FHWA-NJ-2016-003

Alternatives to Nuclear Density Testing

FINAL REPORT
March 31, 2016

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In cooperation with

New Jersey
Department of Transportation
Bureau of Research
And
U. S. Department of Transportation
Federal Highway Administration

DISCLAIMER STATEMENT

TECHNICAL REPORT
STANDARD TITLE PAGE

1. Report No. FHWA-NJ-2016-003	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Alternatives to Nuclear Density Testing		5. Report Date **March 31, 2016**
		6. Performing Organization Code
7. Author(s) Mehta, Yusuf, Ph.D., P.E. and Ali, Ayman, Ph.D.		8. Performing Organization Report No.
9. Performing Organization Name and Address Rowan University College of Engineering Glassboro, NJ 08028		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address New Jersey Department of Transportation PO 600, Trenton, NJ 08625	Federal Highway Administration U.S. Department of Transportation Washington, D.C.	13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract
The performance of pavements is highly dependent on compaction quality control of unbound subgrade and base/subbase layers. Distresses in pavements can be directly linked to compaction defects within these layers. In current practice, the nuclear density gauge (NDG) is utilized for evaluating the compaction quality of these layers. Highway agencies, such as the New Jersey Department of Transportation (NJDOT), employ minimum density requirements, typically 95% of the Proctor maximum dry density (MDD), for evaluating the compaction quality of these layers. However, there are several concerns and safety risks associated with using the NDG. This study was initiated with the aim of replacing the NDG with non-nuclear alternative method(s) that can be used as acceptance tools during the compaction of unbound base/subbase layers. To achieve this goal, a laboratory procedure for compacting large samples was developed to facilitate testing using three non-nuclear devices: Briaud compaction device (BCD), light weight falling deflectometer (LWD), and dynamic cone penetrometer (DCP) on four types of aggregates, two subgrade soils, one dense graded aggregate (DGA), and one recycled concrete aggregate (RCA). Each device was evaluated for its sensitivity to moisture content, compaction effort applied, aggregate type, and testing time. Based on laboratory testing, a multiple linear regression model to predict DCP field measurements was developed. The model was then calibrated using field data. Using the calibrated model, minimum recommended DCP values that would ensure satisfactory compaction of pavement layers in the field were determined. A draft specification for use of the DCP was also developed within this report. Based on testing results and analyses conducted subsequently, the following conclusions were made:

- The DCP was the most suitable device for capturing the change in moisture contents within the samples while all other devices showed mixed trends within their results, specifically when preparing samples at 2% below and 2% above OMC.
- The DCP prediction model was found to be adequate at predicting laboratory and field DCP measurements. The model was also found to be significantly dependent on moisture content and material properties (i.e., %passing sieve No. 4 and sieve No. 200).
- The DCP prediction model was used successfully for identifying a set of recommended DCP penetration rates that would ensure satisfactory compaction of unbound pavement layers in the field.
- A specifications for using the DCP as a compaction acceptance tool for natural soils and engineered aggregates was successfully developed.

17. Key Words: MSCR, binder specification, elastic recovery	18. Distribution Statement		
19. Security Classif (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 107	22. Price

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENT

The authors would like to acknowledge the New Jersey Department of Transportation and the Federal Highway Administration for funding the study presented in this report. Their support is greatly appreciated. The comments received from Ms. Eileen Sheehy, Dr. Giri Venkiteela, and other members of the NJDOT bureau of research and project panel, throughout the course of this study, are highly appreciated. Their input made this study much more valuable.

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EXECUTIVE SUMMARY

Naturally existing soils and quarry-produced aggregates play a crucial role in highway infrastructure. These materials are typically used to construct base or subbase layers in rigid and flexible pavements. During the construction of these pavements, it is essential to properly compact base/subbase and subgrade materials to suitable density levels. This is primarily because the performance of rigid or flexible pavements is highly dependent on the quality of the compacted subgrade and unbound base/subbase layers. In other words, any compaction defects in these layers typically result in distresses in the upper hot mix asphalt (HMA) or Portland cement concrete (PCC) layers. In practice, highway agencies employ specifications that rely on selecting a specific aggregate type and a minimum density level (e.g., 95% of the Proctor maximum dry density). The density requirement is determined using the nuclear density gauge (NDG), which is currently considered the primary tool for assessing the quality of compacted base/subbase and subgrade layers. As an example, the New Jersey Department of Transportation (NJDOT) currently uses the NDG for assessing the compaction quality of Embankments, Aggregate and Base Courses, and Foundation/Backfill of Structures. The popularity of the NDG is mainly due to its portability, ease of use, accuracy, and timely results.

Despite the popularity and advantages of the NDG, there are several concerns and safety risks associated with using this device. Strict regulations for using the NDG require specific transportation and storage methods/procedures only appropriate for nuclear devices. These regulations also require having trained licensed personnel to operate the NDG, making the NDG onerous and expensive. In addition, when using the NDG, the operator may be exposed to harmful radiation; thus, the NDG can pose a safety risk. Furthermore, the NDG only measures a density value as opposed to a modulus or design-specific value. From a design perspective, the engineer uses an assumed modulus value for designing pavement structures, while in the field compaction quality is controlled using a density value. This results in a gap between the mechanistic-empirical pavement design stage and the quality control stage during the construction of pavement structures. Therefore, it is highly desirable to evaluate other methods/devices that can replace the NDG and provide design engineers with design-specific measurements that can help in avoiding over/under designed pavements.

This study was initiated with the goal of identifying alternative methods/technologies to nuclear density gauges for use in the acceptance of compacted soil aggregates and quarry processed aggregates pavement layer in the State of New Jersey. To fulfill this objective, the study was divided into two main phases. Phase I (Determine State of Practice) focused on documenting the current state of practice through conducting a comprehensive literature review pertaining to available non-nuclear devices/methods and a sending out a survey to State DOTs, device manufacturers and industry professionals. Three devices were selected based on the outcomes of Phase I; the Dynamic Cone Penetrometer (DCP), the Light Weight Falling Deflectometer (LWD), and the Briaud compaction device (BCD). In Phase II (Lab and Field Evaluation), a procedure for compacting samples in the laboratory was developed to facilitate testing using the selected devices and the NDG. Using this procedure, samples were compacted in the laboratory to evaluate the impact of aggregate moisture content, compaction effort, and delayed testing on results obtained from the selected devices.

Thus, formulating the basis for comparing and determining the most suitable alternative non-nuclear device/method. Based on the laboratory testing results it was determined that the most suitable device for replacing the NDG was the DCP.

In order to facilitate the use of the DCP for evaluating the quality of compacted unbound base/subbase and subgrade pavement layers, specifications were needed and developed as a part of this study. The first step in preparing these specifications was to develop a linear regression model for predicting the DCP values and defining a set of acceptable DCP values that can be used in the field. Therefore, a multiple-factor linear regression analysis was conducted to develop the DCP prediction model. In this analysis, several factors were considered including: aggregate moisture content and aggregate gradation parameters (i.e., % passing sieves No. 4 and No. 200) and was conducted using 60% of the laboratory results. The remaining 40% were used to validate the ability of the developed model at predicting the DCP results. The validated model was then calibrated using field testing results collected from three constructions locations (two locations on Route 35 restoration project and one on I-295 I-76 interchange). This calibration procedure was necessary because major differences exist between the controlled laboratory environment and the more variable field environment. For example, the moisture content in the field might not be as uniform as that controlled in the laboratory.

The second step in preparing the DCP specifications involved using the calibrated DCP prediction model in determining a set of minimum acceptable DCP values for use in accepting compacted unbound pavement layers. The procedure for determining the recommended DCP minimum values accounted for the variability in the aggregate moisture content, percent passing No. 4, and percent passing No. 200. The consideration of the variability in these factors was necessary for balancing the risk between NJDOT and contractors and ultimately for recommending practical DCP values. These acceptance values along with the DCP prediction model were then utilized to develop a framework (or specifications) for using the DCP a compaction quality acceptance tool.

Based on the laboratory and field testing results and the subsequent analyses, the following conclusions were drawn:

- The laboratory procedure developed for compacting large samples was found to be satisfactory. The actual moisture contents and densities were within ± 0.5% and ±5 lbs./ft^3 of their targeted values, respectively.
- Based on the comparison of the standard error of the mean results, variability was similar for all non-nuclear devices. In addition, DCP showed higher variability when the soils had higher moisture content than the OMC.
- All of the selected devices were able to distinguish between the four aggregate types.
- The moisture content within the compacted samples (up to ± 2% of OMC) was sensitive to parameters measured from all devices evaluated. The DCP was the most suitable device for capturing the change in moisture contents within the samples while all other devices showed mixed trends within their results, specifically when preparing samples at 2% below and 2% above OMC.
- The DCP prediction model developed was found to be adequate at predicting laboratory and field DCP measurements. The model was also found to be

significantly dependent on moisture content, percent passing sieve No. 4, and percent passing sieve No. 200.

- The DCP prediction model, which was developed and calibrated as a part of this study, was used successfully for identifying a set of recommended DCP penetration rates that would ensure satisfactory compaction of unbound pavement layers in the field.
- A specifications for using the DCP as a compaction acceptance tool for natural soils and engineered aggregates was successfully developed.

INTRODUCTION

Background

Naturally existing soils and quarry-produced aggregates play a crucial role in highway infrastructure. These materials are typically used to construct base or subbase layers in rigid and flexible pavements. During the construction of these pavements, it is essential to properly compact base/subbase and subgrade materials to suitable density levels. This is primarily because the performance of rigid or flexible pavements is highly dependent on the quality of the compacted subgrade and unbound base/subbase layers. In other words, any compaction defects in these layers typically result in distresses in the upper hot mix asphalt (HMA) or Portland cement concrete (PCC) layers.

In practice, highway agencies employ specifications that rely on selecting a specific aggregate type and a minimum density level (e.g., 95% of the Proctor maximum dry density). The density requirement is determined using the nuclear density gauge (NDG), which is currently considered the primary tool for assessing the quality of compacted base/subbase and subgrade layers. As an example, the New Jersey Department of Transportation (NJDOT) currently uses the NDG for assessing the compaction quality of Embankments, Aggregate and Base Courses, and Foundation/Backfill of Structures [1]. The popularity of the NDG is mainly due to its portability, ease of use, accuracy, and timely results.

Despite the popularity and advantages of the NDG, there are several concerns and safety risks associated with using this device. Strict regulations for using the NDG require specific transportation and storage methods/procedures only appropriate for nuclear devices. These regulations also require having trained licensed personnel to operate the NDG, making the NDG onerous and expensive. In addition, when using the NDG, the operator may be exposed to harmful radiation; thus, the NDG can pose a safety risk. Furthermore, the NDG only measures a density value as opposed to a modulus or design-specific value. From a design perspective, the engineer uses an assumed modulus value for designing pavement structures, while in the field compaction quality is controlled using a density value. This results in a gap between the mechanistic-empirical pavement design stage and the quality control stage during the construction of pavement structures. Therefore, it is highly desirable to evaluate other methods/devices that can replace the NDG and provide design engineers with design-specific measurements that can help in avoiding over/under designed pavements.

Objectives

The overall goal of this study is to evaluate alternative non-nuclear methods for use during the acceptance of soil and quarry produced aggregate compaction. The specific objectives to achieve this goal include:

- Determining the current state-of-practice as related to using alternative non-nuclear methods for assessing the quality of compacted soil and subbase/base pavement layers.
- Selecting and evaluating the accuracy of the non-nuclear density/strength/moisture-based testing device or procedures.
- Developing a laboratory procedure for compacting large soil/aggregate samples.
- Conducting field evaluations of the proposed technology(s).

- Conducting a cost analysis comparison between the selected non-nuclear device/method and the NDG.
- Developing a draft specification for the most promising alternative device/method.
- Providing recommendations to NJDOT.

Report Organization

This report is organized into nine chapters. In Chapter one, the problem statement, objectives, and outline of the report are presented. Chapter two presents a comprehensive literature review summarizing the current state of practice for compaction quality control of unbound pavement layers. Chapter three describes the basis for selecting alternative devices/methods to be considered as a part of this study. Chapter four provides a discussion related to the materials selected and their characteristics as determined using a basic sieve analysis and the modified Proctor test. In Chapter five, a detailed discussion of the research approach and methodology is presented. Chapter six discusses the results obtained from laboratory testing including an analysis of the sensitivity of selected alternative devices/methods to varying moisture contents and compaction efforts applied to the samples as well as different aggregate types and delayed testing. In chapter seven, the development and calibration of a multiple linear regression model is discussed. This chapter also includes a discussion of the recommended minimum acceptance criteria. Chapter eight discusses the proposed draft specifications and Chapter nine presents the conclusions and recommendations made.

LITERATURE REVIEW

Introduction

This chapter includes a comprehensive discussion of previous studies conducted on modulus-based devices/methods as tools for evaluating unbound subgrade and base/subbase pavement layers. The reviewed studies focus on the compaction of large samples as well as the effects of different measured parameters on results obtained from modulus-based devices/methods. Correlations between representative laboratory and field moduli are also presented as a part of this chapter.

Modulus-Based Methods used in Compaction Quality Control

Researchers have conducted studies to evaluate the potential of using modulus-based devices/methods as tools for quantifying the quality of compacted unbound subgrade and base/subbase pavement layers. In a study done by Lenke et al. [2], for example, the GeoGauge, which is a modulus measuring device, was evaluated as a potential alternative to the Nuclear Density Gauge (NDG). Laboratory tests were conducted on different dry sand and cohesive soil materials to determine if GeoGauge measurements were consistent with theoretical and empirical soil mechanics concepts. Based on the results of this study, Lenke et al. [2] reported that the GeoGauge could successfully measure moduli of compacted unbound pavement layers. The researchers also reported that the GeoGauge is problematic when used to obtain targeted stiffness values in the laboratory. Ultimately, these problems were attributed to the dynamic nature of the measurements obtained, and the associated constraints of the device. Lenke et al. [2] also reported that any future specifications developed for the GeoGauge might require specific field moisture control.

Alshibli et al. [3] conducted a study to evaluate various non-nuclear density devices and their potential for use in accepting compacted subgrade and/or base/subbase pavement layers. In their study, the researchers evaluated the GeoGauge, the Light Weight Deflectometer (LWD), the Dynamic Cone Penetrometer (DCP), and the static plate load test. These devices were used to conduct testing on laboratory compacted samples prepared using silty clay, clayey silt, cement-treated clay, sand, gravel, recycled asphalt pavement, and limestone aggregates. Based on testing results, it was reported that both the GeoGauge and LWD could be used to determine the laboratory elastic modulus of these compacted layers.

Studies conducted by Weidinger et al. [4] evaluated the use of the Briaud compaction device (BCD) as a field compaction quality control device for compacted soil. In this study, a series of laboratory tests were conducted using the BCD on compacted silt materials. In addition to the BCD tests, ultrasonic pulse velocity tests were performed on the same compacted silt samples to obtain the elastic moduli (Young's and shear moduli) of the material. It should be noted that repeated BCD testing was performed to determine the device's ability to replicate results on the samples. The modulus values obtained from the BCD were then compared to the results of the ultrasonic pulse velocity tests. Based on the results of this study, Weidinger et al. [4] concluded that the BCD modulus correlated well to ultrasonic pulse velocity results with a coefficient of determination (R-squared) of 0.8 or better. In addition, the BCD showed a variation of 4% of the mean; proving the device could accurately measure the modulus of compacted soil samples.

In a study done by Chen et al. [5] the DCP was assessed for its ability to evaluate base and subgrade layers. In this study, over 60 DCP tests were conducted on two test pavements. Results of these tests were used to validate the pre-established empirical equations for computing moduli from data obtained using the DCP. Chen et al. [5] also evaluated the effect of the test procedure on the DCP results. These results were correlated to results obtained using the multidepth deflectometer (MDD), falling weight deflectometer (FWD), and laboratory results. From this study, it was concluded that DCP values were dependent on the test procedure, inevitably affecting the results by approximately 10%. The subgrade moduli determined in the laboratory were only slightly higher than results from the DCP and FWD-MDD tests. In addition, the modulus results from the DCP and empirical equations were comparable to FWD and MDD modulus results. Overall, the results of this study confirmed that the DCP could be utilized to evaluate the compaction quality of subgrade and base/subbase layers.

Compaction of Large Aggregate Samples for Modulus-Based Laboratory Testing

As a means for evaluating different modulus-based devices/methods, researchers have utilized laboratory compacted aggregate samples in their studies. The laboratory prepared samples allowed researchers to simulate different field unbound subgrade and base/subbase layers in which these modulus-based devices/methods would be used to test. In addition, the compacted samples allowed researchers to study the effects of different measured parameters on these modulus-based devices/methods, to be discussed in the following section.

As mentioned in the previous section, Alshibli et al. [3] conducted studies to evaluate the GeoGauge and LWD as Qc-Qa devices for testing subgrades, base courses, and compacted soil layers. In this study, testing was conducted at the Louisiana Transportation Research Center (LTRC) laboratory. The compacted aggregate samples utilized were prepared in two identical boxes measuring 60-inches (152.4-cm) in length, 36-inches (91.4-cm) wide, and 36-inches (91.4-cm) deep. At the bottom of each prepared sample was an 8-inch (20.3-cm) thick clay layer, compacted at optimum moisture content (OMC) that served as the subgrade layer for the samples. Two additional 8-inch (20.3-cm) thick lifts were then compacted above the clay layer using the desired soil/base material. Each aggregate sample and corresponding base layer was compacted inside the box using a Wacker Packer plate compactor. Both the GeoGauge and LWD were then used to conduct testing on the compacted samples. In addition, testing was also conducted on the samples using the DCP and PLT. Using the laboratory prepared samples, Alshibli et al. [3] concluded that both the GeoGauge and LWD could be used to determine the elastic modulus of the compacted aggregates.

In a study done by Abu-Farsakh et al. [6] a series of laboratory and field tests were conducted to evaluate the use of DCP in the Qc-Qa process during the construction of pavement layers. In this study, laboratory testing was conducted on twenty-three aggregate samples prepared at different moisture contents and compaction levels. Silty clay and clayey silt materials, typically used in the construction of highway embankments, were used to prepare the compacted samples. Additional materials, such as sand, crushed limestone, and reclaimed asphalt pavement (RAP), were also utilized for laboratory testing. Similar to Alshibli et al. [3], the samples were prepared at the LTRC in two boxes measuring 60-inches (152.4-cm) in length, 36-inches (91.4-cm) wide, and 36-inches (91.4-cm) deep. The samples were compacted in two 8-inch (20.3-cm) thick lifts using a small Bosch compactor and a Wacker Packer plate compactor. After each layer was compacted, DCP tests as well as one PLT test was conducted on the sample to determine the elastic modulus of the aggregate layer. Based on the results of this study, Abu-Farsakh et al. [6] concluded that DCP could be used to determine the stiffness and strength of pavement layers if used for Qc-Qa during pavement construction.

Murad et al. [7] conducted laboratory and field testing to evaluate the DCP, LWD, and GeoGauge for use in determining the strength/stiffness of pavement layers and embankments. Similar to both Alshibli et al. [3] and Abu-Farsakh et al. [6], the aggregate samples were prepared at the Geosynthetic Engineering Research Lab (GERL) at the LTRC using two identical boxes measuring 60-inches (152.4-cm) in length, 36-inches (91.4-cm) wide, and 36-inches (91.4-cm) deep. However, unlike Alshibli et al. [3], who compacted samples above a 7.9-inch (20-cm) thick clay layer, the samples in this study were compacted above a 12-inch (30.5-cm) thick clay layer. In addition, all aggregates samples were compacted in two 8-inch (20.3-cm) thick lifts for a total depth of 16-inches (40.6-cm). A small Bosch compactor as well as a Wacker Packer plate compactor was utilized for compaction. Upon completion of compaction a series of DCP, LWD, and GeoGauge tests were conducted on the samples. Standard testing using the PLT and California bearing ratio (CBR) were also conducted on the prepared samples. Based on the results of this study, Murad et al. [7] concluded that the measurements obtained from the DCP, LWD, and GeoGauge correlated well to those obtained from the standard PLT and CBR tests.

Herath et al. [8] also evaluated the use of the DCP for determining the resilient modulus of subgrades soils. In this study, twelve large aggregate samples were prepared using two aggregate types, subjected to different moisture and compaction levels. The samples were compacted in large boxes measuring 59.1-inches (150-cm) in length, 35.4-inches (89.9-cm) wide, and 23.4-inches (59.9-cm) deep. An electric jackhammer was then used to compact the samples in 7.9-inch (20.1-cm) thick lifts and a series of DCP and resilient modulus tests were then conducted on the samples. The results from testing were used to develop two prediction models to determine the resilient moduli of subgrade soils. The laboratory testing results showed that the resilient modulus values measured through both prediction models corresponded well with the resilient modulus values obtained through the resilient modulus tests. Based on the results of this study, Herath et al. [8] concluded that the DCP could successfully determine the resilient moduli of subgrade soils.

Effect of Different Measured Parameters on Modulus-Based Devices/Methods

Researchers have also conducted studies to determine the effect of different measured parameters on modulus-based devices/methods. As mentioned in the previous section, laboratory samples were prepared at varying moisture contents, compaction levels, and aggregate types. These samples allowed researchers to assess the performance of each device/method when exposed to different types of subbase/base layer conditions. In Lenke et al. [2] the GeoGauge was evaluated for compaction quality control during the construction of pavements. Testing using the GeoGauge was conducted on different dry sand and cohesive soil materials to determine the stiffness of each material. The materials utilized in this study composed of dry granular cohesionless silica sands as well as cohesive silty-sand materials. Based on the laboratory testing results, Lenke et al. [2] confirmed that the GeoGauge measured the stiffness of the different aggregate types. In addition, the results obtained from the cohesive soil samples indicated that as moisture content in the sample increased, the stiffness of the soil decreased, thus providing evidence that the GeoGauge is sensitive to changes in moisture content. In addition, Lenke et al. [2] suggested that any specifications developed for the GeoGauge may require specific field moisture control.

In Alshibli et al. [3], laboratory testing was conducted to evaluate the GeoGauge and LWD for use in the Qc-Qa stage during highway construction. As mentioned in the previous sections, testing was performed on laboratory compacted samples prepared in two identical boxes, above an 8-inch (20.3-cm) thick clay layer. The aggregate types utilized in this study included silty clay, clayey silt, cement-treated clay, sand, gravel, RAP, and limestone aggregates. Each aggregate sample and its corresponding base layer was compacted within the boxes and subjected to a series of GeoGauge, LWD, DCP, and PLT tests. Throughout laboratory testing the cement-treated clay samples were studied to determine the strength improvement of the compacted layers with time and the effect of moisture on the GeoGauge and LWD. The results indicated that the GeoGauge and LWD were able to determine an increase in modulus over the course of 11 days for both the 2% and 4% cement-treated clays. However, for the 6% and 8% cemented-treated clays, the GeoGauge indicated a decrease in modulus over time. In addition, the DCP penetration rate for the cement-treated clays decreased with time. Based on the results of this study, Alshibli et al. [3] concluded that the GeoGauge and LWD were sensitive to changes in moisture and testing time, specifically in cement-treated clay materials. The lack of moisture within the materials caused shrinkage cracks at the surface of the samples inevitably affecting the GeoGauge and LWD measurements. In addition, the testing results varied between the different materials, thus proving the devices' sensitivity to changes in aggregate type.

Hossain et al. [9] conducted laboratory and field testing to evaluate the LWD for determining the moduli of existing pavement layers. In this study, LWD as well as GeoGauge and DCP testing was conducted on seven pavement sections in Virginia. These sections included three compacted subgrades layers, one compacted base layer, and three existing gravel roads. In addition, small scale laboratory testing was conducted on two soil types to determine the effect of moisture content and density on the measured soil moduli. Ultimately the testing results obtained from the LWD were compared to those obtained from the GeoGauge and DCP. The testing results in this study indicated that the stiffness modulus increased as the density of the materials increased for both the LWD and GeoGauge measurements. In addition, the highest correlation between density and soil modulus was observed between the LWD and GeoGauge (R^2 = 0.44). However, no clear relationship could be determined between moisture content and soil stiffness for the subgrade, base aggregates, and gravel road materials. Furthermore, no trend could be determined between moisture content and soil stiffness for the LWD or GeoGauge. However, there was a strong influence of moisture (R^2 = 0.97) on the DCP measurements for all materials tested, such that as the moisture content in the material increased the stiffness measurements decreased.

In a study done by Nazzal et al. [10] several different highway sections in Louisiana were used to evaluate the LWD for measuring the modulus of pavement layers and subgrades. In this study, nine test sections were constructed and tested using the LWD in conjunction with the FWD, PLT, and DCP tests. The testing results were then collected and a linear regression analysis was performed to develop models that related FWD moduli to moduli obtained from the FWD, PLT, and DCP penetration rate. The LWD testing results were also used to develop models to predict FWD and PLT measurements. Similar to studies conducted by Alshibli et al. [3] and Murad et al. [7], the testing results in this study indicated the modulus value measured by the LWD increase with time, for cement-treated materials. In addition, Nazzal et al. [10] concluded that the LWD was influenced by the presence of moisture in the materials. The testing results also showed that the LWD modulus increased with the increase in compaction effort. It is worth noting that, Nazzal et al. [10] also suggested that the correlation between LWD elastic moduli and dry unit weight of the material depended on the aggregate material tested.

Petersen et al. [11] evaluate the use of the LWD for measuring the stiffness of subgrade soils. In order to evaluate the LWD in this study, stiffness measurements were recorded at different locations along nine embankment projects. In addition to measuring the stiffness of the soils, density, and moisture measurements were taken at select locations throughout the projects. The data collected during testing was used to develop correlations between resilient moduli and field moisture content and density. Laboratory soil samples were also collected to determine the resilient moduli of the material at varying density and moisture contents. Based on the testing results, Petersen et al. [11] concluded that the effect of compaction effort on the resilient moduli was dependent on the aggregate type and moisture level. Overall results suggested that the modulus of the material increased with an increase in compaction effort. Petersen et al. [11] also concluded that the modulus of soils decreased as the moisture content in the material increased. It is worth noting that similar trends were observed between the different soil types tested.

Correlation between Representative Laboratory and Field Moduli

In addition to the studies conducted to evaluate the effect of different measured parameters on the devices' testing results, studies have also been performed to develop correlations between representative laboratory and field moduli. As an example, Briaud et al. [12] developed correlations between representative laboratory and field moduli using the BCD. In this study, both laboratory and field tests were conducted using the BCD on the same soil samples. Results from field tests were then compared to PLTs and laboratory testing results. In order to determine if the device could accurately capture field modulus values the results were compared to one another. Based on the results of this study, Briaud et al. [12] concluded that the BCD laboratory results could successfully be correlated to field moduli results.

Nazzal et al. [10] conducted field testing on several highway sections to evaluate the use of the LWD in measuring in-situ modulus of pavement layers and subgrades. In this study, nine field sections were constructed and tested using the Prima 100 model-LWD. FWD, PLT, and DCP tests were also utilized in this study to provide reference measurements for comparing the LWD results. The results from field testing helped facilitate the development of a linear regression model to relate LWD stiffness moduli with the moduli obtained from the FWD, PLT, and DCP penetration rate. In addition to this, multiple linear regression analyses were conducted to develop prediction models for the FWD and PLT, based on the LWD elastic moduli and soil properties (i.e., moisture content and void ratio). Nazzal et al. [10] concluded that the LWD could predict FWD, PLT, and DCP values within a certain level of confidence. The developed prediction models were improved when the soil properties were introduced as variables in the equation.

Mohammad et al. [13] also conducted laboratory and field testing to develop models that predict resilient moduli of soils from test results obtained from the DCP, continuous intrusion miniature cone penetrometer (CIMCPT), dynamic deflection determination (Dynaflect), and FWD. The laboratory testing consisted of repeated triaxial resilient modulus tests along with compaction and physical property tests. Field testing was conducted using the DCP while statistical analysis was performed on the collected laboratory and field data. From the laboratory and field results, Mohammad et al. [13] found a correlation between predicted and measured resilient moduli. Similar to Nazzal et al. [10], the prediction model developed was improved when the soil properties (i.e., moisture content and dry unit weight) were introduced into the equation.

In the study done by Herath et al. [8], correlations were developed to predict field moduli values of subgrade soils from test parameters of the DCP. The DCP test parameters utilized included: (1) aggregate type, (2) moisture content, and (3) dry unit weight. In this study, laboratory testing was conducted on twelve large soil samples using two cohesive soil types. Field testing was also performed using the DCP at six different locations within two existing pavements. Using the results from both laboratory and field testing, Herath et al. [8] developed a model to estimate the resilient moduli of subgrade soils. Based on the developed prediction model, Herath et al. [8] concluded that the model could accurately predict data sets. It was also concluded that the DCP was successful in determining the resilient moduli of pavements and subgrade soils.

Salgado et al. [14] developed correlations between DCP test results to different soil properties (i.e., dry density and moisture). Unlike the previously mentioned studies, Salgado et al. [14] did not correlate DCP results to moduli results obtained using an alternative device. Rather, in this study a series of field and laboratory tests were performed using the DCP and nuclear gauge tests. Seven construction sites were selected for field testing. These seven sections included: four clayey sands, two poor graded sands, and well-graded sand composed of clay. Testing was conducted on the same location for both devices to allow Salgado et al. [14] to compare the DCP results to the nuclear tests results. Ultimately, Salgado et al. [14] concluded that the penetration rate of the soil decreased with an increase in dry density. In addition, the penetration rate increased as the moisture content increased. In the case of clayey sands, it was concluded that the aggregate dry density could be used to predict field DCP results. Due to the uncertainty of the DCP tests, Salgado et al. [14] suggested that the DCP be performed for compaction quality control in conjunction with test methods such as the nuclear gauge.

Development of Modulus-Based Construction Specifications

In addition to correlating representative laboratory and field moduli obtained from alternative non-nuclear devices, studies have also been performed to develop modulus-based construction specifications for use of these devices. For example, Petersen et al. [11] evaluated the feasibility of using the LWD for measuring the stiffness of subgrade soils. In this study, testing using the LWD was conducted on nine embankment projects. Stiffness, density, and moisture values were measured from each location to determine the resilient moduli of the soils at different moisture and density levels within the laboratory. Based on the laboratory and field results, a model to predict resilient modulus was developed. Predicted values were then compared to actual LWD results. Petersen et al. [11] concluded that the predicted moduli, as determined from the established model (based on laboratory resilient modulus tests), did not correlate well with the in-situ stiffness measured using the LWD. As a result, a stiffness-based specification for in-situ embankment compaction quality control could not be developed.

In a study conducted by Davich et al. [15] moisture specifications for granular materials were validated for the DCP and LWD. The moisture specifications evaluated were provided by the Minnesota Department of Transportation (MnDOT). In this study, both the DCP and LWD were tested on multiple laboratory samples. The results of laboratory testing concluded that both the DCP and LWD were effective in assessing the compaction quality of the prepared samples. However, suggestions were provided to improve both device specifications. The recommendations provided by Davich et al. [15] included penetrating the sample past the subgrade layer when using the DCP. In addition, it was suggested that a DCP seating requirement was not necessary, and the acceptable amount of moisture during testing on granular subbase should be at a maximum of 10%. For the developed LWD specifications, Davich et al. [15] recommended using a falling mass of 2.2-lbs. (10-kg), a drop height of 19.7-in. (50-cm), and plate diameter of 7.9-in. (20-cm).

Nazarian et al. [16] also developed a modulus-based construction specification for compaction of earthwork and unbound aggregates using the DCP and alternatives devices. In this study, laboratory and field testing was conducted on three fine-grained soils, two sandy materials, and two unbound granular base materials at different target moisture contents and densities. This method was chosen in order to determine the construction parameters of each geomaterial as well as establish relationships between laboratory and field moduli. Both laboratory and field test results were used to calibrate the modulus prediction models developed for the study. Based on the testing results and prediction models developed, a draft specification was proposed. The proposed specification, provided by Nazarian et al. [16], was tested and improved through additional testing on different construction projects.

Wu et al. [17] also developed and implemented a stiffness-based procedure for using the DCP as an acceptance tool for unbound materials. In this study Wu et al. [17] proposed a set of DCP unbound material acceptance criteria and standards for the Ohio Department of Transportation (ODOT). The procedure and acceptance criteria standards were based off of the findings of the Ohio Research Institute for Transportation and the Environment (ORITE) study in which data was collected and analyzed from 10 different road projects. From both studies, it was concluded that the DCP could be a viable alternative to evaluating different subgrade materials. In addition, the ORITE study suggested that adopting the DCP for unbound material acceptance specifications could greatly improve pavement performance. Based on the DCP results, a threshold for unsuitable materials and stiffness parameters for pavement design rehabilitation was also developed.

In addition to developing specifications for using the DCP, a geotechnical guide performance specifications for embankment and pavement construction was provided by White et al. [18]. These performance specifications were developed using various in-situ testing methods including intelligent compaction (IC) technologies. In this study, testing was performed on different test areas composed of silty clay embankment fill, and crushed limestone aggregate, typically used for stabilizing backfill or pavement subbase. Testing was conducted on these areas using nuclear density moisture content tests, PLT, and DCP tests. Following testing, the DCP and PLT results were analyzed and compared to the traditional quality control methods based on nuclear density/moisture testing. The results of testing concluded that the IC technologies results could be successfully correlated to modulus results obtained using the PLT, and DCP. However, it was observed that these devices did not produce accurate results in areas with high moisture content. Based on the findings of this study, White et al. [18] provided several advantages and specifications for using IC technologies in earthwork construction quality control.

Summary of Literature Review

In summary, the majority of studies found throughout literature indicated that alternative non-nuclear devices could effectively evaluate the quality of compacted subgrade and base/subbase layers beneath rigid or flexible pavements. In addition, prediction models and specifications for using these devices have been established in these reports. However, most of the reports mentioned focused exclusively on validating the use of these devices for measuring the modulus of these compacted pavement layers. Validation of these devices included correlating the devices' laboratory and field moduli results to moduli results obtained through standard tests.

In order to determine a non-nuclear alternative to the NDG, it is necessary to correlate laboratory and field moduli results of these devices to laboratory and field density values that are currently obtained using the NDG. The majority of literature did not comprehensively evaluate the effect of aggregate type, moisture content, compaction effort, and delayed testing on the results obtained from these devices. Furthermore, existing specifications established in the reviewed studies concentrated on developing modulus-based specifications but were limited to subgrade aggregates and did not consider materials that are typically used for constructing base/subbase pavement layers.

ALTERNATIVE DEVICES AND TESTING METHODS: BASIS FOR SELECTION

Introduction

The basis for selecting alternative devices for additional laboratory and field evaluation is presented in this chapter. This includes a detailed discussion of the procedure implemented to rank available devices based on a specific set of criteria. This chapter also includes a discussion of the results of a survey prepared and distributed to state DOTs, contractors, and manufacturers. The survey was utilized to obtain the latest feedback on the selected devices and opinions on transiting from density-based testing and towards modulus/stiffness-based methods. A description of the devices selected for further laboratory and field investigation is presented in this chapter.

Ranking of Available Devices

A ranking system was utilized to rank the various non-nuclear devices/methods. This system was developed to better understand the performance and feasibility of using all available devices (e.g., GeoGauge, PaveTracker, BCD, various LWDs, DCP, etc.) as quality acceptance tools for subgrade and unbound base/subbase layers. The likelihood of utilizing these devices for further laboratory and field investigation in this study was based on the potential each device showcased as reported in previous research studies. The ranking system implemented was based on the following nine criteria:

1. Past experiences with alternative devices;
2. Repeatability and time needed for measurements;
3. Data processing and interpretation requirements;
4. Sensitivity to environmental factors, accuracy, and ease of use;
5. Cost of utilization;
6. Ability to account for lower layer properties;
7. Ability to correlate representative laboratory and field moduli;
8. Ability to account for field moisture and density variability; and
9. Sensitivity to various levels of compaction.

Based on these 9 criteria, available devices were scored and ranked. The top three ranking non-nuclear devices were selected for additional evaluation in this study. It is also worth mentioning that the ranking system may be biased towards certain devices due to the availability or unavailability of information in regards to a specific criterion. For example, studies, at the time of preparing the study's literature review, were not available for newly developed/produced non-nuclear devices/methods.

<u>Past Experiences with Alternative Devices</u>

A literature review was performed on the GeoGauge, PaveTracker, BCD, LWD, and DCP to study past experiences, both good and bad, with using the alternative devices. This literature review was necessary to identify how each device performed in previous studies. Understanding how well the devices performed (in the laboratory or field) provided insight on how the devices would have performed if selected for additional testing in this study.

Past experience with the GeoGauge indicated that the device requires similar training and operator capabilities as the NDG [19]. Therefore, if the GeoGauge were selected for this study strict regulations would still exist for using the device. Previous experiences also showed that the GeoGauge calls for prior calibrations, consisting of multiple load resilient modulus tests for specific materials, which are not performed by most agencies. These reports further suggest that the GeoGauge may be difficult to use for this study. In addition, it was reported that the results using the GeoGauge may be inaccurate if used to test thin (less than 4-inches (10.2-cm)) or thick (more than 12-inches (30.5-cm)) layers or on materials with stiffness greater than 23 MN/m. A study also recommended that the device not be used for measuring dry density, even after finding calibration factors [20]. Also, when previously tested on non-cohesive, well-graded sands, there was high variability in the GeoGauge results [20]. These observations suggested that the GeoGauge might pose problematic for this study as different types of fine and coarse materials were used for testing.

Observations have also been made in regards to challenges with using the GeoGauge. Specifically, reports have mentioned that there was difficulty in achieving adequate contact between the GeoGauge ring and the tested soils [21] [22] [23]. In order to ensure a minimum of 80% contact between the foot and the soil the device manufacturers have suggested slightly twisting the device during testing. If 80% contact could not be achieved then the manufacturer recommended placing down a thin layer of sand. However, this thin layer of sand can inevitably impact the testing results of the device. The GeoGauge has also been problematic when calibrated in a laboratory setting as a result of specific boundary conditions, and certain soils influencing the device [2]. Based on the literature, it is evident that the GeoGauge requires similar training and use requirements as the NDG. The device also requires time in order to properly be calibrated. Therefore, past experiences with the GeoGauge suggested that the device might be difficult to use for testing.

The pavement quality indicator (PQI) was introduced as the first non-nuclear density gauge in 1998. In past studies the device experienced several problems when exposed to moisture and could not accurately determine the density of tested pavement. However, the device became more adept to efficiently measuring the density when exposed to moisture as a result of the development of an improved model. Although the recent pavement quality model has been deemed promising, moisture concerns still exist for the device [24]. Unfortunately, additional information regarding the past experiences could not be found for the PQI. The PaveTracker is another non-nuclear based device that functions in a similar fashion to that of the PQI. Available information about the PaveTracker is also limited.

The BCD is considered one of the newer non-nuclear devices studied, for this reason there is limited information regarding the history of evaluations conducted using the device. However, from the existing tests performed using the BCD it has been identified that there is only 0.08-inches (2-mm) of clearance when using the device. In other words, the placement and execution of the BCD must be near perfect, with small room for error, to ensure accurate results [4]. In addition, when utilized on very soft soils, the weight of the BCD may cause the strain plate to sink prior to using the device, inevitably affecting the results of testing [19]. These past studies using the BCD suggest that the device is challenging to use during testing. Therefore, if used in this study, it may be difficult to obtain accurate results if the BCD is not placed precisely. However, the 4.35-lb. (1.76-kg) weight of the device makes the BCD easy to carry and used by one operator. Overall, past studies suggest that the BCD may not provide accurate results due to the general nature of the device.

Past experiences with the LWD suggest that the device is non-destructive when used during testing, however operation of the device requires dropping a 22-lb. (10-kg) mass onto a loading plate. Although the device is defined as non-destructive, the impact caused by the falling mass can result in additional compaction or disturbances within the soil layer. For the purpose of this study, it was important that the device selected for testing did not affect the prepared samples. Therefore, this observation suggests that the LWD might inflict excess force on the samples prepared for laboratory testing.

In regards to operating the LWD, there were no reports of safety concerns associated with using the device [19]. Unlike the NDG, this allows both field inspectors and operators to remain on site during testing without any safety concerns. However, previous studies have observed high spatial variability and moisture effects on the LWD measurements. Therefore it was recommended that the LWD not be used as a quality assurance device for compacted soils until further research is conducted to determine the causes of these effects [9].

Previous literature on the DCP indicated that this test is a simple, rapid, and economical in-situ test for many geotechnical applications [8]. Studies using the device have concluded that the device is easy to use and provides results in a timely manner. Based on the previous success of the device, it was concluded that the DCP might be a suitable device to further investigate in this study. Little has been done in regards to measuring the resilient modulus pavement subgrade soils using the device. However, models have been successful developed for predicting the resilient modulus of subgrade soils using DCP test parameters [8]. The overall past experiences with the DCP and results of these prediction models indicate that the DCP could successfully be used for modulus based testing in this study.

Based on the comprehensive literature review conducted on the past experience of the selected devices, an overall ranking of the devices was developed and summarized in Table 1 below. The ranking in Table 1 is based on the past experiences of each device on a scale from 1 to 5; 1 being the most promising of the devices and 5 being the worst based on the criteria or lack of available information.

Repeatability and Time Needed for Measurements

As previously mentioned, when tested on non-cohesive, well-graded sands high variability was observed for the GeoGauge results [20]. Specifically, reports have determined a coefficient of variation (COV) ranging from 6.1 to 9.5% for the device [6]. It should be noted that this study was completed after 54 measurements were taken at 3 different locations. However, other reports have observed excellent repeatability with the GeoGauge when measurements were taken consecutively on different soil types [25]. These observations suggest that even after repeated measurements using the GeoGauge, high variability might still be experienced within the results if not measured immediately after the initial measurement. In addition, it has been reported that the GeoGauge results were “extremely inconsistent and highly dependent on the seating procedures and the operator” [22] [26]. Despite this observation, the GeoGauge had similar or better repeatability than other in-situ test devices, with lower spatial variability than the LWD and DCP [19].

Table 1 - Past Experiences with Alternative Devices.

Device	Overall Past Experience	Rank
GeoGauge	- Difficult compared to NDG - Tedious calibration - Non-destructive	3
PaveTracker	- Not very difficult or complicated to use - Sensitive to moisture, lack of available information - Non-destructive	5 (very poor)
BCD	- Extremely user-friendly: No calibration needed - Placement and execution must be exact - Non-destructive	2
LWD	- Simple and quick procedure (comparable to DCP) - Currently not recommended for quality control/quality assurance due to high variability - Non-destructive, but may introduce additional soil compaction and disturbance	4
DCP	- Successful; Simpler than NDG - Evaluation of resilient modulus not well known - Destructive	1 (best)

Based on previous studies using the GeoGauge reports have noted that each measurement required 75 seconds to complete, as opposed to the NDG, in which only 60 seconds are required. In addition, the time for using the GeoGauge doubles when the preparation and clean up time is considered. The observations made in these studies suggested that high variability might be experienced if the GeoGauge were to be used for additional testing. Moreover, a longer period of time will be required to obtain the results from laboratory and field testing.

The manufacturers of the PQI recommended that five readings be obtained for each area tested. Specific instructions insisted that the initial reading be measured normally and the following four readings be obtained by rotating the device to approximately 2, 5, 8, and 11 o'clock positions respectively. The five readings can then be averaged together to obtain the appropriate density value. The manufacturer of the PaveTracker suggested a similar protocol, however, only four readings were recommended at 12, 3, 6, and 9 o'clock positions [24]. Based on these recommendations it can be inferred that individual readings for both devices may be slightly skewed. Therefore more than one measurement is necessary to ensure accurate results. Two concerns arise from these recommendations, which include the amount of variability in the test results, and the additional time needed to operate both devices.

According to the device manufacturers, the BCD test involves taking four measurements, 90^o apart, in order to obtain an average modulus value [12]. The procedure mentioned requires 5 seconds to complete testing in both the laboratory and field. In a previous report, the BCD was tested to determine the level of accuracy of the device. In this study, the device was tested on the same rubber block eight times. Results of this test concluded that the COV of the strain output for the BCD was 0.5% [19]. In addition, further tests on the actual variability of the individual test results concluded that modulus results varied within 4% or 0.85 MPa of each other [4]. The results of these studies suggested that although the BCD provides timely results, there might be high variability with using the device, which may pose as a concern if used repeatedly in both laboratory and field tests.

Several reports regarding the use of the LWD have revealed that the device produces a wide distribution of results because of its poor repeatability. In a previous study, the LWD was utilized for cement-treated clay to monitor the strength gain with time of materials [3]. The results of this study concluded that the LWD yielded unreliable measurements. Similar observations were made in a study preformed using two different LWD models on the same aggregate type [9]. These studies suggested that the LWD might not be capable of reproducing results.

As previously established, the DCP has been used for various geotechnical applications. Operation of the device requires applying an initial seating load onto the area being tested. Many studies have been done in regards to the performance of the DCP. These studies have suggested that the load applied onto the material enhances the consistency of the DCP device [8]. Testing was also performed using the DCP on ten different soil types and locations. Based on the findings of this study, it was reported that the device was capable of replicating accurate testing results.

Table 2 below quantifies the repeatability and time for measurement of each device. Included in Table 2 is a ranking of each device based on a scale from 1 to 5; 1 being the most promising of the devices based and 5 being the worst of the devices based on the criteria.

Table 2 - Alternative Devices Repeatability and Time Needed for Measurements.

Device	Repeatability	Time Needed for	Rank
GeoGauge	- Variable with non-cohesive, well-graded sands	- Twice as long as NDG	3
PaveTracker	- Testing easily repeatable, but readings are variable - Sensitive with moisture	- Multiple readings needed - Exact time not known	5 (very poor)
BCD	- Minimal device variability - Repeatability associated with user placement	- 5 seconds to obtain readings - Rapid testing, but multiple readings recommended	1 (best)
LWD	- Wide scatter and poor repeatability - Especially sensitive with cement-treated clays	- More rapid than NDG - Comparable to DCP	4
DCP	- Applied load remains constant - Variable rest period which is operator dependent	- More rapid than NDG - Comparable to LWD	2

Data Processing and Interpretation Requirements for Alternative Devices

According to the device manufacturers, the stiffness and modulus values measured using the GeoGauge can be automatically displayed or stored in the device and downloaded to a computer at a later time [27]. The modulus values obtained are a function of the materials moisture content and density, while the stiffness measurements are a function of the materials structure. The GeoGauge measures the stiffness of the soil at each frequency and automatically displays an average value. These results can be used to develop relationships between modulus growth and compaction effort in unbound layers [20]. The only drawback to the device is that the load applied to the soil does not represent the actual stress levels encountered in the field, therefore the GeoGauge modulus must be corrected to account for design loads [19]. Despite this minor drawback, the data obtained using the GeoGauge can be easily processed and interpreted.

The PQI and the PaveTracker operate with similar methodologies in that both devices are capable of detecting changes in density throughout a pavement layer. These changes in the density within the layer are attributed to the changes in the electric field caused by the introduction of dielectrics within the layer. Both devices output a direct density reading of the area being tested [24]. Based on previous literature, it can be concluded that both the PQI and the PaveTracker provide direct density measurements without difficultly. In addition, no prior calibrations are needed in order to obtain the results from testing.

The data processing and interpretation of the BCD is simple in that the four electrical strain gauges, attached to the top of the plate, are used to measure the strain values of the soil. The remaining four electrical strain gauges are used for hoop measurements. The load cell above the plate detects the load applied by the operator and a modulus reading is automatically outputted. The soil modulus is then calculated using the bending strains detected by the gauges. A computer processes the bending strains and the modulus of the soil is displayed. It should be noted that the computer automatically applies pre-calculated field and laboratory calibrations for the device [12] [19]. The literature review conducted on the BCD indicates that both laboratory and field modulus values can be easily outputted from the device.

In order to obtain modulus and stiffness values from the LWD a falling weight is dropped onto the device's loading plate. The impact from the falling weight onto the loading plate causes an impulse load on the compacted material. The resulting deflection values from the loading plate are calculated and are immediately displayed on the device. Assuming an elastic half space medium, the applied surface load and deflection measurements are used to estimate elastic modulus of the tested layer. It is to be noted that studies suggest that no three consecutive modulus values, measured at the same location, should vary by 10%, nor should the number of drops conducted exceed 10 for a single location [9].

Testing using the DCP consists of applying a force onto a pushing rod that drives a cone tip into the soil layer. The device automatically records the number of hammer blows and depth of penetration of the cone. The values obtained from the device can be used to calculate the penetration rate of the cone. It is to be noted that in order to determine the strength of the tested soil using the device necessary correlations must be made between the penetration rate and modulus/strength of the soil [6]. Due to the

limitations of the device, if used to determine the compaction quality of pavement layers, several correlations will be required in order to obtain the appropriate values.
Table 3 below ranks the alternative devices data processing and interpretation requirements based on effort, time, and difficulty. It should be noted that a ranking of 1 corresponds to the best device while 5 corresponds to the device associated with the most tedious and difficult data processing and interpretation.

Table 3 - Data Processing and Interpretation Requirements for Alternative Devices.

Device	Ranking
GeoGauge	2
PaveTracker (Non-Nuclear)	3
BCD	1 (best)
LWD	5 (very poor)
DCP	4

<u>Sensitivity to Environmental Factors, Accuracy and Ease of Use</u>

As mentioned in a previous section, a thin layer of sand must be laid down on the testing location prior to testing. Calibrations must also take place before using the GeoGauge on any specific material. In the circumstance that the surface being testing is rough, the sand applied must be moist to ensure at least 75% contact with the surface. These studies suggested that the positioning and use of the GeoGauge might be difficult depending on the material being tested. Furthermore, the GeoGauge manual stated limitations for the readings obtained using the device. These limitations included: (1) stiffness values in the range of 3 to 70 MN/m, and (2) modulus values in the range of 26.2 to 610 MPa [27]. There are also concerns in regards to the device malfunctioning due to vibrations caused by passing vehicles, such as compaction equipment or trains [23]. These restrictions mentioned may limit the GeoGauge to only certain aggregates and locations, which can make the device very challenging to use in this study.
Previous testing performed using the PQI concluded that the device was problematic when the moisture content within the test area was high. Studies have suggested that moisture levels must remain constant to obtain any type of meaningful data [24]. These studies also concluded that the moisture content within the test locations might negatively affect the PQI and PaveTracker results. In addition, as previously mentioned, the procedure for using both devices require multiple readings and prior device calibration, making the devices tedious to operate.
The process for operating the BCD is fairly simple in that an appropriate test spot is located, a 50.1-lb. (223-N) load is applied onto the device, and an average modulus value is outputted. The device automatically provides a modulus reading at 50.1-lbs. (223-N), so if one were to exceed this amount there would be no repercussions. Although the device is easy to operate, its range for modulus is from 5 to 150 MPa [19]. Previous laboratory studies showed that the BCD could not be used on soils with modulus values below 3 MPa due to bearing capacity failure [12]. In other words, the device sinks into very soft soils under its own weight [19]. In addition, it has been reported that in very stiff soils the bending of the device plate does not adequately measure strains of the soil [19].
Previous studies have suggested that many factors can influence the modulus readings obtained using the LWD. These factors include: (1) falling mass, (2) drop height, (3)

plate size and contact stress, (4) type and location of the deflection transducer, (5) usage of load transducer, (6) loading rate, and (7) bugger stiffness. These factors suggest that the LWD might not provide accurate results due to the different types of influences on the device. In addition, previous studies have also reported that the LWD was sensitive to seasonal variations in pavement stiffness on both asphalt and gravel surfaces. In order to ensure a uniform surface it was recommended that sand be used for the seating of the LWD and that up to 4-inches (10.2-cm) of compacted material be removed prior to testing. It was also recommended that the testing be limited to pavements with a gradient less than 5% [9].

The DCP has been reported to be simple and economic, requiring minimum maintenance, providing easy-to-access sites, and continuous measurements of the penetration rate of the sample [6]. Based on the literature provided for the device, it has been suggested that device is relatively easy to use, however, some studies conducted using the DCP have indicated that the values obtained from the DCP are dependent on the conditions in which testing is performed. In a previous study, testing was conducted using the DCP on an asphalt surface, through a hole drilled into the asphalt surface, and on a base layer stripped of its asphalt surface. Based on this study, it was concluded that the results of the device varied between each method. Therefore in order to account for the environmental effects on the device, it was recommended that the DCP test be conducted through a drilled hole [5]. Although minor recommendations for testing have been provided for the DCP, previous studies confirm the devices ease of use if used for this study.

The ranking of the devices are tabulated in Table 4 below. This table illustrates the individual rankings according to the environmental factors, accuracy, and ease of use for each device. The overall rankings were determined by adding up the individual rankings. The devices were ranked from the lowest total (the best device) to the highest total (the worst device). Although the DCP and the GeoGauge were equivalent in overall ranking, the DCP proved to have more established research and ranked the highest in two categories opposed to the GeoGauge which ranked highest in only one category.

Table 4 - Sensitivity to Environmental Factors, Accuracy, and Ease of Use.

Device	Environmental Factors	Accuracy	Ease of Use	Overall Ranking
GeoGauge	3	2	1	2
Non-Nuclear (PaveTracker)	4	4	2	4
BCD	2	3	3	3
LWD	5	5	5	5 (very poor))
DCP	1	1	4	1 (best)

Cost of Utilizing Alternative Devices

For the purpose of determining the appropriate devices for additional laboratory and field testing it was necessary to rank the devices according to price. This ranking procedure was developed to facilitate selecting the devices for this study. The price of each device is tabulated in Table 5 below. It should be noted that the devices for which pricing could not be found are indicated with “N/A” in the table. For the commonly used

NDG the price of the device ranges from $8,000 to $9,000. The GeoGauge was at $5000-$5500 according to Mooney et al. [27], or $6720 according to the device manufacturer Humboldt [28]. The cost of the BCD is listed as $14,065, making the BCD nearly twice as expensive as the NDG.

The LWD falls approximately in the same price range as the NDG between $7,850 and $8,850. The cheapest device was one of the lower-end DCP models sold by Humboldt at $545. The most expensive DCP models were listed at $1620. It is worth noting that during testing it is required to replace the drive cone on the DCP, as the cone may become lost within the sample. According to the device manufacturer Humboldt [28], each drive cone costs $32. However, even if the cost of the cones were considered in the price for the most expensive models the DCP still ranks in as the cheapest device. The low cost of the DCP can be attributed to the lack of electronics required to operate the device. Based on the cost of the DCP in conjunction with the previously discussed criteria on the DCP, it can be concluded that the DCP might a suitable device for additional laboratory and field evaluation.

Table 5 - Cost of Utilizing Alternative Device.

Device	Cost
GeoGauge	$6,720
Non-Nuclear (PaveTracker)	N/A
BCD	$14,065
LWD	$7,850 - $8,850
DCP	$545 - $1,620

Alternative Devices Ability to Account for Lower Layer Properties

An important factor to consider for the devices selected for this study is the impact of lower layer properties on the devices measurements. In other words, it is necessary to monitor the performance of each device on the test areas to determine if the layers beneath the test location effected the measurements obtained from each device. Based on the evaluation conducted for this criterion, the devices were ranked accordingly.

The GeoGauge was reported to measure average modulus values up to 12-inches (30.5-cm) below the surface. In addition, the GeoGauge was particularly sensitive to the top 2-inches (5.1-cm), and the seating procedure required for the device [19] [20]. These results indicated that the GeoGauge was able to account for impacts caused by lower layer properties at the layers closest to the surface. According to a study conducted on the BCD, results suggested that device had an influence depth ranging from 4.8 to 12.2-inches (12.2 to 30.9-cm) as the modulus of the material increased from 3 to 300 MPa under large loads [4]. However, the actual influence depth was much smaller under the normal testing load. The results of this study suggest that the BCD is significantly influenced by the surface in which it is testing on; therefore if used for this study the results obtained from the device may contain high variability. It is to be noted that sufficient information regarding the impacts of lower layer properties on the measurements for the PQI and the PaveTracker could not be determined.

In a previous test conducted, the FWD was tested on an asphalt concrete layer to determine the impact the layer had on the measured results. Based on the results of this study, it was reported that the resilient moduli measured at a layer thickness less than 2.95-inches (7.5-cm) or at shallow bedrock were not accurate. Testing was also performed using the LWD and the results of testing indicated that the device might not be suitable for testing on thicker, stiffer foundations [6]. The conclusions made for the FWD and LWD suggests that if tested on different samples, the thickness of the sample may have an influence on the device's measurements. This would pose a concern for this study, as the samples prepared for laboratory testing had a thickness of 12-inches (30.5-cm).

Studies have also been conducted to evaluate the ability of the DCP to detect changes in the layers in which testing was performed on. In a previous study, the DCP was tested on low volume road pavements in order to identify the strength and thickness of different pavement layers of newly constructed roads [28]. The measurements obtained from the DCP were compared with actual on site measurements. It is to be noted that an evaluation of the tests were made for a period of two years and the changes in the penetration resistance for different layers were also measured. Based on the results of this study, it was concluded that the DCP was able to depict the number of pavement layers and thicknesses of each layer. The results measured for the DCP varied within 10% of the actual measurements. The observations made in this study suggest that, if used in this study, the DCP would be able to detect the changes of the samples when compacted at different density levels.

Table 6 below shows the ranking each device was given on their ability to account for the impacts of the lower layer properties on their measurements. The effect of the lower layers influenced each device differently. Based on the literature, the DCP was the only device that was capable of accounting for these lower layer properties. Furthermore, the DCP was able to identify these layers as well, thus it was concluded that the DCP was the best device to account for lower layer properties without loss of accuracy. As previously mentioned, the lowest number correlates to the device best able to account for these properties and the highest number corresponds to device least able to account for these properties.

Table 6 - Alternative Devices Ability to Account for Lower Layer Properties.

Device	Overall Ranking
GeoGauge	2
Non-Nuclear (PaveTracker)	5 (very poor))
BCD	3
LWD	4
DCP	1 (best)

Alternative Devices Ability to Correlate Representative Laboratory and Field Moduli

Based on a previous study field evaluations were conducted to determine the practicality of utilizing the GeoGauge for compaction quality control in pavement construction [20]. Testing was performed on different flexible pavement layers including HMA, base, and subgrade materials during construction. Additional testing was performed upon completion of construction. The results of this study concluded that the GeoGauge was capable of correlating laboratory and field moduli values. In addition, both laboratory and field values were comparable to values obtained through a resilient modulus regression equation [20]. Studies have also been performed on the PQI and PaveTracker to determine if these devices could be used to determine the density of HMA pavements. Both devices were utilized for laboratory and field testing. Comparisons were made between the laboratory and field results for both devices. Results indicated that the PaveTracker did not correlate well with the measured core densities. The density readings obtained by the PaveTracker were statistically different from the core densities in 68% of the projects cited [24]. It was also reported that the PQI did not correlate well with measured core densities in that the density values obtained using the device were statistically different in 54% of those projects.

In order to validate the use of the BCD for compaction quality control in pavement construction several studies have been performed using the device. As previously discussed, a series of field tests were conducted using the BCD on six different soil types and pavement bases [12]. Testing was also done on the same locations using the PLT. In order to determine if the BCD accurately captured the modulus values of these pavement layers, laboratory testing was conducted on prepared soil aggregate samples. The field results obtained using the BCD were then compared to the PLT and laboratory results. The results of this study indicated that both laboratory and field moduli could successful be correlated to one another using the BCD.

Throughout literature, multiple tests have been performed using the DCP to validate the use of the device for measuring the modulus of pavement layers. The results of these tests have been correlated to field moduli values measured using different non-nuclear devices. Specifically, in a past study, DCP field and laboratory tests were conducted in conjunction with the PLT. Results of these tests were then compared to field results obtained using the FWD and to laboratory CBR test results [6]. The results of the regression analysis discovered that the models developed for the DCP could successfully predict the measured FWD results with a R-squared equal to 0.91 for both devices. In addition, it was also observed that the results from the DCP tests correlated well with the CBR values. The conclusions made through this study suggested that the DCP could adequately evaluate the stiffness and strength of pavement layers if used for further evaluation.

Table 7 below displays the ranking of how well each device performed with correlating representative laboratory and field moduli results. The highest ranking corresponded to the device that best correlated between laboratory and field moduli. The devices with the lowest ranking represented those that poorly correlated these values.

Table 7 - Ability to Correlate Representative Laboratory and Field Moduli.

Device	Overall Ranking
GeoGauge	3
Non-Nuclear (PaveTracker)	5 (very poor)
BCD	1 (best)
LWD	4
DCP	2

Alternative Devices Ability to Account for Field Moisture and Density Variability

One of the main objectives developed for this study was to evaluate the NDG and selected devices on their ability to account for different moisture contents and density levels. In order to determine the sensitivity of the devices to these two factors a literature review was conducted on the devices past performances. Based on the results of the literature review the devices were then ranked according to their ability to account for field moisture and density variability.

As previously mentioned, a study was conducted using the GeoGauge on different dry sands and cohesive soils. Testing was performed on these materials to determine if the GeoGauge measurements were consistent with soil mechanics concepts. Based on the results of this study it was concluded that the stiffness measured from the device decreased as the moisture content increased [2]. The results of this study suggest that the GeoGauge is moisture sensitive and can detect the changes in the moisture within the tested area. Therefore, if used for additional laboratory evaluation, the device could effectively account for the moisture variability between the samples.

A study was conducted to evaluate if the PQI could be used to determine the density of HMA pavements. In this study comparisons were made between laboratory density values of HMA and density values obtained from the PQI. The laboratory tests conducted indicated that the PQI could detect changes in density of the HMA for a single asphalt mixture. However, the device could not accurately detect density when tested in the field. In addition, the PQI proved to be problematic when operated at high moisture contents. In order to obtain meaningful data, the moisture level of the tested area must remain constant [24]. Based on these observations, it was suggested that if used for field testing the device would require certain correction factors to correct for moisture and density variability. It is to be noted that information regarding the impact of field moisture and density variability could not be obtained for the PaveTracker.

Previous laboratory testing was conducted to evaluate the impact of moisture and dry density on the results obtained using the BCD. In this study a series of compaction tests were performed on laboratory prepared samples. The samples were prepared at varying moisture contents in order to compare the variability of BCD modulus with moisture content and dry density. The results of this study indicated that the measured modulus was 75% of the maximum. In addition, the BCD was more sensitive to moisture content than to dry density [12]. Overall, this study suggests that the BCD is sensitive to changes in moisture content and dry density; therefore it would be suitable for additional testing in this study.

As previously established, the LWD is sensitive to cement-treated clay materials [3]. This sensitivity was directly linked to the lack of moisture within the material. In other words, the lack of moisture affected the strength gain with time for cement-treated clays and caused shrinkage cracks near the surface of the material. These surface cracks significantly affect the results of the LWD measurements. In addition, the LWD was also sensitive to field moisture and density variability (i.e. void ratio changes) in which calibration curves were necessary for accurate readings. Similar to the BCD results previously discussed, it is concluded that the LWD was also sensitive to changes in aggregate moisture content and density.

Based on previous literature, the DCP test results were influenced by the moisture content, dry unit weight, and soil type. The DPI increases with the increase in moisture content and it decreases with the increase in dry unit weight. The resilient modulus was also influenced by the moisture content, dry unit weight, and soil type in that the resilient modulus decreases with the increase in moisture content and it increases with the increase in dry unit weight [8]. Based on the previous studies conducted using this device, it is evident that the DCP is capable of detecting changes in the moisture and density within the tested area. These capabilities of the DCP are crucial for the devices selected for evaluation in this study.

Table 8 below ranks each of the devices based on ability to account for the impacts of field moisture and density variability on measured moduli.

Table 8 - Ability to Account for Field Moisture and Density Variability.

Device	Ranking
GeoGauge	1 (best)
PaveTracker (Non-Nuclear)	5 (very poor))
BCD	2
LWD	4
DCP	3

<u>Sensitivity of Alternative Devices to Various Levels of Compaction</u>

To account for the variability of compaction over short distances, it is suggested that multiple measurements be taken using the GeoGauge. The data collected can then be averaged together to obtain one measurement. In addition, it is suggested that measurements using the GeoGauge be obtained in increments of 2-feet (0.6-m) or less, at locations in a straight line of one another [27]. Based on previous studies, it can be seen that there are many recommendations for using the device in order to account for the variability in compaction. Therefore it can be concluded that the device is sensitive to different levels of compaction and if used in this study, the device will be capable of detecting changes in density of the compacted samples. It is to be noted that sufficient information regarding the sensitivity of the PaveTracker, BCD, and LWD to various levels of compaction could not be determined.

Through a comprehensive literature review it is evident that the DCP is also sensitive to various levels of compaction. Previous studies reported the wear and tear of the DCP cones used to penetrate the test area when repeatedly exposed to stiff materials. This suggests that the DCP is capable of detecting different levels of compaction. In addition, previous literature discusses properly compacted granular base materials having uniform penetration rate values. Furthermore, for lightly compacted materials the DCP penetration rates were higher. These results suggest that DCP was able to detect the increase in strength and stiffness of the material as a result of compaction [27]. Based on these studies, it is evident that the DCP has the ability to verify both the level and uniformity of compaction, making it a suitable device for additional laboratory and field evaluation.

Table 9 below ranks each of the devices based on sensitivity of the device to various levels of compaction. Devices that did contain sufficient information received a ranking of 5 because, as previously stated, the lowest number correlates to the device most sensitive to account for these properties and the highest number corresponds to the least sensitive device.

Table 9 - Sensitivity of Alternative Devices to Various Levels of Compaction.

Device	Overall Ranking
GeoGauge	2
Non-Nuclear (PaveTracker)	5 (very poor)
BCD	4
LWD	3
DCP	1 (best)

Overall Ranking of Alternative Devices

The overall ranking of each device per criteria is presented in Tables 10 and 11 below. Table 10 presents the evaluation of each alternative device based on all criteria, including the cost to utilize each device. Table 11 presents the same results, however this evaluation eliminates the cost criteria. This was done in order to rank the devices based on performance alone, if money was not a concern.

Table 10 - Evaluation of Alternative Devices Based on all Criteria.

Device	Criteria									Overall Ranking
	One	Two	Three	Four	Five	Six	Seven	Eight	Nine	
GeoGauge	3	3	2	2	2	2	3	1	2	2
Non-Nuclear (PaveTracker)	5	5	3	4	5	5	5	5	5	5 (very poor)
BCD	2	1	1	3	4	3	1	2	5	3
LWD	4	4	5	5	3	4	4	4	3	4
DCP	1	2	4	1	1	1	2	3	1	1 (best)

Table 11 - Evaluation of Alternative Devices Based on Non-Cost Criteria.

Device	Criteria									Overall Ranking
	One	Two	Three	Four	Five	Six	Seven	Eight	Nine	
GeoGauge	3	3	2	2	--	2	3	1	2	2 (tie)
Non-Nuclear (PaveTracker)	5	5	3	4	--	5	5	5	5	5 (very poor)
BCD	2	1	1	3	--	3	1	2	5	2 (tie)
LWD	4	4	5	5	--	4	4	4	3	4
DCP	1	2	4	1	--	1	2	3	1	1 (best)

Survey of State DOTs, Contractors and Manufacturers

In order to obtain the most recent feedback on the alternative devices and opinions on transiting from density-based testing and towards modulus/stiffness-based methods, a survey was developed. Prior to this report, the National Cooperative Highway Research Program (NCHRP) released a substantial report on alternatives to the NDG. Based on the results, it was reported that most state DOT agencies still employ the NDG as their primary tool for the acceptance of unbound subgrade and base/subbase layers. However, the study also reported that 44% of agencies said they would move to a non-nuclear device and modulus-based quality control method because a nuclear certification was too inconvenient. Of the same group, 41% said certification was also too expensive. 37% of this group mentioned safety concerns as reasons for transitioning to modulus-based quality control. Based on the responses of the NCHRP report, a set of survey questions was developed. The survey prepared for this study can be found in Appendix A.

The survey presented in this chapter was developed using Survey Monkey and was sent out to state DOTS in Indiana, Iowa, Illinois, Louisiana, Minnesota, Missouri, and Texas. In addition, the survey was sent to local (i.e., New Jersey) and national contractors/manufacturers. The objectives of this survey included:

- Determine problems and concerns of using nuclear and non-nuclear devices in highway construction;
- Identify if other non-nuclear devices or modulus-based specifications are currently used/considered for the near future;
- Identify technical and institutional issues that may lead to abandoning quality acceptance based on nuclear methods; and
- Determining existing difficulties of using non-nuclear devices or challenges transitioning to another acceptance methodology.

Unfortunately, only three responses were obtained from the developed survey. The responses from the three respondents are presented in this section. Initially, the surveyed experts were asked for their opinions on the factors that attributed to the popularity of the NDG as a tool for compaction quality control. There was a general agreement among the three respondents that NDG results were timely and easy to analyze and interpret. The second set of questions was to gauge the respondents' views on the drawbacks of the NDG. The two major drawbacks all respondents agreed on were (1) the requirements for specialized/isolated storage, and (2) density measurements as opposed to strength/modulus parameters. The drawbacks provided by the three respondents were consistent with the major concerns, previously established in literature, with using the NDG.

Survey respondents were then asked to rank the desired attributes sought out in alternative devices. This ranking was based on a scale from 1-not important at all to 6-extremely important. The responses are displayed in Table 12 below. The most essential attributes that gained the highest ranking were repeatability and time needed for measurements. In addition to the specific attributes surveyed, the respondents were given a chance to provide an additional set of attributes they would like to have in an alternative device. The attributes that the respondents mentioned were (1) devices that require simple training to conduct testing, (2) devices that are simple and easily understood, and (3) devices with no licensing requirements.

Table 12 - Surveyor Ranking of Alternative Device Attributes.

Attribute	Respondent Number 1	Respondent Number 2	Respondent Number 3	Total Ranking
Repeatability of measurements	6[2]	6	6	12
Time for measurements	5	5	3	10
Ease of data processing	2	4	4	6
Sensitivity to environmental	3	2	1	5
Ease of use an accuracy	4	3	5	7
Cost	1[1]	1	2	2

[1] not important
[2] extremely important

The surveyed experts were then asked to provide opinions on the attributes of the major alternative devices identified through the literature review. These devices included the GeoGauge, PaveTracker, BCD, LWD, and DCP. The respondents were given the option to skip questions regarding a specific device if they did not have prior knowledge of the device. Unfortunately, all three respondents only had knowledge of the GeoGauge and DCP. The results are listed in Tables 13 and 14 below.

The respondents were allowed to provide additional comments on both devices. However, no comments were made for the GeoGauge. As for the DCP, respondents mentioned that the device was easy to use, and did not require supervision during testing. In addition, testing could be conducted at a later time and that the device was a good diagnostic tool.

The disadvantage of using the DCP, as the respondents listed, was that the device is sensitive to moisture. The results obtained through the provided survey were consistent with the literature review in that both the GeoGauge and DCP were practical devices and might be suitable alternatives to the NDG.

Table 13 - Surveyor Opinions on the GeoGauge.

Attribute	Respondent Number 1	Respondent Number 2	Respondent Number 3
Accuracy & repeatability of measurements	Disagree	Neutral	Disagree
Ease of analysis and interpretation of results	Disagree	Neutral	Agree
Output obtained in a timely manner	Disagree	Agree	Agree
Portability of the device	Neutral	Agree	Agree
Influence of environmental factors	Neutral	Neutral	Disagree
Influence of lower layer properties	Neutral	Disagree	Neutral
Readings are representative of field conditions	Neutral	Neutral	Neutral
Cost of device	Neutral	Neutral	Disagree

Table 14 - Surveyor Opinions on the DCP.

Attribute	Respondent Number 1	Respondent Number 2	Respondent Number 3
Accuracy & repeatability of measurements	Strongly Agree	Agree	Disagree
Ease of analysis and interpretation of results	Strongly Agree	Strongly Agree	Disagree
Output obtained in a timely manner	Strongly Agree	Strongly Agree	Agree
Portability of the device	Strongly Agree	Strongly Agree	Agree
Influence of environmental factors	Strongly Agree	Disagree	Neutral
Influence of lower layer properties	Neutral	Agree	Neutral
Readings are representative of field conditions	Strongly Agree	Strongly Agree	Agree
Cost of device	Strongly Agree	Strongly Agree	Disagree

Once the respondents provided their opinions on the GeoGauge, PaveTracker, BCD, LWD, and DCP they were then asked to rank these devices on a scale of 1-being an excellent alternative to the NDG to 5-being a very poor alternative to the NDG. It is to be noted that "N/A" was listed for the respondents who had no prior experience/knowledge with a particular device. The overall ranking of the alternative devices is displayed in Table 15 below. Consistent with the literature the DCP achieved the highest ranking out of all the devices.

Table 15 - Overall Surveyor Ranking of Alternative Devices.

Alternative Device/Method	Respondent Number 1	Respondent Number 2	Respondent Number 3
GeoGauge	4	3	2
Non-Nuclear (PaveTracker)	4	5	N/A
BCD	4	4	4
LWD	4	2	4
DCP	1	1	2
Others	N/A	N/A	N/A

The final segment of the survey asked the respondents to provide their opinions on transitioning to non-nuclear alternative device and the factors that may hinder the implementation of a new device. The results obtained from the three respondents are displayed in Table 16 below.

Table 16 - Surveyor Opinions on Transitioning.

Question	Respondent Number 1	Respondent Number 2	Respondent Number 3
Agencies interest in strength/stiffness device	Moderate	Substantial	Extremely
Agencies interest in implementing	Moderate	Substantial	Extremely
Possibility of transitioning	Maybe	No	Yes

From the results obtained through the survey, the respondents displayed an interest in transitioning to an alternative device. However, all respondents commented on factors that may hinder the possibility of transitioning towards an alternative non-nuclear device. Respondents mentioned that a lack of familiarity as well as trained personnel with the new device would keep agencies from transitioning. Furthermore, the devices' sensitivity to moisture poses as a major concern in transitioning.

Based on the literature review conducted in this study and the survey sent to state DOT materials engineers, device manufacturers, and contractors, three devices were selected for further investigation as an alternative to the NDG. The devices selected were the BCD, LWD, and DCP.

Description of Selected Devices

<u>Briaud Compaction Device (BCD)</u>

The BCD consists of a 6-inch (15.2-cm) diameter flexible plate retrofitted with eight radial and axial strain gauges, located at the bottom end of a rod. To operate the device it is first placed on top of the layer being tested. The operator then gradually applies a load of 50-lb. (222.4-N) magnitude onto the device handles. The flexible plate, at the bottom of the rod, then measures the plate's deformation as the load is applied onto the device. Higher deformation values, measured by the device, usually indicate lower modulus values for the compacted soil. According to the device manufacturer, it is recommended that four measurements be taken 90^{o} apart at one testing location for a better reading [12]. The collected measurements are then automatically stored for

retrieval at a later time. A schematic of the BCD is shown in Figure 1 and a final prototype of the BCD is illustrated in Figure 2 below.
The concept behind the device is simple in that the stiffer the soil is the less the plate will bend and vice versa for softer soils. Therefore, strain measurements of the plate are directly related to the modulus of the soil beneath the device. All necessary corresponding calibrations are done internally within the device [12].

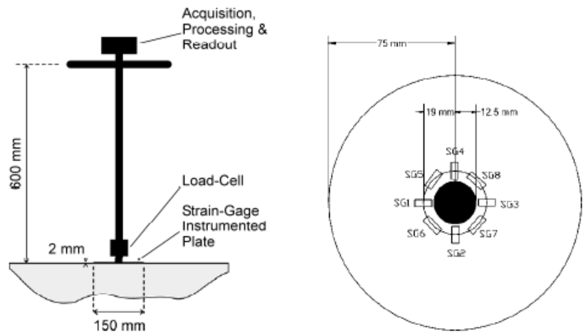


Figure 1. Initial BCD with Corresponding Plan View of Plate [12].

Figure 2. Final Prototype of BCD [12].

<u>Light Weight Falling Deflectometer (LWD)</u>
The LWD is a portable device utilized to determine the dynamic modulus of compacted aggregate layers. The LWD was first developed in Germany and has been utilized during the construction of pavement foundations [10]. Due to its portability and potential for estimating fundamental material properties, the LWD has gained much attention for quality control during pavement construction. One of the most popular LWDs is the Prima 100, developed by Carl Bro Pavement Consultants in Kolding, Denmark. The LWD is operated under the ASTM E2583-07 specification [19]. The procedure for using the LWD requires applying three seating loads onto a 7.8-inch (19.8-cm) bearing plate using a standard weight of 22-lbs. (9.9-kg). Following the required seating blows, a final dynamic load is applied freely onto the plate. The bearing plate, containing geophone sensors, then measure the aggregate layer’s dynamic deflection modulus caused by the impact of the falling weight. The device automatically outputs and stores the measured deflection values. The measured deflection at the center of the plate is then used to calculate the dynamic deformation modulus ELWD using Boussinesq equation as follows:

$$E_{LFWD} = \frac{k(1-\nu^2)\sigma R}{\delta_c}$$ Equation 1

Where:
E_{LWD} = Dynamic deformation modulus
k = π/2 for rigid and 2 for flexible plates
υ = Poisson's ratio, (default value of 0.35)
σ = Applied stress
R = Radius of the plate
δ_c = Center deflection

Dynamic Cone Penetrometer (DCP)
Initially developed in South Africa for in-situ evaluation of pavements, the DCP has been recently implemented in South Africa, United Kingdom, Australia, New Zealand, and several states in the United States, specifically the U.S. Army Corps of Engineers, for characterization of pavement layers and subgrades [6]. The device consists of a 22.6-inch (57.5-cm) upper fixed rod with a 17.6-lb. (8-kg) falling mass. At the bottom of the device is a lower 0.63-inch (16-mm) diameter rod containing an anvil and 0.79-inch (20-mm) diameter steel cone with an apex angle of 60 degrees [6]. A schematic of the device can be seen in Figure 3 below. The DCP test is conducted according to ASTM D6951 or ASTM D7380 standards. The DCP requires two operators, one for lifting and dropping the hammer and one for measuring and recording the penetration depth for each blow [8].

Operation of the device requires dropping the standard hammer weight of 17.6-lbs. (17.9-kg) from a height of 22.6-inches (57.4-cm) onto the anvil attached to the top of a pushing rod. The force from the weight onto the pushing rod then drives the cone tip into the soil layer. The device then records the number of hammer blows and the depth of penetration into the soil. The number of blows recorded can be plotted against depth to obtain the penetration rate (mm/blow), which can then calculated and correlated to the modulus and strength of the tested pavement sections [6]. The DCP results are usually normalized with penetration depth. Therefore, it can be hypothesized that the higher number of blows required to penetrate 12-inches (30.5-cm) of soil, the better the compaction applied is. The DCP utilized in this study was retrofitted with an automatic ruler that recorded and stored the penetrated depth and number of blows applied to the samples.

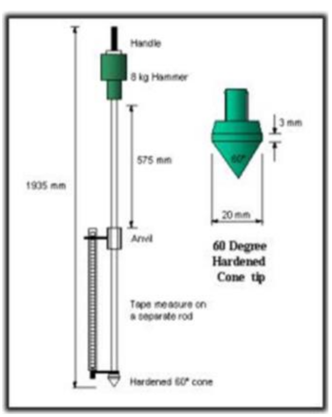


Figure 3. Schematic of the DCP [6].

DESCRIPTION OF MATERIALS

Introduction

This chapter discusses the four aggregate types that were utilized to facilitate laboratory and field testing. In addition, this chapter presents the material properties determined for each aggregate type. The aggregates selected for this study included two subgrade soils, natural sand 1 (NAT-1) and natural sand 2 (NAT-2), as well as two base/subbase materials, dense graded aggregate (DGA) with RAP and recycled concrete aggregate (RCA). The different aggregate types selected for this study were necessary for evaluating the impact of aggregate type on the testing results obtained from the non-nuclear devices and the NDG.

Material Properties

Gradation

Testing was conducted to determine the particle size distribution (PSD) of the selected aggregates. Figure 4 below presents the PSD for NAT-1, NAT-2, DGA, and RCA materials respectively. As can be seen from this figure, both subgrade soils (NAT-1 and NAT-2) can be classified as gap-graded while both base/subbase materials (DGA and RCA) had a well-graded gradation. It can also be observed from Figure 4 that both DGA and RCA materials had lower percent passing values at large sieve openings when compared to percent passing values for both NAT-1 and NAT-2 at the equivalent sizes. This suggests that the base/subbase aggregates had a higher percentage of coarse materials (i.e., having a size larger than a No. 4 sieve opening) than did both subgrade aggregates. In addition, all four aggregates did not have a significant amount of very fine materials (passing sieve No. 200).

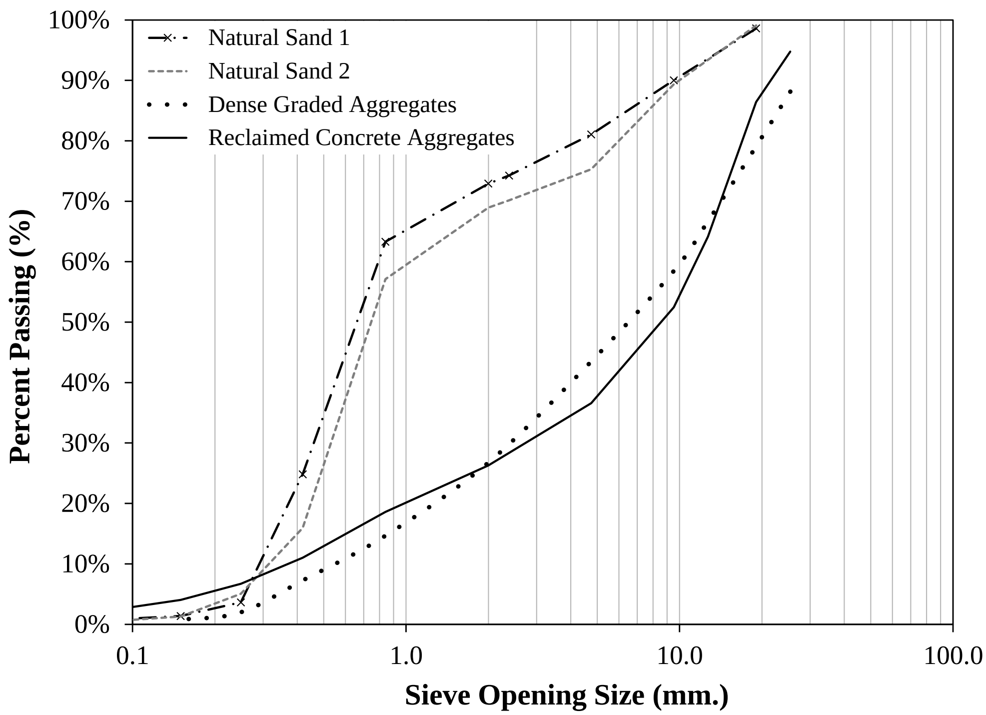


Figure 4. Particle Size Distributions Obtained for Selected Aggregates.

Moisture-Density Relationships

The moisture-density relationship for each material was determined in accordance to the modified Proctor test [30]. NAT-1 and NAT-2 materials were first separated into two groups: (1) material passing the No. 4 sieve, and (2) materials retained on the No. 4 sieve. Using the material passing the No. 4 sieve, five samples were prepared at different moisture contents. The moisture contents selected ranged from 5 to 15% by weight of dry mass. For each of the samples, the material was placed in a 4-inch (10.2-cm) diameter compaction mold using a five-layer scheme. Each layer was then subjected to 25 blows using a compaction hammer. Similar procedures were utilized for both base/subbase materials (DGA and RCA), however the materials were initially separated into two groups: (1) larger than ¾-inch and (2) smaller than ¾-inch. Samples were prepared using the materials smaller than ¾-inch in a similar five-layer scheme. However, each layer was subject to 54 blows using the compaction hammer. Figure 5 below presents the moisture-density relationships obtained for all selected aggregates. Testing using the Proctor test yielded an average OMC of 9.7% and MDD of 110 lbs./ft.^{3} for NAT-1. An OMC of 9.65% and MDD of 120 lbs./ft.^{3} were obtained for NAT-2. DGA material had an average of 8.7% OMC achieving a MDD of 125 lbs./ft.^{3}. The RCA had an OMC of 10.7% and MDD of 138 lbs./ft.^{3}.

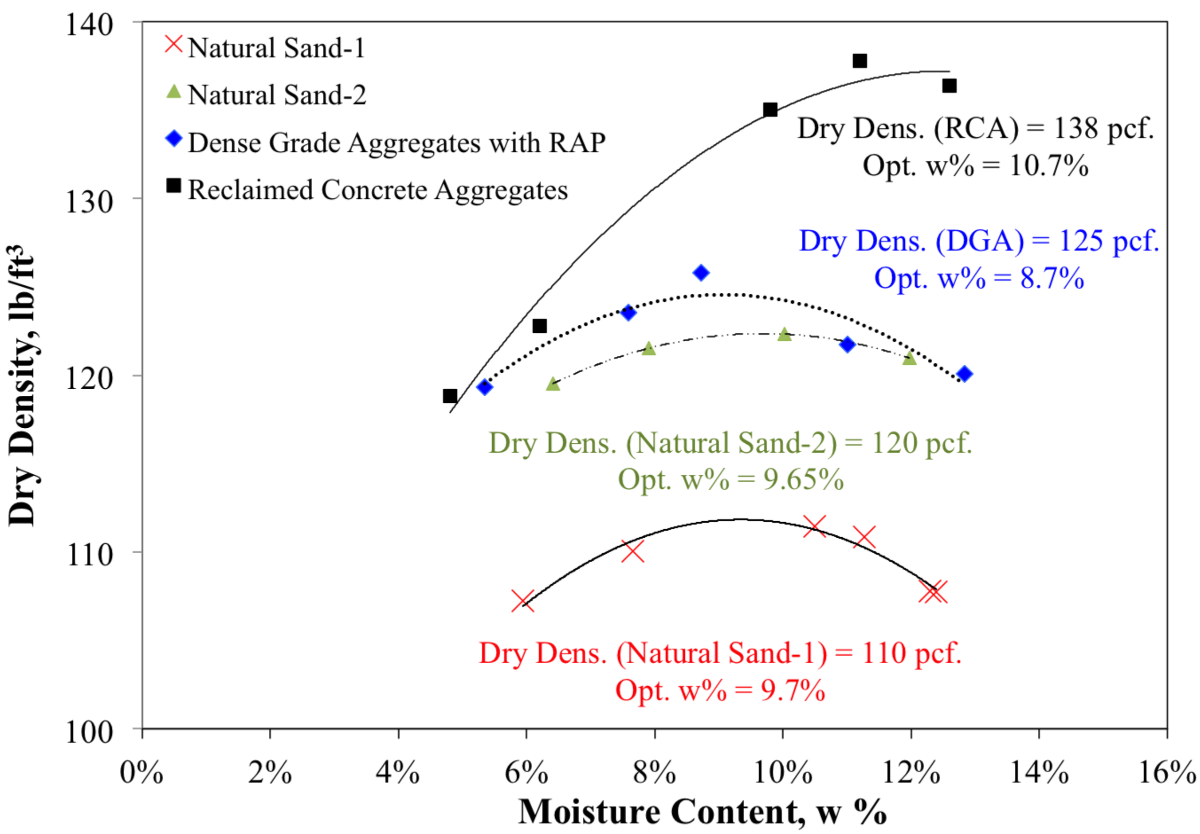


Figure 5. Moisture-Density Relationships for Selected Aggregates.

LABORATORY SAMPLE PREPARATION & TESTING METHODOLOGY

Introduction

This chapter includes a description of the sample preparation procedure developed for laboratory testing. The laboratory testing plan prepared to evaluate the effect of different parameters on the results obtained from the NDG and selected non-nuclear devices are also discussed in detail. This chapter also includes a discussion of field sections and field testing conducted as a part of this study.

Laboratory Sample Preparation Procedure

In order to evaluate the three selected non-nuclear devices and the NDG, a procedure for compacting large aggregate samples in the laboratory was developed. This compaction procedure was necessary in order to compare/correlate the results obtained using the non-nuclear devices and the NDG while simulating field compaction. The Proctor moisture-density relationships obtained for each aggregate type were utilized to compact samples at different dry densities when changing the moisture content. This was essential for evaluating the effect of the aggregate's moisture content on collected results. A detailed description of the laboratory sample compaction procedure implemented is presented in the following subsections.

Drying of Selected Aggregates

This step involved placing the aggregates on an open floor in the laboratory for air-drying under ambient temperature for a week prior to compaction. During this week, the aggregate were raked frequently to ensure uniform drying. The quantity of aggregates placed at one time for compacting two samples was approximately 1,000 lbs. It is worth mentioning that this step was conducted to ensure that the present moisture content in the aggregates was lower than the targeted moisture content and not to completely dry the aggregates.

Determine Moisture Content of Aggregates

Upon completion of drying the material, the required moisture content for the aggregates was calculated. This was completed by first collecting moisture samples from the air-dried aggregates. Depending on the amount of material being dried, typically five to six samples were collected to determine the existing moisture content of the aggregates. It is worth mentioning that these samples were taken at random throughout the material to ensure accurate assessment of moisture within the aggregate. The weights of the moist aggregates were measured and the samples were dried in an oven that was preheated to 300^{o}F.

After an hour of drying, the samples were then removed from the oven and the weights of the dried aggregates were measured. Based on the dry weights determined for each sample, an average moisture content was computed for the material. This average moisture content was used in determining the amount of water needed to reach the targeted moisture content for the aggregates. As an example, if the targeted moisture content of NAT-1 was 9.7% and the existing moisture of the material was 2% then roughly 7.7-lbs. (3.5-kg) of water was required for every 100-lbs. (45.4-kg) of material used. It was crucial to calculate the amount of water needed to reach the target moisture content to ensure that the molds were prepared at the appropriate moisture content and not at moisture contents significantly below/above the target. In addition, the determined amount of water required for every 100-lbs. (45.4-kg) of material was utilized during the mixing and placement of the aggregates to be discussed in the following subsection. An average moisture content was determined for all the aggregates prepared in this study.

Mixing and Placement of Aggregates

Once the amount of water required to reach the targeted moisture content was determined, water was mixed with the air-dried aggregates. The aggregates were mixed for five minutes using a concrete mixer to ensure that the water was uniformly distributed within the aggregates.

Using a mallet, blows were repeatedly applied to the sides of the mixer to ensure that the material did not adhere to the inside walls during mixing. The concrete mixer utilized for this study is illustrated in Figure 6a below.

Once the aggregates were mixed with the required amount of water, the aggregates were then weighed and placed into the mold. Depending on the material and quantity of water used for each material, each lift required approximately 100 to 130-lbs. (45.4 to 58.9-kg) of dry aggregates. Additional information regarding the weight of each lift is discussed in the following subsection.

The mixing procedure described in this section was performed three times for each sample. This was done in order to place the aggregate in three consecutive 4-inch (10.2-cm) thick lifts. Moisture samples were taken between each mixing process to confirm that the targeted moisture content was reached for each lift.

Compaction of Aggregates

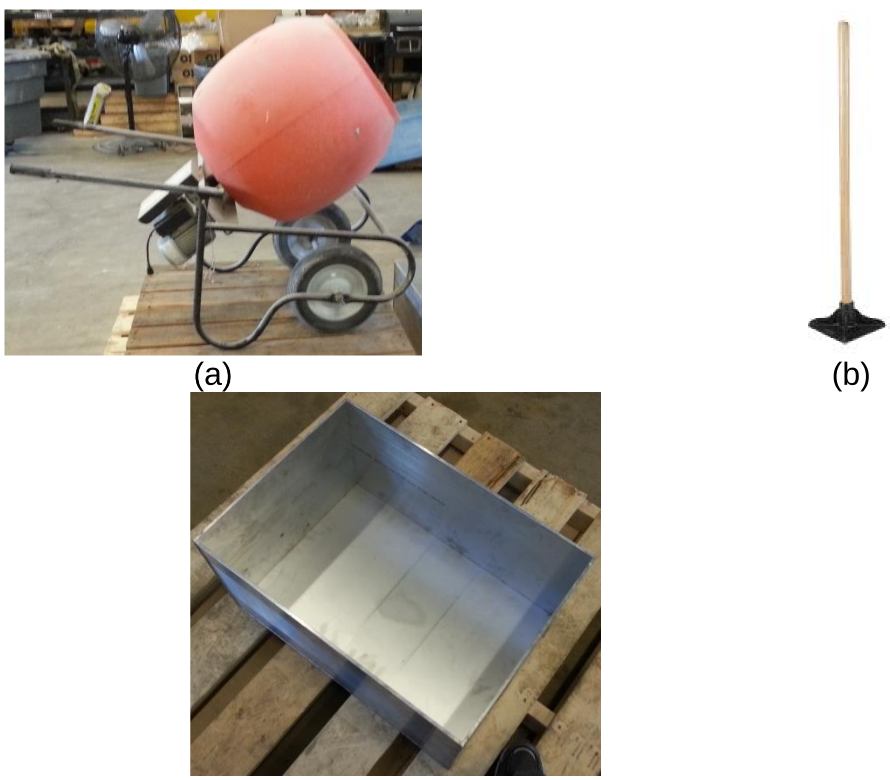
Each sample prepared for this study was prepared in a large aluminum mold that was 24-inches (60.9-cm) in length, 17-inches (43.2-cm) wide, and 12-inches (30.5-cm) deep. A picture of one of the aluminum molds used for preparing samples is presented in Figure 6c below. As previously mentioned, the aggregates were placed in three 4-inch (10.2-cm) thick lifts. Depending on the parameter being evaluated (i.e., moisture content or compaction effort) the amount of aggregates needed for each lift was determined based on three factors: (1) the aggregate moisture-density relationship, (2) mold and lift dimensions, and (3) targeted moisture content/density level. For example, if the targeted moisture content for the material was the OMC then the Proctor MDD and volume of the mold (2.82 ft^2) were utilized for calculating the required weight per lift using the well-known density-mass-volume relationship.

Similarly, this procedure was implemented for samples at varying compaction efforts; however, density values significantly higher/lower than the MDD were selected and used for computing the required lift weights. As an example, if the targeted density for NAT-1 was below MDD (112 lbs./$ft.^3$) then 105 lbs./$ft.^3$ was used to calculate the necessary lift weight. The density values selected for these samples are discussed in the Chapter 6.

Once the required lift weights were determine, the aggregates were weighed and placed into the aluminum molds. A manual steel tamper was used to compact the samples prepared at OMC and above/below OMC. It is to be noted that for samples prepared at higher/lower compaction effort either a manual steel tamper or jackhammer was used. Figure 6b below illustrates the steel tamper used to compact the samples. Once each lift reached a thickness of 4-inches (10.2-cm) the compaction process was deemed complete. This process was repeated two additional times to completely fill the 12-inch (30.5-cm) thick mold with aggregates.

Verification of Compaction Quality

The moisture content and density values measured before and after the compaction process was used to verify the quality of the compaction procedure discussed above. As mentioned previously, throughout the mixing process, moisture samples were collected for each lift. These samples were used to confirm whether the targeted moisture content was reached for each mold. Based on the moisture samples collected for each lift, an average moisture content was calculated and the results were compared to the targeted moisture content. Based on these results, it was observed that the actual moisture contents measured were within ±0.5% of the targeted moisture content.
In addition, following compaction, testing was conducted on each sample using the NDG. The density values measured using the NDG were used to verify whether the targeted density was achieved. This was achieved by comparing the density values obtained from the NDG to the density values calculated using the three lift weights and mold volume. The comparison between these values confirmed that the density of samples were within ±5 lbs./ft^3 of the targeted value for all aggregate types. Based on the analysis conducted, it was confirmed that the aggregate samples prepared for laboratory testing were adequately compacted.



(a) (b) (c)

Figure 6. Equipment Used for Sample Preparation; (a) Concrete Mixer, (b) Compaction Steel Tamper; and (c) Sample Mold.

Laboratory Testing Plan

Effect of Moisture Content

In order to evaluate the effect of moisture content on the testing results obtain from the NDG and non-nuclear devices, three moisture levels were selected. These moisture contents included the OMC, 2% higher than OMC, and 2% lower than OMC. The corresponding densities for each aggregate, as previously determined using the Proctor moisture-density relationships, were then used to determine the weight required for each lift during the mold compaction procedure to be discussed in the following section. For each aggregate type two large samples were compacted for all moisture contents. It should be noted that, in order to account for any possible variability in the testing results, two samples were prepared for each aggregate type and averaged together to obtain one measurement. The compacted samples were then tested using the NDG, BCD, LWD, and DCP devices immediately (i.e., within 1 hour) after compaction, 24 hours after compaction, and 48 hours after completion of compaction. This testing scheme was implemented to evaluate the effect of delayed testing on the results collected from these devices. Table 17 below presents the moisture contents selected for evaluated for the NAT-1, NAT-2, DGA, and RCA materials respectively.

Effect of Compaction Effort

In order to evaluate the impact of different compaction efforts on testing results obtained from the NDG and non-nuclear devices three density levels were selected for the compacted samples. It is noted that all samples compacted to evaluate the effect of compaction effort were kept at constant moisture content (i.e., the OMC). Initially, Proctor test moisture-density relationships were developed using higher/lower compaction efforts (i.e., 50% higher/lower blows than standard number of blows) to obtain the density value needed to prepare samples at higher/lower compaction efforts. However, these relationships yielded densities that were within ±5 $lbs./ft.^3$ of the values determined using the Proctor standard number of blows. To ensure truly applying distinctive compaction efforts, density levels were selected based on the density results obtained through testing at the Proctor MDD rather than using higher/lower compaction efforts. The densities selected for testing included the Proctor MDD, 5 to 20 $lbs./ft.^3$ higher than MDD, and 5 to 15 $lbs./ft.^3$ lower than MDD. The specific density values used to evaluate the effect of compaction effort on the testing results for each material are also presented in Table 17 below.

Field Testing Plan

Selected Field Sections

In addition to laboratory prepared samples, the testing plan prepared for this study involved evaluating field-compacted unbound subgrade and base/subbase layers using the NDG and non-nuclear devices. For the purpose of this study, three 100-ft (30.5-m) long field sections were selected for testing.

The first two 100-ft (30.5-m) long sections were located at the Route 35 Restoration Project located in the boroughs of Mantaloking, Lavalette and Ocean Beach, New Jersey. Testing was conducted on the stretch from milepost 4.0 – 9.5. The two 100-ft (30.5-m) long sections consisted of a compacted NAT-1 soil layer overlaid with a compacted DGA layer. It should be noted that the first 100-ft (30.5-m) section located along 6th Ave was tested immediately following fine grading, 24 hours, and 48 hours after preparation. The second 100-ft (30.5-m) long section was tested prior to compaction, immediately after preparation, 24 hours, and 48 hours after. Reference densities of 143.7 lbs./ft3 and 123.7 lbs./ft3 for both sections were provided on site. The third field section was located at Interstate 295 at the divide between I-295 and I-76 in Haddon Heights, New Jersey. The third section consisted of a NAT-2 subgrade layer overlaid with an RCA base layer. Around 30 points within each field section were evaluated using the NDG and non-nuclear devices. It is worth mentioning that due to the limitations of construction all field sections were tested at constant moisture content. In addition, moisture content samples were only collected for the first two field sections.

Table 17 - Target Moisture and Density Values Utilized for Compacting Aggregates.

Experiment	Level Tested	NAT-1	NAT-2	DGA	RCA
Effect of Moisture Content (%)	2% Below OMC	7.7	7.7	6.7	8.7
	Opt. Moist. Cont.	9.7	9.7	8.7	10.7
	2% Above OMC	11.7	11.7	10.7	12.7
Effect of Compaction Effort* (lbs./ft.^{3})	Below MDD	105	105	115	115
	Max. Dry Density	112	120	125	125
	Above MDD	120	135	145	130

* Moisture contents were kept constant at OMC

ANALYSIS OF LABORATORY TESTING RESULTS

Introduction

This chapter presents the results collected for samples compacted at different moisture contents and density levels. The effect of moisture content, compaction effort, delayed testing, and aggregate type on the test results measured using the NDG and non-nuclear devices are also discussed in this chapter. This chapter also presents the results of a multi-factor analysis of variance (MANOVA) conducted to evaluate the significance of these factors on the NDG and selected devices. It is worth mentioning that this analysis was performed using the Statistical Package for Social Sciences (SPSS). It is noted that all error bars shown in the figures below represent a 95% confidence interval of the mean.

Effect of Moisture Content

Figure 7 presents the results obtained from testing compacted samples prepared at different moisture contents using the NDG and selected non-nuclear devices. Figure 7a presents the density values obtained for all aggregate types. As can be seen from this figure, the NDG density values for samples compacted at moisture contents 2% above and 2% below OMC were lower than those compacted at OMC. This was expected since it is a similar trend that is seen in laboratory developed Proctor moisture-density relationships. This trend was observed only for NAT-2 and RCA aggregates. In the case of NAT-1 and DGA, the density values for samples at 2% above OMC were slightly higher (within 2 lbs./ft.^{3}) than those for samples compacted at OMC and 2% below OMC. Although this contradicts the expected moisture-density relationship trend, it is believed that the NDG might not be sensitive enough to capture differences in density when increasing/decreasing the moisture by 2%. The results presented in Figure 7a also show that the NDG measured densities for the NAT-1 samples compacted at OMC ranged from 105 to 112 lbs./ft.^{3}, which is overlapping with the results obtained for the 2% above OMC samples. The Proctor moisture-density relationships for this material also showed variability within 3 lbs./ft.^{3} when the moisture was increased/decreased by 2% higher or lower than OMC. A similar observation was made for DGA aggregates. The modulus results obtained using the BCD are presented in Figure 7b. As shown in this figure, the modulus values for NAT-1 and NAT-2 decreased with the increase in aggregates' moisture content. For DGA and RCA aggregates, the modulus values increased when the moisture content increased. These observations generally might indicate that the BCD was sensitive to the changes in moisture content within the samples. It is noted that the four modulus values, collected using the BCD from one location within the sample, varied significantly (between 5 and 35 MPa as shown in Figure 7b) for all aggregates. In addition, this high variability might be the reason why the DGA and RCA data is not showing a similar trend to that seen for NAT-1 and NAT-2. The modulus values (Figure 2b) for the natural sand materials (NAT-1 and NAT-2) and dense graded aggregates (DGA and RCA) were similar to each other. However, the modulus values of the sands (between 15 and 30 MPa) were significantly greater than the dense graded aggregates (between 7 and 11 MPa). These observations indicate that the BCD was able to capture differences between the aggregate types. The conclusions made from a study conducted by Weidinger et al. [4] suggest that the placement of the BCD must be near perfect to ensure accurate results; thus, explaining the different results obtained for DGA and RCA as these aggregates contain larger aggregate particles than the natural sand materials. In addition, Nazzal et al. [10] concluded that the BCD results might be affected when tested on very soft materials. Moreover, as can be seen from Figure 7c, NAT-1 and RCA had similar modulus values from LWD for all moisture contents (i.e., 2% below OMC, at OMC, and 2% above OMC). This might indicate that the LWD was not influenced by the changes (up to ±2% of OMC) in the samples' moisture content. In the case of NAT-2 and DGA, the LWD modulus values decreased with the increase in moisture content. For these particular aggregates, the results suggest that the LWD was able to capture the change in modulus as the moisture content increased. In addition to the factors considered (aggregate type and moisture content), it is noted that the results of the LWD might have been influenced by mold size; explaining the mixed trends observed. In literature, Nazzal et al. [10] reported the influence depth of the LWD ranges between 10.6 to 11 inches. The mold (12 inch thick and 17 inches wide) used in this study was larger than the influence zone determined by Nazzal et al. [10]; however, since it is not significantly larger (about 1 inch larger) the results might be influenced by the mold. Finally, the results presented in Figure 7c show that the LWD was capable of capturing the differences between samples prepared using the selected aggregates. Additional testing using samples compacted in larger molds were conducted. The results of these testing indicated that there is no significant difference between large mold and small mold LWD results. A complete discussion of these additional tests are presented in the following subsection.

Figure 7d presents the DCP number of blows required to penetrate the 1-ft. thickness of the compacted samples. As shown in this figure, the required DCP blow count for all aggregates were slightly decreasing (from 15 to 5 blows for DGA) with the increase in the samples' moisture content. This was expected due to the lubrication effect of the water, that helps reduce the friction resistance of the penetrating cone. This observation also suggests that the DCP might be influenced by the change in the moisture content (up to 2% below/above OMC). Figure 7d also shows that the DCP values for the two natural sand aggregates were lower than the dense graded aggregates (i.e., DGA or RCA). The natural sand materials had DCP values on between 1 and 6 blows while the DGA and RCA aggregates had values between 12 and 26. This was expected since the DGA and RCA aggregate consisted of larger sized particles and had a well-graded dense gradation. These observations indicate that the DCP is capable of capturing the difference between aggregates.

Overall, the results presented in Figure 7 suggest that the DCP was the only device that can be classified as statistically significant to capture all the differences between the compacted samples (i.e., capturing the effect of moisture content). The results for both the BCD and LWD devices were for the most part similar and were not influenced by the change in moisture content for up to ±2% from OMC.

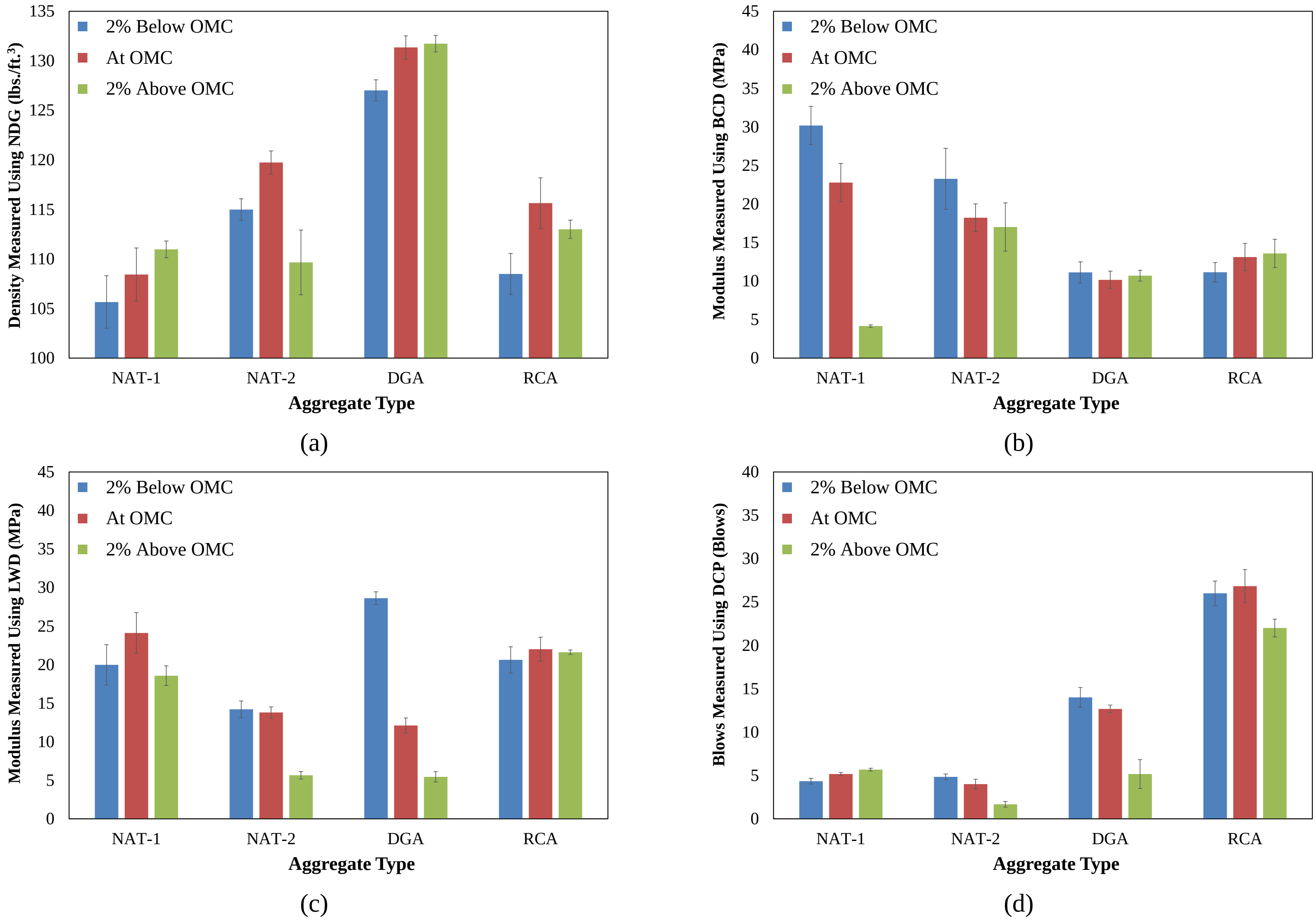


Figure 7. Effect of Moisture Content on Testing Results; (a) NDG Results, (b) BCD Results, (c) LWD Results; and (d) DCP Results.

Effect of Compaction Effort

Figure 8 presents the results from samples prepared at varying density levels (i.e., at MDD, above MDD, and below MDD). Figure 8a presents the NDG density results for all aggregate type considered. As can be seen from this figure, the NDG density values for all aggregate types were the lowest at density levels below MDD and highest at levels at above MDD. This was expected because the densities of the samples were increasing; therefore, the NDG values should have increased as well. The results also show, for all aggregates, that the differences between NDG density values at MDD levels and above MDD levels were within 3 lbs./ft^3. It should be noted; however, that when compacting samples for the above MDD density levels a jackhammer was used to ensure higher targeted densities were achieved. Therefore, the results might suggest that the NDG was not capable of capturing the differences between MDD and above MDD.

The BCD modulus values for the samples compacted using different compaction efforts are presented in Figure 8b. As shown in this figure, the modulus values for all density levels were relatively similar (i.e., within 5 MPa) indicating that the BCD was not able to capture the differences between the compaction efforts applied. In addition, by comparing the BCD modulus values for the natural sand materials (gap-graded) with the dense graded aggregates (DGA and RCA), it can be seen that NAT-1 and NAT-2 aggregates had similar modulus values (around 20 MPa) but different than those obtained for DGA and RCA aggregates (around 10 to 15 MPa). These observations might suggest that the BCD was able to capture the differences in aggregate size and gradation.

Figure 8c illustrates the LWD modulus values obtained for samples compacted at different density levels. As demonstrated in this figure, the trends observed were dependent on aggregate type. Meaning, the modulus values for the NAT-1 and NAT-2 (gap-graded) were higher for samples compacted at MDD than those below MDD. This was expected since modulus increases as the compaction effort applied increases. In the case of DGA and RCA (dense graded) the modulus values obtained for samples compacted at MDD and below MDD were similar (i.e., within 5 MPa). This might suggest that the LWD is influenced by the aggregate type. As observed from the LWD results obtained by varying moisture, NAT-2 and DGA modulus values decreased with an increase in compaction effort. Based on these findings, it is concluded that the LWD is able to detect changes in compaction effort. In the case of NAT-1 and RCA modulus values increased as compaction increased. These results suggest that the LWD was able to capture the change in modulus with an increase in compaction. As previously mentioned, the mixed trends obtained at above MDD might be attributed to the LWD being influenced by mold size.

The DCP number of blows required to penetrate the 1-ft. thick samples are shown in Figure 8d. As can be seen from this figure, the DCP blows increased with the increase in compaction effort for all aggregates; indicating that the DCP was capturing the differences in compaction levels applied. This trend was expected because the denser the aggregate structure is the harder (i.e., higher number of blows) it is to penetrate. It can also be observed from Figure 8d that the DCP values obtained for the natural sand aggregates were lower than those obtained for the dense graded aggregates. This difference is more significant at higher compaction levels than lower compaction levels.

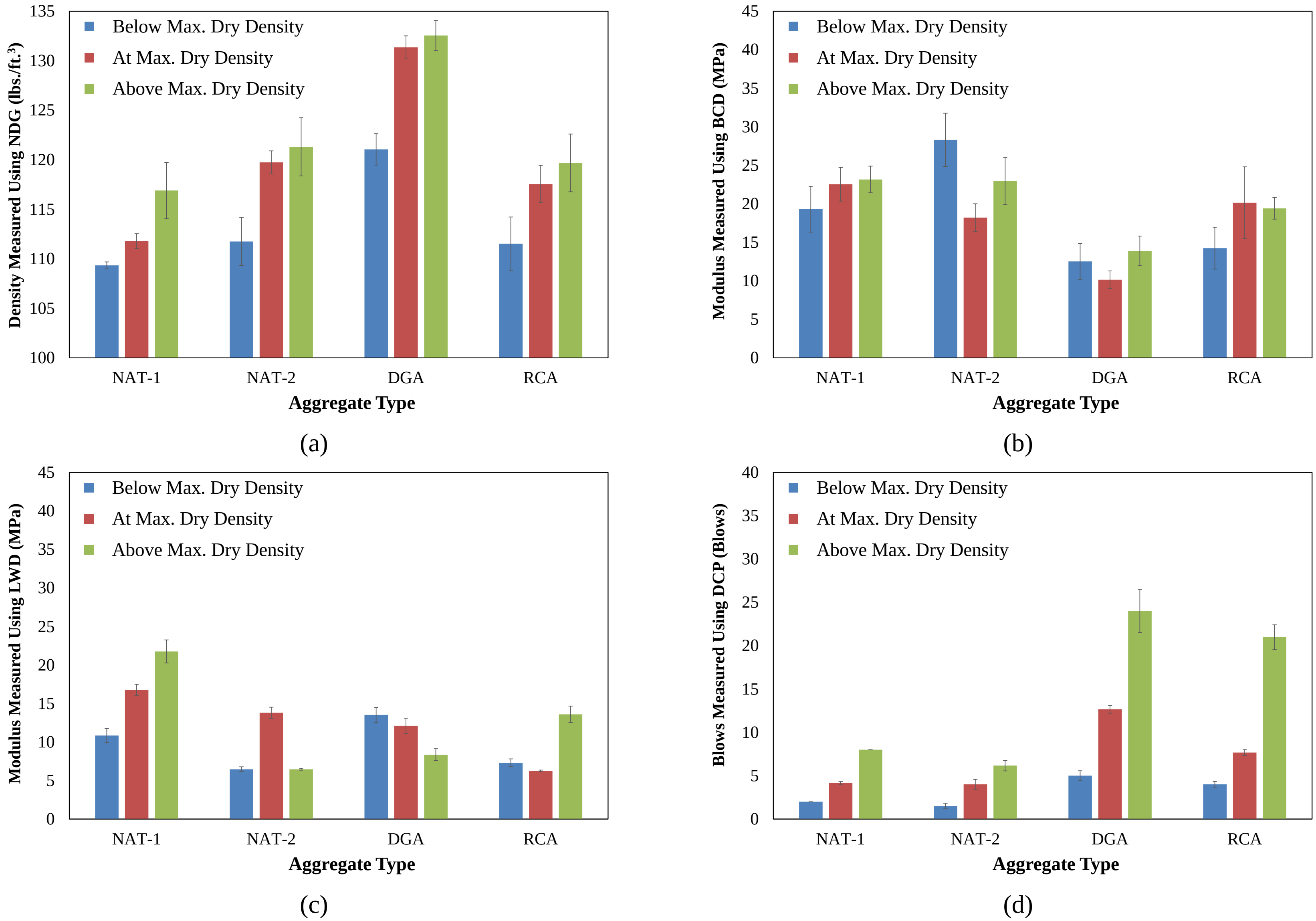
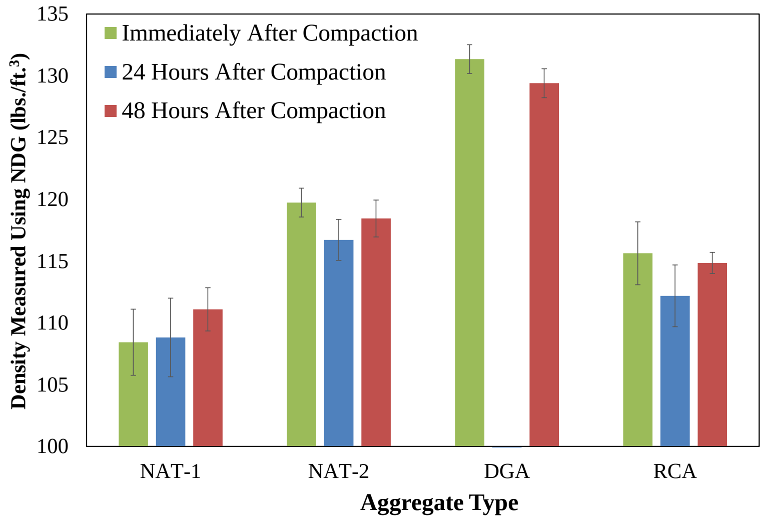


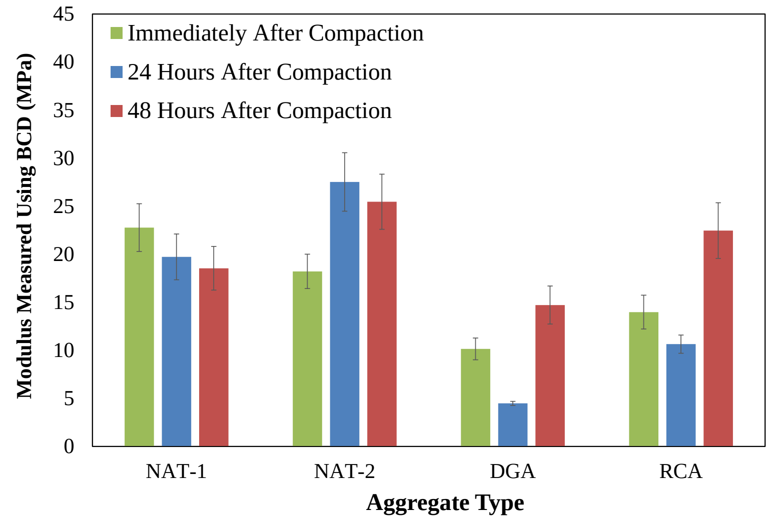
Figure 8. Effect of Compaction Effort on Testing Results; (a) NDG Results, (b) BCD Results, (c) LWD Results; and (d) DCP Results.

Based on these observations, it is concluded that the DCP was capable of capturing the difference between the aggregate types.
In summary, similar to the discussion presented for the effect of moisture content, the results presented in Figure 8 show that the DCP appears to be the most sensitive of the three non-nuclear devices to the different compaction efforts applied. Both the BCD and LWD did not capture these differences.

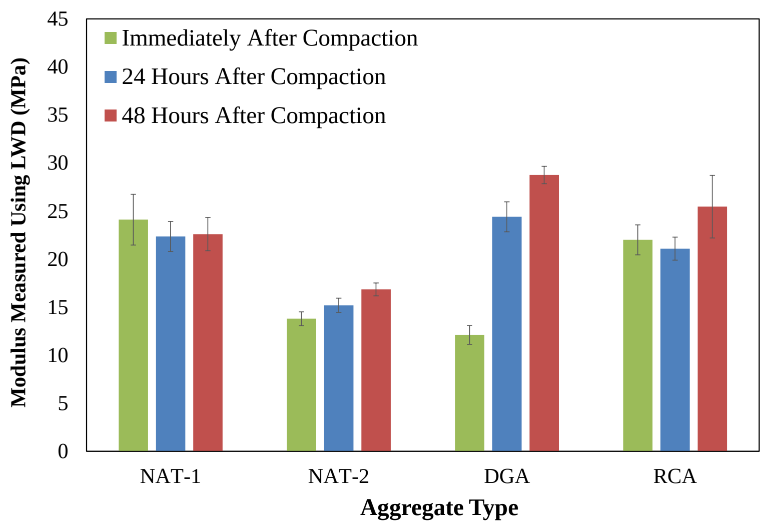
Effect of Testing Time on Accuracy and Repeatability of Selected Devices
The results for samples compacted at OMC/MDD and tested immediately after compaction, 24 and 48 hours after compaction for the all devices are presented in Figure 9. As can be seen from Figure 9a, the density values for all testing times were relatively similar (i.e., within 5 lbs./ft.^{3}) with a slight increase in density as testing was delayed. This was the case for all aggregate types and might be mainly attributed to the migration of water to the bottom of the samples. To elaborate more, the aggregates are uniformly mixed with water before compaction using a concrete mixer. After one or two days of compaction, the water uniformly distributed (at the time of compaction) within the sample might seep to the bottom of the mold due to gravity; explaining the slight increase in density as measured using the NDG. These observations strongly suggest that the NDG was capable of reproducing results between testing days and was not influenced even if used for testing samples compacted 48 hours earlier. Furthermore, it is noted that NDG testing for DGA aggregates was only conducted immediately and 48 hours after compaction. This was because the NDG and the certified technician were not available for that particular day.
The BCD modulus values for testing at different days are presented in Figure 9b. As shown in this figure, the modulus values obtained immediately after compaction were either higher or lower than those obtained through testing 24 hours and 48 hours after compaction depending on the aggregate type. This mixed trend in the results coupled with the high variability of the BCD (i.e., obtaining modulus values ranging from 5 to 35 MPa for the same location) might be the reasons behind these observations. Nonetheless, the results presented in Figure 4b indicate that the BCD was unable to replicate results due to the influenced of testing time. Therefore, it might be necessary to conduct field testing immediately after compaction in order not to over or underestimate the modulus of the sample.
Figure 9c presents the LWD modulus values obtained for samples tested immediately, 24 and 48 hours after compaction. As illustrated in this figure, the modulus values for were either relatively similar or having an increasing trend (with the further delayed testing) depending on the aggregate type. This observation might be attributed to the migration of moisture to the bottom of the sample and effect of mold edges on the LWD. The results in general indicate that the LWD could reproduce similar modulus results time after time, however the device might be influenced by testing time. Similar to the BCD, it is recommended to conduct LWD testing immediately after compaction to avoid overestimating the modulus values.



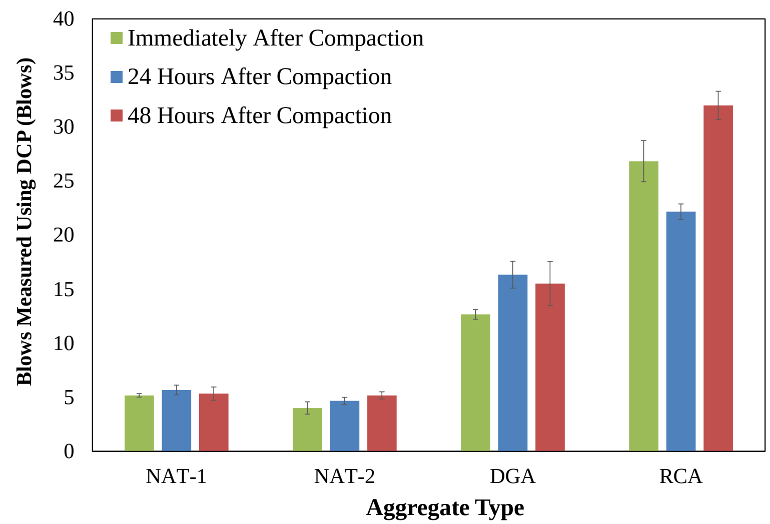
(a)



(b)



(c)



(d)

Figure 9. Effect of Delayed Testing on Results; (a) NDG Results, (b) BCD Results, (c) LWD Results; and (d) DCP Results.

The DCP number of blows obtained for samples tested at various days is presented in Figure 9d. This figure shows the DCP values obtained immediately, 24 and 48 hours after compaction for the natural sand aggregates were relatively similar (within 1 blow). These results suggest that the DCP could reproduce results up to 48 hours. For the DGA and RCA materials an increase in DCP values can be seen (Figure 9d) as the testing delay time is increased. These observations, again, might be attributed to the migration of water to the bottom of the mold and the higher permeability for DGA and RCA samples. Since the DGA and RCA aggregates have higher permeability, the water within the sample will seep faster to the bottom of the mold; thus, explaining the increase in DCP values needed to penetrate the 1-ft. thick mold. These observations suggest conducting DCP testing immediately after compaction for high permeability aggregate and up to 48 hours after compaction for low permeability aggregates. It is recommended; however, to conduct DCP testing in the field immediately after compaction in order to avoid overestimating the measured values.
The numbers of blows required to penetrate the 1-foot (30.5-cm) thick samples using the DCP over time is presented in Figure 9d below. The results presented in the figure show that the DCP values obtained for NAT-1 and NAT-2 aggregates immediately, 24 hours, and 48 hours after compaction were relatively similar (i.e., within 1 blow). The results obtained for both natural sand samples indicate that the DCP is capable of reproducing results up to 48 hours following compaction. Herath et al. [8] made similar conclusions in that the DCP was able to replicate the testing results on different soils types and locations.

Effect of Mold Size on LWD Testing Results
Additional testing was conducted on by compacted aggregates in a large mold (36 inch in diameter and 24 inch in height), shown in Figure 10, in order to evaluate the effect of mold size on testing result as obtained from the LWD. This additional testing also involved comparing the results of the NDG to another alternative device developed by Troxler Electronic Labs, Inc. (i.e., E-Gauge). It is important to note that the additional testing was only conducted using Nat-2 and RCA compacted materials.

Figure 10. Large Mold Utilized for Evaluating the Effect of Mold Size.

Tables 18 and 19 present LWD and E-Gauge testing results obtained from small and large molds respectively. As can be seen from Table 18, the LWD results obtained from the small mold (i.e., mold used in conducting the majority of testing) were relatively similar to those obtained from large mold samples. This was the case for both materials types considered for this additional testing (NAT-2 and RCA). These observations suggest that mold size did not have an impact on the LWD testing results. In addition to evaluating the impact of mold size on LWD testing results, the E-Gauge was utilized to conduct additional testing. Table 19 below present the results obtained from the E-Gauge and the traditional NDG. As shown in this table, density values obtained from the E-Gauge were, on average, higher than those obtained from the NDG. This result might indicate that the E-Gauge overestimated the density of compacted samples. However, since minimal testing was conducted using the E-Gauge this observation should not be considered a conclusive outcome.

Table 18 - LWD Testing Results Obtained for Large and Small Molds.

	Nat-2		RCA	
	LWD Large Mold (MPA)	LWD Small Mold (MPA)	LWD Large Mold (MPA)	LWD Small Mold (MPA)
	5.45	6.053	11.84	14.5
	6.28	7.943	12.01	14.4
	5.48	6.053	16.04	13.5
	8.1	7.403	23.86	13.3
	7.95	5.923	18	14.0
	6.59	7.830	21.59	15.2
Avg.	6.6417	6.8678	17.2233	14.1622
StDev	1.1612	0.9580	4.9250	0.7066

Table 19 - E-Gauge Testing Results Obtained for Large and Small Molds.

	Nat-2		RCA	
	NDG (PCF)	E-Gauge (PCF)	NDG (PCF)	E-Gauge (PCF)
	120	126.400	114.9	130.3
	118.3	128.800	113.9	129.8
	119.9	129.500	114.4	128.5
	117.3	128.400	118.8	117.3
	112.9	122.400	121.7	111.2
	120.8	125.700	113.3	111.3
Avg.	118.2000	126.8667	116.1667	121.4000
StDev	2.8914	2.6288	3.3357	9.1983

Precision of Measurements

The standard error of the mean (SEM) was calculated for data collected immediately after compaction and it was determined as a percentage of the mean (Table 20). The SEM was based on the standard deviation (STD) of results at each moisture content tested (i.e. 2% below, at OMC and 2% below) divided by the square root of the total amount of replicates measured from each device. In our case, we had six measurements. The SEM provides insight on the variability of the sample mean. The data showed that the variability of all non-nuclear devices were similar (range of 5-8%) to each other. However, they were greater than that of the Nuclear Density Gauge, which had a standard error of the mean of 1%. In addition, the variability at different moisture contents was similar for NDG, BCD and LWD. On the other hand, DCP blows at 2% above OMC had slightly variability (by an algebraic difference of 6%). This indicates that moisture content within 2% of OMC has minimal impact on measured values, except in the case of DCP where excess moisture causes the DCP blows to become more variable.

Table 20 - Standard Error of the Mean of the Results Measured from all Devices (Expressed as a Percent of the Mean Value).

	Standard Error of the Mean of NDG, %			**Average Error of All Materials, %**
	2% Below	OMC	2% Above	1%
NAT-1	2%	2%	1%	
NAT-2	1%	1%	2%	
DGA	1%	1%	0%	
RCA	1%	2%	1%	
Average	1%	1%	1%	
Standard Error of the Mean of BCD, %				
	2% Below	OMC	2% Above	8%
NAT-1	6%	8%	3%	
NAT-2	12%	7%	13%	
DGA	9%	8%	5%	
RCA	8%	10%	10%	
Average	9%	8%	8%	
Standard Error of the Mean of LWD, %				
	2% Below	OMC	2% Above	5%
NAT-1	9%	8%	5%	
NAT-2	5%	4%	6%	
DGA	2%	6%	9%	
RCA	6%	4%	1%	
Average	6%	5%	5%	
Standard Error of the Mean of DCP, %				
	2% Below	OMC	2% Above	7%
NAT-1	5%	2%	2%	
NAT-2	5%	10%	14%	
DGA	6%	3%	23%	
RCA	4%	5%	3%	
Average	5%	5%	11%	

DEVELOPMENT OF DCP MULTIPLE LINEAR REGRESSION MODEL

Introduction

The development of a multiple linear regression model to predict field DCP blow counts is presented in this chapter. This chapter also discusses minimum DCP acceptance requirements established based on the developed DCP prediction model. A comprehensive discussion of the step-by-step process followed to develop the prediction model is also presented in this chapter.

Separation of Collected Laboratory Data

The first step in developing the prediction model involved separating the laboratory testing results collected from the NDG and selected devices. The collected data in this study consisted of 134 total points that were separated into two groups. The data was separated by first randomly assigning each point with an appropriate identification number. A random table generator in Excel was then utilized to randomly select the first group of data points. The first set of data selected contained about 60% (i.e., 80 points) of the original data. This set of data served as the foundation for developing the model. The second group of data consisted of the remaining 40% (i.e., 54 points) that were used to validate the developed prediction model.

Model Formulation

The next step was to formulate an initial DCP prediction model using 60% of the collected data. The initial prediction model formulated was based on several factors that included: (1) density, measured using the NDG, (2) difference between the actual moisture content and the OMC of the sample, (3) day of testing, (4) aggregate bulk specific gravity, and (5) aggregate gradation, represented by percent passing the No. 4 sieve and percent passing the No. 200 sieve. The difference in moisture content between the actual moisture content measured and the OMC was used to ensure capturing the correct physical behavior of the DCP in that the required number of blows increase/decrease with an increase/decrease in the aggregate moisture content.

It is noted that prior to developing the model, the DCP values were normalized by depth of compacted samples. This method was performed in order to account for the thickness of the sample. In addition, this procedure proved necessary when laboratory predicted DCP values were correlated to those collected through field testing in the following sections. Notice that the scale in which laboratory testing was conducted for this study was much smaller to that in which field testing was performed. Therefore, normalizing the DCP values by depth allowed both laboratory and field values to be adequately correlated to one another. Based on the factors considered, an initial DCP prediction model was established and is presented in Equation 2 below.

$$\boldsymbol{Y = AX_1 + BX_2 + CX_3 + DX_4 + EX_5 + FX_6 + G} \qquad \text{Equation 2}$$

Where:

$\mathrm{A, B, C, D, E, F \text{ and } G}$ = Model parameters

Y = Predicted DCP blow values (blows/inch.)

$\mathrm{X_1}$ = Sample density, lbs./ft.^{3}

X_2 = Moisture content difference, %

$\mathrm{X_3}$ = Testing day

X_4 = Aggregate dry bulk specific gravity
X_5 = Cumulative percent passing sieve No. 4, %
X_6 = Cumulative percent passing sieve No. 200, %

Development of Revised Model

Table 21 below presents the results of the regression analysis performed using the initial DCP prediction model established in Equation 2. The results presented in this table include the considered model parameters previously discussed and the corresponding significance value associated with each factor. As can be seen from the analysis, the moisture content difference had a significant impact on the model (α = 0.001). In addition, aggregate gradation, represented by percent passing No. 4 and No. 200 sieves, also had significant impacts on the developed model ($\alpha < 0.05$). However, density measured using the NDG, as well as testing day and aggregate bulk specific gravity did not have significant impacts on this model ($\alpha > 0.05$). Based on the results presented in Table 21, the insignificant factors were removed from the initial model. A regression analysis was conducted on the revised prediction model (Table 21). As can be seen in the table, moisture content difference and aggregate gradation remained significant on the revised model ($\alpha < 0.05$).

In order to determine if the revised model was able to capture the real physical behavior of the DCP it was necessary to study the values associated with the model parameters utilized for its development. As can be seen in Table 21, moisture content difference (coefficient B) had a value of -0.107. This value suggests that as the moisture content difference increases for the sample, the required number of DCP blows will decrease. In other words, if the actual measured moisture content is higher than OMC then the number of blows required to penetrate the soil will decrease. Similarly, as the moisture content difference decreases (i.e., actual moisture content is below OMC) the number of blows needed to penetrate the sample will increase. This trend was expected as a result of the lubricating effect water has on the DCP. To further elaborate, as the water in the sample increases, the frictional resistance of the penetrating cone will decrease; therefore the number of blows needed to penetrate the soil is expected to decrease. It is worth mentioning that this trend was consistent with the observations made when the DCP was tested on laboratory samples prepared at varying moisture contents.

Moreover, the coefficient associated with percent passing sieve No. 4 (coefficient E) is -0.022. In the case of the percent passing No. 200 sieve (coefficient F), the parameter value was 0.429. These values indicate that the amount of materials passing the No. 4 sieve increases with a decrease in predicted DCP values. An opposite trend is observed for the other gradation parameter (% passing sieve No. 200); as materials passing the No. 200 sieve decreases with the predicted DCP values increase. These trends were expected because materials passing the No. 4 sieve contain more fine particles than material passing the No. 200 sieve, therefore the finer the material the lower frictional resistance applied to the penetrating cone. A lower frictional resistance will result in a lower number of blows needed to penetrate the material. These observations were also made when the laboratory testing results were compared for the well-graded aggregates (NAT-1 and NAT-2) and the dense-graded aggregate (DGA and RCA). The results of the laboratory tests showed that both natural sand materials (NAT-1 and NAT-2) required less blows than the DGA and RCA materials.

As can be seen in Table 21 the initially developed model had an R-squared value of approximately 60%. The revised model, however, had an R-squared of 56%. The slight decrease in the R-squared values between the models can be attributed to the removal of the insignificant factors from the initial model. As mentioned above, the density measured using the NDG, testing day, and aggregate bulk specific gravity did not have significant impacts on the initial prediction model; therefore, the slight reduction in the R-square value can be considered insignificant as well. Based on the observations made for both the initial and revised model it can be concluded that the model developed adequately captures the physical behavior of the DCP.

Table 21 - Initial and Revised DCP Prediction Models.

Initially Developed Model			
Model Parameters	**Parameter Value**	**t-value**	**α -value**
A: NDG Density	0.004	0.894	0.374
B: Moisture Content Diff.*	-0.115	-3.324	0.001
C: Testing Day	0.132	1.975	0.052
D: Agg. Specific Gravity	-2.410	-0.853	0.397
E: % Passing Sieve No. 4	-0.022	-4.350	0.000
F: % Passing Sieve No. 200	0.429	2.391	0.019
G: Constant	7.471	1.057	0.294
Model R^2	58.9%		
Revised Model			
Model Parameters	**Parameter Value**	**t-value**	**α -value**
B: Moisture Content Diff, %	- 0.107	-3.302	0.001
E: % Passing Sieve No. 4	- 0.025	-7.034	0.000
F: % Passing Sieve No. 200	0.264	2.630	0.010
G: Constant	2.210	8.218	0.000
Model R^2	56.0%		

The final model developed for predicting DCP blow values is as follows:

$$\mathbf{Y = -0.107X_2 - 0.025X_5 + 0.264X_6 + 2.210} \quad \text{Equation 3}$$

Where:
Y = Predicted DCP blow values (blows/inch.)
X_2 = Moisture content difference, %
X_5 = Cumulative percent passing sieve No. 4, %
X_6 = Cumulative percent passing sieve No. 200, %

Attempts to Improve Final Prediction Model

Once the final DCP prediction model was developed, attempts were made to improve the model. As mentioned in the previous sections, the prediction model required separating the collected laboratory data from the NDG and selected non-nuclear devices into two groups that aided the development and validation stage of the prediction model. The first set of data selected contained about 60% (i.e., 80 points) of the original data and the second set composed of the remaining 40% (i.e., 54 points) of the laboratory data.

In order to improve the developed DCP prediction model, additional data separation combinations were evaluated. The first attempt at improving the final model involved splitting the collected laboratory data into two groups; 80% (i.e., 107 points) for model development and 20% for model validation. A regression analysis was then performed, using the same significant factors discussed above, and the results are presented in Table 22 below. As can be seen from this table, all factors were significantly influenced the DCP prediction model ($\alpha < 0.05$). In addition, the coefficients associated with each model parameter followed the same trend as the previously established model (Equation 3). However, the R-squared value decreased from 56% to 47% when 80% of the original data was utilized to develop the model.

Table 22 - Prediction Model Using 80% of Data.

Model Attempt 1 Using 80% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	-0.907	0.026
E: % Passing Sieve No. 4	-0.303	0.000
F: % Passing Sieve No. 200	2.773	0.023
G: Constant	26.994	0.000
Model R^2	47%	
Model Attempt 2 Using 80% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	-0.667	0.094
E: % Passing Sieve No. 4	-0.336	0.000
F: % Passing Sieve No. 60	0.62	0.192
G: Constant	28.191	0.000
Model R^2	46%	
Model Attempt 3 Using 80% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	-0.69	0.122
E: % Passing Sieve No. 60	-5.126	0.000
F: % Passing Sieve No. 100	9.507	0.000
G: Constant	16.315	0.000
Model R^2	35%	
Model Attempt 4 Using 80% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	-0.408	0.381
E: % Passing Sieve No. 60	-2.844	0.001
F: % Passing Sieve No. 200	11.192	0.000
G: Constant	15.004	0.000
Model R^2	27%	

Three additional attempts were made to improve the final model by varying aggregate gradation parameters. For these attempts, 80% of the original data was utilized for developing the model; however, rather than using percent passing No. 4 and No. 200 sieves, different gradation combinations were introduced into the model. The aggregate gradation combinations included: (1) percent passing the No. 4 and No. 60 sieve, (2) percent passing the No. 60 and No. 100 sieve, and (3) percent passing the No. 60 and No. 200 sieve. The results of the regression analysis performed on these models are presented in Table 22 below. As can be seen in the table the coefficients associated with each model parameter were consistent with the final prediction model. However, the moisture content difference was not significant on any of the models ($\alpha > 0.05$). In addition, the R-squared values for these models fell below 50%.

The second attempt made to improve the final DCP prediction model involved using 70% (i.e., 94 points) of the collected laboratory data. The results of the regression analysis performed on the model are presented in Table 23 below. All factors were significant on the model ($\alpha < 0.05$). However, the coefficients associated with the model parameters were not consistent with the final prediction model established in Equation 3. That is, the moisture content different (coefficient B) had a value of 1.483. This value indicates that as the moisture content difference increases for the sample, the number of DCP blows will increase. If the moisture in the sample increases the frictional resistance of the penetrating cone will decrease therefore, the number of DCP blows should decrease. In addition, the R-squared value decreased from 57% to 50% when 70% of the original data was utilized for developing the model.

Based on these results, it can be concluded that the final prediction model presented in Equation 3 was the most capable of predicting DCP values. In addition, the model was able to capture the real physical behavior of the DCP. Therefore, the model formulated in Equation 3 would serve as the final DCP prediction model for developing a proposed minimum DCP acceptance criteria that would ensure satisfactory field compaction quality of subgrade and base/subbase layers during pavement construction.

Final Model Validation

Once the final prediction model was developed it was necessary to validate the model. As discussed in this chapter, laboratory testing results were separated into two groups. The first set of data, consisting of 60% of the original data, facilitated the development of the model discussed above. The second group consisted of the remaining 40% of data that were used to validate the final model. Validation of the model was completed by first predicting the field DCP values based on the considered factors (i.e., moisture difference, percent passing sieve No. 4, and percent passing sieve No. 200). The predicted DCP blows for each aggregate type were then plotted against the measured DCP blows in Figure 11a below. It should be noted that an equality line between the measured and predicted DCP values is also displayed in the figure.

Based on the results presented in Figure 11a it is observed that the prediction model, on average, overestimated the DCP blows up to 1.25 blows/inch. This is the case because the majority of predicted values fell above the equality line. Since the values presented in this portion of the figure cover both natural sand materials (NAT-1 and NAT-2) it can be concluded that the developed model overestimated the DCP values for fine materials. In addition, the results presented in Figure 10a indicate that the prediction model underestimated DCP values for more coarse materials. This observation was made since the predicted values fell below the equality line for DCP values greater than 1.5 blows/inch.

Table 23 - Prediction Model Using 70% of Data.

Model Attempt 1 Using 70% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	1.483	0.000
E: % Passing Sieve No. 4	-0.306	0.000
F: % Passing Sieve No. 200	1.965	0.000
G: Constant	27.618	0.000
Model R^2	50%	
Model Attempt 2 Using 70% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	1.225	0.002
E: % Passing Sieve No. 4	-0.332	0.000
F: % Passing Sieve No. 60	0.204	0.665
G: Constant	29.686	0.000
Model R^2	49%	
Model Attempt 3 Using 70% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	1.382	0.003
E: % Passing Sieve No. 60	-5.03	0.000
F: % Passing Sieve No. 100	9.139	0.000
G: Constant	16.27	0.000
Model R^2	36%	
Model Attempt 4 Using 70% Data		
Model Parameters	**Parameter Value**	**α -value**
B: Moisture Content Diff, %	1.159	0.017
E: % Passing Sieve No. 60	-2.78	0.001
F: % Passing Sieve No. 200	10.763	0.000
G: Constant	14.716	0.000
Model R^2	26%	

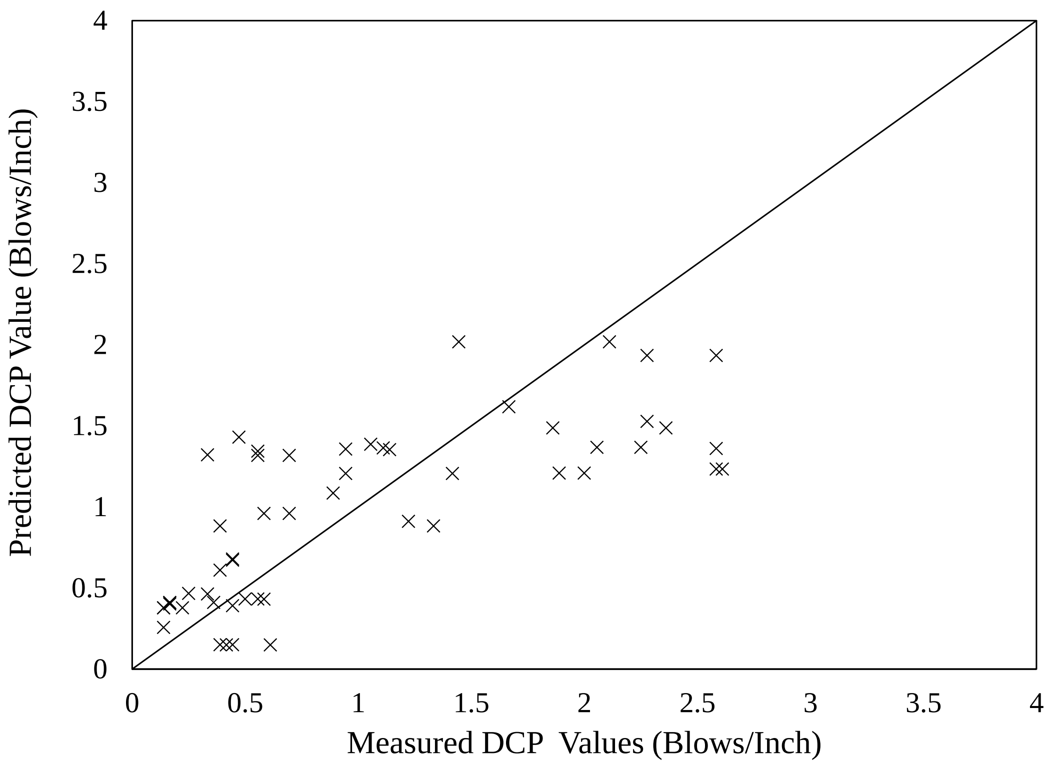
As illustrated in Figure 11a, the variation (points scatter) of the plotted data around the equality line is relatively low for the fine aggregates (i.e., lower than 1.5 blows/inch.) when compared to coarse aggregates (i.e., greater than 1.5 blows/inch.). The trend was expected since the variability of the results obtained for the coarse aggregates (i.e., DGA and RCA) was greater than those obtained for the finer aggregates (i.e., NAT-1 and NAT-2). Nonetheless, the overall distribution of DCP values around the equality line is generally uniform. Based on these observation, it can be concluded that the final DCP model developed effectively predicted the measured DCP values.

In order to further validate the ability of the model at accurately predicting the measured DCP values, the absolute relative error for all the data points was calculated as the absolute difference between the predicted and the measured DCP values. The frequency distribution of the computed relative error values is presented in Figure 11b. The high variability within the data is mainly attributed to the natural non-uniformity of the soils/aggregates considered in this study. The results presented in Figure 11b also show that the majority of the predicted values (around 75% of the points) have an error less than 0.5 blows per inch. This observation also supports the hypothesis that the model is capable of predicting the measured DCP values.

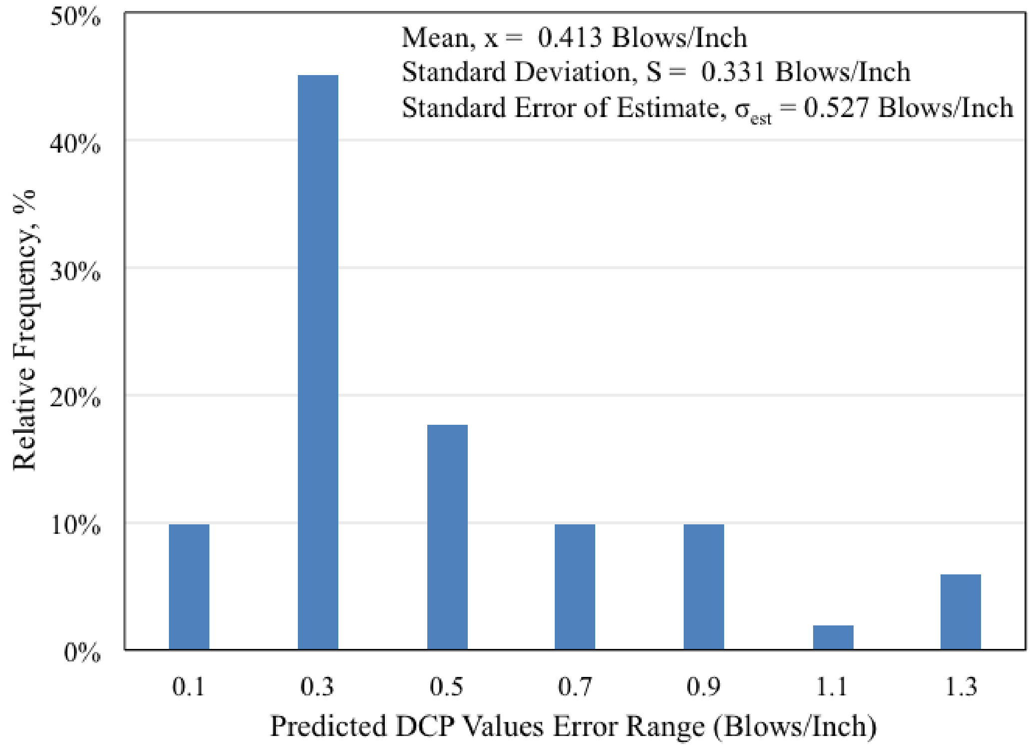
Calibration of Final Prediction Model Using Field Data

As mentioned previously, the compaction quality of three field sections was evaluated using the DCP and the NDG. The data collected from these sections was used to calibrate the laboratory based DCP prediction model. This calibration procedure was necessary because major differences exist between the controlled laboratory environment and the more variable field environment. For example, the moisture content in the field might not be as uniform as that controlled in the laboratory. Therefore, it is of highest importance to calibrate the model using field data.

The model calibration procedure involved categorizing the collected field data into four groups based on aggregate type. This was implemented because the DCP values are dependent



(a)



(b)

Figure 11. Verification of DCP Prediction Model; (a) Predicted vs. Measured DCP Values; and (b) Distribution of Relative Error Values.

on the aggregate type evaluated. To elaborate more, the DCP values for fine aggregates are lower than those for coarse aggregates. As a result, it was essential to calibrate the model by introducing an aggregate specific correction factor that would correct the laboratory based DCP predictions. Accordingly, for each aggregate type, DCP values were predicted based on the moisture content measured in the field and the aggregate gradation characteristics (% passing sieve No. 4 and No. 200). It is noted; however, that field moisture content samples were only collected for the DGA aggregates. This was mainly because of the limited amount of time that was allowed for the testing crew to conduct DCP and NDG testing in the field. In addition, the subgrade layers (i.e., those constructed using NAT-1 and NAT-2 aggregates) were not accessible because they were overlaid with a base layer before testing. Therefore, the moisture content was difficult to obtain without introducing a defect into the compacted layers. For the layers in which moisture content samples were not collected, the moisture content was assumed to be zero (completely dry). Through visual inspection it was also determined that the compacted aggregates were dry. This coupled with the results obtained for the DGA (moisture content ranging between 1.5 and 2.0%) suggest that this assumption is valid.

A correction factor for each material was computed as the ratio of the average field measured DCP value to the average predicted DCP value. Figure 12 presents an example of the computational procedure utilized for determining the correction factor for NAT-1 aggregates. As illustrated in Figure 12, the model was corrected by multiplying the correction factor with all the terms in the laboratory-based model. A similar procedure was utilized for determining the correction factors for all other aggregate types. Equation (4) presents the modified model along with the values of the correction factors for each aggregate type.

$$\mathbf{Y} = \boldsymbol{\beta}(-\mathbf{0.107X_2} - \mathbf{0.025X_5} + \mathbf{0.264X_6} + \mathbf{2.210}) \qquad \text{Equation 4}$$

Where:

Y = Predicted DCP blow values (blows/inch.)

β = Aggregate material field correction factor (For NAT-1 use 1.785, for NAT-2 use 1.522, for DGA use 1.776 and for RCA use 2.857)

X_2 = Moisture content difference, %

X_5 = Cumulative percent passing sieve No. 4, %

X_6 = Cumulative percent passing sieve No. 200, %

The correction procedure discussed above was implemented because the field DCP measured values were uniform and did not change significantly from one location to another. For example, the DGA field sections had an average DCP field value that ranged, based on a 95% confidence level (average = 3.327, standard deviation = 1.17 blows/inch, and sample size = 121), between 3.118 and 3.537 blows/inch. This range clearly indicates that the collected data were uniform and did not have significant deviation from the mean. Similar results were obtained for all other sections. Therefore, all the values collected in the field for a particular aggregate type were considered as one point (i.e., the average value).

Recommended Minimum DCP Acceptance Criteria

The developed and calibrated DCP prediction model was a step towards replacing the NDG when evaluating the compaction quality of subgrade and base/subbase layers constructed using soils or aggregates. Specifically, the model can be used to identify limiting DCP values that would ensure satisfactory field compaction. It is worth mentioning that the NDG data collected provided evidence that the field sections were meeting the NJDOT compaction quality requirements (i.e., the density was higher than 95% of the Proctor MDD). Therefore, all the recommended DCP limiting values will qualify as the minimum DCP requirements for ensuring satisfactory field compaction of subgrade and aggregate base/subbase layers.

The procedure for determining the recommended DCP minimum values is illustrated in Figure 13 for New Jersey soil aggregates (or subgrade natural sands). According to NJDOT specifications, these soil aggregates follow gradation designations I-1 through I-15. As can be seen from Figure 13, the variability in the moisture content difference, percent passing No. 4, and percent passing No. 200 was considered when determining the minimum DCP values. The consideration of the variability in these factors was necessary for recommending practical DCP values. Figure 13 shows that the values selected for the percent passing sieve No. 200 were varied from 0 to 4%. The selection of these particular input values was based on the allowable range of values specified by the NJDOT for this sieve.

Currently, NJDOT specifies a range between 0 to 8% of soil aggregates (NAT-1 and NAT-2 in this study) passing sieve No. 200. The selected values represent the minimum (i.e., 0%) and the average of the maximum and minimum values (i.e., 8 and 0) of the control range. In addition, the example presented in Figure 13 shows that the input values for the percent passing sieve No. 4 were varied within the range of 70 to 85%.

Similar to the sieve No. 200 factor, these values were selected based on the control range for sieve No. 4 (i.e., between 40 and 100% with an average of 70%) in natural sands. The input values for the percent passing sieve No. 4 and sieve No. 200 were determined using a similar procedure for the DGA and RCA aggregates.

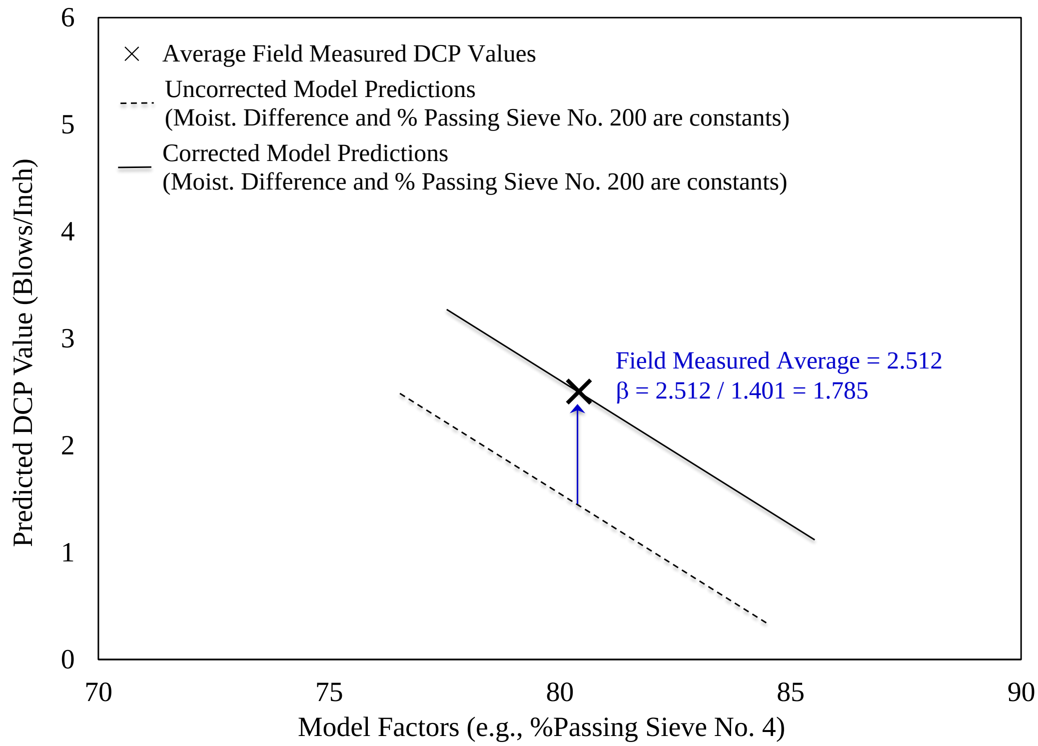


Figure 12. Computational Procedure Utilized for Computing NAT-1 Aggregates Field Correction Factor.

As presented in Figure 13, the minimum DCP value for natural sand having moisture content between OMC and 2% lower than OMC (i.e., 0 and -2% moisture difference) was approximately 1.62 blows for every inch of penetration. This value was computed as the overall average of all predicted DCP values. Recommending an average DCP value as a minimum requirements rather than taking the absolute minimum or the maximum value balances the risk between the contractor and the agency. Using the concept explained above, minimum DCP values were calculated for the four aggregate types, different moisture contents, and different aggregates gradations (shown in Table 24). It is noted; however, the minimum DCP values for the natural sands (i.e., NAT-1 and NAT-2) were averaged. The same procedure was also applied to dense graded aggregates (DGA and RCA). This was implemented to simplify the recommended specifications.

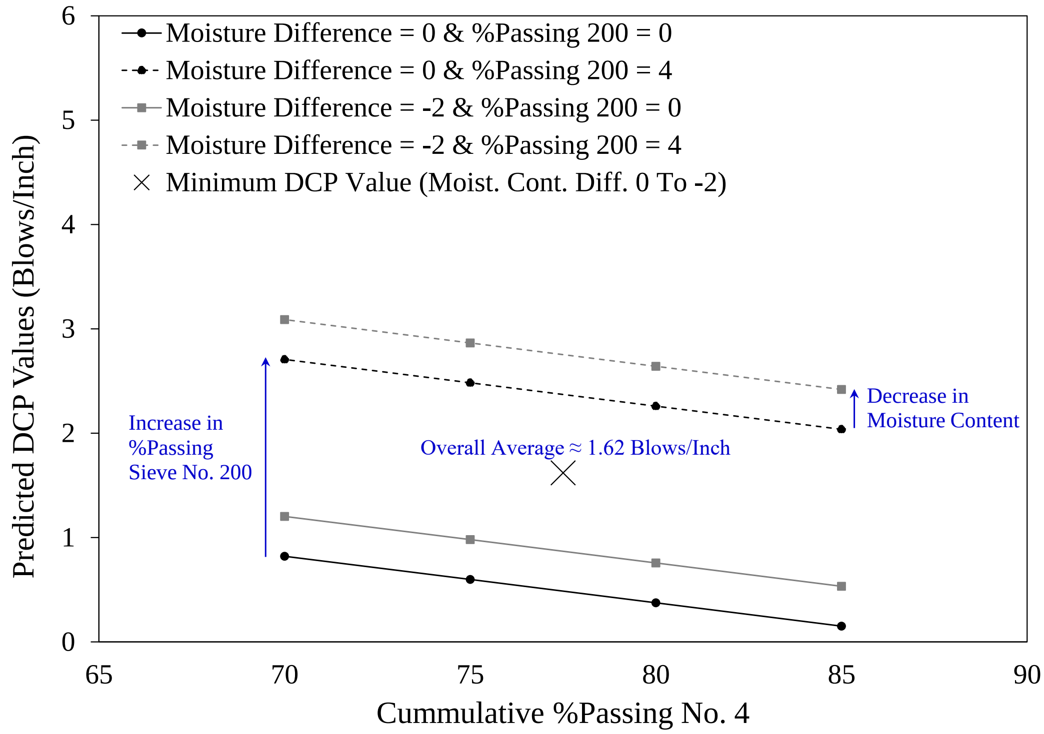


Figure 13. Example of Computed Minimum DCP Value for NJDOT NAT-1 Aggregates.

Table 24 - Recommended Minimum DCP Values for Ensuring Satisfactory Field Compaction.

Aggregate Type	Model Input Values						Recommended Minimum DCP Value (Blows/Inch)	Recommended Minimum DCP Blows for (1-ft layer) (rounded to the nearest 5 DCP blows)
	%Passing Sieve No. 4		%Passing Sieve No. 200		Moist. Cont. Diff. (%)			
	Min	Max	Min	Max	Min	Max		
NJDOT soil aggregates (NAT-1 & NAT-2)	70	85	0	4	0	2	1.3	16 (15)
	70	85	0	4	-2	0	1.5	18 (20)
	70	85	0	4	-4	-2	1.9	23 (25)
	70	85	0	4	-6	-4	2.2	27 (25)
	70	85	0	4	-8	-6	2.6	32 (30)
	70	85	0	4	-10	-8	2.9	35 (35)
NJDOT dense graded aggregates (DGA & RCA)	30	45	0	4	0	2	3.2	39 (40)
	30	45	0	4	-2	0	3.4	41 (40)
	30	45	0	4	-4	-2	3.8	46(45)
	30	45	0	4	-6	-4	4.1	50 (50)
	30	45	0	4	-8	-6	4.5	54 (55)
	30	45	0	4	-10	-8	4.9	59 (60)

DEVELOPMENT OF DCP DRAFT SPECIFICATION

Introduction

The development of a draft specification for use of the DCP for compaction quality control of unbound subgrade and base/subbase pavement layers is discussed in this chapter. The draft specification developed for this study was based on the recommended minimum DCP values discussed in the previous chapter. The minimum DCP acceptance criteria developed would ensure satisfactory field compaction during the construction of unbound flexible pavements. The following subsections discuss earlier modulus-based specifications that have been developed and the process implemented to develop the DCP draft specification presented in Appendix B.

Previously Developed DCP Specifications

As mentioned in the literature review (Chapter 2), modulus-based specifications have been developed for using the DCP during the compaction quality control stage of pavement construction. The MnDOT, Missouri Department of Transportation (MoDOT), and the Indiana Department of Transportation (InDOT) have been the leading state DOTs to develop such specifications. Nazarian et al. [16] has also developed modulus-based construction specifications for compaction of earthwork and unbound aggregates.

Minnesota Department of Transportation (MnDOT)

In the MnDOT specifications, DCP penetration index is used for the acceptance of three types of unbound granular materials [32]. These materials consisted of base and edge drain trench filter aggregates, and granular subgrade materials. Based on the MnDOT specifications, testing using the DCP is to be conducted on the compacted materials and the readings for the first five drops are to be recorded. Using the first two values as seating drops, a SEAT value is computed with the following equation:

$$\text{SEAT} = \text{Depth of penetration (2 blows)} - \text{Initial depth of penetration} \qquad \text{Equation 5}$$

It is worth mentioning that the SEAT value is determined in order to ensure that the aggregate base layer has necessary surface strength that would support the weight of the equipment during construction. In addition, the penetration depth measured following the 5th drop is used to compute the DPI as follows:

$$\mathbf{DPI} = \frac{(\textbf{Depth of penetration after 5 blows} - \textbf{Depth of penetration after two blows})}{\mathbf{3}} \qquad \text{Equation 6}$$

In addition to testing using the DCP, the MnDOT specifications require that the gradation and in-situ moisture content be determined for the compacted material. The gradation of the material is determined by performing a sieve analysis with the 25, 19, 9.5, 4.75, 2.00-mm, 425-micometer, and 75-micrometer sieves. Using the determined moisture content and gradation values the maximum allowable DPI can be calculated with the following equation:

$$\textbf{Max. Allow. DPI}\left(\mathbf{mm/_{blow}}\right) = \mathbf{4.76GN + 1.68MC - 14.4} \qquad \text{Equation 7}$$

Where:
MC = Moisture content at the time of testing
GN = Grading number obtained using the following equation:

$$GN = \frac{\begin{array}{c}25\ mm + 19\ mm + 9.5\ \mu m + 4.75\ mm \\ +2.00\ mm + 425\ \mu m + 75\ \mu m\end{array}}{100}$$

Based on the specifications provided by the MnDOT, the compacted material is accepted if the measured SEAT and DPI values are found to be less than or equal to the calculated maximum allowable values. The maximum allowable SEAT and DPI values determined by the MnDOT are presented in Table 25 below.

Table 25 - MnDOT Maximum Seat and DPI Values [32].

Grading Number	Moisture Content	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Test Layer in. (mm)
3.1 – 3.5	< 5.0	40	10	4 -6 [100 - 150]
	5.0 – 8.0	40	12	
	> 8.0	40	16	
3.6 – 4.0	< 5.0	40	10	4 -6 [100 - 150]
	5.0 – 8.0	45	15	
	> 8.0	55	19	
4.1 – 4.5	< 5.0	50	13	5 -6 [100 - 150]
	5.0 – 8.0	60	17	
	> 8.0	70	21	
4.6 – 5.0	< 5.0	65	15	6 - 12 [100 - 150]
	5.0 – 8.0	75	19	
	> 8.0	85	23	
5.1 – 5.5	< 5.0	85	17	7 - 12 [100 - 150]
	5.0 – 8.0	95	21	
	> 8.0	105	25	
	< 5.0	100	19	

<u>Missouri Department of Transportation (MoDOT)</u>
The DCP specification provided by the MoDOT has a similar framework to that of the MnDOT. The MoDOT specification however is primarily for Type 7 aggregate base materials (limestone or dolomitic, and crushed stone or sand and gravel bases) under roadways and shoulders [32]. The MoDOT specifications requires materials to be compacted to achieve an average DPI value less than or equal to 0.4-inch/blow (10-mm/blow). In addition, the measured average DPI should compare within 0.1-inch/blow (2.54-mm/blow) of the determined average DPI provided by the MoDOT. The DPI values for these materials are calculated using Equation 6 as proposed by the MnDOT.

Furthermore, under the MoDOT specifications, it is required that testing be conducted within 24 hours after compaction using a standard DCP device with a 40-lb. (18-kg) hammer.

Indiana Department of Transportation (INDOT)

The InDOT developed a DCP specification for the acceptance of clay, silty, or sand soils, granular soils, and chemical modified soils [33]. Granular soils used in this specification were of aggregate sizes smaller than ¾-inch (19-mm), structural backfill size of 1-inch (25.4-mm), ½-inch (12.7-mm), and No. 4 and 30. The DCP acceptance criteria developed is based on the type of soil being tested, and the materials MDD and OMC values. According to the InDOT specifications the DCP is to be tested on clay soils for every 6-inches (15.2-cm) of compaction. However for silty and sandy soils, the DCP is tested for each 12-inches (30.5-cm) of compaction. In addition, for chemically modified soils the DCP is tested for every 8-inches (20.3-cm) of compacted material, and for granular materials testing is conducted for every 12-inches (30.5-cm) of compaction.

According to the InDOT specifications, a modified version of the one-point Proctor test is to be used for determining the materials MDD and OMC values. The values obtained through testing using the DCP are to be compared to the minimum required DCP values presented in Table 26 or computed using Equation 8 below. In addition, under the InDOT specifications the compacted material is to be maintained within -3% to +1% of the OMC and the moisture content is to be measured every day of testing. Figure 14 below also illustrates the diagram used to determine the DCP acceptance criteria based on the MDD and OMC of the material.

Table 26 - InDOT Minimum Required DCP Values [33].

Optimum Moisture Content (%)	(NDCP) req.|0 ~ 12 in.
10	18
11	16
12	14
13	13
14	11

$$(\boldsymbol{NDCP})\boldsymbol{req}|\ \mathbf{0}\sim\mathbf{12}\ \boldsymbol{in.} = \mathbf{59}^{-\mathbf{0.12}\boldsymbol{OMC}} \quad \text{Equation 8}$$

Where:

OMC = Optimum moisture content

$(NDCP)req|0\sim12\ in.$ = Minimum required blow count for 0 to 12 in. penetration rounded to nearest integer.

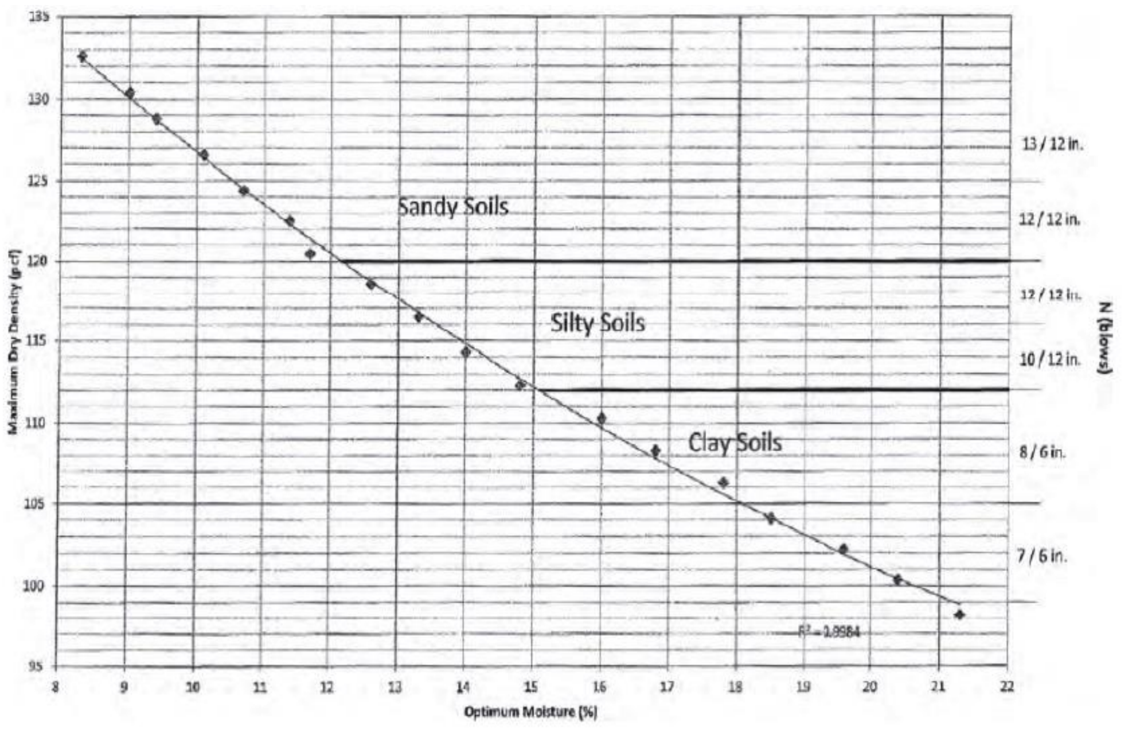


Figure 14. InDOT DCP Acceptance Criteria Based on MDD and OMC of Soil [33].

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Nazarian et al. [16] also developed a standard specification for modulus-based quality management of earthwork and unbound aggregates. The specifications pertained to the construction of embankments and pavement layers composing of subgrade, subbase, and base materials. The DCP specifications were based on the materials gradation, moisture content, and density at compaction. According to provided specifications the acceptable materials are to meet the gradation requirements presented in Table 27. Any unacceptable material is to be corrected by the contractor. Any material that is corrected or replaced is to be sampled and tested to ensure the material passes the gradation requirements.

Table 27 - NCHRP Material Gradation Requirements [16].

Material	Percent Difference from Target Gradation			
	Sieve 1-inch. (25.0 mm)	Sieve No. 4 (4.75 µm)	Sieve No. 40 (425 µm)	Sieve No. 200 (75 µm)
Embankment (if applicable)	10%	10%	10%	10%
Subgrade	10%	10%	10%	10%
Subbase	5%	8%	5%	3%
Base	5%	8%	5%	3%

In addition to the gradation requirements for the material, the NCHRP specifications calls for a specific range of moisture content in which the material can fall within during the compaction process. The moisture content specifications are presented in Table 28 below. In addition, moisture content samples are to be taken at random prior to compaction. If the materials do not meet the requirements the materials are to be corrected until the appropriate moisture content is reached.

Table 28 - NCHRP Moisture Content Requirements [16].

Optimum Moisture Content (OMC)	Moisture Content	
	Min.	Max.
<10%	OMC - 2%	OMC + 2%
≥10%	0.8 OMC	1.2 OMC

The final requirements, as determined by the NCHRP specifications, are that each lift is to be compacted to no less than the percent of maximum dry density presented in Table 29. According to the specifications, samples for density testing will be taken at random prior to compaction. Once again, if the material does not meet the set requirements it is to be corrected accordingly. Testing using the DCP should be conducted in a timely manner prior to the moisture content of the layer falling below 1% of the moisture content measured during the time of compaction. For materials with an OMC greater than 10%, the moisture content is not to fall below 2% of the moisture content.

Table 29 - NCHRP Relative Density Requirements for Compaction [16].

Material	Min. Required Relative Density
Embankment	85% of Maximum Dry Density
Subgrade	90% of Maximum Dry Density
Subbase	95% of Maximum Dry Density
Base	95% of Maximum Dry Density

Development of DCP Draft Specification

The existing draft specifications provided through literature concentrated on developing construction specifications using values predicted from modulus-based devices. However, a majority of these studies were limited to certain subgrade aggregates and did not extensively cover materials that are generally used for pavement construction. In addition, the draft specifications presented contain required moisture content specifications. As a result, a draft specification for use of the DCP for compaction quality control based primarily on material characteristics (i.e., gradation) for subgrade and base\subbase materials was developed. It was necessary to develop such specification in order to shift from density-based acceptance that encompasses moisture content within its specifications to modulus-based acceptance of materials.

Appendix B presents the proposed DCP draft specification titled “Compaction Quality Control of Unbound Subgrade and Base/Subbase Layers Through Use of the Dynamic Cone Penetrometer.” The proposed specification includes a set of guidelines for implementing the DCP as an acceptance tool for the compaction quality control stage of pavement construction. Specifically within the specification are two recommended procedures for conducting the DCP test. In addition, a set of material gradation and moisture content acceptance criteria are proposed. The following subsections discuss the components that make up the developed DCP specification and the justification behind each proposal.

Device and Materials

The first two components of the draft specification comprise of the device description and general material use requirements. The DCP test is to be conducted in accordance to ASTM D6951 or ASTM D7380 standards [34]. Within the specifications it is recommended that the contractor use aggregate materials that conform to the NJDOT 901.11 requirements of the Standard Specifications for Road and Bridge Construction [1]. This step is necessary to ensure that material is suitable for the intended use during construction. In addition, it is worth noting that adequate compaction of a material will not necessarily guarantee the success and long-term endurance of the material. Therefore, it is important that the materials used for the development of the subgrade or base/subbase layers met the specifications as provided by the NJDOT. It is also important to note that the specifications developed were only based on NJ natural sand, DGA, and RCA. Therefore, the developed specifications will not be applicable to other materials; unless they are relatively similar with regard to gradation.

DCP Test Procedure

The proposed specification provides two procedures for conducting DCP tests which include: (1) a control strip, and (2) random selection of test points. The two test procedures were provided to allow different test method options for various types of construction sites.

The first proposed test method requires constructing a 400-square yard (334.5-square meter) or greater control strip at a designated location within the construction site. Once the control strip is compacted the DCP test can be conducted at 10 randomly selected locations within the area.

The second test method provided in the specification is a random selection of test points. Based on this procedure, it is recommended to conduct the DCP test at 10 randomly selected locations within a construction site at a minimum of 3-feet (0.9-m) increments of each other. This test method was provided for when a control strip was not necessary for the designated site. However, since a definite testing boundary is not specified a minimum of 3-feet (0.9-m) increments between DCP tests is recommended. It is also worth mentioning that the methods described above were similar to the procedure proposed in 203.03.02B of the NJDOT specifications for determining the compaction requirements based on density acceptance [1]. Utilizing similar testing methods makes it easier for contractors and resident engineers to execute the developed specifications. Using either test methods provided, at least nine of the ten tested locations must have DCP values that are higher than the minimum DCP acceptance criteria in order to be considered compacted adequately. The proposed specification also recommends that the DCP test be conducted until a depth of 15-inches (38.1-cm) of the compacted layer is reached. For areas in which the depth of the layer being tested is less than 15-inches (38.1-cm) the test should be conducted for the entire thickness of the layer. It is to be noted that during laboratory testing with the DCP, mold samples were prepared at a depth of 12-inches (30.5-cm), therefore a value of 15-inches (38.1-cm) was deemed appropriate for the purpose of developing the DCP test procedure requirements. In addition, it is recommended that the test be performed within 24 hours of the placement and compaction of the aggregate layer. This requirement was based on results of laboratory testing that showed higher variability for the DCP when tested on compacted samples prepared 48 hours after compaction. In order to avoid overestimating DCP measurements, it is essential that testing be conducted no later than 24 hours after compaction.

Acceptance Criteria

The final component of the developed DCP specification was the minimum acceptance criteria for the compacted material layer. The acceptance criteria utilized for developing the proposed specification (Table 30) was based on the material characteristics that included: (1) gradation, and (2) moisture content within the material.

To determine the minimum acceptable DCP values for a specific construction site one must first determine the moisture content in the field during compaction and the Proctor OMC for the material being compacted. The moisture difference (i.e., actual field moisture content minus OMC) is then determined. The gradation and moisture content requirements and the corresponding minimum DCP blow values can then be used to determine the minimum acceptable DCP value using either Table 30 or the developed DCP model equation. It is important to note that the developed specifications also recommend measuring moisture contents in the field using “speedy moisture” methods in order to obtain results in a timely manner.

Table 30 - Minimum Acceptable DCP Values Based on Gradation & Moisture Content.

Material	Percent Passing (%)							
	Sieve No. 4 (4.75 mm)		Sieve No. 200 (75 μm)		Moist. Cont. Diff. (%)		Minimum DCP Value (blows/inch.)	Minimum DCP Blows for 1-ft layer (rounded to the nearest 5 DCP blows)
	Min.	Max.	Min.	Max.	Min.	Max.		
NJDOT Subgrade	40	100	0	8	0	2	1.3	16 (15)
	40	100	0	8	-2	0	1.5	18 (20)
	40	100	0	8	-4	-2	1.9	23 (25)
	40	100	0	8	-6	-4	2.2	27 (25)
NJDOT Base/Subbase	25	50	3	10	0	2	3.2	39 (40)
	25	50	3	10	-2	0	3.4	41 (40)
	25	50	3	10	-4	-2	3.8	46 (45)
	25	50	3	10	-6	-4	4.1	50 (50)

Document Results

The final component of the developed draft specification requires documenting the results from the DCP test conducted. The following information is to be recorded and submitted to the RE:

(1) The number of blows required to penetrate the layer at each selected testing location;
(2) Cumulative depth of penetration after each set of hammer blows;
(3) Difference in cumulative penetration between each reading;
(4) The penetration depth per blow for each location;
(5) The rate of penetration between each test reading; and,
(6) Assessment on acceptable/unacceptable compacted material.

CONCLUSIONS AND RECOMMENDATIONS

Summary and Conclusions

This study focused on evaluating and identifying the most suitable non-nuclear methods that can replace the NDG during quality control of unbound compacted subgrade and base/subbase pavement layers. The main motivation for the study is mainly related to existing concerns and safety risks associated with using the NDG as an acceptance tool. A comprehensive literature review was conducted and a survey was prepared and distributed to State DOTs, device manufacturers, and device users (i.e., pavement industry). Based on the literature review and survey results, three non-nuclear devices were selected for further evaluation. Laboratory tests to evaluate the effect of aggregate type, moisture content, compaction effort, and delayed testing on the measured parameters from the NDG, BCD, LWD, and DCP was conducted. Field testing was also conducted using all selected devices. Laboratory testing results were utilized to develop a multiple linear regression model and field results were used to calibrate this model. Based on this model, a set of guidelines for implementing the DCP, in the form of a specifications, as a quality acceptance tool in the compaction quality control stage of pavement construction were prepared.

Based on the collected testing results and the subsequent statistical analyses, the following conclusions were drawn:

- The laboratory procedure developed for compacting large samples was found to be satisfactory. The actual moisture contents and densities were within ± 0.5% and ±5 lbs./ft^3 of their targeted values, respectively.
- Mold size did not have a significant impact on testing results (especially in the case of LWD). This is the case because testing results obtained from large samples were statistically similar to those obtained from small samples.
- The moisture content within the compacted samples (up to ± 2% of OMC) was sensitive to parameters measured from all devices evaluated. The DCP was the most suitable device for capturing the change in moisture contents within the samples while all other devices showed mixed trends within their results, specifically when preparing samples at 2% below and 2% above OMC.
- Based on the comparison of the standard error of the mean results, variability was similar for all non-nuclear devices. In addition, DCP showed higher variability when the soils had higher moisture content than the OMC.
- All of the parameters measured from these four devices were able to distinguish between the four aggregate types.
- The DCP prediction model developed was found to be adequate at predicting laboratory and field DCP measurements. The model was also found to be significantly dependent on moisture content, percent passing sieve No. 4, and percent passing sieve No. 200.
- The DCP prediction model, which was developed and calibrated as a part of this study, was used successfully for identifying a set of recommended DCP penetration rates that would ensure satisfactory compaction of unbound pavement layers in the field.
- A set of specifications for using the DCP as a compaction acceptance tool for natural soils and engineered aggregates was successfully developed.

Recommendations for Future Research

The following recommendations are made based on testing results and study conclusions:

- It is recommended that NJDOT implements the procedure developed as a part of this study for specifying minimum DCP values for quality acceptance of unbound subgrade and base/subbase layers during the construction of roadway pavements. It should be noted; however, that this procedure is limited to only non-plastic granular materials (i.e., NJ natural sands, DGA, and RCA).
- Due to the limited number of field sections tested and the types of aggregates considered in this study, it is recommended to conduct testing on additional field sections constructed using different types of aggregates than those considered as a part of this study. This will further widen the implementation of the developed specifications.
- It is recommended that future research evaluates the ramifications of waiving the requirement for measuring field moisture content as this directly impact the practicality aspect of the developed DCP specifications and might hinder implementation efforts.

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Appendix A

A.1 Survey Questions

1. Which of the following best describes your profession?
 a. Manufacturer of the nuclear density gauge
 b. Manufacturer of alternative device (specify)
 c. Contractor
 d. DOT personnel/engineer
 e. Other:

2. Are you familiar with the nuclear density gauge? With (1) being no knowledge whatsoever, and (5) being used/researched on a regular basis.
 a. Not at all (1)
 b. Slightly (2)
 c. Moderately (3)
 d. Substantially (4)
 e. Expert (5)

3. What are the major advantages of using the nuclear density gauge?
 a. Repeatability and accuracy (1) (2) (3) (4) (5)
 b. Quick/Timely device measurement output (1) (2) (3) (4) (5)
 c. Ease of data processing and interpretation (1) (2) (3) (4) (5)

4. What are the major disadvantages of using the nuclear density gauge?
 a. Expensive and timely training and certification (1) (2) (3) (4) (5)
 b. Specialized and isolated storage (1) (2) (3) (4) (5)
 c. Expensive cost and operation cost (1) (2) (3) (4) (5)
 d. Potential safety hazards (1) (2) (3) (4) (5)
 e. Density measured rather than a design property (1) (2) (3) (4) (5)

5. Select all of the following devices you have previously used:
 a. GeoGauge
 b. Dynamic cone penetrometer
 c. Light weight falling deflectometer
 d. Briaud compaction device
 e. PaveTracker
 f. Other:
 g. None

6. For alternative devices to the nuclear density gauge, please rank the importance of the following criteria, 1 being not important 5 being extremely important:
 a. Repeatability of field measurements (1) (2) (3) (4) (5)
 b. Time needed for field measurements (1) (2) (3) (4) (5)
 c. Ease of data processing and int. (1) (2) (3) (4) (5)
 d. Sensitivity to enviro. factors (moisture) (1) (2) (3) (4) (5)
 e. Ease of use and accuracy (1) (2) (3) (4) (5)
 f. Cost (1) (2) (3) (4) (5)
 g. Additional comments about the factors listed as well as other factors/parameters not listed:

7. The GeoGauge: *(Where 1 is Strongly Disagree, 5 is Strongly Agree)*

a. Has high repeatability and accuracy (1) (2) (3) (4) (5)
b. Provides easy data processing (1) (2) (3) (4) (5)
c. Has optimal operation and testing time (1) (2) (3) (4) (5)
d. Contains high ease of use (1) (2) (3) (4) (5)
e. Is not affected by enviro. factors (moisture) (1) (2) (3) (4) (5)
f. Not negatively affected by lower layer properties (1) (2) (3) (4) (5)
g. Has reasonable cost (1) (2) (3) (4) (5)
h. Readings properly represent field conditions (various levels of compaction/density)

8. Based on your experience with the GeoGauge, state the negative and positive experiences unique to this device:

9. The dynamic cone penetrometer: *(Where 1 is Strongly Disagree, 5 is Strongly Agree)*

a. Has high repeatability and accuracy (1) (2) (3) (4) (5)
b. Provides easy data processing (1) (2) (3) (4) (5)
c. Has optimal operation and testing time (1) (2) (3) (4) (5)
d. Contains high ease of use (1) (2) (3) (4) (5)
e. Is not affected by enviro. factors (moisture) (1) (2) (3) (4) (5)
f. Not negatively affected by lower layer properties (1) (2) (3) (4) (5)
g. Has reasonable cost (1) (2) (3) (4) (5)
h. Readings properly represent field conditions (various levels of compaction/density)

10. Based on your experience with the dynamic cone penetrometer, state the negative and positive experiences unique to this device.

11. The light weight falling deflectometer:

a. Has high repeatability and accuracy (1) (2) (3) (4) (5)
b. Provides easy data processing (1) (2) (3) (4) (5)
c. Has optimal operation and testing time (1) (2) (3) (4) (5)
d. Contains high ease of use (1) (2) (3) (4) (5)
e. Is not affected by enviro. factors (moisture) (1) (2) (3) (4) (5)
f. Not negatively affected by lower layer properties (1) (2) (3) (4) (5)
g. Has reasonable cost (1) (2) (3) (4) (5)
h. Readings properly represent field conditions (various levels of compaction/density)

12. Based on your experience with the light weight falling deflectometer, state the negative and positive experiences unique to this device.

13. The Briaud compaction device:

a. Has high repeatability and accuracy (1) (2) (3) (4) (5)
b. Provides easy data processing (1) (2) (3) (4) (5)
c. Has optimal operation and testing time (1) (2) (3) (4) (5)
d. Contains high ease of use (1) (2) (3) (4) (5)
e. Is not affected by enviro. factors (moisture) (1) (2) (3) (4) (5)
f. Not negatively affected by lower layer properties (1) (2) (3) (4) (5)
g. Has reasonable cost (1) (2) (3) (4) (5)
h. Readings properly represent field conditions (various levels of compaction/density)

14. Based on your experience with the Briaud, state the negative and positive experiences unique to this device.

15. The PaveTracker:

a. Has high repeatability and accuracy (1) (2) (3) (4) (5)
b. Provides easy data processing (1) (2) (3) (4) (5)
c. Has optimal operation and testing time (1) (2) (3) (4) (5)
d. Contains high ease of use (1) (2) (3) (4) (5)
e. Is not affected by enviro. factors (moisture) (1) (2) (3) (4) (5)
f. Not negatively affected by lower layer properties (1) (2) (3) (4) (5)
g. Has reasonable cost (1) (2) (3) (4) (5)
h. Readings properly represent field conditions (various levels of compaction/density)

16. Based on your experience with the PaveTracker, state the negative and positive experiences unique to this device.

17. Overall, rank the suitability of the following devices in the replacement of the nuclear density gauge from 1-5 with 1 being a very poor alternative and 5 being an excellent alternative.

a. GeoGauge (1) (2) (3) (4) (5) (NA)
b. Dynamic cone penetrometer (1) (2) (3) (4) (5) (NA)
c. Light weight falling deflectometer (1) (2) (3) (4) (5) (NA)
d. Briaud compaction device (1) (2) (3) (4) (5) (NA)
e. PaveTracker (1) (2) (3) (4) (5) (NA)

18. Based on your knowledge of the following alternative devices to the nuclear density gauge, if you had to theoretically select one of the devices for implementation, which device would you use?

a. GeoGauge
b. Dynamic cone penetrometer
c. Light weight falling deflectometer
d. Briaud compaction device
e. PaveTracker
f. Other:

g. I still prefer nuclear density gauge

19. Please explain your rationale to the previous question.

20. Specify your agency's level of interest in stiffness/strength based devices for compaction control of unbound materials:

a. Not interested
b. Slightly interested
c. Moderately interested
d. Substantially interested
e. Extremely interested

21. Specify your agency's level of interest in implementing stiffness/strength based devices for compaction control of unbound materials:

a. Not interested in implementing it
b. Interested, but have not implemented it
c. Interested and will implement it
d. Interested and have already implemented it
e. Other:

22. Ultimately, do you feel a transition to an alternative device is possible?

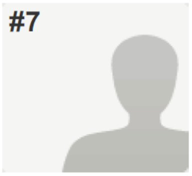
a. Yes
b. No
c. I don't know

23. Which factors/obstacles do you feel will be most challenging in the widespread implementation of a new device with (1) being not challenging and (5) being extremely challenging?

a. Need for new equipment (1) (2) (3) (4) (5)
b. Lack of funds (1) (2) (3) (4) (5)
c. Lack of trained personnel (1) (2) (3) (4) (5)
d. Familiarity of contractors with such devices (1) (2) (3) (4) (5)

24. Additional comments regarding factors that you feel will affect the widespread implementation of a new device, alternative devices, nuclear density gauge, or other aspects not covered in this survey:

A.2 Survey Results



#7

COMPLETE

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Last Modified: Monday, May 26, 2014 2:00:09 PM
Time Spent: 00:06:39
IP Address: 174.20.163.24

PAGE 2: Introductory Questions

Q1: **Which of the following best describes your profession?**

DOT Personnel/Engineer

Q2: **Please specify the level of knowledge/experience you have with the nuclear density gauge and its pavement engineering applications:**

Moderately knowledgeable

Q3: **Please rank the following statements regarding the use of the nuclear density gauge as compaction quality control method for unbound material. (1: not important and 4: the main reason it is used)**

The data collected from the nuclear density gauge is easily analyzed and interpreted	4
The data collected from the nuclear density gauge is not influenced by the presence of moisture	3

Q4: **Please rank the following statements regarding the nuclear density gauge. (1: not a problem and 5: detrimental to normal operation)**

The nuclear density gauge requires timely training/certification	1
The nuclear density gauge requires specialized and isolated storage	5
The nuclear density gauge is expensive to purchase and operate	2
The nuclear density gauge is potentially hazardous	4
The nuclear density gauge only measures density as opposed to strength/stiffness	3

Q5: If an alternative method/device, other than nuclear density gauge, is used as an unbound material compaction quality control method/device, please rank the importance of the following criteria used in selecting this method/device. (1: not important at all and 6: extremely important)

Repeatability of field measurements	6
Time Needed for field measurements	5
Ease of data processing	2
Sensitivity to environmental factors	3
Ease of use and accuracy	4
Cost	1

Q6: Please provide any additional comments, if you have any, about the factors considered in the previous question as well as other factors that might not have been considered: *Respondent skipped this question*

PAGE 3: Alternatives Devices (Geogauge)

Q7: Have you previously used or researched on the Geogauge device? Yes, I have used/researched on the Geogauge

PAGE 4: Geogauge

Q8: Based on your experiences using/researching on the Geogauge, please specify your level of agreement with the following statements:

The Geogauge provides the user with accurate and repeatable readings	Disagree
The data collected from the Geogauge is easily analyzed and interpreted	Disagree
The Geogauge provides the user with outputs in a quick timely manner	Disagree
The Geogauge is portable and easy to use	Neutral
The Geogauge is not affected by site's environmental conditions (e.g. moisture content)	Neutral
The Geogauge is negatively affected by properties of lower layers	Neutral
The Geogauge has reasonable cost	Neutral
The Geogauge provides the user with readings representative of field conditions	Neutral

Q9: Based on your experience, state the negative and positive experiences unique to this device: *Respondent skipped this question*

PAGE 5: Alternatives Devices (Dynamic Cone Penetrometer)

Q10: **Have you previously used or researched on the Dynamic Cone Penetrometer device?**	Yes, I have used/researched on the Dynamic Cone Penetrometer

PAGE 6: Dynamic Cone Penetrometer

Q11: **Based on your experiences using/researching on the Dynamic Cone Penetrometer (DCP), please specify your level of agreement with the following statements**

The DCP provides the user with accurate and repeatable readings	Strongly Agree
The data collected from the DCP is easily analyzed and interpreted	Strongly Agree
The DCP provides the user with outputs in a quick timely manner	Strongly Agree
The DCP is portable and easy to use	Strongly Agree
The DCP is not affected by site's environmental conditions (e.g. moisture content)	Strongly Agree
The DCP is negatively affected by properties of lower layers	Neutral
The DCP has reasonable cost	Strongly Agree
The DCP provides the user with readings representative of field conditions	Strongly Agree

Q12: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 7: Alternatives Devices (Light Falling Weight Deflectometer)

Q13: Have you previously used or researched on the Light Falling Weight Deflectometer device?	*Respondent skipped this question*

PAGE 8: Light Falling Weight Deflectometer

Q14: Based on your experiences using/researching on the Light Falling Weight Deflectometer (LFWD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q15: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 9: Alternatives Devices (Briaud Compaction Device)

Q16: Have you previously used or researched on the Briaud Compaction Device?	*Respondent skipped this question*

PAGE 10: Briaud Compaction Device

Q17: Based on your experiences using/researching on the Briaud Compaction Device (BCD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q18: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 11: Alternatives Devices (PaveTracker)

Q19: Have you previously used or researched on the PaveTracker?	*Respondent skipped this question*

PAGE 12: PaveTracker

Q20: Based on your experiences using/researching on the PaveTracker, please specify your level of agreement with the following statements	*Respondent skipped this question*
Q21: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 13: Conclusion Questions

Q22: **Overall, rank the following devices/methods from "5" being a very poor alternative to the nuclear density gauge to "1" being an excellent alternative to the nuclear density gauge. Please pick N/A if you haven't had any prior experience with a particular device.**

Geogauge	4
Dynamic Cone Penetrometer	1
Light Falling Weight Deflectometer	4
Briaud Compaction Device	4
PaveTracker	4
Other	N/A

Q23: **Specify your agency's/company's level of interest in stiffness/strength based devices for compaction of unbound materials**	Moderately Interested
Q24: **Specify your agency's level of interest in implementing stiffness/strength based devices for compaction control of unbound materials.**	Moderately Interested
Q25: **Ultimately, do you feel a transition to an alternative device is possible?**	Maybe

Q26: **Based on your experience, please rank the following factors/obstacles that you feel might hinder or negatively influence the widespread implementation of a new device/method as an alternative to the nuclear density gauge. (1: no to very low influence and 4: significantly high influence)**

Need for new equipment	1
Lack of funds	2
Lack of trained personnel	3
Familiarity of devices	4

Q27: **Based on your experience, please fill in the following box with any additional comment about other factors/obstacles that you believe might hinder or negatively influence the implementation of a new device/method for use as an alternative to the nuclear density gauge:**	*Respondent skipped this question*

#8

COMPLETE

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Time Spent: 16:50:28
IP Address: 108.59.48.1

PAGE 2: Introductory Questions

Q1: **Which of the following best describes your profession?**	DOT Personnel/Engineer
Q2: **Please specify the level of knowledge/experience you have with the nuclear density gauge and its pavement engineering applications:**	Moderately knowledgeable

Q3: **Please rank the following statements regarding the use of the nuclear density gauge as compaction quality control method for unbound material. (1: not important and 4: the main reason it is used)**

The nuclear density gauge provides the user with accurate and repeatable readings	2
The nuclear density gauge provides the user with outputs in a quick timely manner	3
The data collected from the nuclear density gauge is easily analyzed and interpreted	1
The data collected from the nuclear density gauge is not influenced by the presence of moisture	4

Q4: **Please rank the following statements regarding the nuclear density gauge. (1: not a problem and 5: detrimental to normal operation)**

The nuclear density gauge requires timely training/certification	3
The nuclear density gauge requires specialized and isolated storage	4
The nuclear density gauge is expensive to purchase and operate	1
The nuclear density gauge is potentially hazardous	2
The nuclear density gauge only measures density as opposed to strength/stiffness	5

Q5: If an alternative method/device, other than nuclear density gauge, is used as an unbound material compaction quality control method/device, please rank the importance of the following criteria used in selecting this method/device. (1: not important at all and 6: extremely important)

Repeatability of field measurements	6
Time Needed for field measurements	5
Ease of data processing	4
Sensitivity to environmental factors	2
Ease of use and accuracy	3
Cost	1

Q6: Please provide any additional comments, if you have any, about the factors considered in the previous question as well as other factors that might not have been considered:

Train to perform the test, similicity, easy to understand(No blackbox) by contractor,,No licensing,etc

PAGE 3: Alternatives Devices (Geogauge)

Q7: Have you previously used or researched on the Geogauge device?	Yes, I have used/researched on the Geogauge

PAGE 4: Geogauge

Q8: Based on your experiences using/researching on the Geogauge, please specify your level of agreement with the following statements:

The Geogauge provides the user with accurate and repeatable readings	Neutral
The data collected from the Geogauge is easily analyzed and interpreted	Neutral
The Geogauge provides the user with outputs in a quick timely manner	Agree
The Geogauge is portable and easy to use	Agree
The Geogauge is not affected by site's environmental conditions (e.g. moisture content)	Neutral
The Geogauge is negatively affected by properties of lower layers	Disagree
The Geogauge has reasonable cost	Neutral
The Geogauge provides the user with readings representative of field conditions	Neutral

Q9: Based on your experience, state the negative and positive experiences unique to this device:

None

PAGE 5: Alternatives Devices (Dynamic Cone Penetrometer)

Q10: **Have you previously used or researched on the Dynamic Cone Penetrometer device?**	Yes, I have used/researched on the Dynamic Cone Penetrometer

PAGE 6: Dynamic Cone Penetrometer

Q11: **Based on your experiences using/researching on the Dynamic Cone Penetrometer (DCP), please specify your level of agreement with the following statements**

The DCP provides the user with accurate and repeatable readings	Agree
The data collected from the DCP is easily analyzed and interpreted	Strongly Agree
The DCP provides the user with outputs in a quick timely manner	Strongly Agree
The DCP is portable and easy to use	Strongly Agree
The DCP is not affected by site's environmental conditions (e.g. moisture content)	Disagree
The DCP is negatively affected by properties of lower layers	Agree
The DCP has reasonable cost	Strongly Agree
The DCP provides the user with readings representative of field conditions	Strongly Agree

Q12: **Based on your experience, state the negative and positive experiences unique to this device:**

Easy to use , understand by field technician, No need to watch contractor , test can be performed later, good diagonastic tool. sensitive to moisture.

PAGE 7: Alternatives Devices (Light Falling Weight Deflectometer)

Q13: Have you previously used or researched on the Light Falling Weight Deflectometer device?	*Respondent skipped this question*

PAGE 8: Light Falling Weight Deflectometer

Q14: Based on your experiences using/researching on the Light Falling Weight Deflectometer (LFWD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q15: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 9: Alternatives Devices (Briaud Compaction Device)

Q16: Have you previously used or researched on the Briaud Compaction Device?	*Respondent skipped this question*

PAGE 10: Briaud Compaction Device

Q17: Based on your experiences using/researching on the Briaud Compaction Device (BCD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q18: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 11: Alternatives Devices (PaveTracker)

Q19: Have you previously used or researched on the PaveTracker?	*Respondent skipped this question*

PAGE 12: PaveTracker

Q20: Based on your experiences using/researching on the PaveTracker, please specify your level of agreement with the following statements	*Respondent skipped this question*
Q21: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 13: Conclusion Questions

Q22: Overall, rank the following devices/methods from "5" being a very poor alternative to the nuclear density gauge to "1" being an excellent alternative to the nuclear density gauge. Please pick N/A if you haven't had any prior experience with a particular device.

Geogauge	3
Dynamic Cone Penetrometer	1
Light Falling Weight Deflectometer	2
Briaud Compaction Device	4
PaveTracker	5
Other	N/A

Q23: Specify your agency's/company's level of interest in stiffness/strength based devices for compaction of unbound materials

Substantially Interested

Q24: Specify your agency's level of interest in implementing stiffness/strength based devices for compaction control of unbound materials.

Substantially Interested

Q25: Ultimately, do you feel a transition to an alternative device is possible?

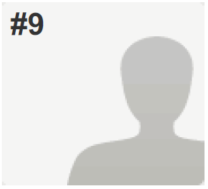
No

Q26: Based on your experience, please rank the following factors/obstacles that you feel might hinder or negatively influence the widespread implementation of a new device/method as an alternative to the nuclear density gauge. (1: no to very low influence and 4: significantly high influence)

Need for new equipment	1
Lack of funds	2
Lack of trained personnel	3
Familiarity of devices	4

Q27: Based on your experience, please fill in the following box with any additional comment about other factors/obstacles that you believe might hinder or negatively influence the implementation of a new device/method for use as an alternative to the nuclear density gauge:

Other devices sensitive to moisture. Construcrion folks see the moisture control is hinderance to progress.



#9

COMPLETE

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Last Modified: Tuesday, September 02, 2014 6:12:47 AM
Time Spent: 00:17:36
IP Address: 24.37.41.131

PAGE 2: Introductory Questions

Q1: **Which of the following best describes your profession?**

Manufacturer of an alternative device

Q2: **Please specify the level of knowledge/experience you have with the nuclear density gauge and its pavement engineering applications:**

Slightly knowledgeable

Q3: **Please rank the following statements regarding the use of the nuclear density gauge as compaction quality control method for unbound material. (1: not important and 4: the main reason it is used)**

The nuclear density gauge provides the user with accurate and repeatable readings	3
The nuclear density gauge provides the user with outputs in a quick timely manner	4
The data collected from the nuclear density gauge is easily analyzed and interpreted	1
The data collected from the nuclear density gauge is not influenced by the presence of moisture	2

Q4: **Please rank the following statements regarding the nuclear density gauge. (1: not a problem and 5: detrimental to normal operation)**

The nuclear density gauge requires timely training/certification	3
The nuclear density gauge requires specialized and isolated storage	2
The nuclear density gauge is expensive to purchase and operate	1
The nuclear density gauge is potentially hazardous	5
The nuclear density gauge only measures density as opposed to strength/stiffness	4

Q5: If an alternative method/device, other than nuclear density gauge, is used as an unbound material compaction quality control method/device, please rank the importance of the following criteria used in selecting this method/device. (1: not important at all and 6: extremely important)

Repeatability of field measurements	6
Time Needed for field measurements	3
Ease of data processing	4
Sensitivity to environmental factors	1
Ease of use and accuracy	5
Cost	2

Q6: Please provide any additional comments, if you have any, about the factors considered in the previous question as well as other factors that might not have been considered:	*Respondent skipped this question*

PAGE 3: Alternatives Devices (Geogauge)

Q7: Have you previously used or researched on the Geogauge device?	Yes, I have used/researched on the Geogauge

PAGE 4: Geogauge

Q8: Based on your experiences using/researching on the Geogauge, please specify your level of agreement with the following statements:

The Geogauge provides the user with accurate and repeatable readings	Disagree
The data collected from the Geogauge is easily analyzed and interpreted	Agree
The Geogauge provides the user with outputs in a quick timely manner	Agree
The Geogauge is portable and easy to use	Agree
The Geogauge is not affected by site's environmental conditions (e.g. moisture content)	Disagree
The Geogauge is negatively affected by properties of lower layers	Neutral
The Geogauge has reasonable cost	Neutral
The Geogauge provides the user with readings representative of field conditions	Disagree

Q9: Based on your experience, state the negative and positive experiences unique to this device: *Respondent skipped this question*

PAGE 5: Alternatives Devices (Dynamic Cone Penetrometer)

Q10: **Have you previously used or researched on the Dynamic Cone Penetrometer device?** Yes, I have used/researched on the Dynamic Cone Penetrometer

PAGE 6: Dynamic Cone Penetrometer

Q11: **Based on your experiences using/researching on the Dynamic Cone Penetrometer (DCP), please specify your level of agreement with the following statements**

The DCP provides the user with accurate and repeatable readings	Disagree
The data collected from the DCP is easily analyzed and interpreted	Disagree
The DCP provides the user with outputs in a quick timely manner	Agree
The DCP is portable and easy to use	Agree
The DCP is not affected by site's environmental conditions (e.g. moisture content)	Neutral
The DCP is negatively affected by properties of lower layers	Neutral
The DCP has reasonable cost	Agree
The DCP provides the user with readings representative of field conditions	Disagree

Q12: Based on your experience, state the negative and positive experiences unique to this device: *Respondent skipped this question*

PAGE 7: Alternatives Devices (Light Falling Weight Deflectometer)

Q13: Have you previously used or researched on the Light Falling Weight Deflectometer device? *Respondent skipped this question*

PAGE 8: Light Falling Weight Deflectometer

Q14: Based on your experiences using/researching on the Light Falling Weight Deflectometer (LFWD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q15: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 9: Alternatives Devices (Briaud Compaction Device)

Q16: Have you previously used or researched on the Briaud Compaction Device?	*Respondent skipped this question*

PAGE 10: Briaud Compaction Device

Q17: Based on your experiences using/researching on the Briaud Compaction Device (BCD), please specify your level of agreement with the following statements	*Respondent skipped this question*
Q18: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 11: Alternatives Devices (PaveTracker)

Q19: Have you previously used or researched on the PaveTracker?	*Respondent skipped this question*

PAGE 12: PaveTracker

Q20: Based on your experiences using/researching on the PaveTracker, please specify your level of agreement with the following statements	*Respondent skipped this question*
Q21: Based on your experience, state the negative and positive experiences unique to this device:	*Respondent skipped this question*

PAGE 13: Conclusion Questions

Q22: **Overall, rank the following devices/methods from "5" being a very poor alternative to the nuclear density gauge to "1" being an excellent alternative to the nuclear density gauge. Please pick N/A if you haven't had any prior experience with a particular device.**

Geogauge	2
Dynamic Cone Penetrometer	2
Light Falling Weight Deflectometer	4
Briaud Compaction Device	4
PaveTracker	N/A
Other	N/A

Q23: **Specify your agency's/company's level of interest in stiffness/strength based devices for compaction of unbound materials**

Extremely Interested

Q24: **Specify your agency's level of interest in implementing stiffness/strength based devices for compaction control of unbound materials.**

Extremely Interested

Q25: **Ultimately, do you feel a transition to an alternative device is possible?**

Yes

Q26: **Based on your experience, please rank the following factors/obstacles that you feel might hinder or negatively influence the widespread implementation of a new device/method as an alternative to the nuclear density gauge. (1: no to very low influence and 4: significantly high influence)**

Need for new equipment	1
Lack of funds	3
Lack of trained personnel	2
Familiarity of devices	4

Q27: Based on your experience, please fill in the following box with any additional comment about other factors/obstacles that you believe might hinder or negatively influence the implementation of a new device/method for use as an alternative to the nuclear density gauge:

Respondent skipped this question

Appendix B: Compaction Quality Control of Unbound Subgrade and Base/Subbase Layers Using the Dynamic Cone Penetrometer.

1. Scope

1.1 This specification covers the compaction quality control of unbound soil/aggregate pavement layers consisting through the use of the Dynamic Cone Penetrometer (DCP).

2. Referenced Documents

2.1 ASTM Standards.

D 6951 Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications

D 7380 Soil Compaction Determination at Shallow Depths Using 5-lb (2.3 kg) Dynamic Cone Penetrometer

D 1557 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort

2.2 AASHTO Standards.

T 2 Standard Method of Test for Sampling of Aggregates

2.3 NJDOT Standards.

200 Standard Specifications for Road and Bridge Construction: Earthwork

300 Standard Specifications for Road and Bridge Construction: Subbase and Base Courses

3. Significance and Use

3.1 This procedure is utilized for the acceptance of compacted unbound subgrade and base/subbase pavement layers.

4. Device

4.1 The Dynamic Cone Penetrometer includes a 22.6-inch (575-mm) upper fixed steel rod containing a 17.6 lbs. (8-kg) steel hammer. Located at lower end of the device is a 0.629-inch (16-mm) diameter rod with an anvil that acts as a lower stopping mechanism for the falling hammer. In addition, the anvil serves as a connector between the two rods and allows the device to be dissembled for easy transport. The length of the lower rod is 24-inch (609.6-mm). At the base of the lower rod is a 0.79-inch (20-mm) diameter steel cone with an apex angle of 60 degrees (Note - 1). The device is tested in accordance to ASTM D6951 or ASTM D7380 standards. The device is to be retrofitted with an automatic ruler that is marked in 0.2-inch (5-mm) increments to indicate the required penetration of the device onto the steel rod and resulting penetration per blow values.

Note 1 – The cone tip may be replaced throughout testing as it becomes trapped in the soil during the extraction of the DCP from the compacted layer. This generally pertains to more coarse materials that contain larger aggregate particles that restrict the cones upward movement.

5. Materials

5.1 The Contractor is to use aggregate materials that conforms to the requirements of the specifications listed in Table 5.1.

Table 5.1 Material Specifications.

Material	Specification
NJDOT Subgrade	NJDOT 901.11
NJDOT Base/Subbase	NJDOT 901.11

5.2 Unless specified otherwise, the Contractor is to provide necessary stockpile at the designated site that meets the specifications provided in Table 5.1.

5.3 The Contractor accepts full responsibility for the placement and compaction of acceptable material at the designated site.

5.4 Should the material not meet the specifications listed in Table 5.1 the RE may require the Contractor to replace or exclude such material prior to compaction of the subgrade or base/subbase layer.

5.5 It is noted that the developed specifications are only applicable for Natural Sands, Dense Graded Aggregates (DGA), and Reclaimed Concrete Aggregates (RCA).

6. Procedure

6.1 Assemble the DCP equipment and attach the replaceable cone tip to the foot of the lower rod as shown in Figure B.1 below. Before proceeding with testing, ensure all parts are securely fastened.

6.2 Unless specified otherwise, it is recommended to conduct DCP testing by any one of the following methods:

6.2.1. Control Strip. A control strip of 400-square yards (334.5-square meters) or greater is to be constructed to perform the DCP test at 10 randomly selected locations (Note - 2).

Note 2 – The procedure for conducting DCP testing shall be in accordance to methods specified in 203.03.02.B of the NJDOT specifications for determining compaction requirements based on density acceptance.

6.2.2. Random Selection of Test Points. DCP testing should be conducted at 10 randomly selected locations within the designated site at a minimum of 3-ft. (0.9-m) increments of each other (Note – 3).

Note 3 – It is recommended to conduct DCP testing in a similar fashion as to the methods specified in 203.03.02.D or 302.03.01B of the NJDOT specifications.

6.3 Using either method provided in Section 6.2, record the DCP value for each location tested.

6.4 The DCP test shall be conducted until a depth of 15-inches (38.1-cm) of the compacted material is reached.

6.5 For sites in which the thickness of the layer is less than 15-inches (38.1-cm) it is recommended to conduct the DCP test for the entire thickness of the layer.

6.6 Testing shall be conducted using the DCP at the designated site within 24 hours of placement and final compaction.

6.7 Testing should not to be conducted later than 24 hours to avoid overestimating DCP measurements.

7. Acceptance Criteria

7.1 Gradation. Use aggregate material that is in satisfying NJDOT requirements for natural sands, DGAs, and RCAs.

7.2 The gradation specifications shall apply to the material following the placement and compaction at the designated site (Note – 4).

Note 4 – If compaction is not anticipated the aggregates material must meet gradation specifications during its placement at the designated site.

7.3 Acceptable gradation specifications are to be maintained through implementing one of the random sampling procedures as specified in AASHTO T 2.

7.4 Moisture Content Control. The material will be deemed acceptable based on the following acceptance criteria:

7.4.1 Acceptable materials are in compliance with the requirements of the specifications presented in Table 7.2 (Note – 5).

Note 5 – Samples for moisture content must be collected from selected testing locations during compaction. The random sampling procedure detailed in AASHTO T 2 can be utilized.

Table 7.2 Minimum Acceptable DCP Values.

Material	Percent Passing (%)				Moist. Cont. Diff. (%)		Minimum DCP Value (blows/inch.)	Minimum DCP Blows (1-ft layer)
	Sieve No. 4 (4.75 mm)		Sieve No. 200 (75 µm)					
	Min.	Max.	Min.	Max.	Min.	Max.		
NJDOT Subgrade	40	100	0	8	0	2	1.3	16 (15)
	40	100	0	8	-2	0	1.5	18 (20)
	40	100	0	8	-4	-2	1.9	23 (25)
	40	100	0	8	-6	-4	2.2	27 (25)
NJDOT Base/Subbase	25	50	3	10	0	2	3.2	39 (40)
	25	50	3	10	-2	0	3.4	41 (40)
	25	50	3	10	-4	-2	3.8	46 (45)
	25	50	3	10	-6	-4	4.1	50 (50)

7.5 Based on measured field moisture content and Proctor Optimum Moisture Content (OMC), one can then determine the moisture content difference (i.e., field moisture content minus OMC).

7.6 Table 7.2 or final DCP prediction model can be utilized to determine the minimum acceptable DCP values for the site being evaluated.

7.7 At least nine of the ten tested locations must achieve higher DCP values that the minimum acceptable value in order for the tested site to be deemed compacted adequately.

8. Report

While conducting the DCP test document the following information and submit to the Resident Engineer (RE):

8.1 The number of hammer blows required at each testing location.
8.2 Cumulative depth of penetration after each set of hammer blows.
8.3 Difference in cumulative penetration between each reading.
8.4 The penetration depth per blow (Note – 6).
(Note 6 – This value is computed as the ratio of number of blows at each location to depth of penetration at that location.)
8.5 Assessment on acceptable/unacceptable compacted material.

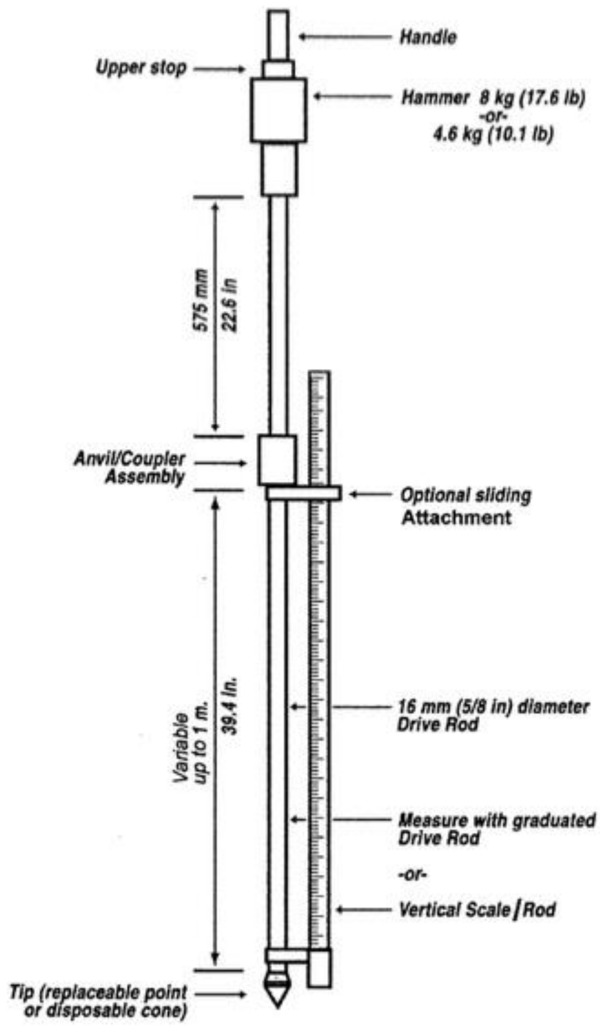

Figure B.1: Assembly Schematic of the DCP [33]