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Common Sense Compaction for Soils/Embankment

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16. Abstract
This report details a comparative study on three different methods for evaluating soil compaction in roadway construction: the Nuclear Moisture and Density Gauge, the Dynamic Cone Penetrometer (DCP), and the Light Weight Deflectometer (LWD). The study's primary objectives were to review state specifications that have adopted performance-based testing methods and to conduct field tests comparing the three devices. The research was motivated by a growing industry shift away from density-based quality control toward performance-based specifications, which provide more direct insights into soil stiffness and load-bearing capacity. The review of specifications from states like Minnesota, Indiana, and Florida (FDOT) showed that these agencies have successfully integrated LWD and DCP testing, often in combination with density measurements, to improve quality assurance. Field testing was performed on two sites to compare the consistency and correlation between the three devices. The Nuclear Gauge, while efficient, was found to be limited by its reliance on lab-established Proctor tests and struggled with coarse-grained materials. The DCP, while providing valuable information on penetration resistance, was found to be labor-intensive, time consuming and prone to errors. In contrast, the LWD proved to be the most valuable tool for evaluating structural performance, as its stiffness measurements were found to be more indicative of a compacted layer's structural integrity than the density values from the Nuclear Gauge. The LWD also demonstrated the ability to distinctly differentiate between material types and provide consistent readings without relying on a Proctor curve. Based on these findings, the report recommends implementing the LWD as a complementary tool for projects with uniform soil conditions and as a standalone tool for projects with highly variable materials, such as embankments.

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1. INTRODUCTION

Roadway construction heavily depends on effective compaction to guarantee the stability and long-term performance of pavements. Proper compaction is essential for reducing settlement, increasing shear strength, and decreasing the permeability of the soil. Traditionally, in-situ compaction quality has been assessed through density-based methods, most notably with the use of sand cone tests and nuclear density gauges. However, there is a growing interest in alternative technologies, such as the Light Weight Deflectometer (LWD) and the Dynamic Cone Penetrometer (DCP), which offer a more direct insight into soil stiffness and load-bearing capacity. This shift in inspection methods towards performance-based specifications aims to enhance quality assurance and control in construction projects.

Current testing protocols primarily focus on determining the moisture content and density of compacted materials, as these factors are highly influential on material stability and durability. A key objective of this report is to conduct a comprehensive review of specifications and practices from various state Departments of Transportation (DOTs) that have adopted DCP and LWD technologies. This includes an examination of how these states, such as Minnesota (MnDOT), Indiana (INDOT), and Florida (FDOT), have integrated performance-based testing into their quality assurance frameworks. For instance, MnDOT has been a leader in this area, emphasizing performance-based testing over traditional density-based methods. Their approach uses calibration areas and proof-testing zones to ensure reliability and has found that LWD and DCP provide a stronger correlation to critical mechanical characteristics like stiffness modulus and shear strength. The report also details field testing conducted using these three methods: the nuclear moisture and density gauge, the DCP, and the LWD. A comparative analysis evaluates the consistency and correlation between the results from these three testing methods. This report highlights that each tool possesses distinct strengths and weaknesses. The nuclear gauge, for example, is efficient but is limited by its reliance on accurate Proctor test results, especially in non-uniform soils such as embankments. The DCP while providing direct measurements of soil strength, is time consuming, effort heavy, and prone to errors. The LWD is proposed as a complementary or standalone tool to address these limitations. This is based on its ability to provide direct measurements of soil stiffness, which are more indicative of structural performance. The LWD is particularly useful for projects involving highly variable materials where a representative Proctor curve is impractical to establish. In such cases, the LWD provides a robust and efficient method for evaluating compaction quality without relying on traditional density-based data. The final section of the report provides recommendations for implementing LWD technology, building on the comparative field testing and proposed strategies.

2. REVIEW OF OUT-OF-STATE SPECIFICATIONS

The main objective of this section was to conduct a comprehensive review of specifications and practices from other state Departments of Transportation (DOTs) that have adopted Dynamic Cone Penetrometer (DCP) and Light Weight Deflectometer (LWD) technologies.

2.1Soil/Embankement compaction

Compaction is a critical process in roadway construction as it ensures soil stability and long-term pavement performance. Proper compaction minimizes settlement, increases shear strength, and reduces permeability. This is typically achieved through the use of vibratory or static rollers, which compact the soil in controlled layers. The moisture content of the soil must be carefully monitored to stay close to the optimum moisture content determined in the lab for each soil type, typically using the Modified or Standard Proctor test.

2.2Compaction inspection

Traditionally, in-situ compaction quality has been evaluated through density-based methods, especially using the sand cone test and nuclear density gauge. However, modulus-based alternatives like the LWD and DCP have gained attention for their ability to provide more direct information on soil stiffness and load-bearing capacity. Inspection methods are shifting toward performance-based specifications to improve quality assurance and control.

Most of the current testing protocols for this purpose focus on determining the moisture content and density of the compacted material, as these two factors are well known to be heavily interrelated with a significant impact on the material stability and durability. Examples of common nondestructive devices used to determine in-situ density and moisture content include nuclear moisture density gauges (NDG) and electromagnetic sensors or electrical density gauges (EDG). In addition to utilizing density-based devices, there has been significant progress in using stiffness/modulus-based devices

2.2.1 Nuclear Moisture and Density Gauge

The determination of in-situ density and moisture content has traditionally relied on the nuclear gauge, a device that delivers quick results but demands operator certification and adherence to radiation safety protocols. Its operation is based on the emission of gamma and neutron radiation, functioning primarily in two modes: direct transmission and backscatter.

The gauge emits gamma rays, which interact with electrons in the underlying material via mechanisms such as absorption, Compton scattering, and the photoelectric effect. These rays are detected by a sensor positioned opposite the source within the device. The count of gamma rays captured by this detector correlates directly with the density of the pavement or subgrade. Depending on the mode of operation, different mathematical relationships are used to convert these counts into density values.

In the direct transmission mode, the nuclear gauge's retractable rod is inserted into a pre-drilled hole in the compacted material (Figure 1). This hole is typically created by driving a steel rod of similar diameter into the surface. Once in position, the source emits gamma rays that pass into the surrounding material, where they interact with electrons. During these interactions—through absorption or scattering—some gamma rays lose energy or are deflected away from the detector. As a result, only unscattered or minimally scattered rays reach the detector. Since denser materials cause more frequent interactions, fewer gamma rays make it to the sensor, creating an inverse relationship between detector count and material density. To calculate actual density, a calibration factor is applied to the gamma count.

In contrast, the backscatter mode keeps the retractable rod flush with the detector inside the instrument housing (Figure 1). Gamma rays are still emitted into the material, but here the gauge counts those that are redirected back toward the detector. Denser materials increase the likelihood of gamma ray backscatter, meaning the detector count increases with density. Like in direct transmission, a calibration factor is used to translate the gamma count into a density value.

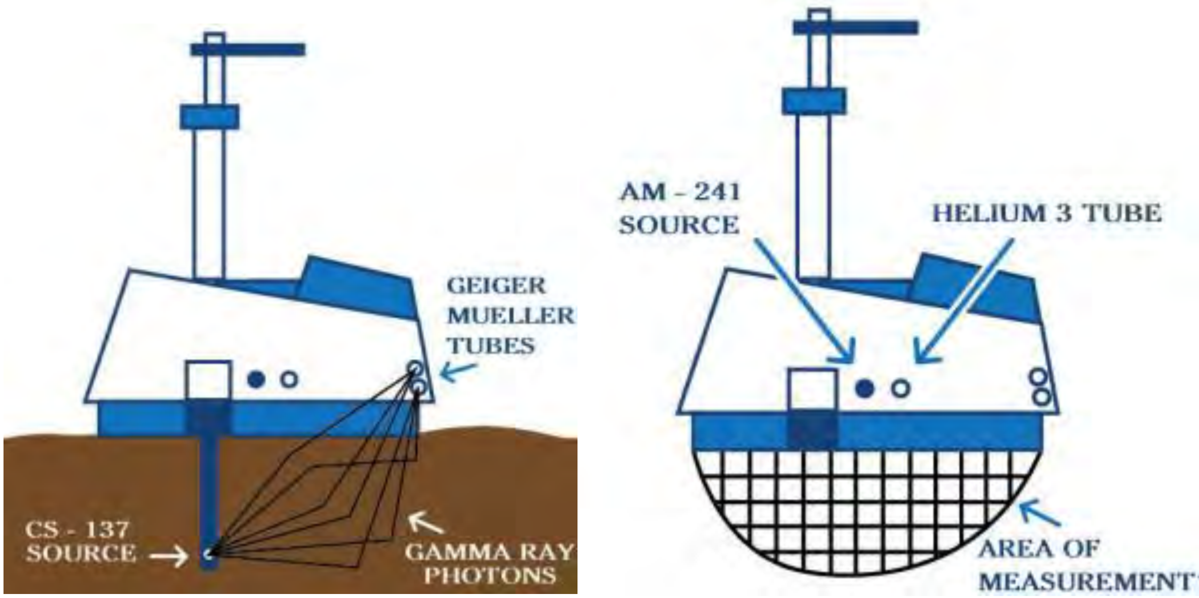


Figure 1: Nuclear gauge modes of operation: (a) Direct Transmission Method, and (b) Backscatter Method (Adapted from APNGA, 2009)

Despite its efficiency, limitations persist—particularly in handling coarse-grained materials, where large aggregate sizes can interfere with accurate compaction measurements.

2.2.2 Light Weight Deflectometer (LWD)

The Light Weight Deflectometer (LWD) is a compact, mobile device designed to evaluate the stiffness—or elastic modulus—of compacted soils and unbound aggregate layers. The system comprises several core components: a falling weight mechanism, a rigid load plate, a load cell, a deflection sensor, and an integrated data acquisition and storage unit. The testing process simulates the stress induced by a 10-ton axle load traveling at 80 km/h, applying a surface pressure of approximately 0.1 MN/m^2 over a brief 18-millisecond interval (Jardine et al., 2004). By dropping a weight onto a loading plate, it replicates the dynamic stresses typically applied to pavement structures, transmitting the load into the ground in a controlled manner. This method provides rapid readings with minimal surface disruption, positioning the LWD as a practical and efficient alternative to conventional density-based testing approaches.

Typically, six drops are performed during each test cycle. The initial three serve as seating drops to stabilize the contact between the plate and the surface, while the final three are used for recording data. A velocity sensor or accelerometer captures the downward motion of the plate, registering either its speed or acceleration at impact (Kessler, 2009).

LWD devices are produced by numerous manufacturers, such as Zorn, Dynatest, Keros, Prima, Loadman, Olson, and others (Schwartz et al., 2017). Measurement outcomes can vary depending on several factors including load plate diameter, stiffness of the plate, contact stress distribution, buffer characteristics, drop height, and the position and type of deflection transducer used. The modulus values recorded by the LWD are influenced by several factors, including the level of compaction effort, the moisture condition of the soil, and the characteristics of the underlying layers.

2.2.3 Dynamic Cone Penetrometer (DCP)

The Dynamic Cone Penetrometer (DCP) is a widely recognized and practical tool for assessing the in-situ strength of compacted soils and unbound pavement layers. As an evolution of the traditional hand cone penetrometer, the DCP offers a more refined, portable, and cost-effective approach for rapid field evaluations. Its simplicity, efficiency, and low operational cost make it a popular choice for geotechnical and pavement engineers.

The device features a steel rod with a 60-degree cone tip and an 8-kg hammer, which is dropped from a height of 575 mm onto an anvil at the top of the rod. As the hammer impacts the anvil, the cone penetrates the ground, and the depth of penetration is measured after each drop. This measurement yields the Dynamic Cone Penetration Index (DPI or PI), which is calculated as the total penetration depth divided by the number of hammer blows (Morian et al., 2012; Sawangsuriya & Edil, 2005). This index provides a direct indication of the material's stiffness—higher DPI values reflect lower stiffness and strength. Makwana and Kumar (2019) found a strong relationship between LWD modulus and DCP results, with a coefficient of determination (R^2) of 0.81.

2.3 State Specifications

2.3.1 PennDOT

PennDOT calls for specific compaction levels for different materials used in pavement layers. The requirements are set for the maximum thickness of the compacted layers and the compaction equipment based on the material type. For example, Table 1 presents compaction requirements for two material categories, “Soil” and “Granular (Type 1),” commonly used within pavement structures as subgrade and base layers, respectively. These requirements are based on in-situ testing using a nuclear gauge according to PTM 402. It is worth mentioning that the top 90 cm (3 ft) of the compacted layers must have a higher compaction level (or higher shear resistance), as it experiences higher stress levels induced by traffic load. Also, the moisture-density (M-D) relation needs to be established in the laboratory before field compaction to calculate the maximum dry density and the optimum moisture content. PennDOT uses PTM No. 106, which is adopted from AASHTO T-99 test method to determine the M-D curves. Then, the field density and moisture content are measured using a nuclear gauge according to PTM No. 402.

Table 1: Compaction density thresholds for PennDOT (PENNDOT, 2020)

Material	Depth	Maximum Dry Density
Soil	< 3 ft	100%
	> 3 ft	97%
Granular (Type I)	< 3 ft	100%
	> 3 ft	97%

As of the 2020 Edition, Change #4, of PennDOT Publication 408, Sections 206, 208, 210, and 350 do not include specific acceptance criteria or procedures for LWD or DCP testing. Nevertheless, PennDOT is actively exploring the implementation of these performance-based tools for quality assurance of subgrade, subbase, and base layer compaction.

2.3.2 MnDOT

Minnesota DOT has been at the forefront of integrating LWD and DCP testing into pavement construction practices. Rather than relying solely on density-based methods, MnDOT's approach emphasizes performance-based testing to evaluate compaction quality. Before allowing widespread field application, MnDOT requires the use of calibration areas and proof-testing zones to ensure reliability. Their specifications offer detailed guidance on both testing methodology and acceptance criteria.

Back in 2006, MnDOT initiated evaluations of LWD and DCP as part of their effort to adopt new technologies in construction quality assurance. While traditional density testing had long been used, it was observed that LWD and DCP provided stronger correlations to key mechanical characteristics, such as stiffness modulus and shear strength. As a result, these methods offer more direct insights into the structural performance of compacted layers, which supports both pavement design and quality control processes. Additionally, the enhanced repeatability and operator safety associated with these devices led to shorter testing durations and improved field efficiency (Geotechnical Section MnDOT, 2017).

According to MnDOT's 2020 standard specifications, presented in Table 2, compaction requirements vary depending on the lift thickness and material type. These standards incorporate a combination of density, DCP, and LWD test results. The DCP test is performed in accordance with ASTM D6951, with minor procedural adjustments. Notably, MnDOT defines performance criteria not only for DPI and LWD modulus, but also for maximum allowable seating values, all based on the material's grading number (GN), which is derived from sieve analysis using the Equation below.

$$GN\ (\%passing) = \frac{25mm + 19mm + 9.5mm + 4.75mm + 2mm + 425\mu m + 75\mu m}{100}$$

Table 2: Compaction Specifications from MnDOT (MnDOT, 2020)

Material Type	Location	Required Compaction *
Materials meeting the requirements of 3149.2B, "Granular and Select Granular Materials"	All depths and locations	100 percent specified density, Quality Compaction, penetration index, and LWD
Materials not meeting the requirements of 3149.2B, "Granular and Select Granular Materials"	> 3 feet below Grading Grade of Road Core, trails, or Sidewalks	95 percent specified density, and LWD when the Engineer performs a correlation test between 95 percent specified density, and an LWD.
Materials not meeting the requirements of 3149.2B, "Granular and Select Granular Materials"	≤ 3 feet below Grading Grade of Road Core, trails, or Sidewalks	100 percent specified density, Quality Compaction, and LWD
All Materials	All depths within an excavation trench and backfill of Structures, 2451, "Structure Excavations and Backfills"	100 percent specified density, Quality Compaction, and LWD
*See 2106.3G.1, "Specified Density," 2106.3G.2, "Quality Compaction," 2106.3G.3, "Penetration Index," and 2106.3G.4, Light Weight Deflectometer (LWD) Method" for compaction requirements.		

The basis for this specification stems from the study *Validation of DCP and LWD Moisture Specifications for Granular Materials* (Davich et al., 2006), which informed the development of a Special Provision for the use of the Dynamic Cone Penetrometer (DCP). According to the report, the Special Provision should be limited to specific applications involving select granular borrow materials that are compacted at moisture contents ranging from 1% to 2% below their optimum moisture content. This ensures more reliable and consistent DCP readings under field conditions.

MnDOT's *Standard Specifications for Construction* (2020, Volume II - Division II) includes detailed requirements for DCP testing. Specifically, Table 3 outlines the Maximum Allowable DCP Penetration Index (DPI) values for different granular materials, providing standardized acceptance criteria for construction quality assurance.

Table 3: MnDOT DCP: Maximum Seat and DPI (MNDOT, 2020)

Grading Number *	Moisture Content‖	Maximum Allowable SEAT, [millimeter]	Maximum Allowable DPI, [millimeter/blow]	Test Layer, [inches]†
3.1 – 3.5	< 5.0	40	10	4 – 6
	5.0 – 8.0	40	12	
	> 8.0	40	16	
3.6 – 4.0	< 5.0	40	10	4 – 6
	5.0 – 8.0	45	15	
	> 8.0	55	19	
4.1 – 4.5	< 5.0	50	13	5 – 6
	5.0 – 8.0	60	17	
	> 8.0	70	21	
4.6 – 5.0	< 5.0	65	15	6 – 12
	5.0 – 8.0	75	19	
	> 8.0	85	23	
5.1 – 5.5	< 5.0	85	17	7 – 12
	5.0 – 8.0	95	21	
	> 8.0	105	25	
5.6 – 6.0	< 5.0	100	19	8 – 12
	5.0 – 8.0	115	24	
	> 8.0	125	28	

* As determined by *Form G&B-204*.

‖ Percent of dry weight.

† If Layer to be placed is thinner than the Test Layer, use 2211.3D.2.b, "Quality Compaction Method."

Note: When recycled bituminous content is ≥ 50 percent, compact to achieve a penetration index value of 10 millimeter and a seating value of 40 millimeter, as determined by *Form G&B-205*.

Note that a moisture test is not required if the Material meets the toughest requirements for the Grading Number.

The report *Advancement of Grading & Base Material Testing* (MNDOT, 2004) outlines the methodology used to establish DCP thresholds, particularly the DPI, by referencing the concept of "quality compaction" at field test locations. At each site, the engineer in charge subjectively assessed the quality of compaction and labeled sections as either acceptable or unacceptable based on visual inspection and field observations. Only those locations deemed to have achieved "quality compaction" were used to define acceptable DCP performance, while sections with insufficient compaction were considered to have failed the DCP assessment.

This classification served as the basis for correlating DCP results with field performance. A total of 51 valid data points—each tied to a compaction quality rating—were used to develop regression models. These models established quantitative thresholds for both DPI and SEAT values. SEAT, or Seating Penetration, refers to the initial displacement of the cone during the first two hammer drops of the DCP test. It is used as an indicator of how easily the uppermost portion of the layer deforms under load, providing additional insight into surface stiffness.

To establish DCP acceptance thresholds, MnDOT developed a penetration acceptance table by segmenting the continuous variables—Grading Number (GN) and Moisture Content (MC)—into discrete ranges. For each range, the upper boundary was conservatively used to calculate the maximum allowable penetration index (DPI), ensuring stricter acceptance criteria under variable field conditions.

For LWD testing, MnDOT defines target values in accordance with the *Grading & Base Manual*, Section 5-692.256, which outlines the procedure for LWD use and the determination of target modulus values (LWD-TV). According to MnDOT Specification 2106, the minimum elastic modulus for granular materials is 40 MPa, while for clay or clay foam it is 20 MPa. Specifications 2211 and 2215 set a minimum LWD modulus of 50 MPa for reclaimed or base course materials.

LWD target values are derived from field measurements taken during the deflection test. The LWD-TV is based on the average deflection from the fourth, fifth, and sixth drops of a standard test sequence; the initial three drops serve as seating blows. These deflection readings are then used to compute the corresponding elastic modulus, which must meet or exceed the specified minimum value.

To determine the LWD-TV for a given soil type or source, MnDOT mandates the use of a calibration area. The purpose of this calibration area is to establish representative LWD responses under known compaction and moisture conditions. Guidelines for establishing and maintaining a calibration area include:

1. **Calibration Area Requirements**: Construct a dedicated area for each distinct material type or source to determine the associated LWD-TV.
2. **Reconstruction Criteria**: A new calibration area must be constructed if any of the following occur:

a. A new material source is used, or observable changes in material properties occur;

b. The field moisture content differs by more than ±2% from the calibration area moisture content;

c. The Engineer deems it necessary based on field observations.

3. **Dimensions**: Required calibration area dimensions are defined in Table 4.

Once the calibration area is compacted, it must achieve the LWD-TV values. If quality compaction is not achieved even when the LWD modulus meets the minimum threshold, the specified minimum modulus may be increased. The Engineer has the discretion to apply either the calibration-based target value method or a predetermined target modulus method, depending on the project needs and material variability.

Table 4: MnDOT LWD Calibration Area Dimensions

Embankment	Length	Width (ft)	Fill Thickness
Roadbed Embankment Soil, reclamation, and Base	≥ 50 feet	Equal to the excavated embankment width	Equal to the planned layer thickness for base or reclamation & 12 inch minimum for embankment
Miscellaneous trench, culvert, or other tapered construction	≥ 10 feet	Equal to the excavated embankment width	Equal to the planned layer thickness for base or reclamation & 12 inch minimum for embankment

2.3.3 INDOT

Indiana Department of Transportation (INDOT) formally incorporates both LWD and DCP testing as part of its standard procedure for verifying compaction in pavement construction. Instead of relying solely on density-based criteria, INDOT establishes acceptance thresholds using average and maximum allowable deflections for LWD and penetration indices for DCP, which vary based on soil type, layer function, and site-specific conditions. The agency applies a tiered decision-making approach: if proof rolling is not feasible or effective, the use of LWD becomes mandatory. For chemically stabilized soils, INDOT limits LWD deflections to a maximum of 0.50 mm, while untreated aggregate layers are allowed up to 0.65 mm. Treated layers must also meet a minimum modulus value of 100 MPa. For DCP testing, the maximum allowable DPI is set at 20 mm/blow for untreated granular materials and reduced to 10 mm/blow for chemically treated or stabilized soils. INDOT also provides clear specifications regarding equipment type, drop height, and load plate dimensions to ensure testing consistency across projects.

According to INDOT's 2020 standard specifications, compaction verification using LWD requires 10 test points evenly distributed along a 68.6-meter (225-foot) test section (Figure 2). The deflection values recorded at these locations are averaged. If the change in average deflection between four and five roller passes exceeds 0.02 mm, an additional vibratory roller pass is mandated to ensure uniform compaction.

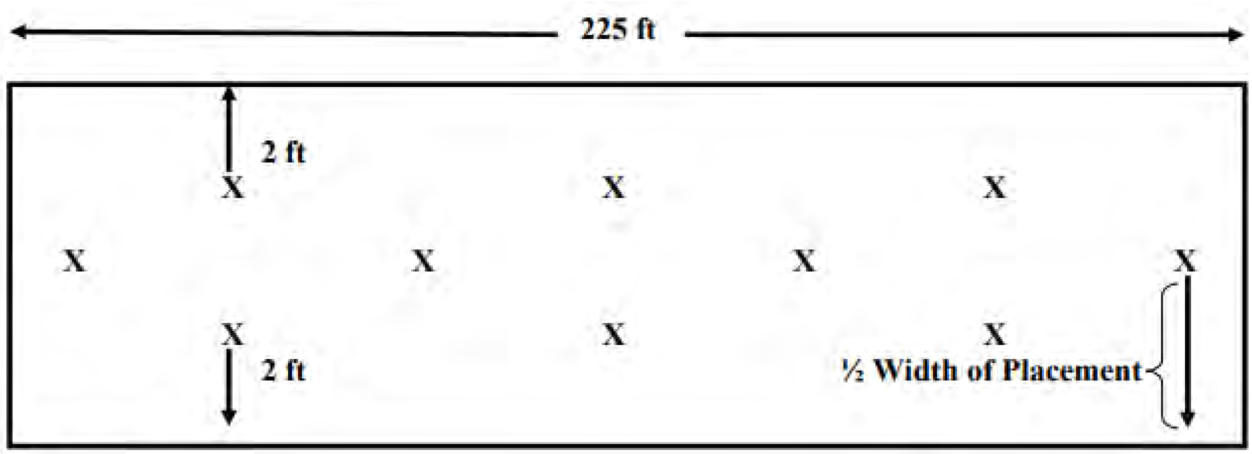


Figure 2: LWD test locations per INDOT recommendations (INDOT, 2020)

Proof rolling is also a key element of INDOT's quality control approach and serves as a preliminary screening tool to assess the load-bearing capacity of unbound layers and the subgrade. Beyond compaction quality, this method can identify subgrade weaknesses, including drainage deficiencies (Dunston et al., 2018). According to INDOT's 2022 specifications (Section 203.26), proof rolling (referred to as test rolling) is conducted using a dump truck. For original ground or embankment construction, the truck must weigh at least 15 tons and have a tire pressure of no less than 90 psi. For subgrade preparation, the requirement increases to a 33-ton vehicle. In both scenarios, the truck must operate at a speed not exceeding 3.2 kph (2 mph). Surface deformation greater than 12.5 mm (0.5 in) necessitates remedial action, while deformations exceeding 75 mm (3.0 in) require escalation to the Department's Geotechnical Engineering Division.

Following proof rolling, LWD testing is conducted on the subgrade and subsequent unbound layers to confirm compliance with specified deflection thresholds. These values depend on material classification and field conditions. For example, chemically modified soils and aggregate layers have different LWD acceptance criteria, while the base course constructed with AASHTO #53 aggregate is evaluated based on thickness and whether proof rolling was used.

Furthermore, INDOT's 2022 specifications (Section 203.24) outline the methodology for strength, stiffness, and density testing, and provide standardized LWD values tailored to various soil types. These are detailed in Tables 5, 6, and 7 of the specifications, which serve as references for acceptable performance ranges during construction quality assurance.

Table 5: Deflection thresholds for treated soils and aggregate over treat soil (INDOT, 2022)

Material Type	Allowable Average Deflection (mm)	Maximum Deflection at a Single Test Location (mm)
Lime Modified Soil	≤ 0.30	0.35
Cement Modified Soil	≤ 0.27	0.31
Aggregate over Lime Modified Soil	≤ 0.30	0.35
Aggregate over Cement Modified Soil	≤ 0.27	0.31

Table 6: Deflection thresholds for aggregate over untreated soils (Proofrolling) (INDOT, 2022)

Material Thickness	Allowable Average Deflection (mm)	Maximum Deflection at a Single Test Location (mm)
6 in. Thick Coarse Aggregate No. 53	≤ 0.51	0.57*
12 in. Thick Coarse Aggregate No. 53	≤ 0.34	0.40**
18 in. Thick Coarse Aggregate No. 53	≤ 0.31	0.35**
* When deflection exceeds this value, the area shall be recompacted or undercut as directed. The failed area will be delineated prior to excavation. Deflection will be measured based on the top 6 in. thick coarse aggregate No. 53 material placed for undercut. ** The Contractor shall recompact the coarse aggregate No. 53 in accordance with 301.06		

Table 7: Deflection thresholds for aggregate over untreated soils (Without Proofrolling) (INDOT, 2022)

Material Thickness	Allowable Average Deflection (mm)	Maximum Deflection at a Single Test Location (mm)
6 in. Thick Coarse Aggregate No. 53	≤ 0.60	0.65*
12 in. Thick Coarse Aggregate No. 53	≤ 0.47	0.52**
18 in. Thick Coarse Aggregate No. 53	≤ 0.44	0.49**
* When deflection exceeds this value, the area shall be recompacted or undercut as directed. The failed area will be delineated prior to excavation. Deflection will be measured based on the top 6 in. thick coarse aggregate No. 53 material placed for undercut. ** The Contractor shall recompact the coarse aggregate No. 53 in accordance with 301.06 Note: The Engineer will perform the moisture test on in-situ soils prior to placement of coarse aggregate. If the result of the moisture test is > 13%, the Engineer will contact the Department’s Geotechnical Engineering Division.		

In parallel, INDOT also provides standard acceptance values for the Dynamic Cone Penetrometer (DCP), which are used as part of quality control during construction. These standardized thresholds, detailed in Table 8, vary by material type and are aligned with INDOT's performance-based approach to verifying subgrade and base compaction.

Table 8: DCP thresholds for different soils (INDOT, 2022)

Textural Classification	Maximum Dry Density (pcf)	Optimum Moisture Content Range (%)	Acceptable Minimum DCP value for 6 in. for 95% compaction	Acceptable Minimum DCP value for 12 in. for 95% compaction	Acceptable Minimum DCP value for 6 or 12 in. for 100% compaction
CLAY SOILS					
Clay	< 105	19 - 24	6		*
Clay	105 - 110	16 - 18	7		*
Clay	111 - 114	14 - 15	8		*
SILTY SOILS					
Silty	115 - 116	13 - 14		9	*
Silty	117 - 120			11	*
SANDY SOILS					
Sandy	121 - 125	8 - 12		12	*
Sandy	> 125			15	*
GRANULAR SOILS - STRUCTURE BACKFILL and A-1, A-2, A-3 SOILS					
No. 30				6	9
No. 4				7	10
1/2 in.				11	14
1 in.				16	19
Note: * Test section required in accordance with ITM 513.					

Unless otherwise directed, materials compacted in accordance with INDOT Specification 203.23 must achieve a minimum acceptable Dynamic Cone Penetrometer (DCP) value corresponding to 95% of the maximum dry density. In cases where 100% compaction is specified, the subgrade must meet a stricter DCP threshold. These criteria are outlined in the *Indiana Department of*

Transportation Standard Specifications 2022, Section 203.23, and are determined through the construction and evaluation of test sections following procedures detailed in ITM 514.

The full procedure for establishing the DCP acceptance value involves several steps:

1. **Placement and Compaction**:
   The material is placed in two consecutive 6-inch lifts and compacted using the appropriate roller equipment. Four passes are applied across the section, and the roller must not stop or change direction within the test area, ensuring uniform compaction.
2. **Sand Cone Testing**:
   Once compaction is completed, three sand cone density tests are performed according to AASHTO T 191. If the material contains more than 35% fines (passing the #200 sieve), the test is conducted on the top 6 inches. For materials with fewer fines, the test is conducted 6 inches below the surface. The test locations are evenly spaced across the section. The average dry density from these tests is then compared to the lab-determined maximum dry density. If the average reaches at least 95% of the maximum, the compaction is considered adequate.
3. **DCP Testing**:
   The test section is marked according to Figure 3, and 10 DCP tests are conducted at designated points. To maintain accuracy, any test result with fewer than 6 or more than 10 blows per 6 or 12 inches is discarded and replaced with a new randomly selected location to maintain a sample size of 10 valid tests.
4. **Blow Count Averaging**:
   For clayey soils, the average blow count is calculated over the top 6 inches; for silty, sandy, or granular materials, a 12-inch depth is used. If the resulting average blow count aligns with the value associated with 95% compaction, the test section is approved.

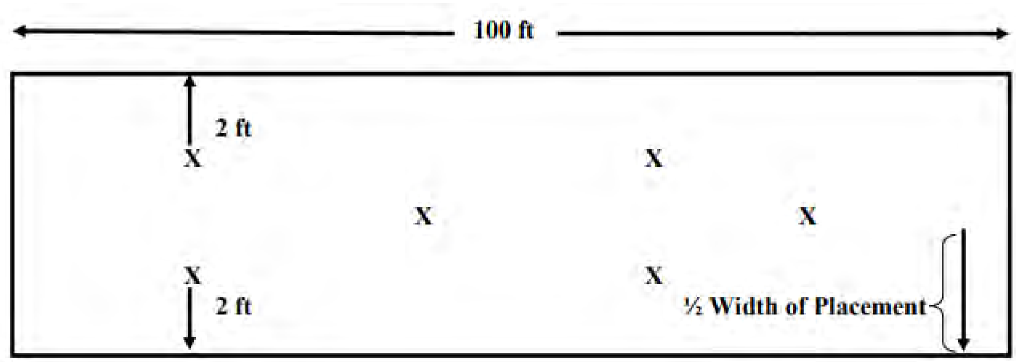


Figure 3: Test locations recommendations from INDOT (INDOT, 2020)

2.3.4 FDOT

Florida Department of Transportation (FDOT) has adopted a performance-based approach to quality assurance and quality control by incorporating LWD and DCP testing into its specifications. Rather than relying solely on traditional density methods, FDOT has prioritized resilient modulus estimates as key indicators of compaction quality.

For base materials, FDOT requires the resilient modulus derived from DCP data to exceed 100 MPa. LWD measurements must be consistent across three successive drops, with allowable variation within 10%. Moisture content, a critical factor influencing modulus, is checked through both oven-dry methods and nuclear gauge readings to ensure accuracy across testing protocols.

In a 2015 study, Glagola et al. developed FDOT's QA/QC specification framework using both LWD and DCP testing methods. Their research proposed two approaches for establishing target values: one based on laboratory-determined parameters such as optimum moisture content and material type, and another using direct field testing on a constructed test strip. In the field method, contractors construct the test section using specified materials and compaction equipment. LWD deflections are measured after four vibratory roller passes, followed by a fifth pass and another round of 10 LWD measurements. If the difference between the average deflection values from the fourth and fifth passes is less than 0.02 mm, the average after the fifth pass becomes the target deflection. If not, the process is repeated until this criterion is satisfied.

The final QA/QC framework, documented in the Performance-Based Quality Assurance/Quality Control (QA/QC) Acceptance Procedures for In-Place Soil Testing Phase 3 report, integrates elements from MnDOT and INDOT practices. The study generated target ranges for both LWD and DCP based on 95% confidence intervals. These standardized benchmarks are presented in Table 9 and Table 10, offering practical guidance for implementing modulus-based quality control in the field.

Table 9: DCP thresholds for FDOT (Glagola et al., 2015)

Phase II Test Pit Data	**Below Optimum (95% Confidence Interval)**				**At Optimum (95% Confidence Interval)**			
DCP Target Values	**< Opt. Target**	**< Opt. Lower CI**	**< Opt. Upper CI**	**Moisture (%)**	**@Opt. Target**	**@Opt. Lower CI**	**@Opt. Upper CI**	**Moisture (%)**
A-2-4 low fines								
DCP depth/blow (mm)	6.99	6.57	7.41	5.67~6.8	8.83	8.29	9.38	8.2~10.0
in./blow	0.275	0.259	0.292	5.6~6.8	0.348	0.326	0.369	
blows/6 in.	22	23	21		17	18	16	8.3~10.0
blows/12 in.	44	46	41		35	37	33	
A-3								
DCP depth/blow (mm)	8.91	8.11	9.71	4.4~4.9	11.63	10.90	12.35	8.2~10.5
in./blow	0.351	0.319	0.382	4.4~4.9	0.458	0.429	0.486	
blows/6 in.	17	19	16		13	14	12	8.2~10.5
blows/12 in.	34	38	31		26	28	25	
Limerock base								
DCP depth/blow (mm)	5.63	4.91	6.35	10.0~10.7	5.74	4.68	6.80	11.8~13.7
in./blow	0.222	0.193	0.250	10.0~10.7	0.226	0.184	0.268	
blows/6 in.	27	31	24		27	33	22	11.8~13.7
blows/12 in.	54	62	48		53	65	45	
Stabilized subgrade								
DCP depth/blow (mm)	14.73	12.63	16.83	7.1~8.7	10.95	9.66	12.24	8.2~10.1
in./blow	0.580	0.497	0.663	7.1~8.7	0.431	0.380	0.482	
blows/6 in.	10	12	9		14	16	12	8.2~10.1
blows/12 in.	21	24	18		28	32	25	

Table 10: LWD thresholds for FDOT (Glagola et al., 2015)

LWD-1 Target Values								
LWD-1 deflection (mm)	**Target**	**Lower CI**	**Upper CI**	**Moisture (%)**	**Target**	**Lower CI**	**Upper CI**	**Moisture (%)**
A-2-4 low fines	0.34	0.31	0.38	5.6~6.8	0.45	0.42	0.48	8.3~10.0
A-3	0.40	0.37	0.43	4.4~4.9	0.43	0.40	0.46	8.2~10.5
Limerock base	0.23	0.19	0.28	10.0~10.7	0.26	0.23	0.29	11.8~13.7
Stabilized subgrade	0.39	0.33	0.44	7.1~8.7	0.55	0.46	0.65	8.2~10.1

2.3.5 NDOT

The Nebraska Department of Transportation (NDOT) employs the Nebraska Group Index (NGI) system to establish allowable LWD deflection limits for different soil classifications. By linking these deflection thresholds to expected performance outcomes, NDOT integrates LWD testing directly into its construction control framework. Additionally, DCP data are correlated with stiffness moduli through DPI-based relationships, with correction factors applied for varying soil types and moisture conditions.

LWD acceptance criteria are defined according to NGI values: higher-performing soils (e.g., NGI 1) must exhibit LWD deflections below 0.6 mm, while lower-performing soils (e.g., NGI 5) may allow up to 1.2 mm. This graduated scale allows NDOT to tailor deflection thresholds based on the expected behavior of the subgrade material. The NDOT Construction Manual (2019 edition) encourages inspectors to perform LWD testing in accordance with NDOT T2835. The key parameter, the Deflection Target Value (DTV), is determined either from a test strip or by correlation with NGI for the soil in question.

Historically, as noted by Schwartz et al. (2017), NDOT established maximum allowable deflections based on the unbound layer's location relative to the pavement surface—distinguishing between layers located within the top 3 feet and those below, as well as whether the pavement was asphalt or concrete. When a specific soil does not fall into the predefined NGI categories, a performance-based procedure is used. In such cases, three LWD tests are conducted after each compaction roller pass, and the average deflection is evaluated. Compaction continues until the difference in average deflections between consecutive passes drops below 10%, indicating stabilization. The final average deflection is then adopted as the LWD target value.

NDOT's Quick Reference Guide for Light Weight Deflectometer (LWD) Field Testing outlines two methods for establishing target values:

Correlation-Based Approach: LWD targets are derived using resilient modulus values linked to the NGI. Moisture content must be verified to be within acceptable limits, and the target deflection thresholds are taken from a standardized table (see Table 11), depending on whether the material is placed beneath concrete or asphalt, and whether it lies within the top 3 feet or deeper.

Test Strip Method: When correlation data are unavailable, a 61-meter (200-ft) test strip is constructed in two lifts of 200 mm (8 in) each. Moisture is tested to confirm it falls within specification. After each roller pass, three LWD tests are performed, and the process continues until the average deflection change between passes is less than 10%. The resulting value is recorded as the LWD target value. Once full compaction is completed, field deflections must not exceed 1.1 times the established target.

Table 11: NDOT LWD thresholds for different materials (Schwartz, et al., 2017)

Nebraska Group Index	Concrete Upper 3' Max Deflection (mm)	Concrete Below 3' Max Deflection (mm)	Asphalt Upper 3' Max Deflection (mm)	Asphalt Below 3' Max Deflection (mm)
-2	0.5	0.5	0.5	0.5
-1	0.5	0.5	0.5	0.5
0	0.5	0.5	0.5	0.5
1	1	1.5	0.5	1.5
2	1	1.5	0.5	1.5
3	2	3	1	3
4	2	3	1	3
5	2	3	1	3
6	2	3	1	3
7	1.5	3	0.75	3
8	1.5	3	0.75	3
9	1.5	3	0.75	3
10	2	4	1	4
11	2	4	1	4
12	2	4	1	4
13	2	4	1	4
14	3	5	2	5
15	3	5	2	5
16	3	5	2	5
17	4	6	3	6
18	4	6	3	6
19	5	8	4	8
20	5	8	4	8
21	5	8	4	8
22	6	9	5	9
23	6	9	5	9
24	6	9	5	9

2.3.6 Comparison of DCP and LWD specifications

The reviewed state specifications show significant differences in how Dynamic Cone Penetrometer (DCP) and Light Weight Deflectometer (LWD) technologies are applied for compaction verification, although there are also emerging similarities across several Departments of Transportation (DOTs).

In the case of DCP specifications, agencies such as MnDOT, INDOT, and FDOT have adopted penetration-based acceptance criteria typically expressed in terms of maximum allowable Dynamic Penetration Index (DPI) or minimum blow counts over a standard depth. MnDOT links maximum DPI values to the Grading Number (GN) of materials, applying more stringent thresholds for finer materials. INDOT uses minimum blow counts over either 6-inch or 12-inch depths depending on material type, establishing thresholds that align with achieving at least 95% laboratory maximum dry density. FDOT specifies target DPI values corresponding to resilient modulus expectations for base and subgrade materials.

For LWD specifications, states also vary but generally either target a minimum elastic modulus value or set maximum allowable deflections under standardized loading conditions. MnDOT requires minimum elastic modulus values of 50 MPa for base and reclaimed materials, and 40 MPa for granular fills. INDOT sets maximum allowable deflections that vary by material treatment (e.g., chemically treated vs. untreated soils), with tighter thresholds for treated layers (0.27 to 0.30 mm allowable average deflection) compared to untreated aggregates (up to 0.60 mm allowable). FDOT, on the other hand, links acceptance to target deflection ranges determined through test strips, aiming to control variability across successive LWD drops. NDOT employs a classification system based on the Nebraska Group Index (NGI), correlating allowable deflection ranges to expected soil performance, with lower deflection values required for better-performing soils.

Overall, both DCP and LWD specifications are moving toward performance-based frameworks rather than traditional density acceptance. Agencies are increasingly correlating penetration or deflection results with key engineering properties such as modulus or CBR values. While the implementation details vary, a common theme is that DCP is preferred for direct strength verification through penetration resistance, whereas LWD provides a non-destructive evaluation of stiffness through surface deflections. This trend illustrates a broader shift toward mechanistic quality assurance approaches that better predict long-term pavement and embankment performance.

3. FIELD TESTING

The primary objective of this section was to report on the comparative testing of the three technologies used to estimate the degree and quality of compaction in pavement layers.

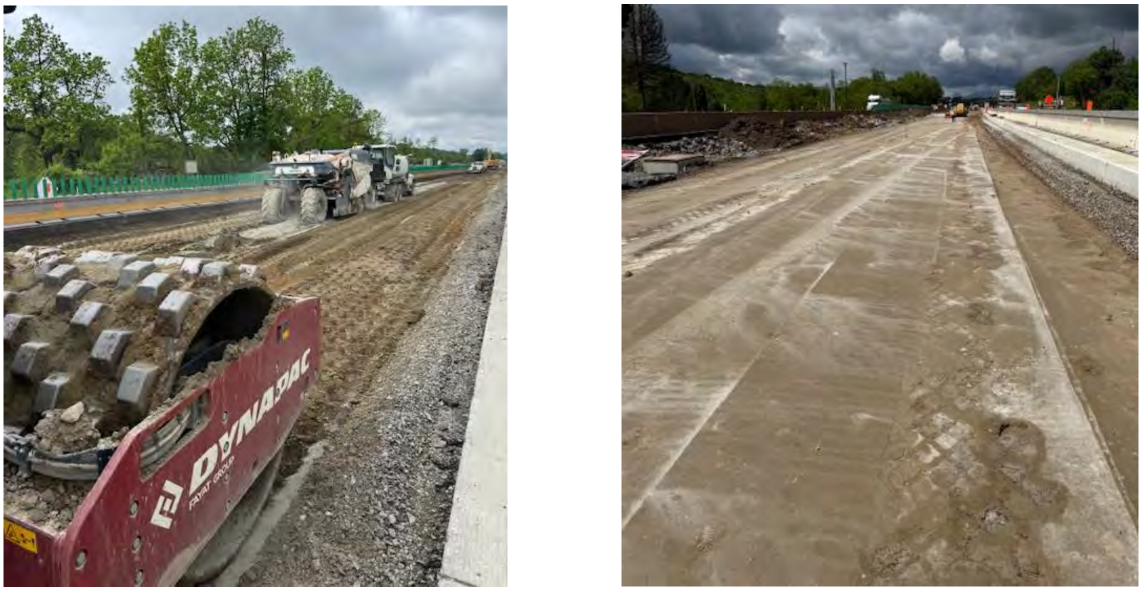
Testing was conducted on the morning of Friday, May 23. In the days leading up to the testing, the area experienced significant rainfall. The weather during testing was overcast with a temperature of approximately 16°C. We arrived at the site office near Belle Vernon, PA, at 10:00 a.m. and were escorted to the first testing location on I-70. Traffic in the area was heavy.

All three devices were used in a side-by-side manner. According to the nuclear gauge operator, standard procedure involves taking one measurement every 50 feet along the center of the lane. We followed this approach and, for select stations, also conducted measurements in the right wheel path, marked with an "R."

For easy comparison of results with design inputs, Appendix A brings the results from the DCP and LWD with corresponding CBR (%) values.

3.1Testing Site

Testing was conducted on active constructions site along the I70 project near Belle Vernon, Pa. The first test site was composed of reinforced subgrade with soil cement. Workers were mixing the soil cement layer for the day (Figure 4a), compaction would start after. Due to construction, weather, and timing restraints, we decided to test the layer compacted the day prior (Figure 4b). We conducted measurements from Station 305 to Station 308. We only conducted 8 measurements with the nuclear gauge and LWD due to rain at the end of the testing.



(a) (b)

Figure 4: Testing Site 1 – Soil cement subgrade: (a) Mixing in progress, (b) Completed compaction.

After the soil cement, we went to another construction areas of I-70 with soil aggregate composed of 2A aggregate (Figure 5). This section was compacted earlier in the week. We performed the testing with the same procedure until rain started. We conducted measurements from station 353 moving backwards to station 349.

Figure 5: Testing Site 2 – Soil-aggregate reinforced subgrade with nuclear gauge device

3.2 Nuclear Moisture and Density Gauge

The nuclear gauge used was the Troxler 3440 Plus (Figure 5), the standard device for site inspections under state specifications. It was operated in backscatter mode, meaning the retractable rod remains inside the housing, avoiding penetration into the layer.

The device emits gamma rays into the material. These rays are scattered by the material and detected by the gauge; denser materials result in higher backscatter counts. A calibration factor, combined with Proctor test results, is used to calculate dry density.

Tables 12 and 13 show the data from both testing sites.

Table 12: Nuclear gauge results for Testing Site 1 – Soil Cement

Station	Proctor (%)	Dry Density (pcf)	Moisture Content (pcf)
305	111.3	123.7	16.8
305+50	107.1	119.0	15.1
306	109.9	122.1	17.1
306+50	113.1	125.7	16.0
307	110.5	122.8	15.7
307+50	118.7	131.9	15.0
308	107.7	119.7	17.5
308 R	110.2	122.4	17.6

Table 13: Nuclear gauge results for Testing Site 2 – Soil Aggregate

Station	Proctor (%)	Dry Density (pcf)	Moisture Content (pcf)
353	101.6	133.3	4.9
352+50	106.6	139.9	6.0
352	107.6	141.2	4.8
351+50	104.4	137.0	4.8
351	94.3	123.7	4.2
350+50	101.0	132.5	6.1
350+50 R	101.8	133.6	5.2
350	105.0	137.8	4.8
349	103.1	135.2	4.1
349 R	106.7	140.0	5.0

As can be seen in Table 12, the testing site material achieved uniform compaction with an average Proctor of 111% (Standard deviation at 3.4%). Slightly elevated moisture content may be due to prior rainfall.

For the 2A aggregate material (Testing Site 2), the compaction efficiency was satisfactory for most points besides Station 351 at 94.3%. Average compaction was lower than the soil cement site at 103% with a standard deviation of 3.7%.

3.3 Dynamic Cone Penetrometer (DCP)

The DCP device used for testing was the Kessler Dynamic Cone Penetrometer (Figure 6). Due to time constraints, five tests were conducted at each site, with each test involving approximately 10 to 12 hammer blows. Additional discussion on this is provided in the comparative analysis section.

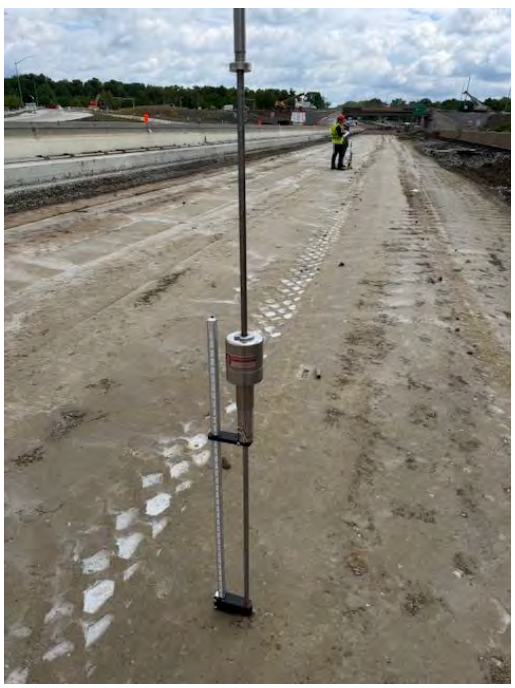
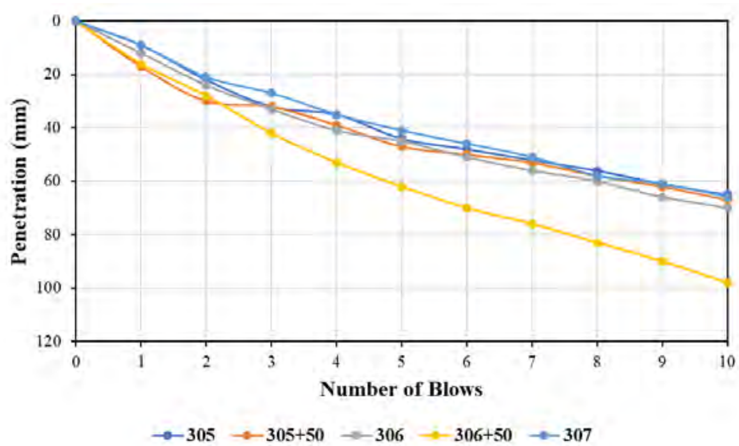


Figure 6: DCP device in use at Testing Site 1.

We calculated the Dynamic Penetration Index (DPI or PI) for each location, defined as the total penetration depth divided by the number of blows.

Penetration results for both sites are shown in Figure 7. The soil-cement layer exhibited more consistent penetration per blow compared to the soil-aggregate layer. This difference may be attributed to the interference of larger aggregate particles, which can disrupt the DCP tip during penetration in granular materials. With the exception of Station 306+50, the soil-cement site showed lower variability in its penetration curves, suggesting a more uniform layer—an observation supported by the consistent compaction levels noted earlier.



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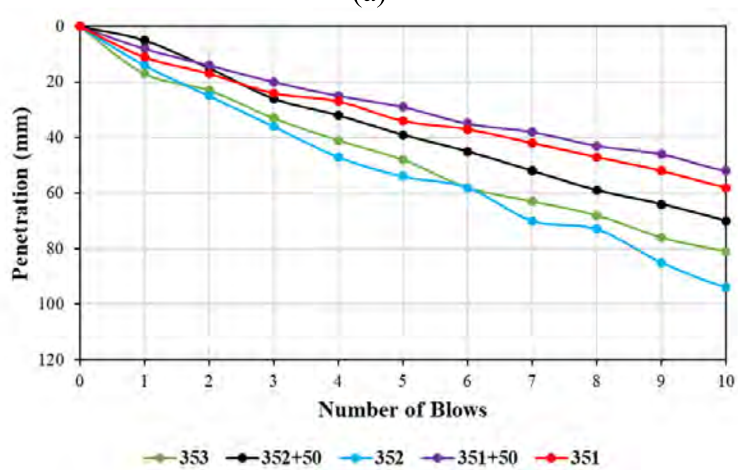


(b)

Figure 7: Penetration for (a) Soil Cement, and (b) Soil Aggregate.

Table 14 summarizes the DPI values for both test sites. Overall, the results fall within acceptable limits based on the specifications reviewed previously. According to MnDOT's more stringent threshold for untreated soils (10 mm/blow), all measurements from Site 2 meet the requirement. Similarly, INDOT specifies a maximum of 20 mm/blow for untreated soils and 10 mm/blow for chemically stabilized soils—criteria that are also satisfied by the soil-cement measurements from Site 1.

Table 14: DPI results for both testing sites

Testing Site 1 - Soil Cement		Testing Site 2 - Soil Aggregate	
Station	DPI (mm/blow)	Station	DPI (mm/blow)
305	6.5	353	8.10
305+50	6.7	352+50	7.00
306	7.0	352	9.40
306+50	9.8	351+50	5.20
307	6.6	351	5.80

3.4 Light Weight Deflectometer (LWD)

The LWD device used was the Zorn Lab-3.0 (Figure 8). This equipment simulates the dynamic loading conditions of a 10-ton axle traveling at 80 km/h by applying a surface pressure of approximately 0.1 MN/m^2 over an 18-millisecond interval (Jardine et al., 2004). The device operates by dropping a weight onto a loading plate, transmitting the load into the ground in a controlled manner to replicate the stress conditions typically experienced by pavement layers under traffic loads.


Figure 8: LWD device on Testing Site 1

Each test cycle consisted of six drops: the first three served as seating drops to ensure proper contact between the loading plate and the surface, while the final three were used to record measurement data.

Tables 15 and 16 present the average deflection and average modulus of elasticity (E) for both sites. The soil cement site exhibited high E values, consistent with expectations for cement-stabilized layers shortly after construction—except for the first measurement. During that test, the operator failed to catch the rebounding weight, causing an unintended second impact on the load cell, likely affecting the result. Despite this anomaly, the soil cement layer still exceeded INDOT's minimum threshold of 100 MPa for chemically stabilized soils. Additionally, it met the deflection criteria set by FDOT and IDOT, remaining below their respective limits of 0.39 mm and 0.27 mm for stabilized layers.

The soil aggregate site also produced consistent results, with an average E of 66 MPa, surpassing MnDOT's minimum requirement of 40 MPa for granular layers. Its average deflections remained within IDOT's allowable limit of 0.65 mm for untreated granular materials.

Table 15: LWD results for Testing Site 1 – Soil Cement

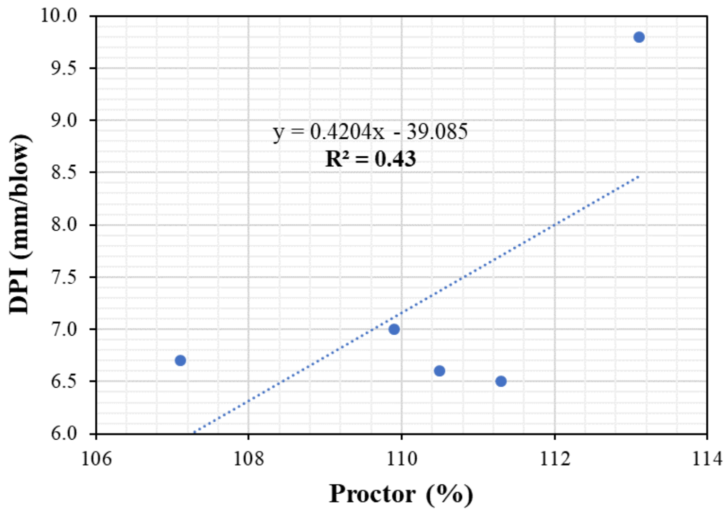
Station	Average Deflection (mm)	Average E (MPa)
305	0.195	115.38
305+50	0.138	163.04
306	0.131	171.76
306+50	0.130	173.08
307	0.129	174.42
307+50	0.109	206.42
308	0.159	141.51
308 R	0.151	149.01

Table 16: LWD results for Testing Site 2 – Soil Aggregate

Station	Average Deflection (mm)	Average E (MPa)
353	0.317	70.98
352+50	0.365	61.64
352	0.354	63.56
351+50	0.348	64.66
351	0.312	72.12
350+50	0.339	66.37
350+50 R	0.374	60.16
350	0.315	71.43
349	0.401	56.11
349 R	0.297	75.76

3.5 Comparative Analysis

Results from the three testing methods were compared to evaluate consistency and correlation. Figure 9 illustrates the relationship between the Dynamic Penetration Index (DPI), derived from DCP penetration data, and compaction levels estimated as a percentage of Proctor maximum density using the Nuclear Gauge. The results indicate a weak correlation between the two measures. Increases in compaction levels, as determined by Proctor percentages, did not correspond to decreased penetration (i.e., increased resistance), suggesting that higher compaction did not necessarily result in a stiffer or more resistant layer.



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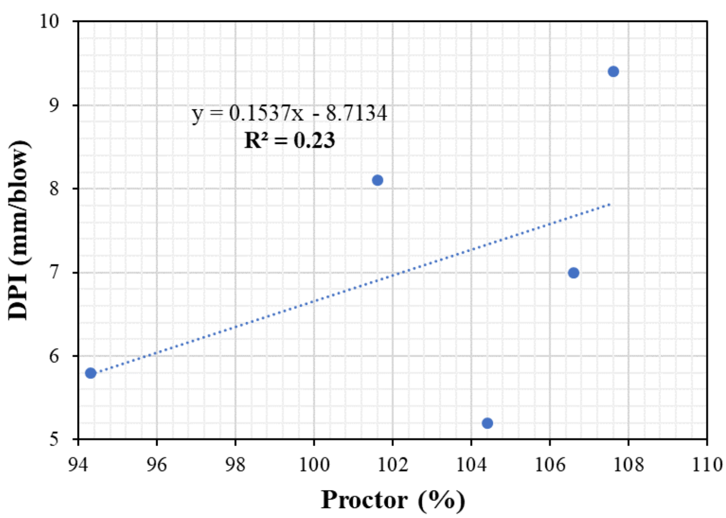
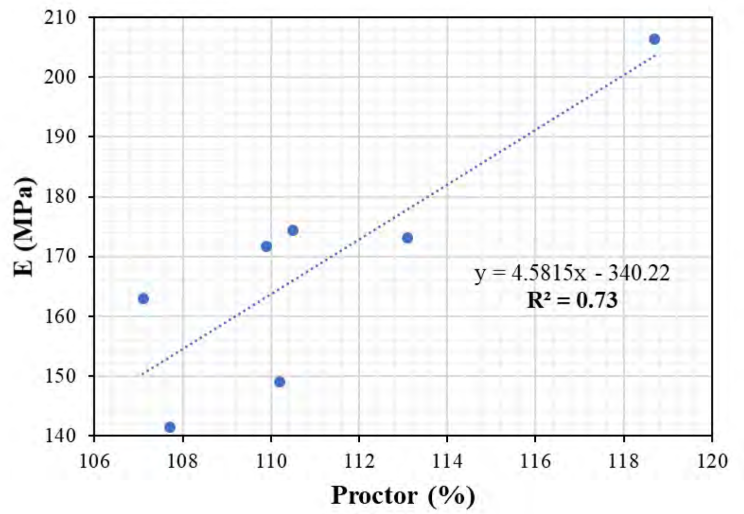


(b)

Figure 9: Nuclear Gauge (Proctor) vs. DCP (DPI) for (a) Testing Site 1 (Soil Cement), and (b) Testing Site 2 (Soil Aggregate)

Figure 10 presents the modulus of elasticity (E), as measured by the LWD device, plotted against compaction levels expressed as a percentage of Proctor maximum density. For the soil cement layer, a moderately strong correlation is observed ($R^2 = 0.73$), indicating that increased compaction is associated with higher stiffness. This relationship supports the expected behavior of a uniformly stabilized layer. However, the soil aggregate layer does not exhibit a similar trend. This disparity may be attributed to the greater heterogeneity of the aggregate layer compared to the more uniform soil cement. Additionally, the Nuclear Gauge is known to be less reliable when testing coarse-grained materials, as large aggregate particles can interfere with accurate compaction readings.

Figure 11 illustrates the relationship between DCP and LWD test results. No clear correlation was observed between the two methods. In particular, higher stiffness values obtained from the LWD did not consistently correspond to lower penetration depths measured by the DCP. This suggests that the two testing approaches may be capturing different aspects of material behavior or are affected differently by factors such as aggregate size, moisture content, or heterogeneity within the layer.



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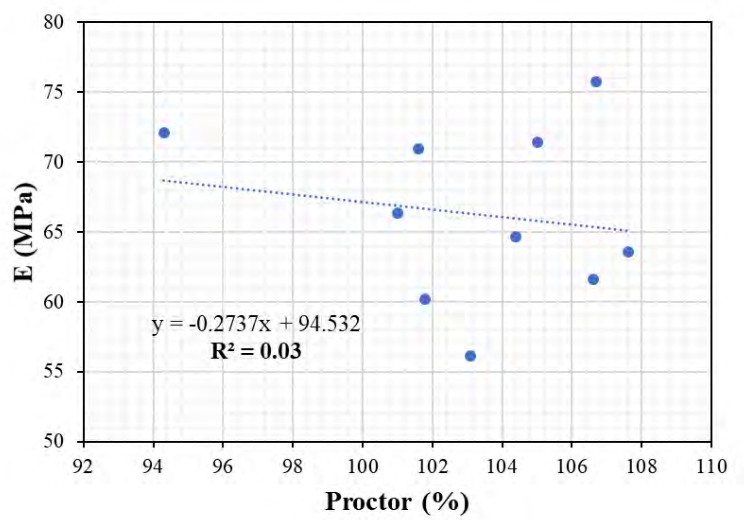

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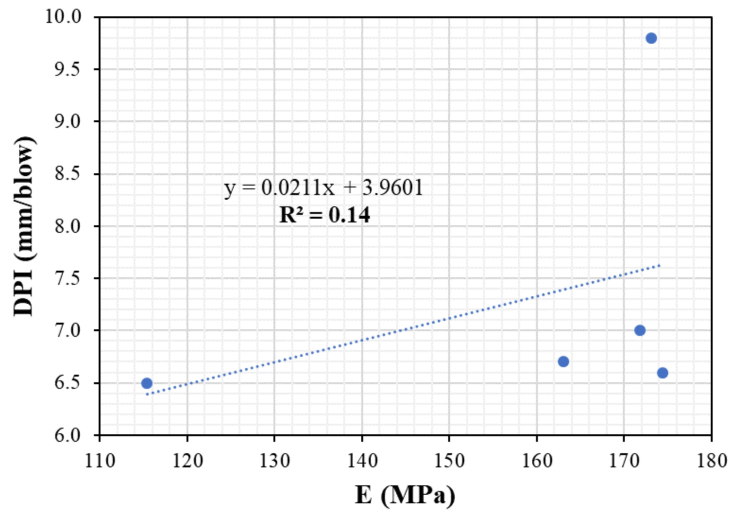
Figure 10: Nuclear Gauge (Proctor) vs. LWD (E) for (a) Testing Site 1 (Soil Cement), and (b) Testing Site 2 (Soil Aggregate)



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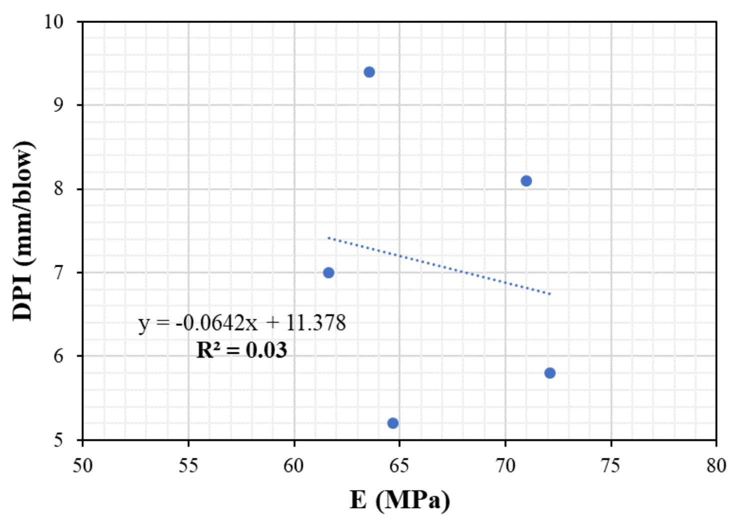

(b)

Figure 11: DCP (DPI)) vs. LWD (E) for (a) Testing Site 1 (Soil Cement), and (b) Testing Site 2 (Soil Aggregate)

3.5.1 Test time

Pre-Measurement Preparation: The Nuclear Gauge requires Proctor test results for the specific layer before measurements can begin, whereas the LWD and DCP are ready for immediate use without prior inputs.

Measurement Duration and Operation: Taking a measurement with the Nuclear Gauge typically takes about 10 seconds. The results are displayed instantly on the device's screen (Figure 12), and the device records the data automatically. A single operator can easily manage the measurements.

Figure 12: Results displayed on the Nuclear Gauge screen

The LWD test involves six drops per measurement cycle—three initial "seating" drops to stabilize the plate on the surface, followed by three drops to record deflection data. The average deflection and modulus of elasticity (E) are shown on the device screen (Figure 13). Each complete test takes less than one minute, and results are stored on a memory card.

Figure 13: Results displayed on the LWD device screen

The DCP test was the most time-consuming. Even with a limited 10-blow test, each measurement required approximately 3 to 5 minutes. Due to increasing rain and time constraints, only five DCP measurements were performed for comparative purposes alongside the Nuclear Gauge and LWD tests. It's important to note that one DCP measurement takes roughly the same amount of time as five combined LWD or Nuclear Gauge measurements. Additionally, DCP results must be recorded manually, adding to the effort.

3.5.2 Test Effort

Equipment Mobility and Setup: The Nuclear Gauge was the easiest to transport, featuring a single-piece design with a convenient carrying handle. The LWD consists of three separate components that need to be moved individually. The DCP was the most cumbersome to move, as it involves multiple parts that must be assembled on-site before testing.

Positioning and Setup at the Testing Site: Positioning the Nuclear Gauge and LWD was straightforward, as both devices rest directly on the surface of the test layer. In contrast, the DCP requires careful adjustment of the tip before it can be inserted into the soil layer, as shown in Figure 14.


Figure 14: Inserting the DCP device in the layer.

Operator Requirements: The Nuclear Gauge can be operated comfortably by a single person. While the LWD can also be operated solo, it is more efficient with two operators—one to perform the weight drops and another to control the device and record data, as illustrated in Figure 15.


Figure 15: Operation of LWD device

The DCP can be operated by one person, but it demands significant physical strength and coordination. Having two operators is preferable for efficiency and safety. The operator must lift and drop the weight manually for every blow, which is labor-intensive and can lead to arm fatigue or muscle strain after extended use.

3.5.3 Test Reliability

The Nuclear Gauge requires Proctor test results for the specific layer before measurements can begin. Incorrect Proctor inputs or errors during Proctor testing may lead to inaccurate compaction measurements. In contrast, the LWD and DCP devices require no prior inputs, reducing the risk of such pre-test errors.

No significant operational errors were observed when using the Nuclear Gauge. For the LWD, small risks exist related to operator technique during the weight drops. For example, if the operator does not lift the load fully before dropping or accidentally strikes the load on its upward motion, measurement errors can occur. Additionally, failing to catch the load as it bounces back can produce faulty results.

The DCP is more susceptible to errors at various stages of testing. During device assembly, inconsistent pressure applied during the first blow may introduce inaccuracies. Since each blow depends heavily on the operator's strength and fatigue level, variability is likely. Furthermore, the operator must manually read the penetration depth on a ruler with small markings and closely spaced lines, making it difficult to record precise measurements, especially in noisy and high-traffic environments (see Figure 14). This can lead to erroneous data recording for each blow.

In addition, the DCP testing leaves a small hole on the pavement surface (Figure 16), which was filled with loose material after completing the test.

Figure 16: Hole left from DCP testing

3.5.4 Summary of comparative testing

Table 17 compiles the performance of each device across several key indicators, including accuracy, efficiency, safety, and suitability for various soil conditions. The results are color-coded to provide a quick visual assessment: green indicates good performance, or a superior result compared to the other technologies; yellow signifies average performance; and red denotes inadequate or poor performance on a given metric.

From the comparative table, it is clear that the DCP performed the least effectively, particularly with respect to device operation, test time and effort, and the reliable recording of data. While the nuclear gauge demonstrated many benefits and strengths, its reliance on accurate Proctor test results significantly limits its practicality for testing non-uniform soils, such as those found in embankments. This analysis highlights the distinct strengths and weaknesses of each tool, forming the basis for the recommendations for implementing LWD technology.

Table 17: Compiled comparative analysis of the three devices

Aspect	Device		
	Nuclear Gauge	**DCP**	**LWD**
Pre-Measurement Information	Requires Proctor Test Results	Ready for Use	Ready for Use
Moving Equipment to test site	Medium weight, self-contained device	Medium weight, multiple-piece device	Medium weight, three-piece device
Setting Equipment Up	Ready for Use	Somewhat difficult assembly	Easy assembly
Position of Device	Directly on surface	Careful adjustment of tip on soil	Directly on surface
Measurement Duration	10 seconds	3 to 5 min	< 1 min
Results	Percentage compaction, density, moisture content	Penetration per blow after some calculations	Average deflection and average modulus of elasticity
Results Recording	Data on display / memory drive	Data must be recorded manually	Data on display / memory drive
Number of crew	Easily 1 person	Difficult operation with a single person. Most likely needs 2	Can be done by 1 person, more efficient with 2
Physical Effort	None (lowering to press a button)	Intense (sequential lift and drop of the weight)	Light (drop and catch of the weight as it bounces back)
Reliability Operation	Accurate Proctor Results*	Very dependent on operator. Pressure on first blow, and constant pressure on remaining blows	Small change of error if operator fails to catch weight as it bounces back
Reliability Recording	None	High change of error due to reading on a small scale and writing on a record sheet with intense noise from traffic	None
Damage to layer	None	Small hole	None

*If Proctor results are inaccurate or not representative of the entire section, the reliability of Nuclear Gauge results is compromised.

Note: A green designation indicates a superior performance metric or a more favorable outcome relative to the other technologies. A yellow designation represents an average or comparable performance. A red designation signifies a substandard or inadequate performance on the specified metric.

4. RECOMMENDATIONS FOR IMPLEMENTATION

Based on the review of other state specifications and the comparative field testing, we recommend the implementation of the Light Weight Deflectometer (LWD) as a complementary tool to the nuclear moisture and density gauge, which is currently specified by PennDOT. The nuclear gauge, while effective, requires a laboratory-established moisture-density (M-D) relationship from a Proctor test to calculate dry density. The LWD, on the other hand, is a modulus-based device that provides a direct measure of soil stiffness, which is more indicative of structural performance. In addition, the LWD can be used to directly evaluate the uniformity of support of compacted layers. We propose a dual-approach for its integration into current specifications:

- **Complementary Use:** For sites where a consistent soil type allows for reliable Proctor testing, the LWD can be used in tandem with the nuclear gauge. This would allow PennDOT to leverage the efficiency and safety of the nuclear gauge for density measurements while also gathering performance-based stiffness data from the LWD. This combined approach aligns with the practices of states like MnDOT, which incorporate a combination of density, DCP, and LWD test results.
- **Standalone Use:** For projects involving highly variable materials, such as embankments or non-uniform subgrades, where establishing a single, representative Proctor curve is impractical, the LWD can be used as a standalone device for quality control and evaluation of support uniformity. In these cases, the LWD's ability to measure stiffness directly, without relying on Proctor data, provides a robust and efficient method for evaluating compaction quality. This approach is supported by the findings of the comparative testing, where the LWD successfully provided consistent modulus readings on both soil-cement and soil-aggregate subgrades, meeting the minimum requirements of other states like INDOT and MnDOT.

4.1 Suggested Next Steps

Building upon the comparative field testing and the proposed implementation strategy, the following next steps are recommended to further validate and refine the use of the LWD within PennDOT's specifications:

- Further LWD Testing in Diverse Conditions: Conduct additional LWD testing on a wider range of challenging sites. Specifically, focus on embankments and non-uniform soil subgrades where traditional methods struggle to provide consistent, reliable data. This will provide a larger dataset to inform the development of LWD-specific acceptance criteria for these variable materials.
- Establish Minimum Elasticity Modulus Values: Based on the results of the expanded field testing, determine and propose appropriate minimum elasticity modulus (E) values for LWD acceptance. The values should be correlated to the performance requirements of different soil types and project applications. The values established by other state DOTs (such as MnDOT's 40 MPa for soil aggregate or INDOT's 100 MPa for stabilized subgrades) can serve as a valuable starting point.
- Develop a Calibration Protocol: Given that LWD results can be influenced by device-specific factors, it is crucial to develop a standardized calibration protocol. This protocol should be used to ensure consistency across different LWD devices and testing sites. The approach taken by MnDOT, which uses a calibration area to determine target LWD values, could be a useful model.
- Develop Training and Certification Program: To ensure the proper and consistent use of LWD technology, a training and certification program for inspectors and contractors should be developed. This program would cover the principles of LWD testing, proper device operation, data interpretation, and the new acceptance criteria. This is particularly important since, unlike nuclear gauges, the LWD does not require radiation safety certification, making it a more accessible tool for a broader range of personnel.

5. CONCLUSION

The research on construction quality assurance for pavement layers indicates a definitive and widespread shift away from traditional density- and moisture-only compaction requirements towards more reliable, performance-based acceptance criteria. A review of national specifications and a comparative field assessment of various testing devices have highlighted the unique strengths of the Lightweight Deflectometer (LWD) in this new framework. States like MnDOT, INDOT, FDOT, and NDOT are leading this transition, widely recognizing the LWD for providing quick, representative assessments of construction quality.

The comparative assessment of the Nuclear Gauge, Dynamic Cone Penetrometer (DCP), and LWD highlighted the distinct strengths and weaknesses of each method. The Nuclear Gauge, while quick to deploy, is limited by its reliance on a laboratory-established moisture-density relationship and struggles with coarse-grained materials. The DCP, while providing valuable information on penetration resistance for assessing relative strength, was found to be more labor-intensive, time-consuming, and susceptible to operator-related variability. Furthermore, the DCP's penetration results did not correlate clearly with the stiffness values provided by the LWD, suggesting the devices reflect different soil properties.

In contrast, the LWD emerged as the most valuable tool for evaluating structural performance. This study found that the LWD could distinctly differentiate between different materials, such as soil-cement and soil-aggregate, and that its stiffness measurements were more indicative of a compacted layer's structural integrity than the density values provided by a Nuclear Gauge. This ability to directly measure a fundamental performance property of the soil, independent of a Proctor curve, makes it a robust and efficient method for evaluating compaction quality, especially for projects with highly variable or non-uniform materials.

Ultimately, the research concludes that a quality assurance framework that incorporates LWD testing provides a balanced and reliable approach to evaluating construction quality. This integrated methodology not only enhances operational efficiency and minimizes subjective judgment during inspection but also ensures that the as-built conditions of embankments and subgrades are more closely aligned with pavement design assumptions, ultimately improving the long-term performance of infrastructure.

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APPENDIX A

Tables A.1, A.2 and A.3 present the results from Dynamic Cone Penetrometer (DCP) and Light Weight Deflectometer (LWD) testing, respectively. These tables also include correlations with California Bearing Ratio (CBR) values. It's important to note that these correlations are based on empirical models from existing literature, and since a primary objective of this project was not to validate these models, the results should be interpreted with caution.

Correlations used to estimate CBR values from other tests are often imprecise due to the highly variable nature of soil. The relationship between a penetration or deflection measurement and a soil's bearing capacity is complex and influenced by several factors, including:

- Soil Type and Gradation: The composition of the soil (e.g., clay vs. sand, fine vs. coarse particles) significantly affects its strength characteristics. Different models are required for different soil types.
- Moisture Content and Compaction: The moisture content and level of compaction at the time of testing can drastically alter the soil's strength and, therefore, the accuracy of any correlation.
- Stress Conditions: CBR is a measure of a soil's resistance under a specific loading condition. Other tests, like DCP and LWD, measure a soil's response under different stress states, which can lead to discrepancies in the correlations.

A more in-depth analysis of the soil's composition—including its grain size distribution, plasticity, and density—can help select or develop a more appropriate and accurate correlation model for CBR, improving the reliability of the estimated values.

Table A.1: DPI results for both testing sites

Testing Site 1 - Soil Cement			Testing Site 2 - Soil Aggregate		
Station	DPI (mm/blow)	CBR (%)*	Station	DPI (mm/blow)	CBR (%)*
305	6.5	36	353	8.10	28
305+50	6.7	35	352+50	7.00	33
306	7.0	33	352	9.40	23.7
306+50	9.8	23	351+50	5.20	46.1
307	6.6	25	351	5.80	40.8

*CBR values were estimated using the US Army Corps of Engineers model CBR = $292/DCP^{1.12}$.

Table A.2: LWD results for Testing Site 1 – Soil Cement

Station	Average Deflection (mm)	Average E (MPa)	CBR (%)**
305	0.195	115.38	19
305+50	0.138	163.04	32
306	0.131	171.76	35
306+50	0.130	173.08	36
307	0.129	174.42	36
307+50	0.109	206.42	47
308	0.159	141.51	26
308 R	0.151	149.01	28

Table A.3: LWD results for Testing Site 2 – Soil Aggregate

Station	Average Deflection (mm)	Average E (MPa)	CBR (%)**
353	0.317	70.98	9
352+50	0.365	61.64	7
352	0.354	63.56	7
351+50	0.348	64.66	8
351	0.312	72.12	9
350+50	0.339	66.37	8
350+50 R	0.374	60.16	7
350	0.315	71.43	9
349	0.401	56.11	6
349 R	0.297	75.76	10

** CBR values were estimated using the Powell et al. (1984) model $E = 17.6 \times CBR^{0.64}$ (MPa).

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