deflectometer (FWD), Light Weight Deflectometer (LWD), and Dynamic Cone Penetrometer (DCP) test methods. The foundation course was tested for moisture content. Data was collected in two phases.

Phase I data collection occurred in July of 2020 after the foundation course was placed and prior to paving. Researchers identified and tested 200 locations on bare bituminous foundation course spaced six feet apart in the middle of the driving lane (MOL). The stations were initially located with GPS, which lost connection about halfway through marking. The remaining stations were located by hand with a 200-ft. tape measure. Researchers tested all 200 stations using FWD, 51 stations using LWD, and 26 using DCP. A total of 18 stations were evaluated using all three methods.

Phase II data collection occurred in September of 2020 on the same project after the concrete pavement was cured. Researchers tested the same Phase I stations using FWD and DCP on top of the pavement. FWD data were collected at 72 MOL stations tested in Phase I, which were all assumed to be exact station matches. Core holes were drilled to accommodate DCP testing at three stations.

Analysts compiled and compared the results of the different test methods. The results provided by each test method were converted from native units to deflection values in either mils or millimeters to facilitate comparison and graphing.

Results

The foundation course modulus was determined using FWD data and Darwin design software ('93 AASHTO). Results from Phase I data collection, which occurred prior to pavement placement, provided a baseline for comparison. The maximum modulus was 398,000 PSI and the minimum was 85,000 PSI, yielding a range of 315,000 PSI and an average modulus of 123,000 PSI over the length of the test plot. The Phase I modulus of the bare foundation course for 200 stations is shown in Figure 4.

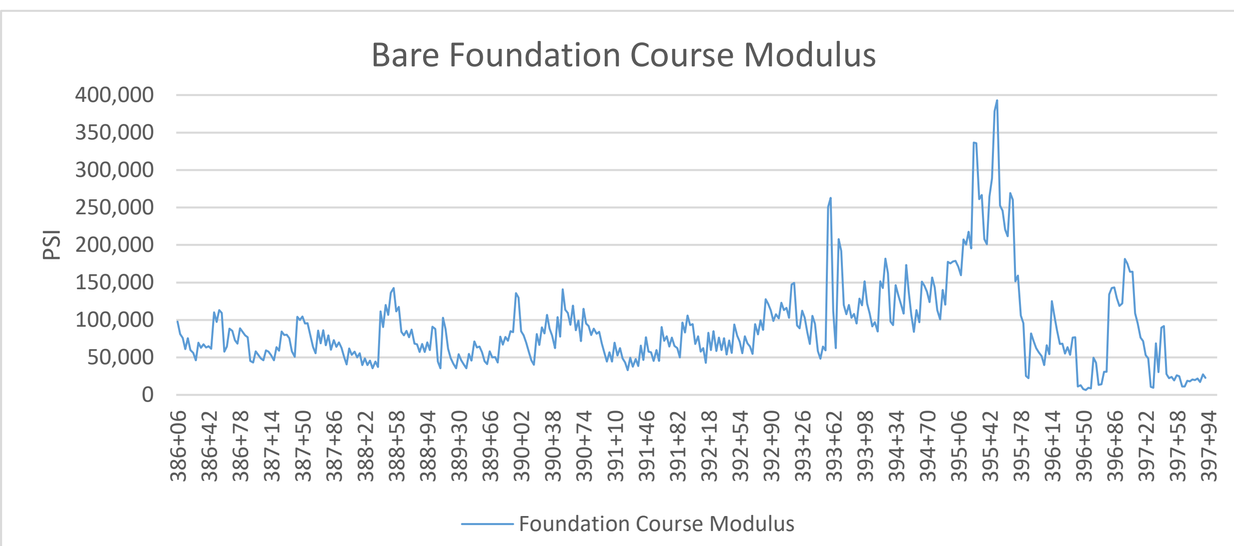

Figure 4- Foundation course modulus calculated from 200 stations of FWD data measured prior to doweled-concrete placement.

Researchers identified 18 Phase I stations as common to all three test methods and plotted the results in Figure 5. The FWD data shows two loads for Sensor D0 measured in mils. D0 is defined as the sensor location at the center of loading. FWD modulus, DCP penetration and LWD deflection, have similar trend lines. The depth of penetration of the DCP, deflection of the LWD with a hand raised weight and mechanically raised weight for the FWD cannot be compared quantitatively since the methods and weight are different. However, the trend lines do show a direct relationship. Measurement definitions for DCP, LWD, and FWD are listed in Table 1.

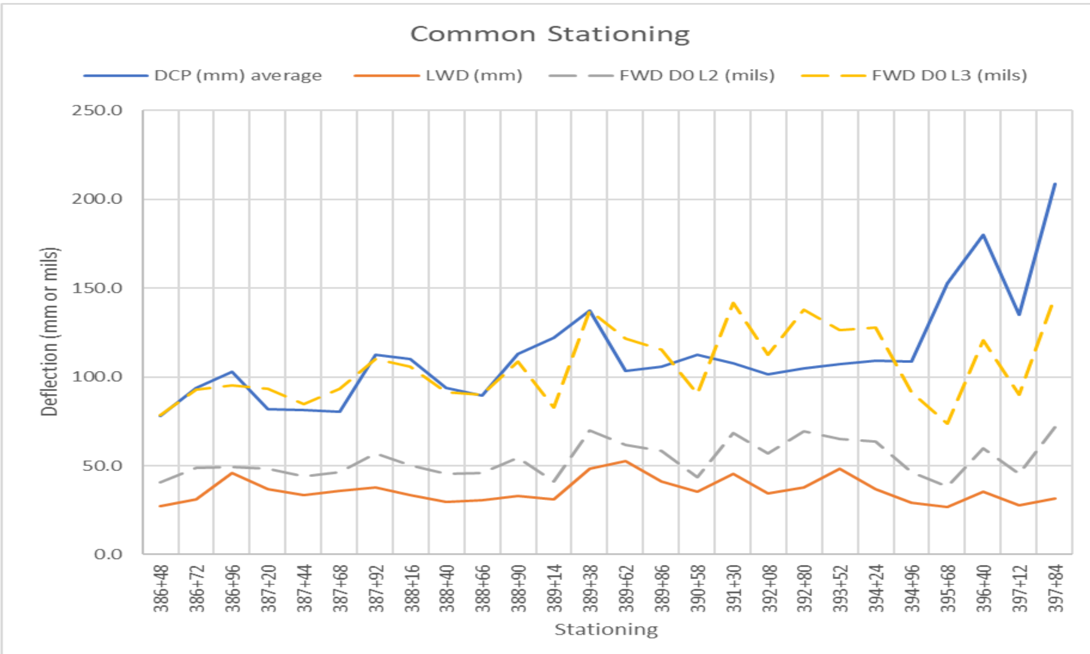

Figure 5 - FWD, LWD, and DCP were tested at 18 common Phase I stations prior to doweled-concrete placement.

Table 1 - Measurement Definitions for DCP, LWD, and FWD

Method	Measurement Units	Measurement Definition
DCP	(mm) average	average depth of penetration per blow for 10.1 lb hammer
LWD	(mm)	average deflection of the third, fourth and fifth drops of 10-kg weight
FWD D0 L2	(mils)	deflection center of the load for 7,500 lbs/SF loading after the initial seating drop
FWD D0 L3	(mils)	deflection center of the load for 12,000 lbs/SF loading

DCP was tested at 3 stations before and after pavement placement. All three stations showed a reduction in penetration (displacement) by about 50% after the doweled concrete was placed. The concrete pavement constrained the foundation course on the top side and is assumed to be responsible for the reduction in penetration.The penetration depths of each station are shown in Figure 6.

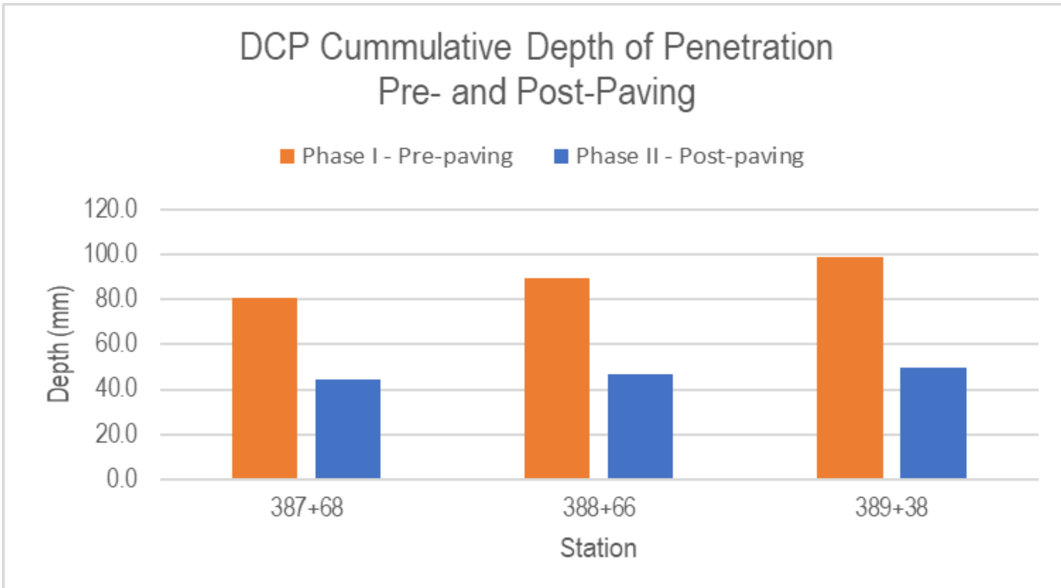

Figure 6 - DCP data before and after pavement placement shows a 50% reduction in penetration depth.

There were 72 stations tested with FWD in Phase I and Phase II. Researchers assumed Phase I and II stations aligned, even though some stations were measured at an offset by one or two feet. The Darwin (AASHTO '93) software used to compute the modulus only has the capability of considering two layers. In Phase I, the top layer was the foundation course, and bottom layer was the subgrade. In Phase II testing, the top layer was the doweled-concrete pavement, and the bottom layer was the foundation course. The Phase I "top layer" calculation and the Phase II "bottom layer" calculation compare the moduli of the foundation course in each respective phase. The modulus on the exposed foundation course was higher after the doweled pavement was placed. The energy from dropping the deflectometer load was absorbed and dispersed primarily by the concrete which resulted in a significantly lower measurement in the foundation course during Phase II testing.

The Phase I and Phase II foundation course FWD modulus (psi) values are plotted by the station in Figure 7. Due to the magnitude difference between Phase I and Phase II moduli, Phase I is plotted on the left-side vertical axis and Phase II is plotted on the right-side vertical axis. The horizontal axis charts the 72 MOL stations tested. The Phase I and Phase II moduli correlated somewhat, however the decrease in modulus between the two phases cannot be predicted quantitatively.

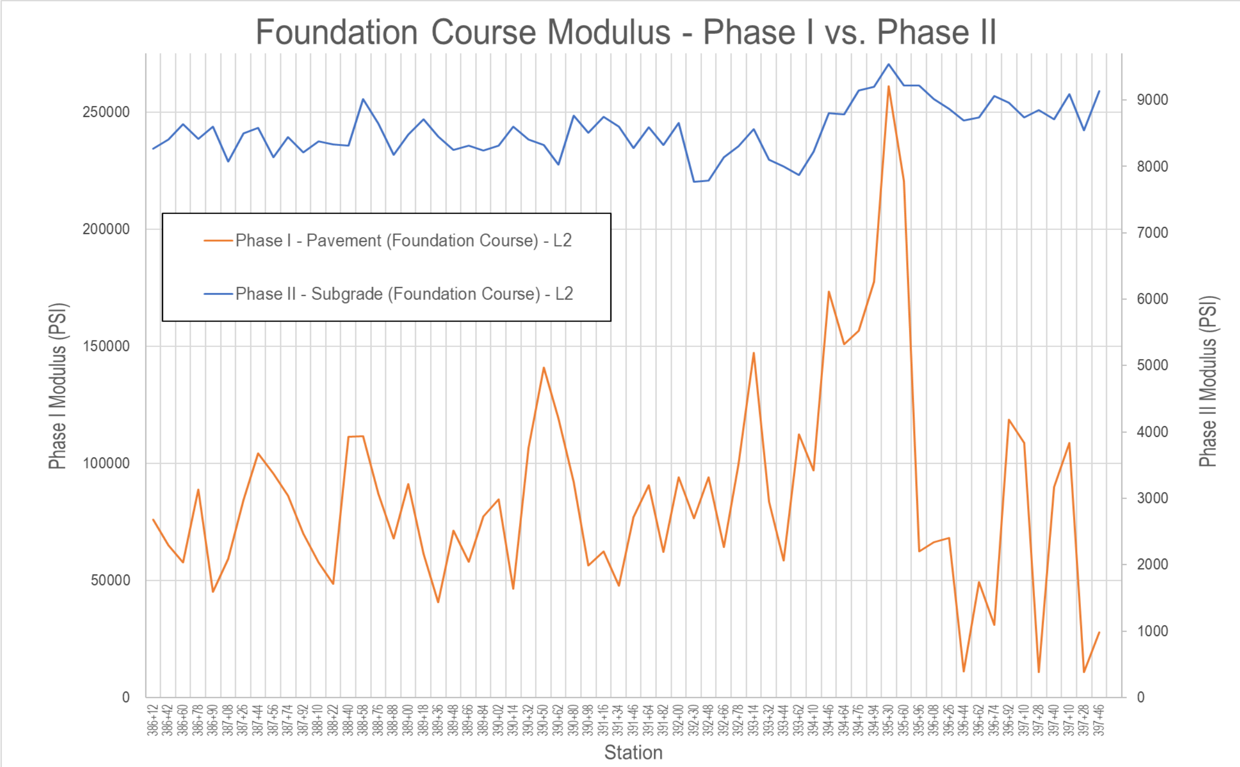

Figure 7- FWD was measured in two phases: Phase I on bare foundation course and Phase II on doweled-concrete. Modulus calculated using Darwin software.

The standard deviation and coefficient of variation (COV) of the Darwin moduli was calculated for the 72 data points common to Phase I and II. The values are shown in Table 2. Testing directly on top of the foundation course in Phase I resulted in a COV of 53%, while testing on top of doweled-concrete pavement in Phase II resulted in a much lower COV of 4%. Looking at only the Phase II COV falsely implies that the foundation course is uniform and consistent throughout the length of the testing strip, whereas the Phase I results indicate a greater variance of modulus values. Further, the value of moduli is much lower in Phase II then in Phase I. The likely cause of the difference is due to the concrete structure absorbing most of the energy from the blow and therefore is not transferring the deflection to the foundation course.

Table 2 - Average Modulus (PSI), standard deviation, and coefficient of variation by phase.

	Phase I Modulus (72 Data Points on foundation course)	Phase II Modulus (72 Data Points on doweled pavement)
Average Modulus (PSI)	86,481	8,543
Standard Deviation	45,422	376
Coefficient of Variation	53%	4%

In addition to using AASHTO '93 Darwin software to calculate moduli, Researchers calculated modulus values using AASHTOware Pavement ME Back Calculation (MEBC) software for the FWD Phase I and Phase II data. This software uses EVERcalc to back calculate moduli and is being presented as an alternate for comparison. The results are plotted in Figure 8. The foundation course modulus, which was the measurement taken on top of the in-place concrete, was consistent for each calculation set, while the data for the subgrade were inconsistent.

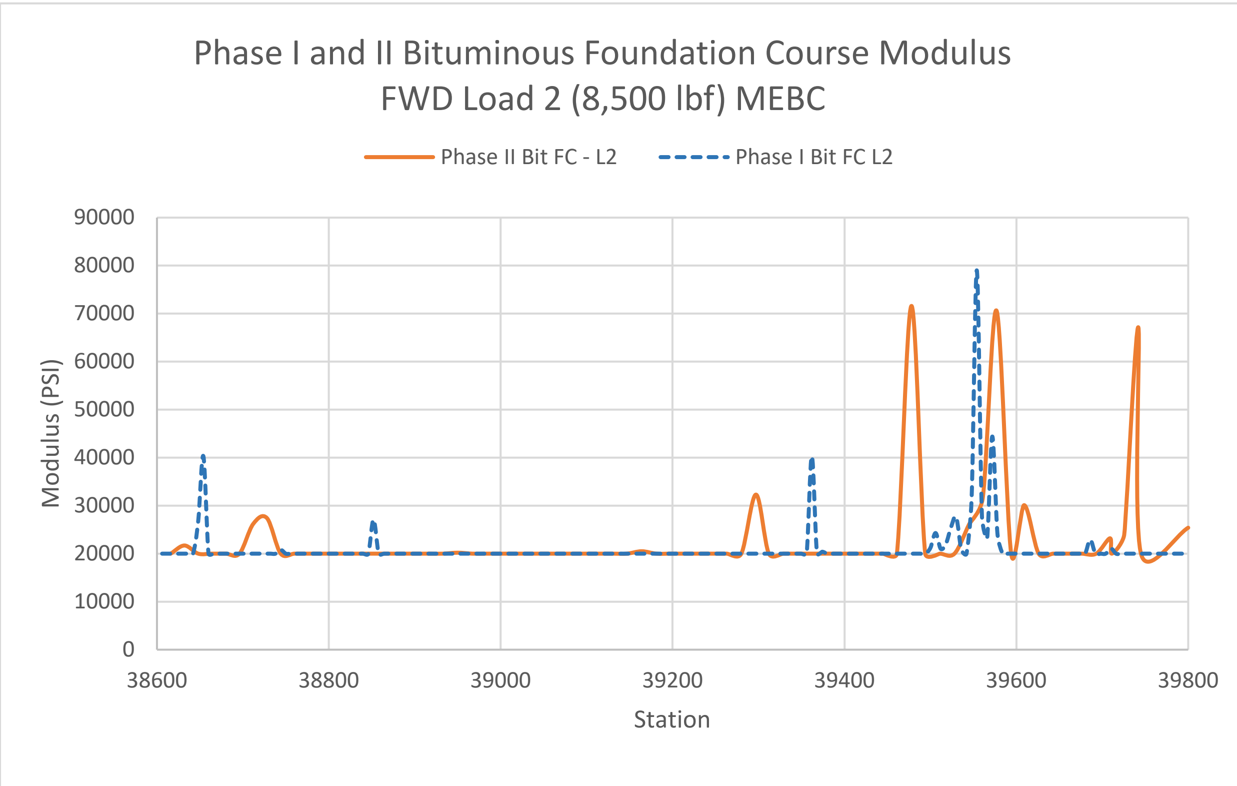

Figure 8- Foundation Course Modulus - ME Back Calculation

Conclusions and Recommendations

Phase I results showed that FWD, LWD, and DCP provided valid results and trended with each other at the stations all three tests were run. This gives confidence that any test method is reliable when used on an exposed bituminous foundation course.

The results of Phase I and Phase II indicate that using FWD testing after concrete is built does not provide an accurate modulus of the foundation course. As demonstrated through the statistical analysis, foundation course moduli cannot be reliably calculated by using FWD on top of doweled concrete pavements and back-calculated using Darwin software or ME Design. Additionally, the COV Phase I data reveals a significantly larger variance than Phase II across the test area proving that uniformity of the foundation course cannot be determined by FWD testing after the concrete pavement is placed.

DCP showed an approximate 50% reduction in the penetration of the foundation course when constrained by concrete in place. However, only a limited number of tests using DCP after the pavement was placed were conducted and therefore no conclusion can be drawn at this time.

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