

MOUNTAIN-PLAINS CONSORTIUM

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EVALUATION OF GRANULAR DENSITY AND MOISTURE TESTING



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16. Abstract The South Dakota Department of Transportation (SDDOT) has been using the Ohio Highway Department's (OHD) moisture-density curves for compaction quality control of granular materials. However, the OHD curves were not developed for granular materials, and their use was found to result in inconsistencies between the lab and field-measured densities. Also, OHD curves were not developed for South Dakota's local materials. The present study was undertaken to verify the family of curves developed in the SD2014-12 research project and the suggested DCP method. Hence, different aggregate bases were compacted in the field, and their density and DCP penetration index values were measured. In addition, the gradation and moisture-density relation of the collected aggregate bases were determined in the laboratory. Furthermore, base materials were compacted in a fabricated test box, and sand cone and DCP tests were conducted. The SDDOT moisture-density curves suggested by the SD2014-12 study were found to predict the moisture-density of the granular bases more effectively compared with OHD curves. The DCP test was found to be effective in screening the compaction quality for most parts. A draft specification being considered by SDDOT for implementation of the DCP test for compaction screening was evaluated and shown effective.			
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ABSTRACT

The South Dakota Department of Transportation (SDDOT) has been using the Ohio Highway Department's (OHD) moisture-density curves for compaction quality control of granular materials. However, the OHD curves were not developed for granular materials, and their use was found to result in inconsistencies between the lab and field-measured densities. Also, OHD curves were not developed for South Dakota's local materials. The present study was undertaken to verify the family of curves developed in the SD2014-12 research project and the suggested DCP method. Hence, different aggregate bases were compacted in the field, and their density and DCP penetration index values were measured. In addition, the gradation and moisture-density relation of the collected aggregate bases were determined in the laboratory. Furthermore, base materials were compacted in a fabricated test box, and sand cone and DCP tests were conducted. The SDDOT moisture-density curves suggested by the SD2014-12 study were found to predict the moisture-density of the granular bases more effectively compared with OHD curves. The DCP test was found to be effective in screening the compaction quality for most parts. A draft specification being considered by SDDOT for implementation of the DCP test for compaction screening was evaluated and shown effective.

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EXECUTIVE SUMMARY

State transportation agencies use different types of geomaterials to construct pavements. Paved roads are surfaced either by asphalt concrete or Portland cement concrete. However, as a layered structure, the pavement must have the necessary load-bearing capacity against vehicular loads. Base, subbase, and subgrade layers in a pavement structure reduce the stress level transferred to the natural soil without excessive deformation that can compromise the overall structural integrity and serviceability of the pavement. Granular materials are widely used by departments of transportation (DOTs) for constructing pavement structures such as base and subbase layers. These layers primarily distribute the traffic loads over subgrade soils in flexible pavements and provide uniform support and drainage for the rigid pavements. While size distribution, shape parameters, texture, and the particles' mechanical properties primarily affect the stiffness of the granular layer, achieved field density as a result of compaction remains the single most crucial parameter known to significantly influence the performance of a granular base subjected to traffic loads. Compaction decreases the void ratio, improves packing and particle interlocking, and increases the unit weight, which results in an improvement in the stiffness of the granular material and leads to a better performance in a layered pavement structure. Therefore, achieving field densities close to the maximum dry density of the granular materials during the construction phase at the proper moisture content is vital to pavement performance and longevity.

Historically, the South Dakota Department of Transportation (SDDOT), among several other DOTs, has been using the Ohio Highway Department's (OHD) typical moisture-density curves for compaction quality control of granular materials and granular soils. However, the OHD curves were not developed for granular materials, and their use for granular materials was found to result in errors and inconsistencies between the lab and field-measured densities. Also, OHD curves were not initially developed for South Dakota's local materials as aggregate base. Therefore, the OHD curves are being phased out by several DOTs, including SDDOT. In response to a need for the development of tests and procedures for compaction quality control of granular materials specific to South Dakota, a research project, SD2014-12, was conducted at South Dakota State University (SDSU). The study's final report provided a summary of the compaction control methods practiced by SDDOT. As a result, it was recommended to replace the OHD moisture-density curves with those developed in the SD2014-12 study for the materials specific to South Dakota. Also, it was suggested to apply a strength-based method using the Dynamic Cone Penetrometer (DCP) instead of relative compaction, which may widely vary in the field. While the aforementioned recommendations are expected to improve current practices significantly, a verification process must be carried out before they can be implemented. The verification process should be carried out to (i) ensure the applicability of the South Dakota moisture-density curves developed in the SD2014-12 project over various materials and different geographical areas through full-scale side-by-side tests on pilot projects; and (ii) the accuracy and applicability of the DCP as a strength-based method should be verified to determine and double-check correlations between the DCP index and density and recommend adjustments to the Minnesota Department of Transportation's (MnDOT) DCP specification based on South Dakota materials, if necessary.

In response to these needs, the present study was undertaken and an evaluation program was designed to verify the South Dakota moisture-density curves developed in the SD2014-12 research project. Also, the suitability of the suggested DCP method as the strength-based approach for determining the in-situ compaction quality was evaluated. Based on this approach, SDDOT's available draft specification language proposed for screening the field compaction applying the DCP test was examined. As a result, the draft specification established the technical criteria based on the outcomes of the field DCP tests required for achieving the desired field compaction. Finally, several recommendations were developed for successful implementation based on observations made in this study. The research objectives were achieved by following a systematic approach employed for literature review, designing a testing program, executing the testing program, data collection and analysis, discussion, and recommendation for implementation. A brief description of the steps followed in this study is provided herein.

1. INTRODUCTION

1.1 Problem Statement

Granular materials are widely used by departments of transportation (DOTs) for the construction of pavement structures such as base and subbase layers. These layers primarily distribute the traffic loads over subgrade soils in flexible pavements and provide uniform support and drainage for rigid pavements (Xiao et al., 2016; Tutumluer et al., 2015). While size distribution, shape parameters, texture, and the particles' mechanical properties largely affect the stiffness of the granular layer, achieved field density as a result of compaction remains the single most crucial parameter known to significantly influence the performance of a granular base subjected to traffic loads (Chen et al., 2018; Martin et al., 2017). Compaction decreases the void ratio, improves packing and particle interlocking, and increases the unit weight, which results in an improvement in the stiffness of the granular material and leads to a better performance in a layered pavement structure (Huang, 1993). Therefore, achieving field densities close to the maximum dry density of the granular materials during the construction phase at the proper moisture content is vital to pavement performance and longevity.

Historically, the South Dakota Department of Transportation (SDDOT), among several other DOTs, has used the Ohio Highway Department's (OHD's) typical moisture-density curves (Joslin, 1958) for compaction quality control of granular materials and granular soils. However, the OHD curves were not developed for granular materials, and their use for granular materials was found to result in errors and inconsistencies between the lab and field-measured densities. Also, OHD curves were not originally developed for South Dakota's local materials and other repurposed materials such as recycled Portland cement concrete (PCC) and reclaimed asphalt pavement (RAP) as aggregate base. Therefore, the OHD curves are being phased out by several DOTs, including SDDOT. In response to a need for the development of tests and procedures for compaction quality control of granular materials specific to South Dakota, a research project, Compaction Testing of Granular Material (SD2014-12), was conducted at SDSU. The final report was submitted to SDDOT (Jones and Weber, 2019), in which the compaction control methods practiced by SDDOT were reviewed. As a result, recommendations in two major areas were made to improve the current practice as follows.

- i) Replace the OHD moisture-density curves with those for materials specific to South Dakota developed as a part of the SD2014-12 study.
- ii) Apply a strength-based method using the Dynamic Cone Penetrometer (DCP) instead of relative compaction, which may widely vary in the field.

While the aforementioned recommendations are expected to improve current practices significantly, a verification process must be conducted before they can be implemented. The verification process should cover two major areas as follows.

- i) To ensure the applicability of the South Dakota moisture-density curves developed in SD2014-12 project over various materials and different geographical areas, the moisture-density curves are to be verified in full-scale side-by-side tests on pilot projects.
- ii) The accuracy and applicability of the DCP as the strength-based method should be verified to determine and double-check correlations between the DCP index and density and recommend adjustments to MnDOT's DCP specification based on South Dakota materials if necessary. Also, the DCP test's repeatability, speed, operation convenience, safety, and limitations are to be determined.

In response to these needs, the present study was undertaken, and an evaluation program was designed to verify the South Dakota moisture-density curves developed in the SD2014-12 research project (Jones and Weber, 2019). Also, the suitability of the suggested DCP method as the strength-based approach for determining the in-situ compaction quality was evaluated. Based on this approach, SDDOT's available draft specification language proposed for screening the field compaction applying

the DCP test was examined. As a result, the draft specification established the technical criteria based on the outcomes of the field DCP tests required for achieving the desired field compaction. Finally, several recommendations were developed for successful implementation based on observations made in this study.

1.2 Objectives

This research project focused on achieving three main objectives as follows.

Objective 1

Design a field test program that will provide side-by-side comparison of the SDDOT moisture-density curves and the DCP test to current compaction testing methods during the 2020 construction season. This objective was achieved by first summarizing the existing literature, including technical reports, specifications, journal papers, technical memorandums, and conference proceedings as well as the SD2014-12 final report (Jones and Weber, 2019). Then, based on the literature review and in close consultation with project's technical panel, a testing program was proposed, which included 10 different field construction projects. Field testing program included DCP, nuclear density gauge (NDG) and moisture content (MC) measurements, and their comparison with sand cone density measurements. Identification of the test sites was carried out in close collaboration with the SDDOT research office and the project's technical panel during the 2020 and 2021 construction seasons.

Objective 2

Based on results of the side-by-side comparison, evaluate the suitability of the SDDOT moisture-density curves and the DCP test as replacements for current granular material compaction acceptance. This objective was achieved by analyzing the collected data obtained from fulfilling Objective 1. More specifically, the field-measured dry unit weights (DUW) along with the maximum dry unit weights (MDUW) obtained by implementing both South Dakota and Ohio compaction curves were used to estimate the field densities. In addition, actual MDUW values measured in the laboratory by conducting standard Proctor tests on materials collected from each project were used to calculate the compaction achieved in the field during construction. A side-by-side comparison was carried out between the actual field densities and those estimated based on the SDDOT and Ohio curves to verify the effectiveness of both SDDOT and Ohio curves in predicting the MDUW of the granular base materials. In addition, the DCP test results were analyzed side-by-side with the relative density results and the dynamic penetration index (DPI) values' capability in capturing the compaction adequacy in conjunction with the moisture-density curves developed as a part of the SD2014-12 project (Jones and Weber, 2019).

Objective 3

Recommend specifications for using the SDDOT moisture/density curves and the DCP test in construction involving granular material compaction.

The important observations during execution of the tasks related to Objectives 1 and 2, including the findings related to verification of the South Dakota moisture-density curves and their effectiveness in predicting the MDUW as well as the DCP test's suitability for screening the compaction quality of the granular bases, were compiled and summarized. Based on the outcomes of the aforementioned analyses, a draft specification and a number of recommendations were compiled for the application of the SDDOT curves in the construction. In addition, the draft version of a specification proposed by SDDOT for using the DCP test for characterization of the compaction quality of the granular bases was assessed. Several recommendations were made by the research team before considering the proposed draft specifications for full implementation. Based on the outcomes of the aforementioned analyses, a draft version of a specification proposed by SDDOT for the use of the DCP test for characterization of the compaction quality of granular bases was assessed. Several recommendations

were made by the research team before considering the proposed draft specifications for full implementation. The DCP test's evaluation was carried out in at least five close locations of the same sub-lot for each test site. The standard deviation and coefficient of variation for each set of the DPI measurements were determined and used to evaluate the repeatability of the DCP test. In this case, the draft specification established the technical criteria based on the outcomes of the field DCP tests required for achieving the desired field compaction.

1.3 Research Tasks

Task 1. Project Scope Review

Meet with the project's technical panel to discuss project scope, work plan, and schedule.

The research team prepared a meeting agenda and shared it with the technical panel for review, ahead of the kick-off meeting. The project's technical panel and the research team met on June 16, 2020, at 10:30 a.m. (CDT) via Skype (kick-off meeting) to review the work plan and project scope. A presentation summarizing the project's tasks was delivered by the principal investigator (PI). Important items, including planning, testing, and site selection were discussed during the kick-off meeting. This meeting covered the important technical aspects of the project tasks and the material sources, as well as logistics of the project. Furthermore, comments regarding any important considerations to be taken into account in the course of the execution of the project for successful delivery of the final outcomes were solicited from the technical panel. Important highlights of the meeting were as follows:

- There is a concern about the DCP's capability in capturing the characteristics of very loose material. Therefore, it was decided not to test materials with a very loose nature and start with base materials compacted at a minimum level of 60% of their maximum dry density (MDD). The effectiveness of this method will be examined in the field.
- It will be difficult for Brosz Engineering to use SDDOT labs during the pandemic. Therefore, Brosz's technicians will immediately collect the materials in a Ziploc bag, then have SDDOT lab techs perform the moisture tests. Brosz can run the 1-point test back in Pierre.
- A moisture test for every single DCP test may not be required. Small areas should have a consistent moisture content. Therefore, it was suggested to carry out an extra test alongside the NDG test on compaction levels 2 (75% MDD) and 4 (100% MDD) to address any doubt about the moisture content. The initial testing sites should provide a better understanding of how many moisture tests are needed.
- It was suggested to collect approximately 1,000 lbs. of base material at each site from the windrow. If the material is collected from the stockpile, the SDSU team should be able to adjust the gradation of the sample to be more representative of the project site.
- FDR construction jobs are becoming less available. Therefore, county jobs may be selected. Collecting material is more difficult on county jobs. Derek McTighe pointed out that Brosz personnel could assist in material collection at county jobs.
- Derek McTighe will try to identify six base course projects (only four base course projects are required). An alternative material site could be the Mitchell city job (pounded concrete and reclaimed base course). Another potential site would be Omaha Street in Rapid City (crushed recycled concrete).
- Brosz will send a notice to the project's technical panel and the PI two to three days prior to starting the first field test. Initial testing for the project is predicted to begin later next week (by June 23, 2020).

After reviewing the draft work plan by the project's technical panel and receiving the comments, a revised work plan was prepared and included in the first scheduled progress report. Feedback obtained from the meeting was incorporated into a revised work plan submitted to the project's technical panel after the kick-off meeting. After several discussions with the project's technical panel, the revised work plan was summarized and used throughout the project.

Task 2. Literature Review

Review and summarize literature regarding implementation and validation of moisture-density curves and the DCP.

A substantial literature review on this topic has already been compiled by Jones and Weber (2019) and Siekmeier et al. (2009). The literature review of the foregoing reports was expanded to capture the findings of the recent studies relevant to the objectives of the project. As a result, the important aspects of implementation and validation of moisture-density curves and the DCP, including but not limited to specifications, application, evaluation, performance, and testing, were summarized and included. The literature review also helped the research team design the field test program for side-by-side comparison of the SDDOT moisture-density curves and the DCP test to current compaction testing methods detailed in Task 3.

Task 3. Design of a Comprehensive Field Test Program

In collaboration with the project's technical panel, design a comprehensive field test program for side-by-side comparison of the SDDOT moisture-density curves and the DCP test to current compaction testing methods, including project locations, test procedures and frequency, reporting procedures, and the criteria and analysis needed to evaluate the use of the SDDOT moisture-density curves and the DCP.

The outcomes of the meetings and discussion with the technical panel were revised based on the panel's input, which was applied for designing a comprehensive field test program for side-by-side comparison of the SDDOT moisture-density curves and the DCP test to current compaction testing methods. It was decided to measure field densities using the NDG test, DCP test, and sand cone method at project test sites on granular materials. It is important to ensure compliance of all of the candidate site materials with the definition of granular materials as per AASHTO M 145 (AASHTO, 2015). Also, a sieve analysis test was decided to be conducted on the materials in accordance with AASHTO T 27 (AASHTO 2018). Although final decisions on the test site locations were made after discussion with project's technical panel, the locations were distributed as such to represent diverse material sources with different mineralogies. Therefore, the project sites were selected in counties and projects to cover the widest range of the mineralogy and granular material sources. In view of the material mineralogies and types and in order to cover different regions, at least 10 sites were included. In addition to testing conventional granular materials, one test site included recycled concrete aggregate (RCA) as granular materials in the test matrix. The field tests were conducted on properly compacted materials. The DCP and cone density tests were also carried out on insufficiently compacted materials. This helped examine the effectiveness of the developed methodology in capturing the problematic compaction. Also, the criteria and analysis needed to evaluate the use of the SDDOT moisture-density curves and the DCP test were developed and finalized by implementing the technical panel's input.

Task 4. Technical Memorandum No. 1

Prepare and present to the project's technical panel a technical memorandum summarizing the literature review and recommending the field test and evaluation program.

A revised technical memorandum summarizing the results of the literature review (Task 2) and the comprehensive testing plan (Task 3) was prepared, and submitted on April 26, 2021, and presented to

the project's technical panel on May 10, 2021, at 2:30 p.m. via Microsoft Teams. The first part of this memorandum focused on literature review outcomes. The second part presented the details of the comprehensive field test program for side-by-side comparison of the SDDOT moisture-density curves and the DCP test to current compaction testing methods, test procedures and frequency, reporting procedures, and the criteria and analysis needed to evaluate the use of the SDDOT moisture-density curves and the DCP developed in Task 3.

Task 5. Field Test Observations

Upon approval of the field test and evaluation program, observe initial testing and analyze reported field test data to verify the field test and evaluation program and identify needed improvements.

After receiving the technical panel's approval on the technical memorandum submitted as a part of Task 4, the research team visited a number of project test sites to observe initial testing efforts and record important observations relevant to practicality, speed, convenience, ease of testing, variability, and other important aspects of the field testing. Also, the reported data collected from the initial field tests were analyzed. Based on this analysis, the test repeatability and the technician's feedback on speed, operation convenience, and safety were summarized. Given the high speed of conducting the DCP and sand cone tests, at least five repetitions of each test for each test site were recommended for this task. Also, at least three repetitions of NDG tests for each site were suggested. As another part of the analysis, the DCP test's repeatability was evaluated by repeating the DCP tests at least on five close locations of each sub-lot for each test site. Standard deviation and coefficient of variation for each set of the DPI measurements were determined and used to evaluate the repeatability of the DCP test. Also, onsite observations regarding the time spent for conducting each DCP test, a qualitative measure of the operation's convenience, safety-related observations, and any limiting factors affecting the quality of the test data and efficiency of the operation were summarized. The research team attended a number of selected job sites to observe the process and document important observations associated with field tests. In addition to field observations, the SDSU research team conducted parallel tests in the laboratory. For verification purposes, gradation and standard Proctor tests were conducted in the laboratory on the materials collected from the 10 job sites. Also, an aggregate test box was fabricated in the laboratory at SDSU, and the collected materials were compacted using a hand tamper tool to the relative density levels reported from the Proctor test. The DPI of the compacted material in the test box was then determined using a DCP device. Although this part of the study was not directly a part of the SDDOT project, the findings of the laboratory tests enriched the outcomes of the study by providing an extra tool for verification. Support for the laboratory testing and the required equipment were provided by MPC.

Task 6. Data Collection and Analysis

After all field test data are received, evaluate the suitability of the SDDOT moisture/density curves and the DCP test as replacements for current granular material compaction acceptance.

To facilitate this task, the project manager at SDDOT, the research team's point of contact with SDDOT, communicated any plans for construction with the research team at least one week before construction by e-mailing the project's PI. This was effective method in giving the research team at SDSU an opportunity to plan for attending the job site and performing activities such as collecting site-specific information, taking pictures, and observing the test conducted by the SDDOT's seasonal technician. Also, the collected test data were communicated by the project manager at SDDOT to the research team (PI). During the study's field testing, results were periodically compiled and analyzed as they became available. As a part of this analysis and to verify the applicability of the density curves as per SD2014-12 and the DPI for screening the field compaction, the density measurements obtained by using the sand cone were used as the benchmark values. Efforts to develop a regression model to correlate the measured DPI and predicted relative density values using the density curves as per SD2014-12 with those measured in the field using sand cone techniques were not found feasible due to

the large variability and a small number of data points. However, the actual achieved field densities as per the benchmark data were compared with those obtained by application of the Ohio and SDDOT curves. This comparison was used to assess each method's accuracy in predicting the MDUW of the granular bases. In addition, the research team and the technical panel tried to spot any abnormalities in the test results and take necessary actions to find their root cause. Note that a number of strategies were discussed with the technical panel and applied to reduce errors.

Task 7. Technical Memorandum No. 2

Prepare and present to the project's technical panel a technical memorandum that summarizes the results of testing and evaluation.

The outcomes of Tasks 5 and 6 were summarized and presented to the project's technical panel as a separate memorandum in August 2022. The technical memorandum included the observations and improvements made to the testing plan as a part of Task 5 as well as the data analysis results carried out in Task 6. The research team revised the submitted technical memorandum, after receiving the technical panel's input. In addition to the technical memorandum, a presentation was delivered to the technical panel followed by a question-and-answer session and a discussion.

Task 8. Specification Language

Develop and present to the project's technical panel specification language for use of the SDDOT moisture/density curves and the DCP test in construction involving granular material compaction.

Based on the outcomes of Task 7, the proposed test procedure, observations made during testing, data collection, and outcomes of the test results analysis and other material properties as discussed earlier, a draft specification language for use of the SDDOT moisture-density curves and the DCP test in construction involving granular material compaction is presented as a part of the final report for review by and feedback from the technical panel. Considering MnDOT's success in using the DCP-based specification, SDDOT may adopt a revised version of MnDOT's DCP-based specification modified based on the outcomes of this study. The abovementioned draft specification is being considered by SDDOT for using the DCP test in construction and compaction of granular bases. Since the forgoing specification has already been evaluated in the study, the same proposed specification with some additional comments has been proposed. The draft specification will cover all technical aspects of the testing, methods, materials, and reporting requirements as well as the required techniques and methodologies for conducting the DCP tests and reporting. Currently, procedures, methods, and supplemental specifications for conducting the DCP tests are compiled as a part of Appendix A in the final report of the SD2014-12 project (Jones and Weber, 2019).

Task 9. Final Report

In conformance with the Guidelines for Performing Research for the South Dakota Department of Transportation, prepare a final report summarizing the research methodology, findings, conclusions, and recommendations.

A comprehensive final report prepared by the research team in conformance with the SDDOT guidelines is being submitted. The final report documented all aspects of the project, including the literature review, detailed research methodology and findings, and summarized conclusions and recommendations. Additionally, it includes the developed specifications for use of the SDDOT moisture-density curves and the DCP test in construction involving granular material compaction. The report will be revised as needed to address the technical panel's comments.

Task 10. Executive Presentation

Make an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the project.

At the conclusion of the study, an executive presentation will be made and delivered by the project's PI to the SDDOT Research Review Board at SDDOT's headquarters in Pierre, South Dakota. The presentation will summarize the research activities that were accomplished in this project and all conclusions and recommendations that resulted from the research.

2. LITERATURE REVIEW

2.1 General

To attain a transportation infrastructure with high quality and longevity, an in-depth understanding of the soil and geomaterials used as a foundation for the roads and pavements is required. Specifically, base, sub-base, and subgrade layers designed and constructed as parts of the layered pavement system must meet particular strength and drainage properties, affecting overall pavement performance. In addition, the engineering properties of the soils and aggregate materials are key input parameters for any design project dealing with geomaterials, including those used in pavements. The essential soil, granular base, and subgrade materials' engineering characteristic, which is used as an input parameter in the Mechanistic-Empirical Pavement Design Guide (M-EPDG) (NCHRP, 2004), is the resilient modulus, a measure of material's stiffness and strength (Li et al., 2009). On the other hand, the stiffness and strength of any granular material with a given gradation are primarily controlled by its particle packing characteristic, which is a function of moisture content, compaction effort, and achieved relative density (Cortes and Bandini, 2018). Therefore, achieving the highest practical field densities through adequate compaction, realistic estimation of granular materials' optimum moisture content, and maintaining it during construction is central to obtaining a strong and durable pavement structure (Abu-Farsakh et al., 2004).

A granular material, by definition (AASHTO, 2015), contains less than 35% particles (by weight) passing a No. 200 sieve (<0.075 mm), which covers a group of materials with natures and classifications ranging from stone fragments, gravel, and sand (A-1 group) to fine sand (A-3 group) to silty or clayey gravel and sand (A-2 group). The granular materials from their hydraulic conductivity standpoint may occur in two major classes, (i) free draining and (ii) semi-draining, based on their plastic fine contents (Jones and Weber, 2019; Drnevich, 2017). Each class can be used as an aggregate base or subbase depending on project type, their application, gradation, and construction requirements. To enhance field performance and determine lab unit weight, granular materials are compacted using one or more methods: impact, pressure, kneading, or vibration. Impact compaction, the most common laboratory compaction method, is used to determine the maximum dry unit weight (MDUW) and optimum moisture content (OMC) of the granular materials in the laboratory in accordance with AASHTO T 99 (AASHTO, 2019) and AASHTO T 180 (AASHTO, 2004) standard test methods, representing standard Proctor and modified Proctor compaction efforts, respectively. The laboratory standard and modified Proctor test methods are widely used for determination of the moisture-density relationship of granular materials and are mainly applied for verification and quality control purposes. However, a reliable, quick, easy to conduct, safe, practical, and precise method to determine the achieved field density as a result of compaction is required for construction.

2.2 Field Density Measurement Methods for Granular Materials

A pavement's response when subjected to traffic loading is governed by its resilient deformation as an indicator of its stability and load-carrying capacity, and its permanent deformation, which can lead to premature pavement distresses such as rutting (Lekarp, 1998). The pavement sublayers' density primarily affects their mechanical properties and, therefore, both resilient and permanent responses of the overall pavement structure (Dutta and Kodikara, 2022). As a result, determining the in-situ density of the compacted base, sub-base, and subgrade layers is crucial to ensure the mechanical properties of the pavement layers meet those of the specification (Thai et al., 2022). Therefore, an accurate and quick measurement of the pavement layers' in-situ densities is critically important.

2.2.1 Sand Cone Test

The sand cone test, conducted in accordance with AASHTO T 191 (AASHTO, 2018), is used to determine the in-situ unit weight and density of soils and geomaterials. This method is designed for materials containing particles not larger than 50 mm. For this purpose, a density apparatus consisting of a 4-L jar and a special cap and valve connected to a small funnel is used. It also includes a base plate having a flanged center hole to fit the funnel. To conduct the test, the apparatus is filled with the standard sand, and its total mass is recorded. The base plate is then placed on a prepared surface of the compacted material. A hole is formed by digging the soil at the location of the plate's hole. The removed soil is then placed in a container to avoid moisture loss or material loss. This sample is taken to the lab to measure its moisture content and dry weight. The apparatus is placed on the base plate, and the valve is opened. After the sand has stopped flowing into the hole, the valve is closed, and the apparatus is removed. Finally, the weight of the apparatus after testing is measured. The volume of the hole is determined by calculating the amount of sand displaced into the hole by dividing the mass of the sand by its unit weight. The dry weight of the soil is then divided by the volume of the hole to determine the in-situ dry density of the material. The sand cone test has several benefits, such as its higher accuracy than the NDG method at a lower cost without needing an NDG license. The sand cone device is also relatively inexpensive, and is light and small and easy to take to job sites and transport. However, the sand cone method's drawbacks include sensitivity of the test results to material loss, requiring an experienced operator for good results, sensitivity of the results to vibration during testing, inaccuracies observed in testing samples with high moisture, and the long time needed to obtain results. Additionally, some limitations associated with the repeatability of using the sand cone test in aggregate bases with a high void ratio (drainable and semi-drainable bases) are reported (Jones and Weber, 2019; Ernest et al., 2013; Farrag, 2005). Nevertheless, given its accuracy and ease of performance, it is considered one of the benchmark tests for the compaction quality of the base and subgrade materials in construction.

2.2.2 Rubber Balloon Test

The rubber balloon test, conducted in accordance with ASTM D2167 (ASTM, 2015), is another method for in-situ measurement of the unit weight and density of the compacted soil and geomaterials. The rubber balloon density test has been used with acceptable repeatability and accuracy over the years on different materials, including granular aggregate bases (Sebaaly et al., 2019). This test is better suited for soils or granular materials without considerable amounts of rocks or coarse particles. The rubber balloon test is used to measure the unit weight of soil by measuring the volume of an excavated hole in the soil by filling a calibrated membrane into the cavity with a liquid. The volume of the displaced water from the device filling the membrane is measured and used to calculate the volume of the cavity. The dry weight and water content of the excavated materials, along with the cavity volume, are used to determine the moisture content and the unit weight of the material. Similar to the sand cone test, this method is sensitive to the material and the moisture loss during the testing. Also, it is not recommended to be used with soft soils and clays, which can result in inaccurate volume measurement. In addition, using this method with aggregate materials containing particles with sharp edges, which may result in puncturing the membrane, is not feasible. In addition, obtaining the final results may take time until the soil sample is taken to the lab for drying and measurement of the dry mass. In contrast, this method has higher accuracy than the NDG and does not require a license. The low cost of the equipment and its portability make it a convenient tool for density measurement in the field. Overall, this test method is considered another accurate and effective tool for measuring the unit weight of soil in construction (Coulouma et al., 2021).

2.2.3 Nuclear Density Gauge Test

The nuclear density gauge (NDG) test is conducted in accordance with AASHTO T 310 (AASHTO, 2019) to measure in-place density and moisture content of soil and soil-aggregate in shallow depths. The NDG test method is the most widely used field density (and moisture content) measurement technique with reliable outcomes on various materials (Jones and Weber, 2019; Rathje, 2006). Given its advantages, the NDG is used by several state DOTs for measuring the field densities in road construction projects. The equipment may be operated in different modes, namely direct transmission, backscatter, or backscatter/air-gap ratio methods. The moisture content is measured only by application of the backscatter method by surface measurements. The direct transmission method consists of determining total or wet density of the geomaterial through attenuation of gamma radiation detected at the surface where the radiation source is located at a known depth not more than 300 mm. In the backscatter method, both source and detector are placed on the surface. The NDG method is a rapid (takes few minutes), nondestructive test used for determining wet density and moisture content of compacted geomaterials. Despite its advantages, the equipment is relatively costly to purchase and maintain, requires highly trained and licensed operators, and poses risks of exposure to radiation. The NDG falls short in delivering accurate readings when it comes to measuring moisture content of the recycled PCC due to its technical limitations (Nazzal, 2014). The accuracy of the NDG test results can also be affected by the chemical composition of the materials being tested, sample heterogeneity, and surface texture. Also, the equipment is known to be more sensitive to moisture near the surface than that present at the deeper areas (Dep et al., 2021). Cortes and Bandini (2018) reported that none of the available devices can provide on its own direct measurements of compaction, moisture, and mechanical properties of a compacted geomaterial layer. Also, it was suggested that automation may play a role in the design of a replacement for the NDG, but the real need lies in the development of a new transitional device that can measure density, moisture content, strength, and stiffness.

2.2.4 Screening of Field Compaction Using Dynamic Cone Penetration Test

The Minnesota Department of Transportation (MnDOT) has been using the DCP test with success since 1991 as a strength-based method for determining field compaction adequacy and as a quality acceptance tool (Siekmeier et al., 1998). The idea of applying the DCP test to the Minnesota Road Research Project (Mn/ROAD) project was first proposed by Matt Witcak in 1991. Following that, DCP pilot projects started in Becker, Scared Heart, and Faribault, MN. MnDOT started researching the use of DCP for screening the compaction quality for edge drains and formulated a specification for this purpose in 1992. During the same year, with continuous research efforts and DCP data collection from MnROAD, laboratory tests started to develop correlations between field and laboratory measurements. In 1993, MnDOT began adopting the DCP specifications in field construction. In 1995, it was found that the dynamic penetration index (DPI) did not exhibit a strong correlation with the compaction level in fine soils. As a result, empirical DPI limits based on the material type were introduced. In 1996, the empirical DPI limits were developed and adopted for the compaction of base layers in construction. In 1997, a base layer compaction specification by utilization of the DCP test was fully adopted, and training materials were developed. Conducted research on both the MnROAD and other project sites, in an effort to determine the effectiveness of the application of the DCP test as a compaction quality control tool, has shown promise and resulted in the development of a specification widely used in Minnesota's road construction projects (Burnham, 1997). In 2004, Oman (2004) suggested improvements to MnDOT's existing DCP specification as a result of continuous observations and data collection to address a number of the method's shortcomings. Over the past three decades, MnDOT has found DCP testing an effective tool for quality control of compacted base materials, among other applications.

As a simple, quick, and inexpensive test, the DCP test is based on the penetration rate of a dynamic cone with an 8-kg weight dropping from a 575-mm height measured through compacted materials. The penetration rate of the DCP, in most cases, is related to strength or density when the soil type and moisture content are known. Some DCP devices are equipped with a graduated rod, used for reading the distance the DCP tip has traveled into the compacted material. The DCP operator lifts the slide hammer to the handle and releases it while keeping the device in a position vertical to the soil surface. The impact of the hammer drives the DCP tip into the soil. The penetration recorded for a certain number of DCP blows, also known as the DPI, is used for describing the stiffness, density, or other material characteristics. As a result of conducting the DCP test in accordance with ASTM D 6951 (ASTM, 2016), DPI is determined, which is mainly the penetration per blow. The lower the DPI value, the stronger the tested material, indicating a better compaction quality. Equation 2.1 is used to calculate the DPI.

$$\text{DPI} = (A - B)/3 \quad (\text{Equation 2.1})$$

where, DPI represents the penetration index value (mm/blow), A is the penetration reading after five blows (mm), and B is the penetration reading after two blows (mm). A significant advantage of the DCP test is its capability to be conducted on both conventional and recycled materials and, therefore, does not have the NDG's limitations. A supplemental test procedure for implementing the DCP test for compaction quality control of South Dakota's granular material developed by Jones and Weber (2019) outlines the details of testing and the necessary technical considerations for maintaining accuracy and data quality during the testing.

2.3 Determining Maximum Dry Unit Weight and Optimum Moisture Content

While the methods discussed in the previous sections are widely used in the field to determine in-situ dry unit weight (DUW) of the granular materials, the compaction quality is expressed as a ratio of the existing DUW to the MDUW. Also, it is important to compact the granular materials at a moisture content as close as possible to its OMC to achieve the highest field density.

2.3.1 Standard and Modified Proctor Tests

Standard and modified Proctor tests in accordance with AASHTO T 99 and AASHTO T 180 (AASHTO, 2019) are conducted on soil and aggregate materials to determine their MDUW and OMC values. In this method, the representative aggregate sample is thoroughly mixed and reduced to the appropriate size and dampened to have a moisture content approximately 4% below OMC. A compacted specimen is prepared in a cylindrical mold of 101.6 mm diameter and in three layers of equal thickness while the mold collar is attached. Each layer is compacted by applying 25 blows or of a rammer of 2.5 kg mass (standard Proctor) or 4.54 kg mass (modified Proctor) dropped from a height of 305 mm (standard Proctor) or 457 mm (modified Proctor) depending on the method applied. After compaction of all layers, the collar is removed, and the sample is trimmed before it is removed from the mold and the mass of the sample is determined by subtracting the mass of the empty mold from mass of the mold containing the sample. The sample is then dried to the constant mass to determine its moisture content. This procedure is repeated by adding moisture to the aggregate and repeating the procedure for each moisture content. The OMC and MDUW values are determined by plotting the DUW and MC datapoint points. This process requires testing several samples with different moisture contents to form the moisture-dry unit weight relationship. Although this is an accurate test that should be performed in the laboratory, testing many samples requires spending several hours in the laboratory and drying the samples, which is a time-consuming process.

2.3.2 Families of Compaction Curves

Among many other state DOTs, SDDOT's current practice for determining the MDUW-OMC is based on families of compaction curves by one-point determination by following the AASHTO T 272 standard method (AASHTO, 2018). This method is used for rapid determination of the MDUW and OMC of soil and geomaterials utilizing a family of curves and a one-point DUW-MC. In view of its convenience, many state DOTs (e.g., Indiana DOT, Ohio DOT) have developed a family of curves for determining MDUW and OMC of the geomaterials by applying the one-point method. However, due to the variability of the materials found in different locations, the family of curves should be developed specifically for each state; and each is obtained by compiling several compaction data points of native geomaterials.

SDDOT's current practice for determining the target MDUW-OMC is based on families of compaction curves modified and adopted from the Ohio Department of Transportation's (OHD) typical moisture-density curves. This version of the curves contains additional interpolated curves added by SDDOT (SDDOT, 2015). The aforementioned curves were developed and plotted over a range of dry unit weights (DUW) and moisture contents (MC) of the soil at given intervals of DUW and OMC. Considering a need for developing a family of compaction curves specific to the local granular materials used for pavement construction, a new set of a family of curves was developed by Jones and Weber (2019) for South Dakota's local geomaterials.

To this end, the current study aims to design an evaluation program through an effective research plan to verify the South Dakota moisture-density curves developed in the SD2014-12 research project (Jones and Weber, 2019) and the suggested DCP method as the strength-based approach. Additionally, a specification is proposed for effective implementation of the South Dakota compaction curves and conducting a DCP test. Also, it is envisioned to make a number of practice-based recommendations for the successful implementation of the aforementioned approach based on observations made in this study.

3. MATERIALS AND METHODS

3.1 Overview

The testing program pursued in this study consists of two important components: field testing and laboratory testing. The field-testing program and laboratory testing are needed for a side-by-side comparison of the densities achieved in the field and precise determination of the MDUW and OMC. In addition, laboratory testing helped the research team access more data points for validation and comparison purposes.

3.2 Testing Program

3.2.1 Laboratory Testing Program

The study's laboratory testing program consisted of conducting tests by the SDSU research team on aggregate bases collected from the field construction projects, as follows:

- Determination of MDUW and OMC using standard Proctor method as per SD 104 (SDDOT, 2015)
- Determination of Atterberg limits of the collected materials as per SD 207 (SDDOT, 2015)
- Particle size analysis conducted on the collected materials as per SD 202 (SDDOT, 2015)
- Compaction of aggregate bases to their MDUW and OMC in a test box
- Conducting DCP tests on the materials compacted in the test box as per Jones and Weber (2019)
- Conducting the SCT on the materials compacted in the test box as per SD 105 (SDDOT, 2015)

3.2.1.1 Standard Proctor Test

To develop the moisture-density relations of aggregate bases and determine their MDUW and OMC values, the standard Proctor test was conducted on collected aggregate materials in accordance with the SD 104 (SDDOT, 2015) test method. In this method, four bags of collected aggregate samples were thoroughly mixed and reduced to the appropriate size (Figure 3.1) and dampened to have a moisture content approximately 4% below OMC. A compacted specimen was prepared in a cylindrical mold of 101.6 mm in diameter and in three layers of equal thickness while the mold collar is attached. Each layer was compacted by applying 25 blows of a rammer 2.5 kg in mass dropped from a height of 305 mm (Figure 3.2). After compaction of all layers, the mold collar was removed, and the sample was trimmed before it was removed from the mold. The mass of the sample was determined by subtracting the mass of the empty mold from that of the mold containing the sample. The sample was then dried to a constant mass to determine its moisture content. This procedure was repeated by adding moisture to the aggregate and repeating the procedure for each moisture content level. The OMC and MDUW values were determined by plotting the DUW and MC datapoint points.



Figure 3.1 Reducing the Sample Size Using an Aggregate Splitter



Figure 3.2 Photographic View of an Aggregate Sample in Proctor Mold and Compaction Rammer

3.2.1.2 Sieve Analysis Test

To determine the particle size distribution of the collected granular base materials, sieve analysis was conducted in accordance with SD 202 standard method (SDDOT, 2015). In this method, four bags of collected aggregate samples were thoroughly mixed and reduced to the appropriate size using an aggregate splitter (Figure 3.1). The sample was then dried (Figure 3.3) to a constant mass at a temperature of $110^{\circ} \pm 5^{\circ}\text{C}$ in accordance with SD 108 standard method (SDDOT, 2015). The sample was then allowed to cool until it could be handled comfortably without introducing errors to sieve operations and mass measurements. The loose weight of the samples was measured and recorded as the original dry sample weight to the nearest 0.1 gram. A stack of sieves was arranged in accordance with the sieve sizes indicated in SD 202 (SDDOT, 2015) nested in the order of decreasing opening size from top to bottom. The sample was then placed into the top sieve, and a mechanical sieve shaker was utilized for agitation of the sieves for approximately 10 minutes (Figure 3.4). After the agitation process, the percentage of material retained on each sieve was weighed, recorded, and calculated based on the original dry weight to the nearest 0.1%. The accumulative percent passing each sieve was determined by subtracting the percentage retained on each sieve from 100.



Figure 3.3 Drying Aggregate Samples in an Oven to a Constant Mass



Figure 3.4 An Aggregate Sample being Poured into a Sieve Nest in a Sieve Shaker

3.2.1.3 Atterberg Limits Test

Soil, depending on its moisture content, may be found in solid, semi-solid, plastic, and liquid states. Depending on the soil's state, its mechanical properties will be different. Therefore, it is important to determine the moisture contents under which the soil's state changes from one to another. The Atterberg limits discriminate between silt and clay and their different types. The liquid limit (LL) corresponds to the water content at which a soil's behavior transitions from a plastic to a liquid state. The lowest moisture content at which a soil maintains a plastic state is known as the plastic limit (PL). The numerical difference between the LL and the PL is known as the plasticity index (PI). Note that the Atterberg limits are measured on materials with particle sizes not larger than 0.425 mm (a No. 40 sieve). The Atterberg limits tests were conducted on 500 g of aggregate samples passing a No. 40 sieve in accordance with the SD 207 standard method (SDDOT, 2015). Figure 3.5 depicts the test setup used for conducting the liquid limit test.



Figure 3.5 A Photographic View of the Test Setup Used for Conducting the Liquid Limit Test

3.2.1.4 Laboratory Test Box

A test box was fabricated in the laboratory and used for compaction of the aggregate bases under a controlled condition to achieve the MDUW and OMC determined by conducting the standard Proctor test on aggregate samples collected from the field. The test box had internal dimensions of 610 mm (W) by 610 mm (W) by 457 mm (H). A schematic view of the test box used for this purpose is shown in Figure 3.6. Figure 3.7 shows photographic views of the fabricated test box.

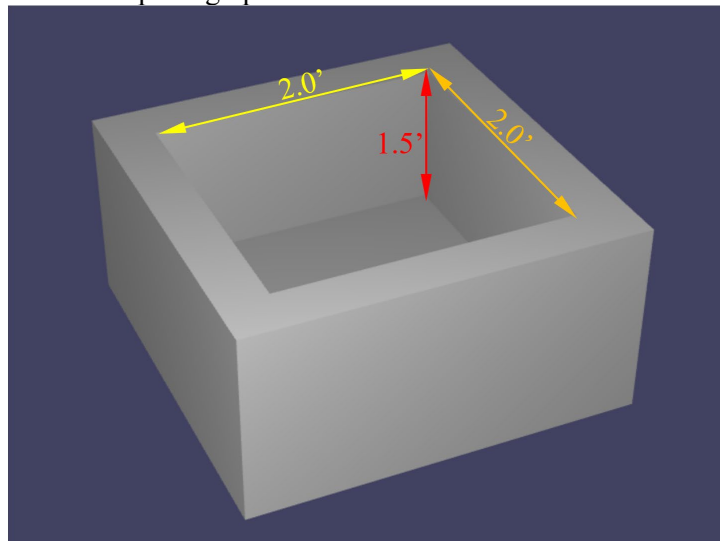


Figure 3.6 A Schematic View of the Test Box



Figure 3.7 Fabricated Test Box

Before compaction of any aggregate base, clean, dry sand was placed in the box and compacted until no further compaction was possible to form a dense layer with a thickness of 100 mm. Then, a layer of 610 mm by 610 mm of a woven geotextile was cut and placed on top of the compacted sand layer as a separator fabric (Figure 3.8).



Figure 3.8 Compacted Sand Layer Covered by a Geotextile Layer in the Test Box

The collected aggregate base was dried and mixed with a predetermined amount of moisture to achieve the OMC. The required mass of the moist aggregate to achieve MDUW when compacted in the test box at a 100-mm-thick layer was calculated. The calculated mass of the moist aggregate was then measured and placed in the standard buckets. The buckets were sealed to preserve moisture (Figure 3.9). The process was repeated to prepare aggregate mass needed for compaction of two aggregate layers, each 100 mm thick. Sealed buckets were kept for 24 hours before compaction. The aforementioned practice was followed to ensure uniform distribution of moisture in the aggregates.



Figure 3.9 Aggregate Base with Optimum Moisture in Sealed Buckets before Compaction

The first layer of the moist aggregate base was uniformly distributed in the box and compacted using a hand tamper, as shown in Figure 3.10a. The layer thickness was frequently controlled to ensure the aggregate base was compacted to form a uniform 100-mm-thick layer (Figure 3.10b). This process was repeated for the second aggregate layer to achieve a 200-mm-thick aggregate base.

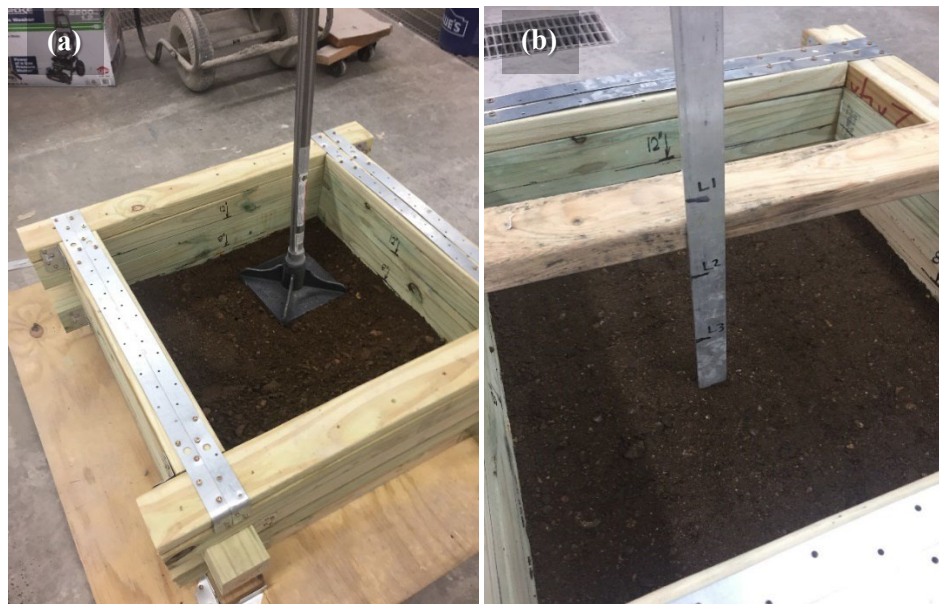


Figure 3.10 Photographic Views of (a) Compaction; and (b) Checking Layer Thickness

Before conducting the first set of tests on the materials compacted in the test box, engineers from the SDDOT Office of Research and a crew from Brosz Engineering Inc. attended SDSU's lab on April 6, 2021, and observed compacting and testing materials in the test box. Also, important comments and suggestions were received. Brosz personnel conducted a number of nuclear density gauge (NDG) measurements and DCP tests on compacted materials. The SDSU research team conducted DCP and sand cone tests, and the readings of two DCP tests were compared (Figure 3.11). Micah Howard, Thad Bauer, Margo McDowell, and Evan Haugh with SDDOT; Kyle Kurth and Jon Herman with Brosz Engineering Inc.; and Rouzbeh Ghabchi with SDSU were present during the test box compaction and testing session on April 6, 2021.



Figure 3.11 Photographic Views of (a) Compacting 042U Base; (b) DCP; (c) NDG; and (d) SCT

3.2.2 Field Testing Program

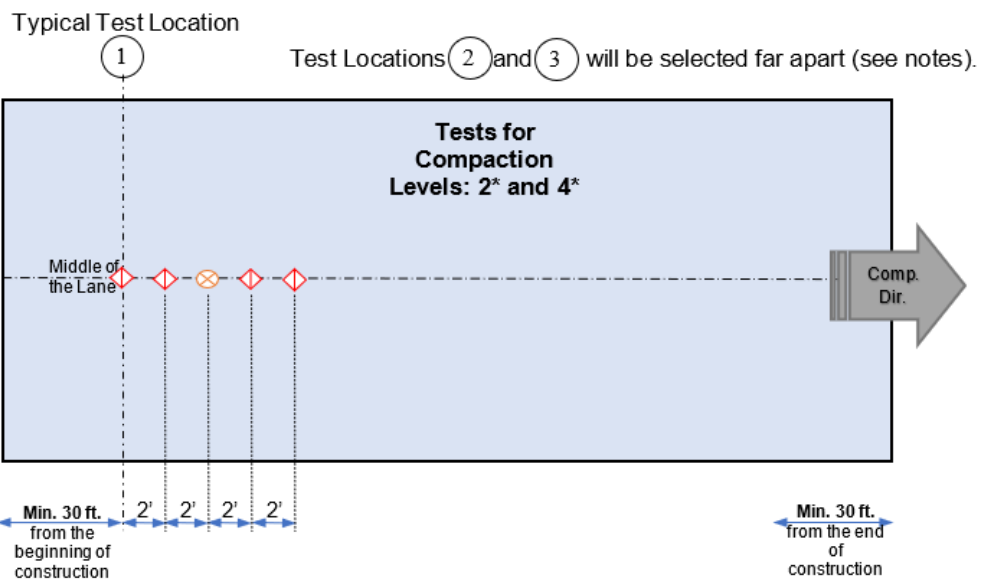
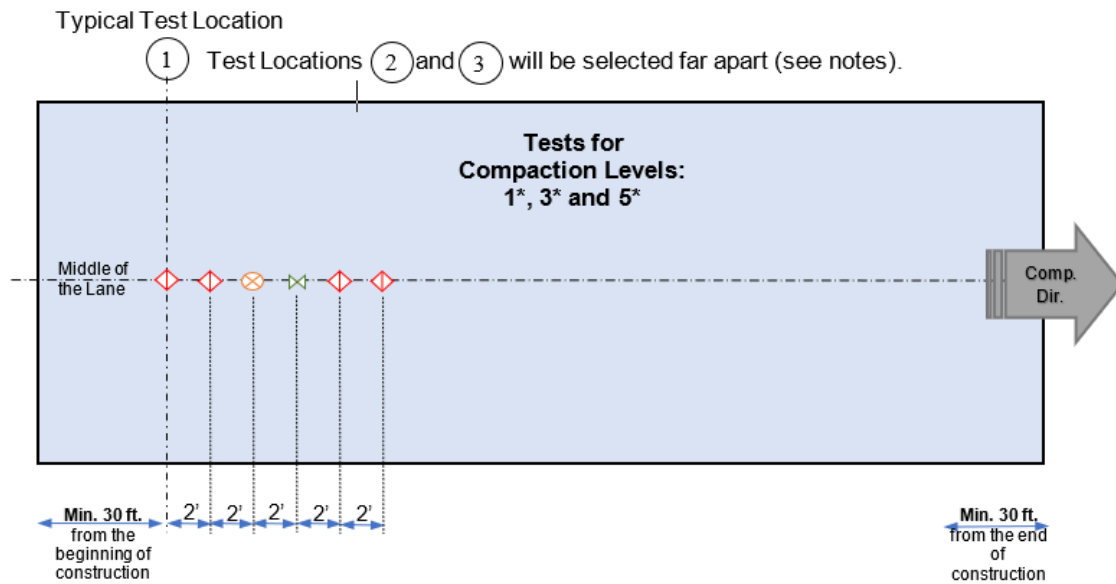
As a result of the project's kick-off meeting, the potential project locations were identified (Table 3.1). Additionally, a comprehensive field-testing program, including an in-situ testing plan for each test section, consistent with the outcomes of the kick-off meeting, and recommendations received from the project's technical panel was prepared and submitted. The plan was further reviewed by the technical panel, and additional comments were shared with the project's PI. After receiving the technical input, SDDOT revised and approved the aforementioned plan (Figures 3.12 and 3.13).

As discussed in kick-off meeting, SDDOT hired an engineering consultant to conduct field testing to support research objectives. The data received from the consultant were used to verify the SDDOT moisture-density curves developed in recently completed research and to evaluate the DCP as a potential acceptance test for compacted granular materials. The consultant was also asked to measure moisture and density by conventional test methods, perform DCP tests, and record observations regarding the effort required to perform the tests. The testing plan was followed during the 2020 and 2021 construction seasons. The final list of the materials tested in the field is shown in Table 3.2. In addition, SDDOT personnel collected about 500 kg of the base materials from each test site and delivered them to SDSU's materials lab for further evaluation.

Table 3.1 Preliminary List of Potential Construction Projects for Field Testing

Letting Date	PCN	Project No.	Type of Work	Highway	County	Base Course Tons	Base Course Salvage Tons	Processed Subgrade Cubic Yards	Full Depth Reclamation Square Yards	Miles	Area	Comments
11/17/2018	03RQ	PH 0212(167)245	Shoulder Widening	US212	Faulk	174,332.80	18,072.10			21.59	Aberdeen	Carry over 24% complete
12/21/2018	04HJ	PH 0037(139)11	Shoulder Widening	SD37	Bon Homme	83,387.60				8.26	Yankton	Carry over 86% complete
01/16/2019	036E	NH-EM 0083(74)55	Grading	US83	Mellette Jones	19,899.70	236,473.60			11.97	Winner	Carry over 45% complete
09/04/2019	025D	P-PH 0046(47)356	Grading, Shoulder Widening	SD46	Clay Lincoln	104,186.50	15,636.20			8.17	Yankton	
09/04/2019	04XH	NH-PH 0018(198)173	Grading	US 18	Bennett	22,881.30	20,209.50			2.53	Winner	
10/02/2019	027B	P 0014(179)419	Urban Grading	US14	Brookings	16,735.60				0.67	Watertown	Reinf. Grid
10/16/2019	068U	NH 0212(188)15	Install turn lane	US 212	Butte	11,185.90				13.42	Belle Fourche	
11/06/2019	05ED	P 0183(26)39	FDR	US183	Tripp		4,167.40		598,357.00	21.57	Winner	
11/06/2019	03W6	IM-FP 0229(65)239	PCC Overlay, AC	I 29	Roberts	44,389.00	8,123.00	17,788.00		9.60	Watertown	
11/20/2019	04HN	NH-PH 0050(114)324	Grading, Shoulder Widening	SD50	Charles Mix Douglas	117,352.10	74,696.40			3.84	Mitchell	
01/22/2020	023V	NH 0050(100)411	Grading, PCC	SD50	Clay Union	3,538.80	7,250.00	74,490.00		5.04	Yankton	
01/22/2020	05F0	NH-P 0042(65)344	FDR, Intersection Improv.	SD42	McCook Minnehaha	5,596.10			396,178.00	16.09	Sioux Falls	
02/19/2020	04D9	IM-FP 0903(106)152	PCCP	I90	Jackson	10,363.30	49,199.20	119,800.00		10.1	Winner	
03/18/2020	04E7	EM 0083(74)55	Grading	US83	Mellette Jones	15,224.80	213,018.70			10.9	Winner	
04/01/2020	5777	P 6480(04)	Grading	Sheridan Lake Rd.	Pennington	87,896.00	59,496.00			12.2	Rapid City	

In-situ Testing Plan for Each Test Section



Legend

- Nuclear Density Gage (NDG)
- Dynamic Cone Penetrometer (DCP)
- Sand Cone Test (SCT)

Number of Tests at Each Location at Each Compaction Level

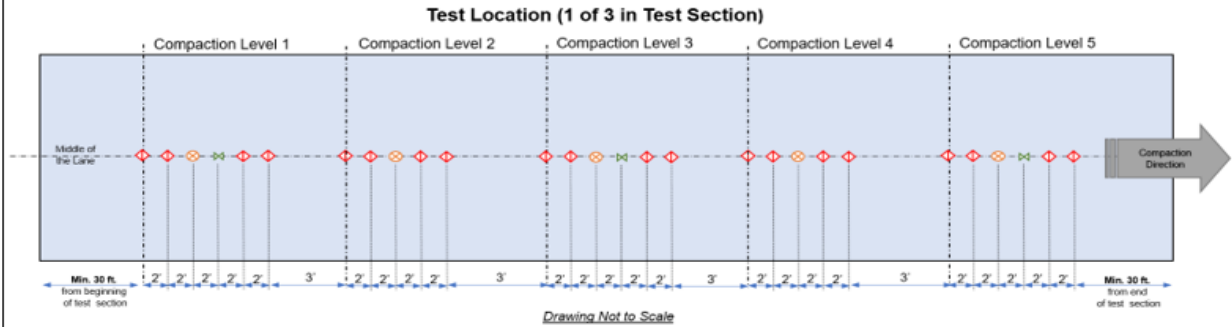
Important: There are 3 locations for each compaction level. In order to obtain the total number of tests required for each test section, the numbers presented in this table should be multiplied by 3.

*Compaction Level	After # of roller passes to target density	# of tests		
		DCP	Nuclear Density Gage	Sand Cone Density
1	60%	4	1	1
2	75%	4	1	0
3	90%	4	1	1
4	100%	4	1	0
5	110%	4	1	1

Figure 3.12 Details of In-Situ Tests Conducted on each Segment of the Test Section

Important Notes

1. Each project will have one (1) designated 300' – 500' **test section**.
2. Within the **test section**, three (3) test **locations** positioned far apart will be identified. The **locations** will be near the middle of a lane, not at roadway centerline or edge. The sketches shown above are a schematic presentation of the tests to be conducted and their typical configurations at each **compaction level** and **location** at each **test section**.
3. At each of the 3 locations, tests will be taken at 5 levels of compaction. Tests will be aligned longitudinally with roadway. Details of the **compaction levels** and numbers of the tests at each **compaction level** and **location** are summarized in a table shown above.
4. Selection of the test locations at each compaction level and among different compaction levels should be carried out such that no overlaps occur, as shown below.



5. NDG test at each location is recommended to be conducted before conducting the SCT at that location. This is to minimize any errors introduced to NDG-measured densities as a result of performing measurement at close proximity of SCT cavity.
6. The methods for conducting the NDG and SCT tests should be in accordance with the SDDOT's current specifications and guidelines, namely SD 114/SD 219 and SD 105, respectively. Method used for conducting the DCP tests should be in compliance with the procedure outlined in the attached document (suggested by SD2014-12 report).
7. Testing contractor will supply NDG and qualified technician.
8. SDDOT technicians will collect and ship bulk material samples.
9. Based on the test configurations and the numbers presented in this document, a total of 60 DCP tests, 15 NDG tests, and 9 SCT measurements will be conducted at each test section.

Figure 3.13 Details of In-Situ Tests Conducted on One Construction Site

Table 3.2 Final List of the Test Sites

Aggregate Base Material Type
04D9 (contains RCA)
03RQ
5777
025D
06DJ
042U
04JY
04D7
04E7
04HK

The engineering consultant performed field tests as follows:

- Sand cone test (SCT) except for reclaimed paving materials according to SD 105 (SDDOT, 2015)
- NDG tests according to SD 114 (SDDOT, 2015)
- NDG density tests according to SD 219 (SDDOT, 2015)
- DCP tests according to the procedure described in the final report of research project SD2014-12 (Jones and Webber, 2019)

Figures 3.14 and 3.15 depict compaction and finished aggregate base surface after compaction, respectively. Figures 3.16, 3.17, and 3.18 present photographic views of the SCT, NDG, and DCP test conducted in the field, respectively.



Figure 3.14 Compaction of a Base Layer (03RQ)



Figure 3.15 A Photographic View of the Surface Texture of a Compacted Aggregate Base (03RQ)



Figure 3.16 SCT Test being Conducted on an Aggregate Base (025D)



Figure 3.17 NDG Test being Conducted on an Aggregate Base (06DJ)



Figure 3.18 DCP Test being Conducted on an Aggregate Base (025D)

4. RESULTS AND DISCUSSIONS

4.1 Overview

In the course of this study, test results obtained by conducting field and laboratory tests were continuously compiled and analyzed. Employing this process allowed the research team to assess the suitability of the SDDOT moisture/density curves and DCP for granular material compaction acceptance. Therefore, this section focuses on presenting the test results to address the two major objectives of this study, as follows:

1. Assess the effectiveness of SDDOT moisture/density curves in accurately predicting the OMC and MDUW of different base materials used in construction.
2. Evaluate the suitability of the DCP test in predicting the achieved relative density of the compacted base course in the field.

For this purpose, two hypotheses related to the aforementioned objectives were set and evaluated. One hypothesis is that the moisture-density curves developed in the SD2014-12 project accurately deliver the relative density. The plausibility of this hypothesis was investigated.

The second hypothesis tested according to the abovementioned methodology was that the DPI can accurately predict the achieved relative density. In both cases (density curves as per SD2014-12 and the DPI), the density measurements obtained by using the sand cone were used as the benchmark values for the statistical analyses. Also, the effectiveness of the draft SDDOT specification proposed to screen the compaction quality of the granular base materials using DCP parameters was verified, and important observations were reported.

4.2 Particle Size Distribution

Particle size distribution plays a vital role in the stability and ability of compaction of aggregate bases. Therefore, sieve analysis was conducted on all aggregate samples collected from the construction sites. Figures 4.1 to 4.10 summarize the particle size distributions obtained from conducting sieve analysis on these aggregate samples: 04D9, 03RQ, 5777, 025D, 06DJ, 042U, 04JY, 04D7, 04E7, and 04HK.

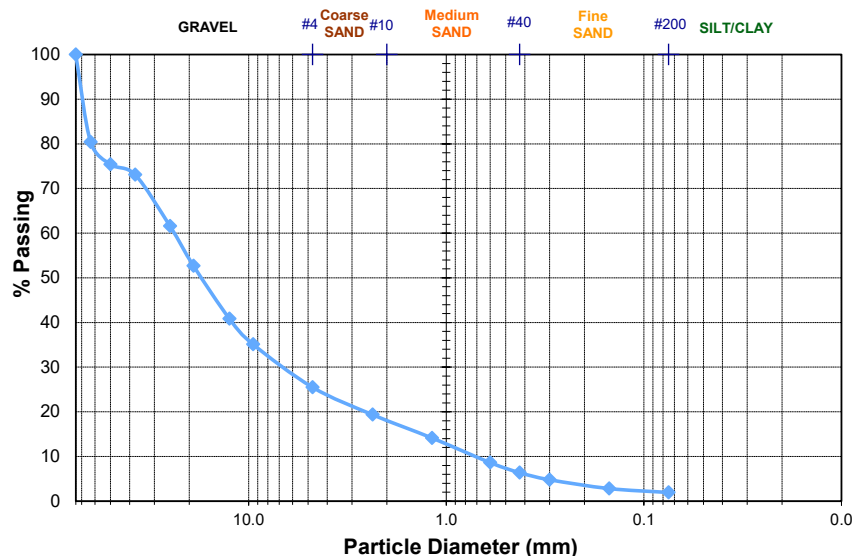


Figure 4.1 Particle Size Distribution of 04D9 Aggregate Base (contains RCA)

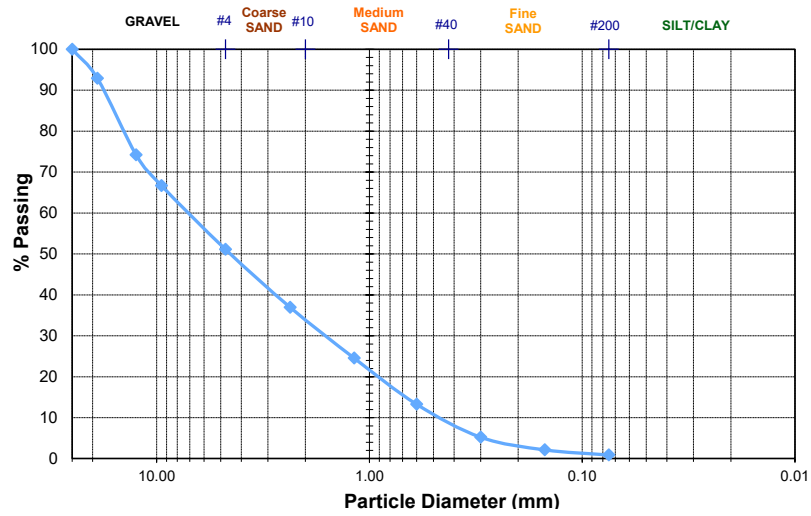


Figure 4.2 Particle Size Distribution of 03RQ Aggregate Base

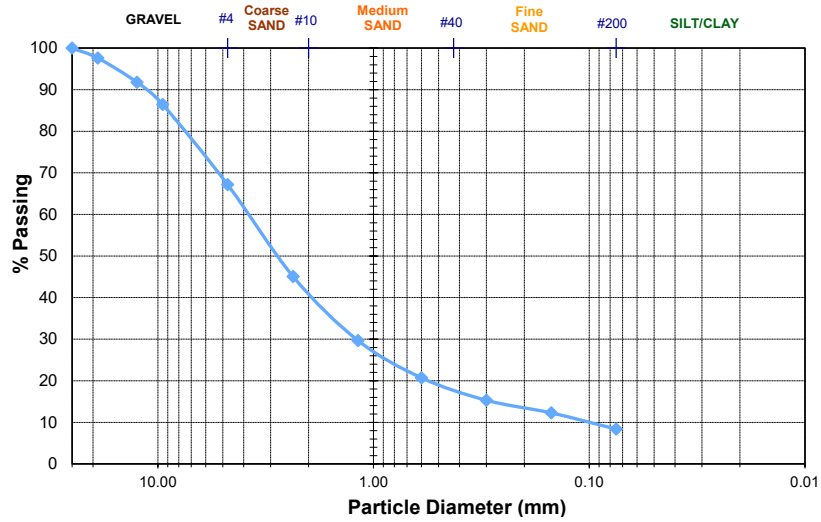


Figure 4.3 Particle Size Distribution Of 5777 Aggregate Base

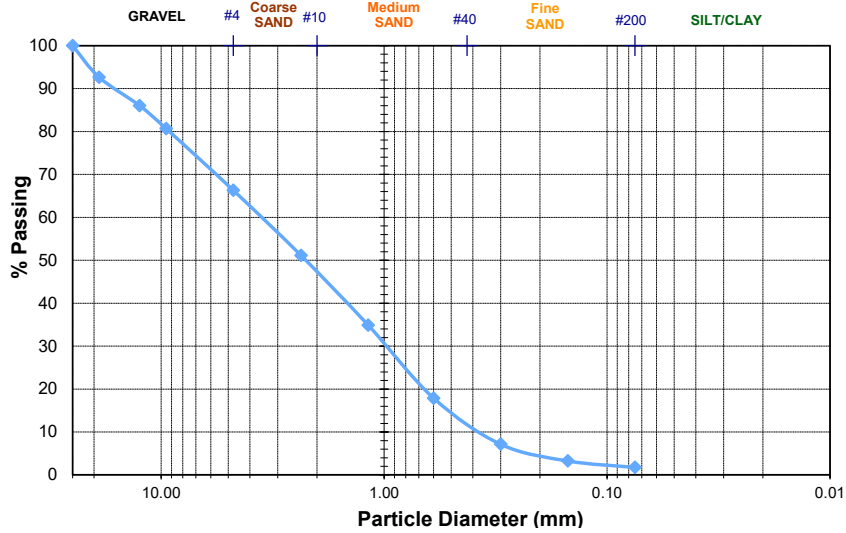


Figure 4.4 Particle Size Distribution of 025D Aggregate Base

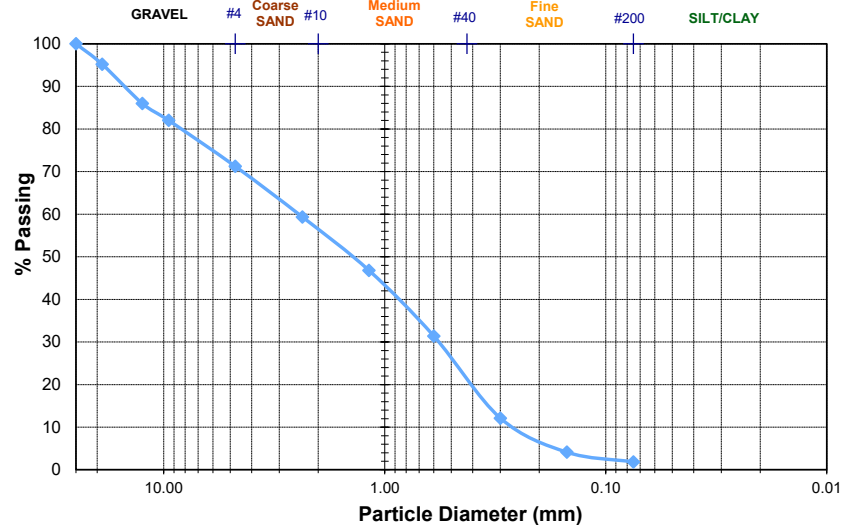


Figure 4.5 Particle Size Distribution of 06DJ Aggregate Base

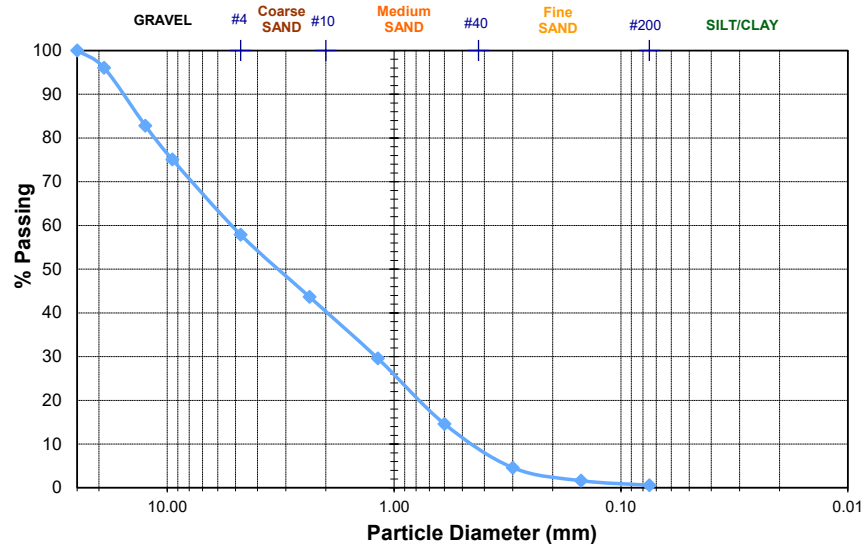


Figure 4.6 Particle Size Distribution of 042U Aggregate Base

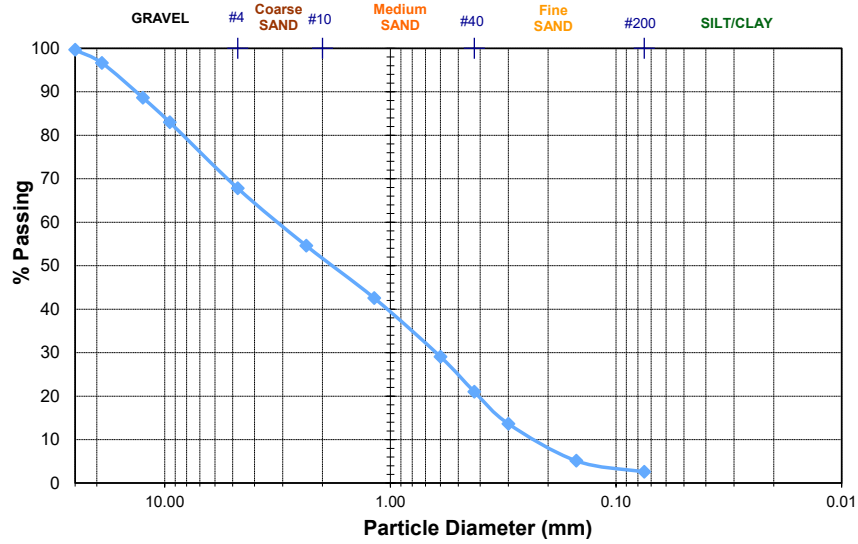


Figure 4.7 Particle Size Distribution of 04JY Aggregate Base

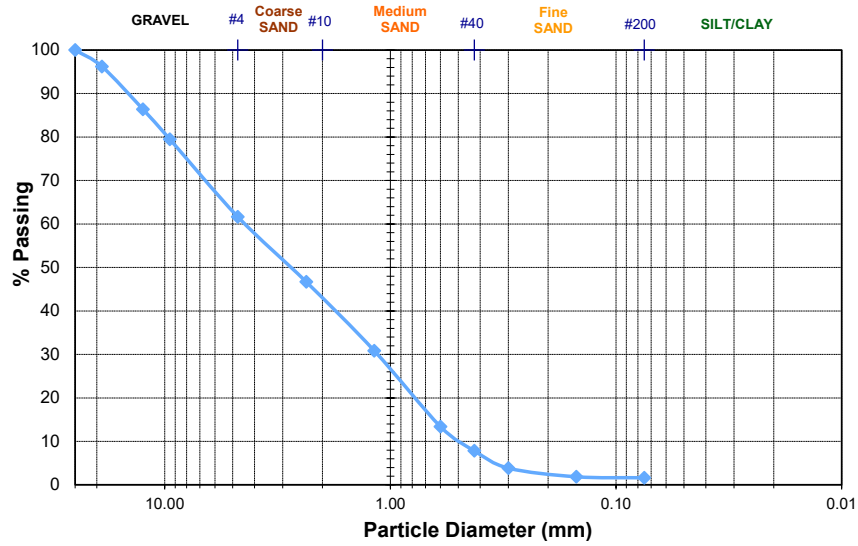


Figure 4.8 Particle Size Distribution of 04D7 Aggregate Base

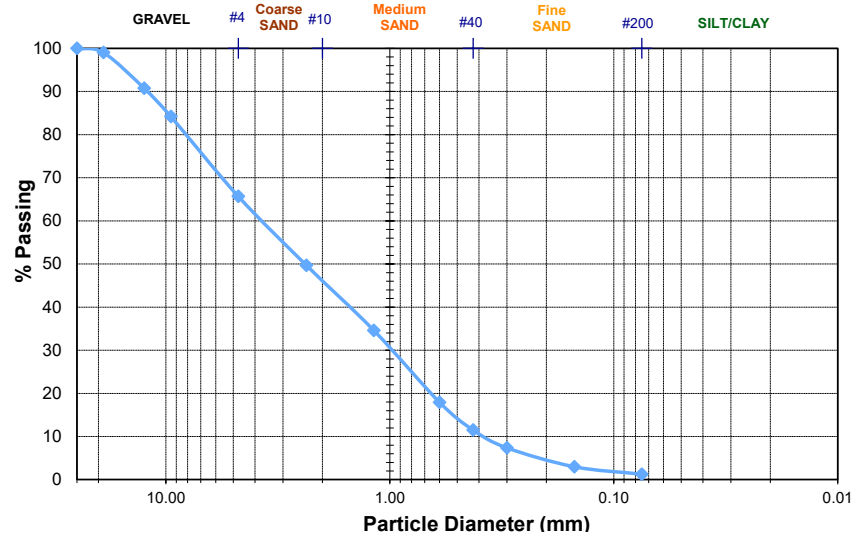


Figure 4.9 Particle Size Distribution of 04E7 Aggregate Base

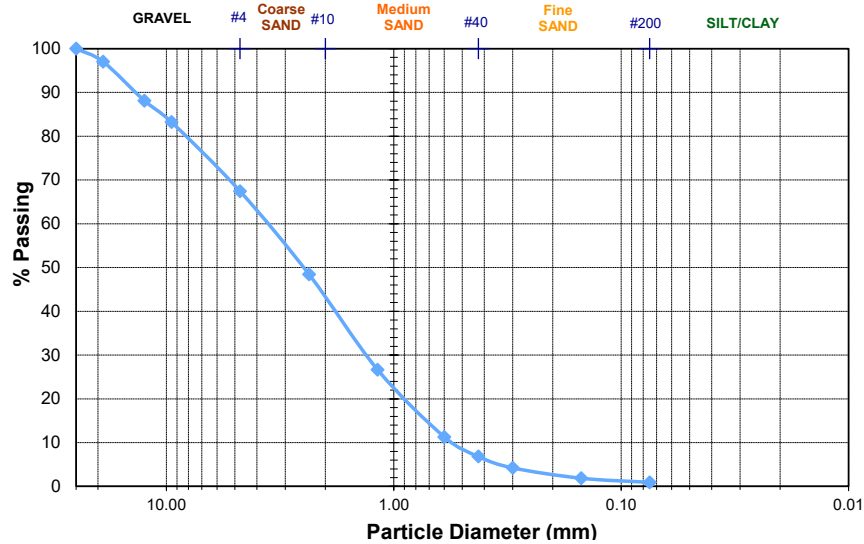


Figure 4.10 Particle Size Distribution of 04HK Aggregate Base

4.3 Atterberg Limits

The Atterberg tests were conducted on aggregate samples collected from the field. Table 4.1 summarizes the liquid limit (LL), plastic limit (PL), and plastic index (PI) values obtained from conducting the Atterberg limits tests on the following aggregate samples collected from projects: 04D9, 03RQ, 5777, 025D, 06DJ, 042U, 04JY, 04D7, 04E7, and 04HK.

Table 4.1 Atterberg Limits of the Collected Aggregate Bases

Aggregate Base Material Type	Plastic Limit, PL (%)	Liquid Limit, LL (%)	Plasticity Index, PI
04D9 (contains RCA)	22	32	10
03RQ	Non-Plastic	-	-
5777	16	18	2
025D	15	20	3
06DJ	8	18	10
042U	Non-Plastic	-	-
04JY	14	22	8
04D7	11	22	11
04E7	13	16	3
04HK	15	19	4

4.4 Optimum Moisture Contents and Maximum Dry Unit Weights

The standard Proctor test was conducted on aggregate samples collected from construction projects. Table 4.2 summarizes the maximum dry unit weight (MDUW) and optimum moisture content (OMC) values obtained from conducting the standard Proctor tests on the aggregate samples. Also, the moisture-density variation of the aggregate bases tested using the standard Proctor from the projects, 04D9, 03RQ, 5777, 025D, 06DJ, 042U, 04JY, 04D7, 04E7, and 04HK, are summarized in Figures 4.11 to 4.20, respectively.

Table 4.2 Atterberg Limits of the Collected Aggregate Bases

Aggregate Base Material Type	Maximum Dry Unit Weight Based on Standard Proctor (pcf)	Maximum Dry Unit Weight Based on Standard Proctor (kg/m ³)	Optimum Moisture Content Based on Standard Proctor (%)
04D9 (contains RCA)	116.7	1869.4	12.0
03RQ	121.1	1939.8	10.9
5777	135.6	2172.1	7.0
025D	132.2	2117.6	9.2
06DJ	128.8	2063.2	9.4
042U	118.1	1891.8	12.8
04JY	126.7	2029.5	8.2
04D7	131.5	2106.4	7.4
04E7	126.8	2031.1	10.7
04HK	130.7	2093.6	9.2

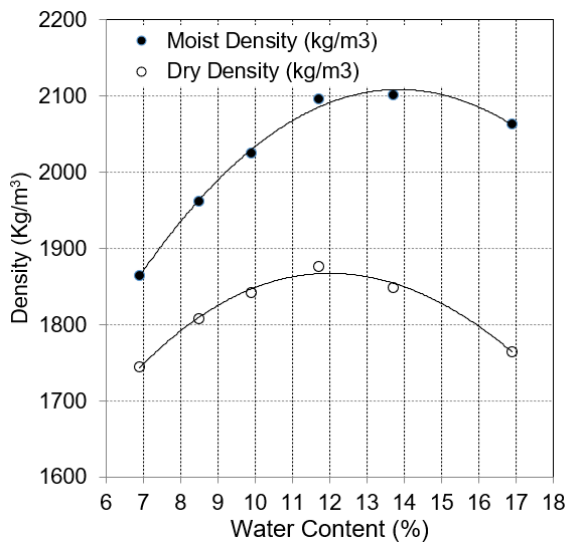


Figure 4.11 Moisture-Density Variation of 04D9

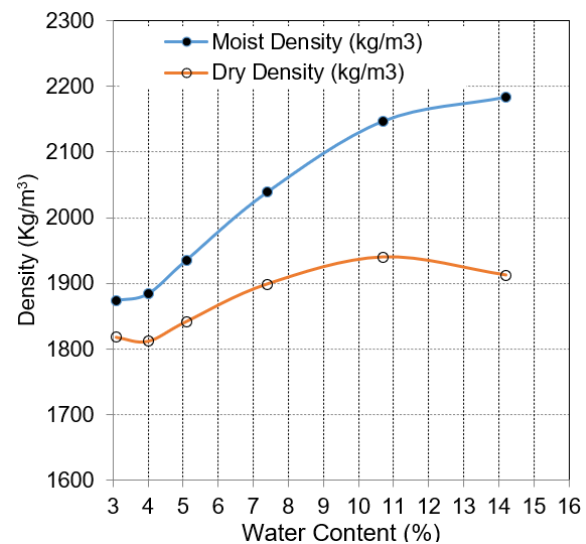


Figure 4.12 Moisture-Density Variation of 03RQ

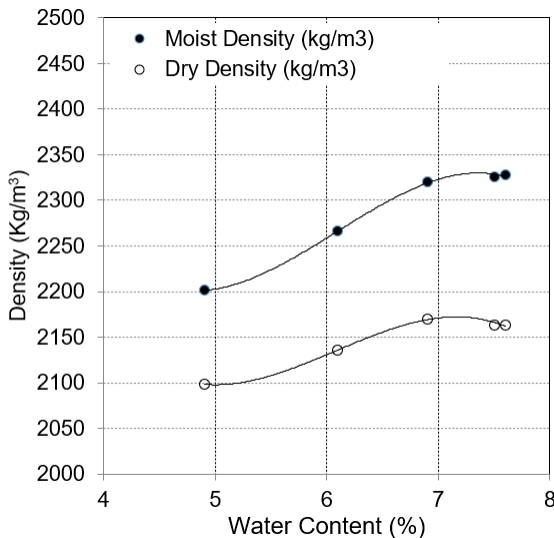


Figure 4.13 Moisture-Density Variation of 5777

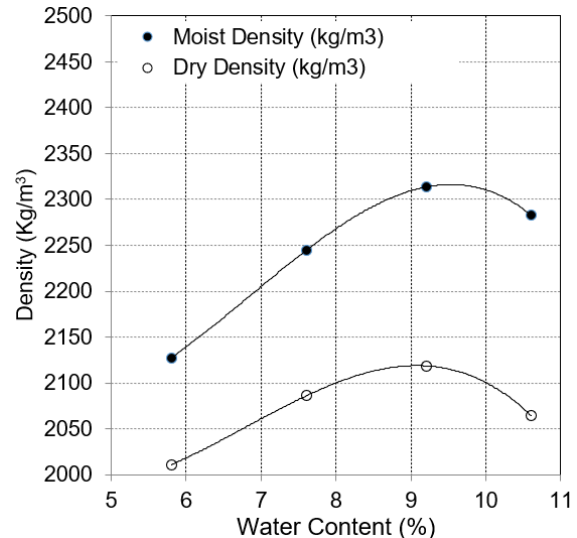


Figure 4.14 Moisture-Density Variation of 025D

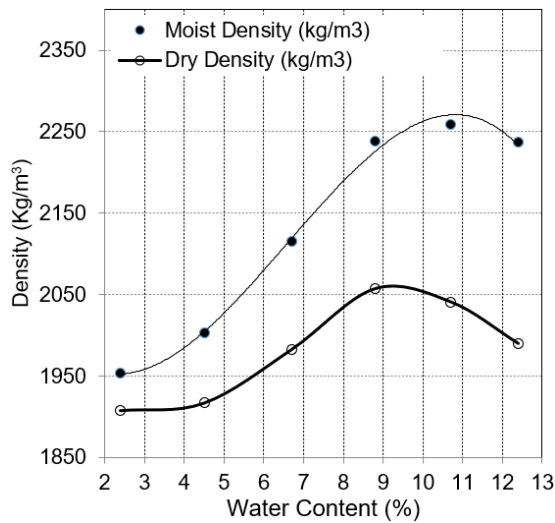


Figure 4.15 Moisture-Density Variation of 06DJ

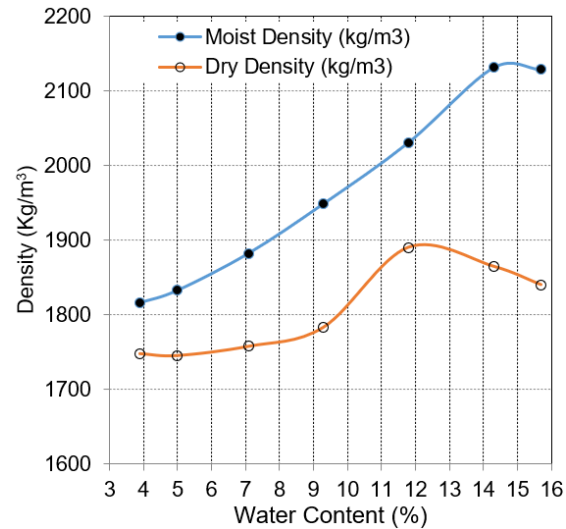


Figure 4.16 Moisture-Density Variation of 042U

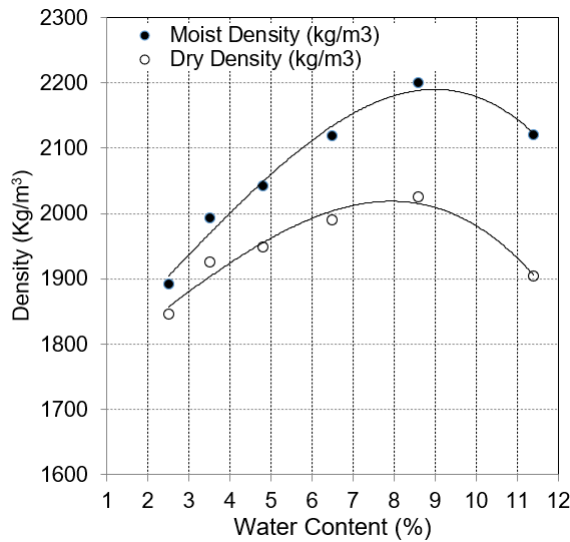


Figure 4.17 Moisture-Density Variation of 04JY

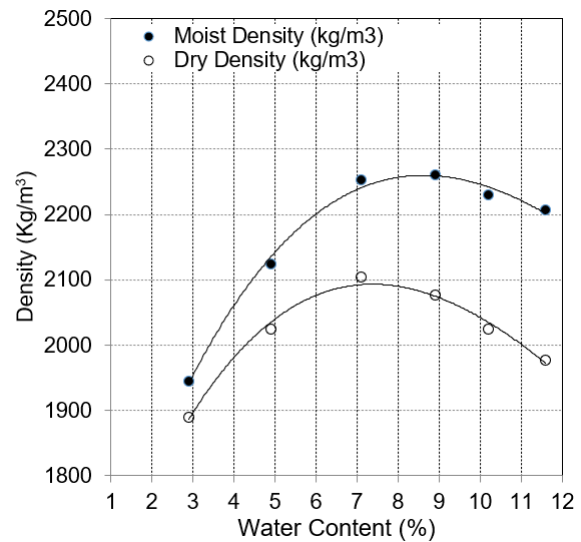


Figure 4.18 Moisture-Density Variation of 04D7

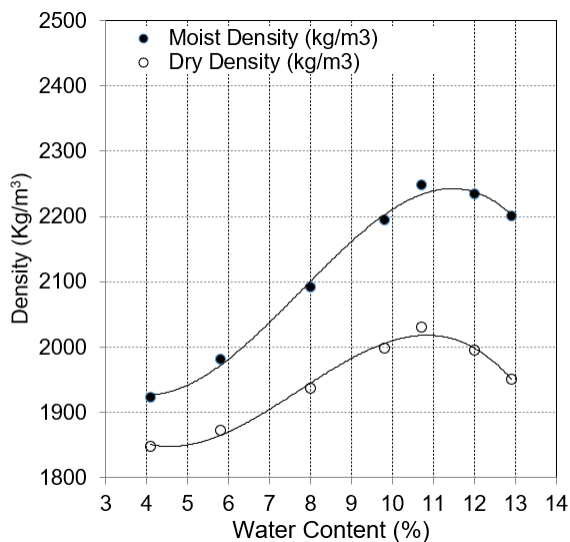


Figure 4.19 Moisture-Density Variation of 04E7

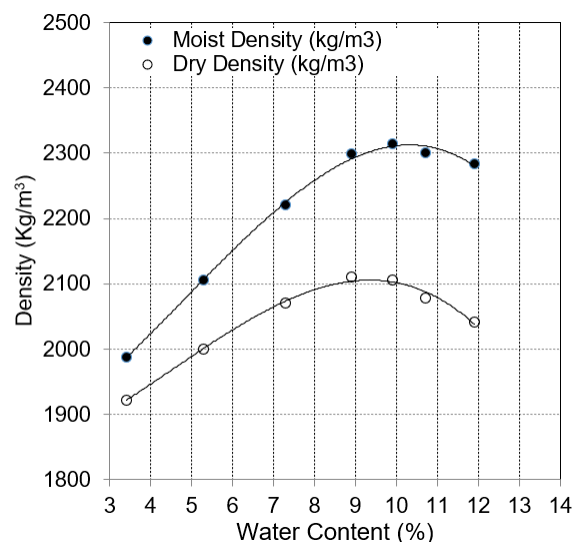


Figure 4.20 Moisture-Density Variation of 04HK

4.5 Dynamic Cone Penetration Index (DPI) Values Measured in the Lab

The DCP tests were conducted in five different locations on each compacted aggregate base in the box. While only readings after two and five blows were needed, the DCP test readings were recorded for each and every blow until the cone traveled through the full depth of the compacted base and 8" penetration was achieved. The penetration variation per blow (DPI based on each blow) with depth for each tested aggregate collected from the projects, 04D9, 03RQ, 5777, 025D, 06DJ, 042U, 04JY, 04D7, 04E7, and 04HK, are summarized in Figures 4.21 to 4.30, respectively. Note that different lines in each figure represent one DCP test (five total for each base material). In addition, a summary of the DPI values calculated from Equation 2.1 is presented in Table 4.3.

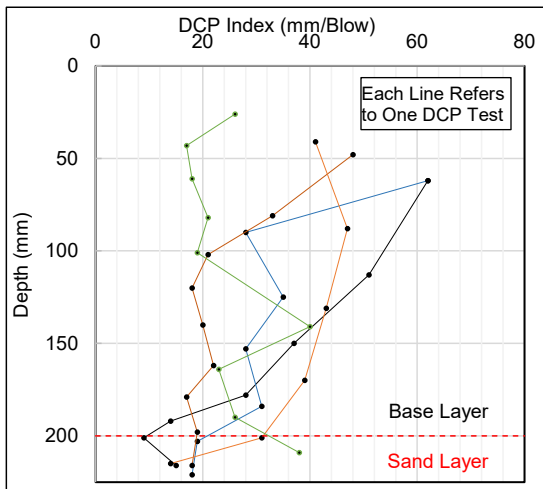


Figure 4.21 DPI Variation of 04D9 with Depth

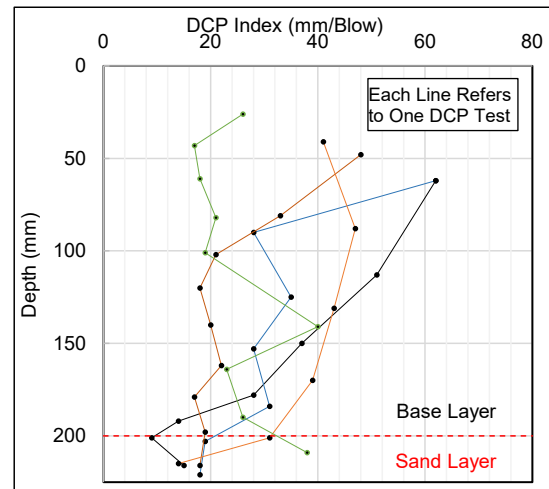


Figure 4.22 DPI Variation of 03RQ with Depth

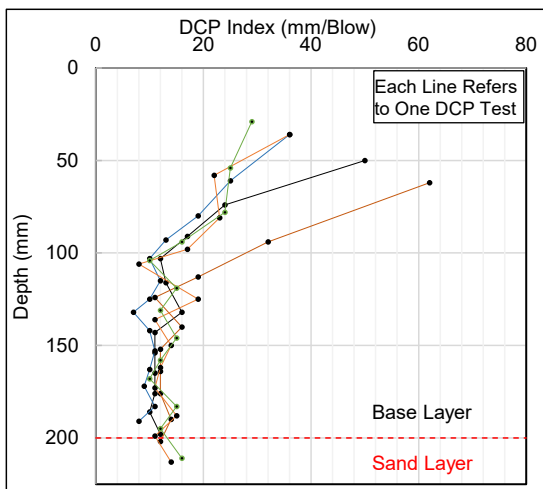


Figure 4.23 DPI Variation of 5777 with Depth

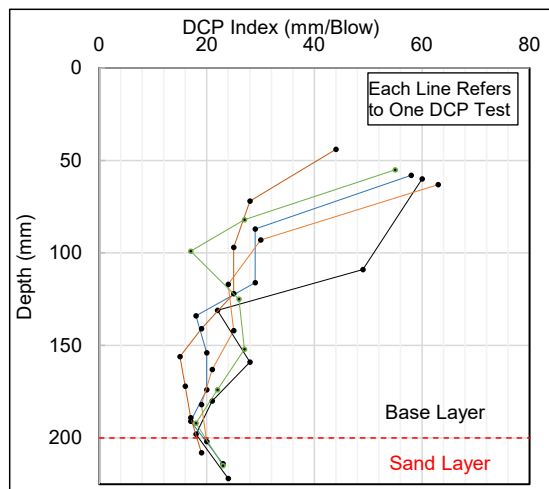


Figure 4.24 DPI Variation of 025D with Depth

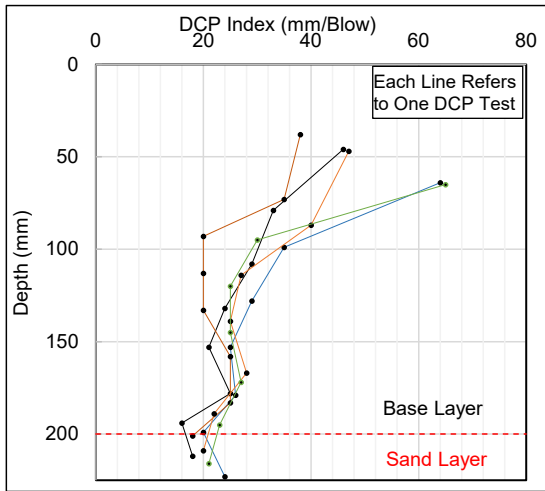


Figure 4.25 DPI Variation of 06DJ with Depth

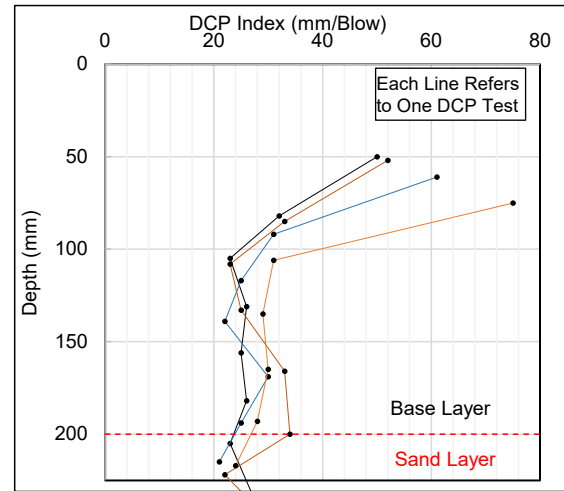


Figure 4.26 DPI Variation of 042U with Depth

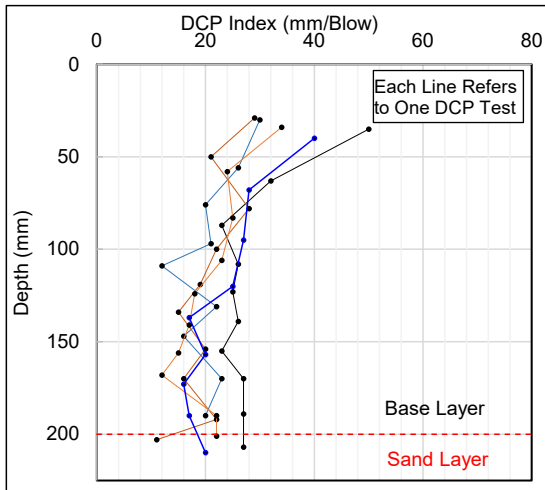


Figure 4.27 DPI Variation of 04JY with Depth

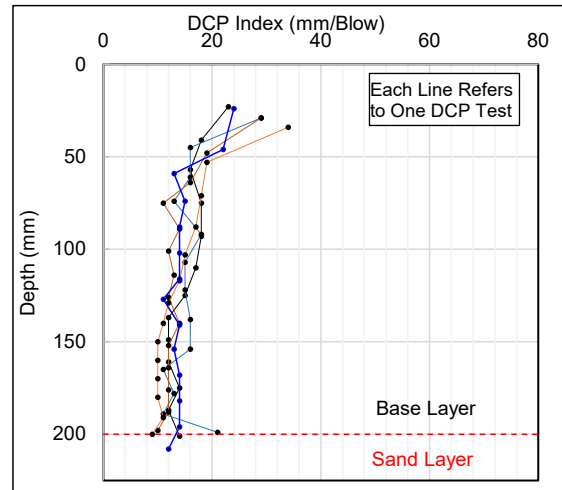


Figure 4.28 DPI Variation of 04D7 with Depth

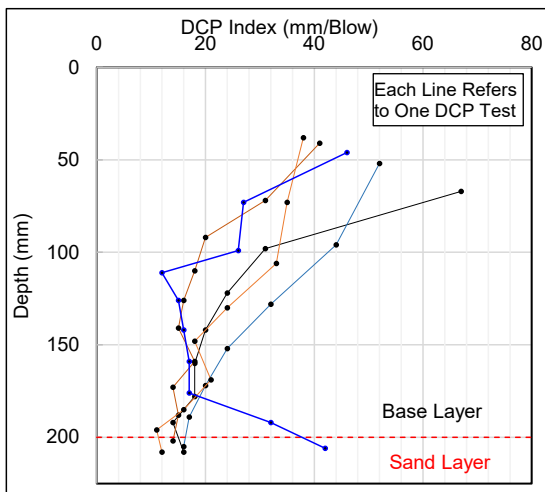


Figure 4.29 DPI Variation of 04E7 with Depth

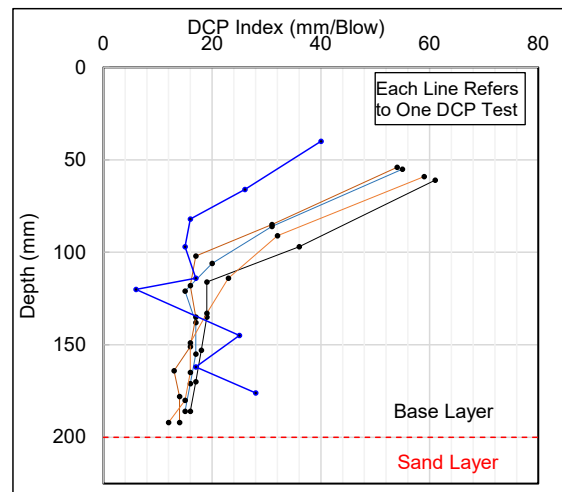


Figure 4.30 DPI Variation of 04HK with Depth

Table 4.3 Measured DPI Values by Conducting DCP Test on Base Materials in the Test Box

Aggregate Base Material Type	Average Measured DPI (mm/blow)	Minimum Measured DPI (mm/blow)	Maximum Measured DPI (mm/blow)	Standard Deviation (mm/blow)	COV (%)
04D9 (RCA)	26.9	19.3	37.7	7.8	29.0
03RQ	19.4	14.3	24.3	4.5	23.2
5777	15.2	14.0	16.7	1.2	7.9
025D	23.1	22.3	23.7	0.5	2.2
06DJ	24.7	20.0	26.7	2.8	11.3
042U	26.6	24.7	29.0	1.9	7.1
04JY	21.1	17.7	23.0	2.3	10.9
04D7	15.5	13.7	17.3	1.6	10.3
04E7	21.3	17.7	25.3	3.7	17.4
04HK	17.6	16.0	19.3	1.4	8.0

4.6 Lab-Measured Test Box Densities by Conducting Sand Cone Tests

A summary of the dry unit weights measured using the sand cone test and the moisture contents of the aggregates compacted in the test box are presented in Table 4.4.

Table 4.4 Lab-Measured Test Box DUW and OMC by Conducting SCT on Base Materials

Aggregate Base Material Type	Dry Unit Weight (pcf)	Dry Unit Weight (kg/m ³)	Achieved Density (%)	Box Moisture Content (%)	Optimum Moisture Content (%)
04D9 (RCA)	109.4	1751.7	93.7	13.1	12.0
03RQ	119.7	1917.4	98.8	11.1	10.9
5777	126.8	2031.7	93.6	4.7	7.0
025D	129.1	2067.2	97.6	9.7	9.2
06DJ	126.4	2024.0	98.1	9.8	9.4
042U	116.7	1869.9	98.9	11.6	12.8
04JY	128.8	2063.9	101.7	7.8	8.2
04D7	133.5	2138.3	101.5	7.5	7.4
04E7	137.0	2194.3	108.1	11.2	10.7
04HK	131.0	2098.0	100.2	9.0	9.2

4.7 Field-Measured DUW, MC, and DPI Values

The summary of the in-situ-measured unit weights, moisture contents, and DPI values of different aggregate bases tested in field sections, 04D9, 03RQ, 5777, 025D, 06DJ, 042U, 04JY, 04D7, 04E7, and 04HK, are summarized in Tables 4.5 to 4.14, respectively.

Table 4.5 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 04D9 Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	88.5	1417.6	7.6	75.9	18.1
	3	102.9	1648.3	5.3	88.2	18.8
	5	100.9	1616.3	8.6	86.5	21.8
Zone 2	1	101.0	1617.9	14.2	86.6	24.1
	3	95.5	1529.8	7.7	81.9	20.7
	5	104.2	1669.1	12.1	89.3	21.0
Zone 3	1	101.6	1627.5	5.5	87.1	16.1
	3	114.5	1834.1	5.0	98.3	17.7
	5	97.3	1558.6	16.5	83.4	25.5

Table 4.6 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 03RQ Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	110.2	1765.2	7.1	91.0	15.0
	3	111.8	1790.9	7.4	92.3	16.7
	5	122.9	1968.7	8.2	101.5	14.8
Zone 2	1	106.3	1702.8	7.1	87.8	13.0
	3	118.3	1895	7.4	97.7	12.8
	5	119.9	1920.6	5.8	99.0	13.9
Zone 3	1	111.6	1787.7	7.3	92.1	14.7
	3	118.8	1903	7.6	98.1	14.2
	5	117.2	1877.4	6.2	96.8	12.8

Table 4.7 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 5777 Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	132.0	2114.4	4.7	97.4	7.9
	3	133.9	2144.9	4.9	98.8	11.9
	5	141.2	2261.8	4.4	104.1	9.7
Zone 2	1	144.1	2308.3	5.2	106.3	8.1
	3	132.0	2114.4	4.2	97.4	9.6
	5	152.1	2436.4	4.5	112.2	9.7
Zone 3	1	139.2	2229.8	5.2	102.7	9.1
	3	147.8	2367.5	5.5	109.0	9.9
	5	145.8	2335.5	4.3	107.5	8.7

Table 4.8 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 025D Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	119.7	1917.4	6.8	90.5	16.5
	3	119.6	1915.8	7.9	90.4	17.3
	5	117.8	1887	6.8	89.1	13.8
Zone 2	1	115.1	1843.7	7.1	87.0	14.2
	3	111.3	1782.9	6.8	84.2	13.3
	5	110.4	1768.4	6.8	83.5	14.4
Zone 3	1	116.3	1862.9	7.5	87.9	13.6
	3	120.4	1928.6	7.6	91.0	17.0
	5	118.7	1901.4	6.0	89.8	15.4

Table 4.9 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 06DJ Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	119.7	1917.4	6.8	93.0	16.1
	3	119.6	1915.8	7.9	92.9	16.3
	5	117.8	1887.0	6.8	91.5	14.0
Zone 2	1	115.1	1843.7	7.1	89.4	16.0
	3	111.3	1782.9	6.8	86.4	21.3
	5	110.4	1768.4	6.8	85.7	15.8
Zone 3	1	116.3	1862.9	7.5	90.3	14.5
	3	120.4	1928.6	7.6	93.5	17.8
	5	118.7	1901.4	6.0	92.2	12.1

Table 4.10 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 042U Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	108.6	1739.6	9.7	92.0	18.9
	3	111.6	1787.7	9.5	94.5	17.8
	5	111.0	1778	10.2	94.0	14.3
Zone 2	1	109.8	1758.8	9.8	93.0	19.1
	3	111.5	1786.1	8.8	94.4	17.3
	5	112.8	1806.9	9.4	95.5	15.3
Zone 3	1	105.0	1681.9	9.2	88.9	17.5
	3	111.5	1786.1	8.6	94.4	15.1
	5	115.2	1845.3	9.6	97.6	15.1

Table 4.11 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 04JY Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	119.0	1906.2	3.3	93.9	18.5
	3	123.5	1978.3	3.5	97.5	13.2
	5	128.8	2063.2	3.8	101.6	9.3
Zone 2	1	119.6	1915.8	3.2	94.4	16.1
	3	123.2	1973.5	4.1	97.2	12.7
	5	129.8	2079.2	4.2	102.4	9.5
Zone 3	1	115.5	1850.1	3.8	91.1	16.4
	3	120.7	1933.4	3.6	95.2	11.7
	5	121.6	1947.8	3.5	96.0	9.5

Table 4.12 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 04D7 Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	107.9	1728.4	4	82.1	23.1
	3	110.5	1770	4.7	84.0	18.8
	5	117.2	1877.4	5	89.1	16.4
Zone 2	1	106.4	1704.4	4.6	80.9	16.9
	3	111.6	1787.7	4.7	84.9	18.2
	5	123.5	1978.3	4.6	93.9	18.7
Zone 3	1	112.4	1800.5	4.9	85.5	18.2
	3	117.2	1877.4	4.8	89.1	18.5
	5	117.6	1883.8	4.4	89.4	16.0

Table 4.13 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 04E7 Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	124.8	1999.1	8.4	98.4	14.3
	3	126.5	2026.3	9.1	99.8	13.4
	5	127.6	2044	8.1	100.6	12.4
Zone 2	1	123.4	1976.7	7.5	97.3	12.5
	3	124.0	1986.3	7.5	97.8	13.0
	5	127.9	2048.8	7.6	100.9	12.6
Zone 3	1	120.6	1931.8	7.4	95.1	13.7
	3	123.7	1981.5	8.6	97.6	14.8
	5	127.9	2048.8	7.8	100.9	12.3

Table 4.14 Field Dry Unit Weight, Moisture Contents, and DPI Measured for 04HK Base

Test Cluster	Compaction Sequence	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	Field Moisture Content (%)	Achieved Field Density (%)	DPI (mm/blow)
Zone 1	1	135.0	2162.5	6.2	103.3	12.5
	3	133.4	2136.9	6.1	102.0	13.5
	5	139.0	2226.6	6.6	106.3	12.3
Zone 2	1	133.8	2143.3	6.3	102.3	10.7
	3	133.2	2133.7	5.9	101.9	11.8
	5	140.9	2257	6.4	107.8	14.0
Zone 3	1	138.2	2213.8	6.4	105.7	12.7
	3	137.4	2200.9	7.2	105.1	13.7
	5	136.2	2181.7	6.9	104.2	13.9

4.8 Data Analysis

4.8.1 SDDOT Moisture-Density Curves' Effectiveness in Predicting OMC and MDUW

In this section, the one-point moisture and density Proctor data were applied to predict the OMC and MDUW values of the tested base materials. For this purpose, each datapoint obtained from conducting the Proctor test was applied separately to predict the OMC and MDUW values using the SDDOT and Ohio moisture-density curves. Tables 4.15 to 2.24 summarize the analysis carried out on OMC and MDUW values of base materials tested in this study. Also, moisture content, dry unit weight, and wet unit weight of the base materials obtained from the Proctor test used for determining the OMC and MDUW are shown. Furthermore, the OMC and MDUW of the base materials were predicted based on the SDDOT and Ohio curves, and their absolute and mean deviations were computed.

From Table 4.15, it was observed that application of the SDDOT curves resulted in 0.9% and 1.5 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 50% and 42% less than those calculated for

Ohio curves, respectively. This observation indicates that SDDOT curves predicted the OMC and MDUW of the 04D9 aggregates more accurately when compared with the Ohio curves.

Table 4.15 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 04D9

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Absolute Deviation		OHIO Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
04D9 (RCA)	12.0	116.7	6.9	108.9	116.4	13.5	116.4	N	13.5	117.0	K	1.5	0.3	1.5	0.3
			8.5	112.9	122.4	12.2	119.3	M	12.7	119.3	J	0.2	2.6	0.7	2.6
			9.9	115.0	126.4	12.2	119.3	M	12.7	119.3	J	0.2	2.6	0.7	2.6
			11.7	117.2	130.9	12.2	119.3	M	12.7	119.3	J	0.2	2.6	0.7	2.6
			13.7	115.4	131.2	13.5	116.4	N	14.1	115.8	k	1.5	0.3	2.1	0.9
			16.9	110.2	128.8	13.5	116.4	N	16.4	110.8	m	1.5	0.3	4.4	5.9
Mean Absolute Deviations												0.9	1.5	1.7	2.5

From Table 4.16, it was observed that application of the SDDOT curves resulted in 0.7% and 1.7 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 87% more and 61% less than those calculated for Ohio curves, respectively. This observation indicated that SDDOT curves could predict OMC and MDUW of the 03RQ aggregates with similar and higher accuracy, respectively, compared with the Ohio curves.

Table 4.16 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 03RQ

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
03RQ	10.9	121.1	3.1	113.5	117.0			-			-				
			4.0	113.1	117.6	10.2	123.1	K			-	0.7	2.0		
			5.1	115.0	120.8	10.2	123.1	K	10.5	126.6	G	0.7	2.0	0.4	5.5
			7.4	118.5	127.3	10.2	123.1	K	10.9	125.4	g	0.7	2.0	0.0	4.3
			10.7	121.1	134.0	11.6	120.8	L	11.6	123.0	h	0.7	0.3	0.7	1.9
			14.2	119.4	136.3	10.2	123.1	K	10.5	126.6	G	0.7	2.0	0.4	5.5
Mean Absolute Deviations												0.7	1.7	0.4	4.3

From Table 4.17, it was observed that application of the SDDOT curves resulted in 0.3% and 1.0 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 59% and 44% less than those determined for Ohio curves, respectively. This observation indicated that SDDOT curves could predict OMC and MDUW values of the 5777 aggregates with higher accuracy than the Ohio curves.

Table 4.17 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 5777

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
5777	7.0	135.6	4.9	131.0	137.4	7.5	135.0	E	7.2	139.1	B	0.5	0.6	0.2	3.5
			6.1	133.3	141.5	7.5	135.0	E	7.6	137.7	b	0.5	0.6	0.6	2.1
			6.9	135.5	144.8	7.1	136.9	D	7.6	137.7	b	0.1	1.3	0.6	2.1
			7.6	135.1	145.3	7.1	136.9	D	7.9	136.3	C	0.1	1.3	0.9	0.7
			7.5	135.1	145.2	7.1	136.9	D	7.9	136.3	C	0.1	1.3	0.9	0.7
Mean Absolute Deviations												0.3	1.0	0.6	1.8

From Table 4.18, it was observed that application of the SDDOT curves resulted in 0.6% and 1.6 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 92% and 80% higher than those determined for Ohio curves, respectively. This observation indicates that the Ohio curves predicted the OMC and MDUW values of the 025D aggregates with higher accuracy than the SDDOT curves.

Table 4.18 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 025D

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
025D	9.2	132.2	5.8	125.5	132.8	8.9	129.1	H	8.8	133.1	d	0.3	3.1	0.4	0.9
			7.6	130.2	140.1	8.7	131.1	G	8.8	133.1	d	0.5	1.1	0.4	0.9
			9.2	132.3	144.4	8.2	133.1	F	9.0	132.0	E	1.0	0.9	0.2	0.2
			10.6	128.9	142.5	8.7	131.1	G	9.4	130.7	e	0.5	1.1	0.2	1.5
Mean Absolute Deviations												0.6	1.6	0.3	0.9

From Table 4.19, it was observed that application of the SDDOT curves resulted in 0.2% and 1.2 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 38% and 54% less than those determined for Ohio curves, respectively. This observation indicates that the SDDOT curves predicted the OMC and MDUW values of the 06DJ aggregates with higher accuracy than the Ohio curves.

Table 4.19 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 06DJ

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
06DJ	9.4	128.8	2.4	119.1	121.9			-			-				
			4.5	119.7	125.0	9.4	127.0	I	9.0	132.0	E	0.0	1.8	0.4	3.2
			6.7	123.8	132.0	9.4	127.0	I	9.4	130.7	e	0.0	1.8	0.0	1.9
			8.8	128.4	139.7	8.9	129.1	H	9.4	130.7	e	0.5	0.3	0.0	1.9
			10.7	127.4	141.0	8.9	129.1	H	9.7	129.3	F	0.5	0.3	0.3	0.5
			12.4	124.2	139.6	9.4	127.0	I	8.5	134.1	D	0.0	1.8	0.9	5.3
Mean Absolute Deviations												0.2	1.2	0.3	2.6

From Table 4.20, it was observed that application of the SDDOT curves resulted in 0.6% and 1.4 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be equal to those determined for Ohio curves, respectively. This observation indicates that the SDDOT curves predicted the OMC and MDUW values of the 042U aggregates with an accuracy similar to that of the Ohio curves.

Table 4.20 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 042U

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
042U	12.8	118.1	3.9	109.1	113.4	12.2	119.3	M	12.7	119.3	J	0.6	1.2	0.1	1.2
			5.0	108.9	114.4	12.2	119.3	M	13.1	118.2	j	0.6	1.2	0.3	0.1
			7.1	109.7	117.5	13.5	116.4	N	13.5	117.0	K	0.7	1.7	0.7	1.1
			9.3	111.3	121.7	12.2	119.3	M	13.1	118.2	j	0.6	1.2	0.3	0.1
			11.8	118.0	126.8	12.2	119.3	M	14.1	115.8	k	0.6	1.2	1.3	2.3
			14.3	116.4	133.1	13.5	116.4	N	13.5	117.0	K	0.7	1.7	0.7	1.1
			15.7	114.9	132.9	13.5	116.4	N	11.9	121.7	I	0.7	1.7	0.9	3.6
Mean Absolute Deviations												0.6	1.4	0.6	1.4

From Table 4.21, it was observed that application of the SDDOT curves resulted in 1.8% and 1.7 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 81% higher and 64% less than those determined for Ohio curves, respectively. This observation indicates that the SDDOT curves predicted the OMC and MDUW values of the 04JY aggregates with lower and higher accuracy than the Ohio curves, respectively.

Table 4.21 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 04JY

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
04JY	8.2	126.7	2.5	115.2	118.1			-			-				
			3.5	120.2	124.4			-			-				
			4.8	121.7	127.5	9.4	127.0	I	8.8	133.1	dd	1.2	0.3	0.6	6.4
			6.5	124.2	132.3	9.4	127.0	I	9.0	132.0	E	1.2	0.3	0.8	5.3
			8.6	126.5	137.4	9.4	127.0	I	9.7	129.3	F	1.2	0.3	1.5	2.6
			11.4	118.8	132.4	11.6	120.8	L				3.4	5.9		
			0.0	0.0	0.0										
Mean Absolute Deviations											1.8	1.7	1.0	4.7	

From Table 4.22, it was observed that application of the SDDOT curves resulted in 1.4% and 2.9 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be 51% and 50% less than those determined for Ohio curves, respectively. This observation indicates that the SDDOT curves predicted the OMC and MDUW values of the 04D7 aggregates with higher accuracy than the Ohio curves.

Table 4.22 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 04D7

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
04D7	7.4	131.5	2.9	118.0	121.4			-			-				
			4.9	126.4	132.6	8.2	133.1	F	8.2	135.2	c	0.8	1.6	0.8	3.7
			7.1	131.3	140.7	8.2	133.1	F	8.5	134.1	D	0.8	1.6	1.1	2.6
			8.9	129.6	141.2	8.7	131.1	G	9.4	130.7	e	1.3	0.4	2.0	0.8
			10.2	126.4	139.2	9.4	127.0	I	10.5	126.6	G	2.0	4.5	3.1	4.9
			11.6	123.4	137.7	9.5	125.1	J	14.6	114.6	L	2.1	6.4	7.2	16.9
Mean Absolute Deviations											1.4	2.9	2.8	5.8	

From Table 4.23, it was observed that application of the SDDOT curves resulted in 0.9% and 2.3 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be approximately 4 and 13 folds higher than those determined for Ohio curves, respectively. This observation indicates that the Ohio curves predicted the OMC and MDUW values of the 04E7 with higher accuracy than the SDDOT curves.

Table 4.23 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 04E7

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
04E7	10.7	126.8	4.1	115.3	120.1	#N/A	#N/A	-			-				
			5.8	116.9	123.7	10.2	123.1	K	10.5	126.6	G			0.2	0.2
			8.0	120.9	130.5	10.2	123.1	K	10.5	126.6	G	0.5	3.7	0.2	0.2
			9.8	124.8	137.0	9.5	125.1	J	10.5	126.6	G	1.2	1.7	0.2	0.2
			10.7	126.8	140.3	9.4	127.0	I	10.5	126.6	G	1.3	0.2	0.2	0.2
			12.0	124.6	139.5	10.2	123.1	K	10.5	126.6	G	0.5	3.7	0.2	0.2
Mean Absolute Deviations												0.9	2.3	0.2	0.2

From Table 2.24, it was observed that application of the SDDOT curves resulted in 0.7% and 1.2 pcf mean absolute deviation from the OMC and MDUW values obtained from conducting the standard Proctor test, respectively. These values were found to be equal to and 66% less than those determined for Ohio curves, respectively. This observation indicated that the SDDOT curves predicted the OMC and MDUW values of the 04HK aggregates with higher accuracy than the Ohio curves.

Table 4.24 Moisture-Density Values from Standard Proctor, SDDOT, and Ohio Curves for 04HK

Base Material	Standard Proctor		Standard Proctor Parameters			SDDOT Curves' Predicted Values			OHIO Curves' Predicted Values			SDDOT Curves' Absolute Deviation		OHIO Curves' Absolute Deviation	
	OMC (%)	MDUW (pcf)	Moisture (%)	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	Curve	OMC (%)	MDUW (pcf)	OMC (%)	MDUW (pcf)
04HK	9.2	130.7	3.4	120.0	124.0			-	8.8	133.1	dd			0.4	2.4
			5.3	124.9	131.5	8.7	131.1	G	8.5	134.1	D	0.5	0.4	0.7	3.4
			7.3	129.2	138.7	8.7	131.1	G	8.5	134.1	D	0.5	0.4	0.7	3.4
			8.9	131.8	143.5	8.2	133.1	F	9.0	132.0	E	1.0	2.4	0.2	1.3
			9.9	131.4	144.5	8.2	133.1	F	8.2	135.2	C	1.0	2.4	1.0	4.5
			10.7	129.7	143.6	8.7	131.1	G	7.9	136.3	C	0.5	0.4	1.3	5.6
Mean Absolute Deviations												0.7	1.2	0.7	3.4

Table 4.25 presents a comparison of the accuracy of the SDDOT and Ohio curves in predicting the OMC and MDUW of different aggregate bases tested in this study. Table 4.25 shows that the SDDOT curves predicted the OMC values of four aggregates (04D9, 5777, 06DJ, and 04D7) out of 10 more accurately than the Ohio curves. At the same time, Ohio curves predicted the OMC of four aggregates (03RQ, 025D, 04JY, and 04E7) out of 10 more accurately than SDDOT curves. The SDDOT and Ohio curves were found to predict the OMC of two aggregates (042U and 04HK) out of 10 with equal accuracy. In other words, the accuracy of the SDDOT and Ohio curves in predicting the OMC was found to be quite similar.

Additionally, from Table 4.25, it was found that the SDDOT curves predicted the MDUW values of seven aggregates (04D9, 03RQ, 5777, 06DJ, 04JY, 04D7, and 04HK) out of 10 more accurately than the Ohio curves. At the same time, Ohio curves only predicted the MDUW of two aggregates (025D and 04E7) out of 10 more accurately than SDDOT curves. The SDDOT and Ohio curves predicted the OMC of one aggregate (042U) out of 10 with equal accuracy. It was concluded that the SDDOT curves more frequently predicted an accurate MDUW value compared with the Ohio curves.

Table 4.25 Accuracy of the OMC and MDUW Values Predicted Using SDDOT and Ohio Curves

Aggregate Base Material Type	More Accurate Method: ●			
	Predicted OMC		Predicted MDD	
	SDDOT Curve	Ohio Curve	SDDOT Curve	Ohio Curve
04D9 (contains RCA)	●		●	
03RQ		●	●	
5777	●		●	
025D		●		●
06DJ	●		●	
042U	Equal	Equal	Equal	Equal
04JY		●	●	
04D7	●		●	
04E7		●		●
04HK	Equal	Equal	●	
Accuracy Score	4	4	7	2

Another important parameter that can be used to compare the moisture-density curves' consistency is the coefficient of variation (COV) of the predicted OMC and MDUW values.

Table 4.26 shows the COV values determined for the OMC and MDUW of aggregate bases obtained from the SDDOT and Ohio curves based on the one-point moisture-unit weight data.

Table 4.26 Coefficients of Variation of OMC and MDUW Values from SDDOT and Ohio Curves

Aggregate Base Material Type	COV (%) OMC		COV (%) MDUW	
	SDDOT Curve	Ohio Curve	SDDOT Curve	Ohio Curve
04D9 (contains RCA)	5.5	10.6	1.3	2.9
03RQ	6.0	4.8	0.8	1.4
5777	3.0	3.8	0.8	0.9
025D	3.5	3.1	1.2	0.9
06DJ	3.0	5.0	0.9	1.4
042U	5.5	5.6	1.3	1.7
04JY	11.1	5.2	2.5	1.5
04D7	7.1	25.4	2.8	6.5
04E7	4.2	0.0	1.4	0.0
04HK	3.2	4.9	0.8	1.2
Average	5.2	6.8	1.4	1.8

From Table 4.26, it is evident that the COV of the predicted OMC values by applying the SDDOT curves varied between 3.0% and 11.1%, with a mean and median COV of 5.2% and 4.9%, respectively. The COV of the predicted OMC values by applying the Ohio curves varied between 0% and 25.4%, with a mean and median COV of 6.8% and 4.9%, respectively. This observation indicates that SDDOT curves predicted the OMC with a lower variability compared with the Ohio curves. In addition, from Table 4.26, it was found that the COV of the predicted MDUW values by applying the SDDOT curves varied between 0.8% and 2.8%, with a mean and a median COV of 1.4% and

1.3%, respectively. The COV of the predicted MDUW values by applying the Ohio curves varied between 0% and 6.5%, with a mean and median COV of 1.8% and 1.4%, respectively. This observation indicates that, overall, SDDOT curves predicted the MDUW values with a lower variability compared with the Ohio curves.

4.8.2 DCP Test's Effectiveness for Screening of Granular Base Compaction

In this section, the DPI values of each aggregate base were applied to evaluate the draft DCP specification considered by SDDOT for adoption. Currently, SDDOT is considering adopting the method used by MnDOT as per section 2211 of its 2018 Specification Book (MnDOT, 2018). The acceptance criteria for DCP readings in the field set by MnDOT are shown in Table 4.27. This includes the DPI value, moisture content (MC), grading number (GN), and SEAT values are required to determine if a compacted base meets the minimum requirements for acceptance.

SEAT (mm) refers to the penetration of the DCP cone in the aggregate base as a result of two initial blows, and GN is determined from Equation 4.1.

$$\text{GN (\% passing)} = \frac{25\text{mm} + 19\text{mm} + 9.5\text{mm} + 4.75\text{mm} + 2.00\text{mm} + 425\mu\text{m} + 75\mu\text{m}}{100} \quad (\text{Equation 4.1})$$

Table 4.27 Maximum DPI and SEAT Criteria for Base Compaction Acceptance (MnDOT, 2018)

Table 2211-3 Penetration Index Method — Maximum Seat and DPI				
Grading Number †	Moisture Content ‖	Maximum Allowable SEAT, [mm]	Maximum Allowable DPI, [mm/blow]	Test Layer, in*
3.1 – 3.5	< 5.0	40	10	4 – 6
	5.0 – 8.0	40	12	
	> 8.0	40	16	
3.6 – 4.0	< 5.0	40	10	4 – 6
	5.0 – 8.0	45	15	
	> 8.0	55	19	
4.1 – 4.5	< 5.0	50	13	5 – 6
	5.0 – 8.0	60	17	
	> 8.0	70	21	
4.6 – 5.0	< 5.0	65	15	6 – 12
	5.0 – 8.0	75	19	
	> 8.0	85	23	
5.1 – 5.5	< 5.0	85	17	7 – 12
	5.0 – 8.0	95	21	
	> 8.0	105	25	
5.6 – 6.0	< 5.0	100	19	8 – 12
	5.0 – 8.0	115	24	
	> 8.0	125	28	

† As determined by Form G&B-204
‖ Percent of dry weight.
* If layer to be placed is thinner than the Test Layer, use 2211.3.D.2.b, "Quality Compaction Method".
Note: When bitumen content is ≥ 2.5%, compact to achieve a penetration index value of 10 mm and a seating value of 40 mm, as determined by Form G&B-205.
Note that a moisture test is not required, if the material meets the toughest requirements for the Grading Number.

The GN values were calculated based on the gradation tests, and the MC, SEAT, and DPI values were summarized for each test conducted on each base material and summarized in Table 4.27. The maximum allowed SEAT and DPI values shown in Tables 4.28 to 4.30 were determined from Table 4.27 and were compared to those measured for aggregate bases. As a result, the compacted aggregate bases were evaluated based on DCP parameters (maximum SEAT and DPI) and actual achieved relative density measured by conducting the sand cone test.

Tables 4.28 to 4.30 show that the DCP-based methodology used for predicting the compaction quality of the granular aggregate bases was able to accurately predict the compaction quality in 71.1% of the cases. In 24.4% of the cases, the DCP method conservatively underestimated the compaction quality. Only in 4.5% of the cases does the DCP method pass an aggregate base with insufficient compaction. This finding suggests that the DCP test, as outlined in the draft SDDOT specification (adopted from MnDOT's specification), can be used for compaction acceptance with a 95% conservative confidence level. However, it cannot be used to precisely single out insufficient compactions. In other words, the DCP requirements can be used as acceptance criteria but not for the rejection of the quality of a compacted base. In addition to the foregoing observations, high variability in the DPI measurements (standard deviation of 7.8 mm/blow) for the base material containing RCA was observed (Table 4.3). Furthermore, DCP equipment was not practical to be operated due to the presence of coarse recycled concrete, which made measured penetrations highly variable and localized. These findings suggest using DCP for base materials containing RCA is not advisable.

Table 4.28 A Summary of DPI, SEAT, Dry Unit Weight, Moisture Content, Relative Density, and Compaction Criteria Based on MnDOT's Spec for 04D9, 03RQ, 5777, and 025D Bases

Base Type	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	GN	MC (%)	Relative Density (%)	SEAT (mm)	PIV (mm/blow)	Max Allowed*		Compaction Quality		
								SEAT (mm)	PIV (mm)	SEAT	PIV	Relative Density >92.5%
04D9 (RCA)	88.5	1417.6	2.0	7.6	75.9	54	18	40	12	Fail	Fail	Fail
	102.9	1648.3	2.0	5.3	88.2	77	19	40	12	Fail	Fail	Fail
	100.9	1616.3	2.0	8.6	86.5	45	22	40	16	Fail	Fail	Fail
	101.0	1617.9	2.0	14.2	86.6	57	24	40	16	Fail	Fail	Fail
	95.5	1529.8	2.0	7.7	81.9	77	21	40	12	Fail	Fail	Fail
	104.2	1669.1	2.0	12.1	89.3	42	21	40	16	Fail	Fail	Fail
	101.6	1627.5	2.0	5.5	87.1	59	16	40	12	Fail	Fail	Fail
	114.5	1834.1	2.0	5.0	98.3	61	18	40	12	Fail	Fail	Pass
	97.3	1558.6	2.0	16.5	83.4	53	26	40	16	Fail	Fail	Fail
03RQ	110.2	1765.2	3.6	7.1	91.0	67	15	45	15	Fail	Pass	Fail
	111.8	1790.9	3.6	7.4	92.3	59	17	45	15	Fail	Fail	Fail
	122.9	1968.7	3.6	8.2	101.5	43	15	55	19	Pass	Pass	Pass
	106.3	1702.8	3.6	7.1	87.8	61	13	45	15	Fail	Pass	Fail
	118.3	1895.0	3.6	7.4	97.7	55	13	45	15	Fail	Pass	Pass
	119.9	1920.6	3.6	5.8	99.0	49	14	45	15	Fail	Pass	Pass
	111.6	1787.7	3.6	7.3	92.1	60	15	45	15	Fail	Pass	Fail
	118.8	1903.0	3.6	7.6	98.1	56	14	45	15	Fail	Pass	Pass
	117.2	1877.4	3.6	6.2	96.8	62	13	45	15	Fail	Pass	Pass
5777	132.0	2114.4	4.2	4.7	97.4	63	8	50	13	Fail	Pass	Pass
	133.9	2144.9	4.2	4.9	98.8	53	12	50	13	Fail	Pass	Pass
	141.2	2261.8	4.2	4.4	104.1	33	10	50	13	Pass	Pass	Pass
	144.1	2308.3	4.2	5.2	106.3	42	8	60	17	Pass	Pass	Pass
	132.0	2114.4	4.2	4.2	97.4	49	10	50	13	Pass	Pass	Pass
	152.1	2436.4	4.2	4.5	112.2	32	10	50	13	Pass	Pass	Pass
	139.2	2229.8	4.2	5.2	102.7	34	9	60	17	Pass	Pass	Pass
	147.8	2367.5	4.2	5.5	109.0	38	10	60	17	Pass	Pass	Pass
	145.8	2335.5	4.2	4.3	107.5	27	9	50	13	Pass	Pass	Pass
025D	119.7	1917.4	4.0	6.8	90.5	51	17	45	15	Fail	Fail	Fail
	119.6	1915.8	4.0	7.9	90.4	60	17	45	15	Fail	Fail	Fail
	117.8	1887.0	4.0	6.8	89.1	58	14	45	15	Fail	Pass	Fail
	115.1	1843.7	4.0	7.1	87.0	70	14	45	15	Fail	Pass	Fail
	111.3	1782.9	4.0	6.8	84.2	57	13	45	15	Fail	Pass	Fail
	110.4	1768.4	4.0	6.8	83.5	58	14	45	15	Fail	Pass	Fail
	116.3	1862.9	4.0	7.5	87.9	45	14	45	15	Pass	Pass	Fail
	120.4	1928.6	4.0	7.6	91.0	58	17	45	15	Fail	Fail	Fail
	118.7	1901.4	4.0	6.0	89.8	62	15	45	15	Fail	Pass	Fail

Table 4.29 A Summary of DPI, SEAT, Dry Unit Weight, Moisture Content, Relative Density, and Compaction Criteria Based on MnDOT's Spec for 06DJ, 042U, 04JY, and 04D7 Bases

Base Type	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	GN	MC (%)	Relative Density (%)	SEAT (mm)	PIV (mm/blow)	Max Allowed*		Compaction Quality		
								SEAT (mm)	PIV (mm)	SEAT	PIV	Relative Density >92.5%
06DJ	119.7	1917.4	4.3	6.8	93.0	49	16	60	17	Pass	Pass	Pass
	119.6	1915.8	4.3	7.9	92.9	55	16	60	17	Pass	Pass	Pass
	117.8	1887.0	4.3	6.8	91.5	55	14	60	17	Pass	Pass	Fail
	115.1	1843.7	4.3	7.1	89.4	44	16	60	17	Pass	Pass	Fail
	111.3	1782.9	4.3	6.8	86.4	70	21	60	17	Fail	Fail	Fail
	110.4	1768.4	4.3	6.8	85.7	56	16	60	17	Pass	Pass	Fail
	116.3	1862.9	4.3	7.5	90.3	67	15	60	17	Fail	Pass	Fail
	120.4	1928.6	4.3	7.6	93.5	73	18	60	17	Fail	Fail	Pass
	118.7	1901.4	4.3	6.0	92.2	95	12	60	17	Fail	Pass	Fail
042U	108.6	1739.6	3.8	9.7	92.0	69	19	55	19	Fail	Pass	Fail
	111.6	1787.7	3.8	9.5	94.5	57	18	55	19	Fail	Pass	Pass
	111.0	1778.0	3.8	10.2	94.0	43	14	55	19	Pass	Pass	Pass
	109.8	1758.8	3.8	9.8	93.0	72	19	55	19	Fail	Pass	Pass
	111.5	1786.1	3.8	8.8	94.4	56	17	55	19	Fail	Pass	Pass
	112.8	1806.9	3.8	9.4	95.5	47	15	55	19	Pass	Pass	Pass
	105.0	1681.9	3.8	9.2	88.9	68	18	55	19	Fail	Pass	Fail
	111.5	1786.1	3.8	8.6	94.4	53	15	55	19	Pass	Pass	Pass
	115.2	1845.3	3.8	9.6	97.6	48	15	55	19	Pass	Pass	Pass
04JY	119.0	1906.2	4.3	3.3	93.9	70	19	50	13	Fail	Fail	Pass
	123.5	1978.3	4.3	3.5	97.5	42	13	50	13	Pass	Pass	Pass
	128.8	2063.2	4.3	3.8	101.6	28	9	50	13	Pass	Pass	Pass
	119.6	1915.8	4.3	3.2	94.4	63	16	50	13	Fail	Fail	Pass
	123.2	1973.5	4.3	4.1	97.2	43	13	50	13	Pass	Pass	Pass
	129.8	2079.2	4.3	4.2	102.4	30	10	50	13	Pass	Pass	Pass
	115.5	1850.1	4.3	3.8	91.1	53	16	50	13	Fail	Fail	Fail
	120.7	1933.4	4.3	3.6	95.2	44	12	50	13	Pass	Pass	Pass
	121.6	1947.8	4.3	3.5	96.0	31	10	50	13	Pass	Pass	Pass
04D7	107.9	1728.4	3.9	4.0	82.1	71	23	40	10	Fail	Fail	Fail
	110.5	1770.0	3.9	4.7	84.0	66	19	40	10	Fail	Fail	Fail
	117.2	1877.4	3.9	5.0	89.1	48	16	45	15	Fail	Fail	Fail
	106.4	1704.4	3.9	4.6	80.9	73	17	40	10	Fail	Fail	Fail
	111.6	1787.7	3.9	4.7	84.9	70	18	40	10	Fail	Fail	Fail
	123.5	1978.3	3.9	4.6	93.9	53	19	40	10	Fail	Fail	Pass
	112.4	1800.5	3.9	4.9	85.5	72	18	40	10	Fail	Fail	Fail
	117.2	1877.4	3.9	4.8	89.1	54	19	40	10	Fail	Fail	Fail
	117.6	1883.8	3.9	4.4	89.4	44	16	40	10	Fail	Fail	Fail

Table 4.30 A Summary of DPI, SEAT, Dry Unit Weight, Moisture Content, Relative Density, and Compaction Criteria Based on MnDOT's Spec for 04E7 and 04HK Bases

Base Type	Dry Unit Weight Sand Cone (pcf)	Dry Unit Weight Sand Cone (kg/m ³)	GN	MC (%)	Relative Density (%)	SEAT (mm)	PIV (mm/blow)	Max Allowed*		Compaction Quality		
								SEAT (mm)	PIV (mm)	SEAT	PIV	Relative Density >92.5%
04E7	124.8	1999.1	4.1	8.4	98.4	54	14	70	21	Pass	Pass	Pass
	126.5	2026.3	4.1	9.1	99.8	48	13	70	21	Pass	Pass	Pass
	127.6	2044.0	4.1	8.1	100.6	58	12	70	21	Pass	Pass	Pass
	123.4	1976.7	4.1	7.5	97.3	54	13	60	17	Pass	Pass	Pass
	124.0	1986.3	4.1	7.5	97.8	57	13	60	17	Pass	Pass	Pass
	127.9	2048.8	4.1	7.6	100.9	51	13	60	17	Pass	Pass	Pass
	120.6	1931.8	4.1	7.4	95.1	57	14	60	17	Pass	Pass	Pass
	123.7	1981.5	4.1	8.6	97.6	54	15	70	21	Pass	Pass	Pass
	127.9	2048.8	4.1	7.8	100.9	42	12	60	17	Pass	Pass	Pass
04HK	135.0	2162.5	4.0	6.2	103.3	61	13	45	15	Fail	Pass	Pass
	133.4	2136.9	4.0	6.1	102.0	62	14	45	15	Fail	Pass	Pass
	139.0	2226.6	4.0	6.6	106.3	42	12	45	15	Pass	Pass	Pass
	133.8	2143.3	4.0	6.3	102.3	66	11	45	15	Fail	Pass	Pass
	133.2	2133.7	4.0	5.9	101.9	61	12	45	15	Fail	Pass	Pass
	140.9	2257.0	4.0	6.4	107.8	46	14	45	15	Fail	Pass	Pass
	138.2	2213.8	4.0	6.4	105.7	59	13	45	15	Fail	Pass	Pass
	137.4	2200.9	4.0	7.2	105.1	59	14	45	15	Fail	Pass	Pass
	136.2	2181.7	4.0	6.9	104.2	62	14	45	15	Fail	Pass	Pass

In order to evaluate the effectiveness of the SEAT and DPI values (DCP parameters) in predicting the adequacy of the compaction, the variations of these values with respect to the achieved density were analyzed. These analyses were conducted in two categories: (i) the cases where the achieved compaction is adequate (relative density $\geq 92.5\%$); and (ii) the cases where the achieved compaction is inadequate (relative density $< 92.5\%$). For each case, the difference between the measured DPI (DPI_{measured}) and the maximum allowable DPI ($DPI_{\text{max. allowable}}$) obtained from Tables 4.28 to 4.30 were determined for each measurement ($\Delta DPI = DPI_{\text{measured}} - DPI_{\text{max. allowable}}$). Similarly, the difference between the measured SEAT ($SEAT_{\text{measured}}$) and the maximum allowable SEAT ($SEAT_{\text{max. allowable}}$) values was determined for each case ($\Delta SEAT = SEAT_{\text{measured}} - SEAT_{\text{max. allowable}}$). Note that the maximum allowable values for SEAT and DPI are functions of the grading number (GN) of each material type. Therefore, only when both $\Delta SEAT$ and ΔDPI values are less than zero will the compaction be declared insufficient as per the DCP test. Finally, the difference between the achieved relative density ($Density_{\text{measured}}$) and the minimum acceptable relative density ($Density_{\text{min. acceptable}}$) values was determined for each case ($\Delta Density = Density_{\text{achieved}} - Density_{\text{min. acceptable}}$). In this case, only when the $\Delta Density$ value is equal to or greater than zero the achieved compaction is adequate. Figure 4.31 shows the variations of the $\Delta SEAT$, ΔDPI , and $\Delta Density$ for cases where the achieved relative density equals or exceeds 92.5%. Figure 4.31 shows no clear trend of variation of the $\Delta SEAT$ and ΔDPI with the $\Delta Density$. Additionally, it was observed that the DPI parameter better spotted the adequately compacted bases compared with the SEAT parameter, as only five points with adequate compaction are positioned above the $\Delta DPI = 0$ line. Figure 4.32 depicts the variations of the $\Delta SEAT$, ΔDPI , and $\Delta Density$ for the cases in which the achieved relative density is less than 92.5% (inadequate

compaction). Figure 4.32 shows no evident trend of variation of the Δ SEAT and Δ DPI with the Δ Density values. However, Figure 4.32 indicates that the SEAT parameter better spotted the inadequately compacted bases compared with the DPI parameter.

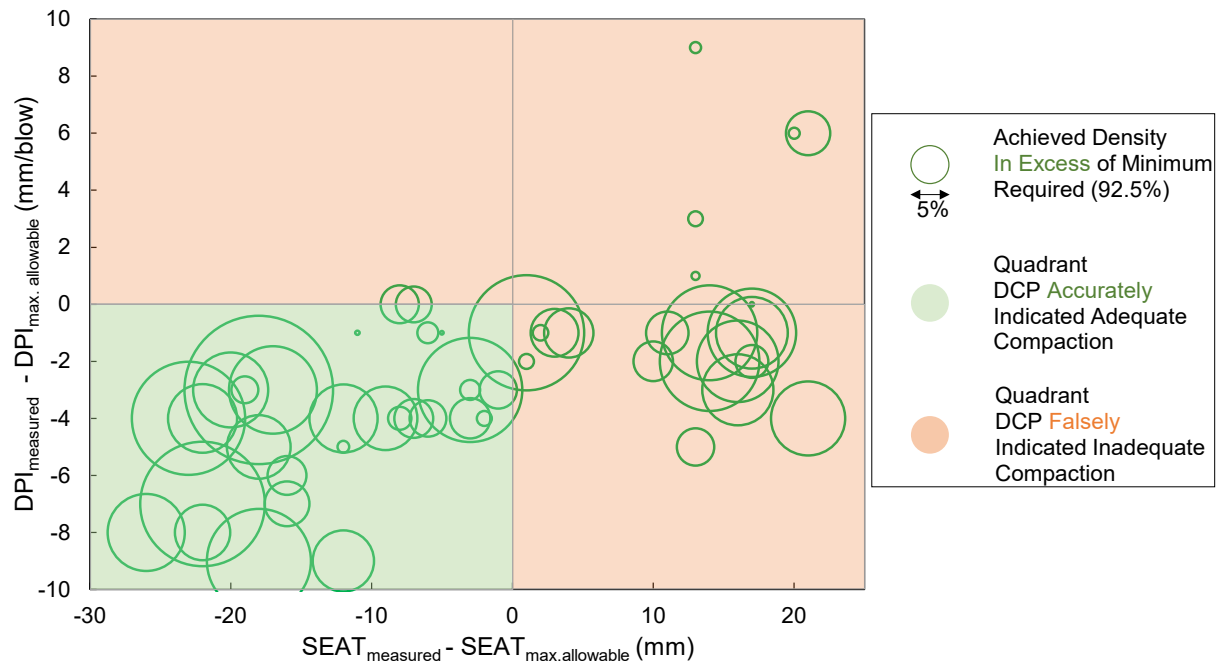


Figure 4.31 Variations of Δ SEAT and Δ DPI with Achieved Relative Density in Excess of 92.5%

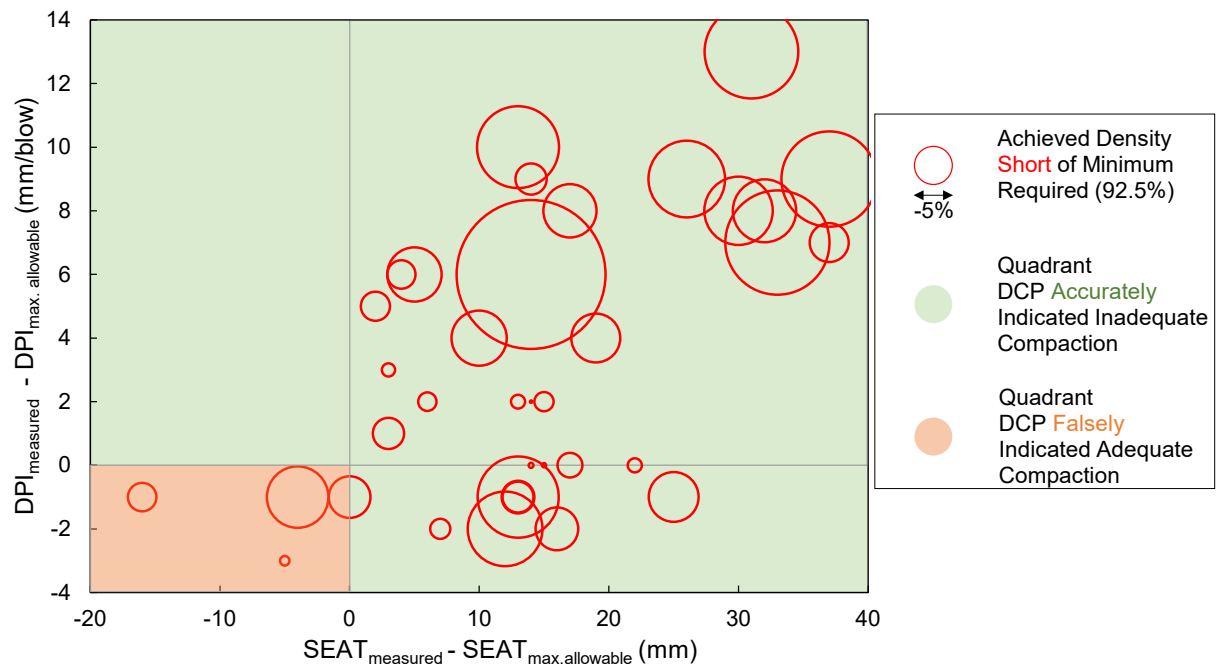


Figure 4.32 Variations of Δ SEAT and Δ DPI with Achieved Relative Density Short of 92.5%

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results, discussions, and observations made in this study, conclusions as follows can be drawn.

- Comparing the SDDOT and Ohio curves along with the laboratory compaction data revealed that the moisture-density family of curves developed for SDDOT could predict the OMC and MDUW values with an accuracy higher than that of the Ohio curves.
- The draft specification recommended by Jones and Webber (2021) for application of the SDDOT family of curves in compaction was found to be effective.
- The recommended criteria for acceptance of the compaction quality of base materials using the DCP test parameters (SEAT and DPI) were found to be a conservative method for field compaction quality assessment. However, in 4.5% of the cases, it produced false unconservative results.
- The draft specification being considered for application of DCP in screening of the compaction quality of the granular aggregate bases in South Dakota (Appendix A) was found to be effective.
- Due to high variability and difficulties associated with conducting the test, the use of the DCP method for acceptance of the compaction quality when RCA is present is not recommended.

5.2 Recommendations

5.2.1 Adjust the SDDOT Moisture-Density Family of Curves

Ohio curves have been developed based on more than a decade-long data collection and field implementation. The first set of curves, for example, was developed in 1936 by testing 461 different materials. These curves were later revised in 1958 after adding the results of an additional 10,149 test sites. Continuous data collection has resulted in revised curves with improved accuracy. Reviewing the Ohio curves indicated that they do not intersect in the range of the moisture contents shown on the graphs. This fact is dictated by the physics of granular materials' packing. If two curves intersect, it suggests that for a given one-point proctor data falling on the point of intersection, two sets of OMC and MDUW values can be assumed for one material depending on which curve one selects to follow. This is not technically possible. In contrast, reviewing the SDDOT curves indicated that extending some curves resulted in intersecting with each other (e.g., curves B and C or G and H or I and J, etc.). As discussed above, theoretically, these curves should be parallel or close to parallel with respect to each other. Therefore, revising some of the curves based on additional testing is recommended. For this purpose, collecting materials (approximately 80 lbs.) from each construction project and sending them to the laboratory for conducting gradation and standard Proctor tests is recommended. The scope of the additional work is limited to only conducting the gradation and Proctor tests in the laboratory and does not require any field testing. Additional moisture and density data are proposed to be shown on the SDDOT curves to adjust the intersecting curves. This effort is suggested to be pursued for at least one construction season.

5.2.2 Implementation of the SDDOT Moisture-Density Family of Curves

In view of the facts summarized in conclusion 1 discussed in section 5.5, the SDDOT curves are recommended to be implemented by SDDOT after recommendation 6.1 is addressed.

5.2.3 SDDOT Moisture-Density Family of Curves Constructed Based on Wet Density

The Ohio moisture-density family of curves was prepared based on the wet density of the Proctor samples, which can be easily determined by dividing the wet weight of the sample by its volume. Currently, the same curves are being used by SDDOT. However, SDDOT's new curves were constructed based on the dry unit weight of the Proctor sample. This needs an extra step in the calculation of the dry unit weight. To eliminate the need for extra calculations, reduce the risk of error, and keep the curves consistent with the current state of practice in South Dakota (wet density curves), it is suggested to convert the new SDDOT family of curves to wet unit weight. This can be easily achieved by using the equation shown below.

$$WUW = DUW(1+MC)$$

where, WUW = wet unit weight; DUW = dry unit weight; and MC = moisture content (a ratio between 0 and 1).

5.2.4 Develop a Computer Program for Using the SDDOT Curves

Using the new SDDOT curves, given the need for extensive interpolations carried out by the user, increases the need for applying individual judgment. This may sometimes increase the risk of error and reduce repeatability. This is partially because the new SDDOT curves are oriented more distantly from each other compared with the Ohio curves, which are oriented more densely. Smaller empty space between the Ohio curves reduces the need for extensive interpolations and eyeballing, leading to higher accuracy. Therefore, to eliminate this concern, the development of a computer program based on the SDDOT curves can help reduce operator-induced error and improve accuracy in predicting the OMC and MDUW. The scope of this computer program will be limited to receiving the one-point proctor test's moisture and density information as input parameters from the user and returning the OMC and MDUW values as output computed in accordance with SDDOT's new curves.

5.2.5 Monitoring of DCP Test's Effectiveness in Screening Compaction Quality

Application of the DCP test by MnDOT for screening of compaction quality began in 1991. This method has been continuously applied over the years in different construction sites. Continuous data collection, observation, analysis, and evaluation carried out through numerous projects have resulted in making several changes to the initial specification during more than three decades until the current MnDOT specification was developed. Conducted research on both the Minnesota Road Research Project (MnROAD) and other project sites in an effort to determine the effectiveness of the application of the DCP test as a compaction quality control tool has shown promise and resulted in the development of a specification widely used in Minnesota's road construction projects. In the current project (SD2019-5), the DCP tests were only conducted on 10 different granular base materials. Unlike MnDOT's approach, which used hundreds of DCP test data points for developing its DCP specification, DCP tests conducted on SDDOT projects (10 projects) do not represent a wide range of South Dakota's materials. To follow a similar incremental approach applied by MnDOT to ensure the suitability of the DCP specification being considered by SDDOT, data collection over at least one construction season is recommended. Given its convenience and speed, DCP is recommended to be conducted in construction projects along with the other density measurement techniques commonly used in SDDOT projects (sand cone and/or NDG) to acquire additional data points for different types

of base materials. Additional DCP test data and field density measurements (commonly collected) will allow for verifying the applicability of the DCP test for SDDOT's materials before it can completely replace the sand cone or NDG. The preceding approach is proposed to be pursued over only one construction season and carried out by the construction crew or SDDOT's field technicians. Therefore, it is not expected to require significant resources. In addition, the proposed approach will serve as a training and pre-implementation period, allowing the construction crew and SDDOT technicians to acquire the necessary equipment and skills before conducting the DCP tests in the field becomes the standard practice.

5.2.6 Feasibility of Using the DCP Test for Screening Compaction in the Field

The draft DCP test specification (adopted from MnDOT's specifications) being considered by SDDOT for implementation as a new specification item was evaluated, and its use was found feasible in most cases. It is recommended that the draft specification be considered for implementation in the field after completing the required work specified in recommendation 6.5.

The following recommendations were made based on the limitations and the scope of the present study.

- Since the moisture conditioned samples were tested after vacuum saturation, an increase in ISS value resulting from moisture conditioning was attributed to suction, resulting in a better interlocking of top and bottom layers. To mitigate this issue, it is recommended to dry the samples before testing.
- The LISST was conducted only at room temperature. Therefore, it is recommended to perform the LISST at different temperatures to evaluate the effect of temperature on ISS values.
- The LISST tests were conducted on laboratory-prepared samples. It is recommended to conduct additional LISST tests on field cores prepared using the same tack coat types tested in this study.

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7. Appendix A: Specification Language for Implementation of DCP for Compaction

In this study, the draft specification being considered by SDDOT for adoption of the MnDOT specification language for implementation was evaluated and found effective. Therefore, the same specification language is being presented herein.

Determination of the Penetration Index Value for Granular Material In-place by the Dynamic Cone Penetrometer Test Methods

1. Scope:

The methods presented are for determining the in-place Penetration Index Value (PIV) for granular material with a maximum particle size of ≤ 2.0 inches. PIV values are used to assess adequate compaction of granular materials. Two methods are presented for different specified material types.

Definitions.

Compaction: The use of equipment to compress soil, aggregate, or mixture into a smaller volume, thus increasing its dry unit weight and improving its engineering properties; strength and stability.

Dynamic Cone Penetrometer (DCP): The device utilized to determine the in-place Penetration Index Value of granular material layers. The device apparatus within this Method and within the SD ### (DCP Procedure). The procedure for using the device is outlined in detail in SD ### (DCP Procedure).

Penetration Index Value (PIV): The measurement obtained during testing utilizing the DCP. The measurement is the amount of penetration per blow and is calculated in increments of 3 blows. The measurement is recorded in units of mm/blow or inches/blow. The calculation is the reading on the DCP measurement rod in mm or in, after 3 standard test blows minus the reading prior to the standard test blows divided by the 3 standard test blows. This measurement can be correlated to various laboratory strength test such as the California Bearing Ratio Test.

$$\text{PIV} = \frac{\text{Reading after 5 blows} - \text{Reading after 2 blows}}{3}$$

SEAT: The SEAT refers to the initial seating of the DCP cone tip. This requires two initial standard blows. The SEAT is the measurement of penetration measurement in mm or in, after the two initial blows.

2. Apparatus:

2.1 The 17.6-lb. (8-kg) DCP is shown schematically in Figure 1 with replaceable cone schematic shown in Figure 2. It consists of the following components: a 5/8-in. (16-mm) diameter steel drive rod with a replaceable point, a 17.6-lb (8-kg) rammer which is dropped from a fixed height of 22.6-in. (575-mm). The apparatus is typically constructed of stainless steel, with the exception of the replacement point tip, which may be constructed from hardened tool steel or a similar material resistant to wear.

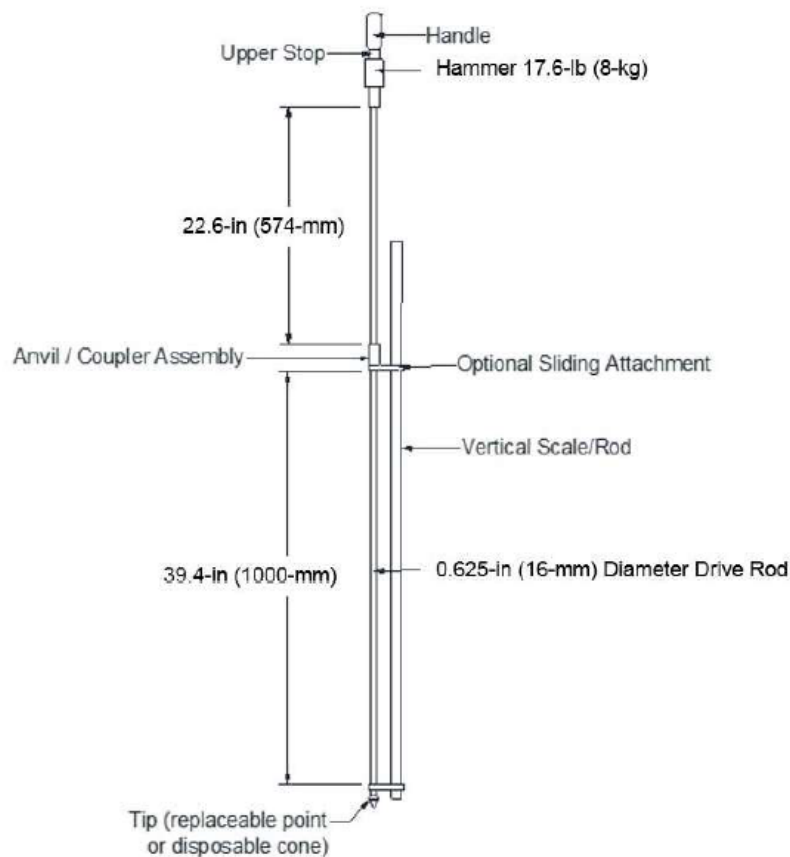


Figure 1 Schematic of DCP

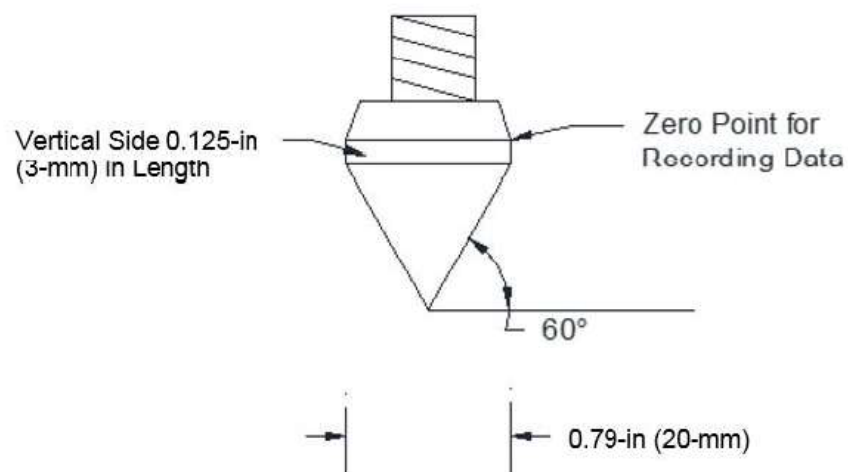


Figure 2. Replaceable Point Tip

- 2.2 The following tolerances are recommended for the apparatus: Hammer weight-measurement of 17.6-lb. (8.0-kg); tolerance is 0.02-lb. (0.01-kg), Drop of rammer-measurement of 22.6-in. (575-mm), tolerance is 0.04-in. (1.0-mm). Tip angle

measurement of 60 degrees included angle; tolerance is 1 degree, and Tip base diameter measurement of 0.79-in. (20-mm); tolerance is 0.01-in. (0.25-mm).

2.3 In addition to the DCP, the following equipment is needed: Tools for assembling the DCP, Lubricating Oil, Thread Locking Compound, and PIV Data Worksheet for recording data (See Attached).

2.4 Depending on the circumstances, the following equipment may also be needed or is recommended: A vertical scale graduated using increments of 0.1 in. (2.0 mm), or measuring rod longer than the longest drive rod if the drive rod(s) are not graduated, an optional sliding attachment for use with a separate scale or measuring rod, and extraction jack.

3. Procedure:

Method 1 For testing virgin aggregate that meets the specific requirements of Subbase, and Base Course as specified by Section 882.2 of SDDOT Standard Specifications for Roads and Bridges.

Method 2 For testing salvaged materials that meet the specific requirements of Milled and Reclaimed as specified by Section 884.2 of SDDOT Standard Specifications for Roads and Bridges. This method is also used when testing Full Depth Reclamation (FDR) asphalt. This method may also be used for materials classified by the SDDOT Standard Specifications for Roads and Bridges as recycled materials.

3.1 Method 1 (Subbase and Base Course)

A. Obtain most recent Sieve Analysis (DOT-3) results for granular material being tested to determine Grading Number (GN). If a sieve analysis has not been previously conducted for the material, conduct a sieve analysis in accordance with SD 202 to obtain results for the GN determination. The analysis shall include the following sieve sizes: 1", 3/4", 3/8", #4, #8, #40, #200. Record the percent passing each sieve and sample ID on DCP Penetration Index Value Worksheet Method 1 under Gradation Data.

B. Calculate the GN to determine SEAT and PIV test acceptance requirements. The GN is calculated by summing the percent passing each of the sieves shown below and dividing the sum by 100. Record GN on DCP Penetration Index Value Worksheet Method 1 under Gradation Data.

$$(GN) = \frac{1" + \frac{3}{4}" + \frac{3}{8}" + \#4 + \#8 + \#40 + \#200}{100}$$

C. Determine the Moisture Content (MC), SEAT, and PIV test acceptance requirements for the calculated GN.

Table 1: SEAT and PIV requirements.

Grading Number	MC (%)	Maximum Allowable Seating (mm)	Maximum Allowable PIV (mm/blow)	Grading Number	MC (%)	Maximum Allowable Seating (mm)	Maximum Allowable PIV (mm/blow)
3.1 – 3.5	< 5.0	40	10	4.6 – 5.0	< 5.0	65	15
	5.0 – 8.0	40	12		5.0 – 8.0	75	19
	> 8.0	40	16		> 8.0	85	23
3.6 – 4.0	< 5.0	40	10	5.1 – 5.5	< 5.0	85	17
	5.0 – 8.0	45	15		5.0 – 8.0	95	21
	> 8.0	55	19		> 8.0	105	25
4.1 – 4.5	< 5.0	50	13	5.6 – 6.0	< 5.0	100	19
	5.0 – 8.0	60	17		5.0 – 8.0	115	24
	> 8.0	70	21		> 8.0	125	28

D. Equipment Check: Before beginning a test, the DCP device shall be inspected for fatigue-damaged parts, in particular the coupler and handle, and excessive wear of the drive rod and replacement point tip. All joints must be securely tightened including the coupler assembly and the replaceable point tip (or the adapter for the disposable cone tip) to drive rod.

E. Locate a level, undisturbed area.

F. To determine the in-situ material SEAT and PIV perform the test in accordance with SD ### (DCP Test Procedure).

G. Record test results on DCP Penetration Index Value Worksheet Method 1 (DOT- ##). If test results do not meet test acceptance requirements, moisture condition the material and compact again before conducting another test.

3.2 Method 2 (Milled, Reclaimed, Salvaged, and FDR)

A. Equipment Check: Before beginning a test, the DCP device shall be inspected for fatigue-damaged parts, in particular the coupler and handle, and excessive wear of the drive rod and replacement point tip. All joints must be securely tightened including the coupler assembly and the replaceable point tip (or the adapter for the disposable cone tip) to drive rod.

B. Locate a level, undisturbed area.

C. To determine the in-situ material SEAT and PIV perform the test in accordance with SD ### (DCP Test Procedure).

D. Record test results on DCP Penetration Index Value Worksheet Method 2 (DOT - ##). If the SEAT value exceeds 0.79-in. (20-mm) relocate to the test to test site at least 12-in. (300-mm) from previous test site and reseat the cone. If the second test site fails the above criteria, compaction is not acceptable, and the area being tested shall be moisture conditioned and compacted again. If the resulting PIV is 15 mm/blow or less, the test passes.

E. No moisture test is required if the hardest penetration requirement is met.

4. Report:

4.1 Calculations.

A. Grading Number (GN)

$$(GN) = \frac{1" + \frac{3}{4}" + \frac{3}{8}" + \#4 + \#8 + \#40 + \#200}{100}$$

Where the percent passing each sieve is used.

B. SEAT value:

$$SEAT = A - B$$

Where:

A = DCP penetration reading after 2 standard blows in mm or inches.

B = DCP penetration reading before 2 standard blows in mm or inches.

SEAT= DCP Seating value in mm or inches.

C. Penetration Index Value (PIV):

$$PIV = \frac{A - B}{3}$$

Where:

A = DCP penetration reading after 5 standard blows in mm or inches.

B = DCP penetration reading after 2 standard blows in mm or inches.

PIV = Penetration Index Value in mm/blow or inches/blow.

4.2 Report.

A. Report the moisture content to the nearest 0.1 percentage point.

B. Report the SEAT value to the nearest 1.0 mm.

C. Report the PIV value to the nearest 1.0 mm/blow.

D. Provided required information on the DCP Penetration Index Value Worksheet.

5. References:

ASTM D6951

DOT - 3

DOT - ## (DCP Penetration Index Value Worksheet Method 1)

DOT - ## (DCP Penetration Index Value Worksheet Method 2)

SD 108

SD ### (DCP Procedure)

Determination of the Penetration Index Value for Granular Material In-place by the Dynamic Cone Penetrometer Test Procedure

1. Scope:

This test is for determining the in-place Penetration Index Value (PIV) for granular material with a maximum particle size of ≤ 2.0 inches and have a non-compacted layer thickness of 6 in. or less. PIV values are used to assess adequate compaction of granular materials.

2. Apparatus:

2.1 The 17.6-lb (8-kg) DCP is shown schematically in Figure 1 with replaceable cone schematic shown in Figure 2. It consists of the following components: a 5/8-in. (16-mm) diameter steel drive rod with a replaceable point, and a 17.6-lb (8-kg) rammer which is dropped a fixed height of 22.6-in. (575-mm). The apparatus is typically constructed of stainless steel, with the exception of the replacement point tip, which may be constructed from hardened tool steel or a similar material resistant to wear.

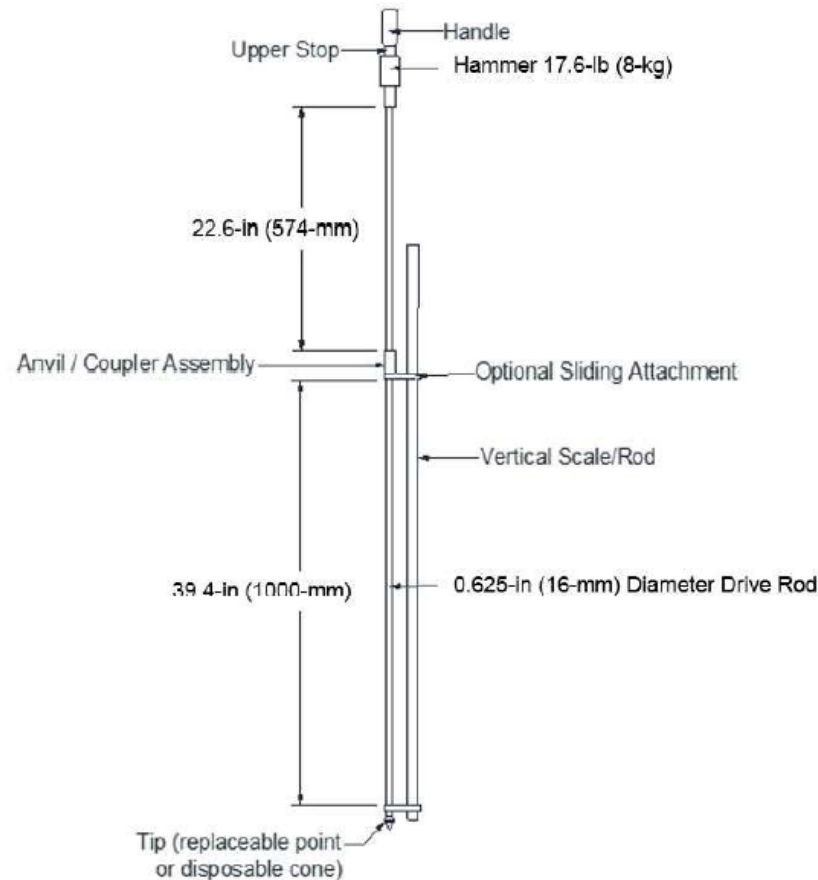


Figure 1 Schematic of DCP

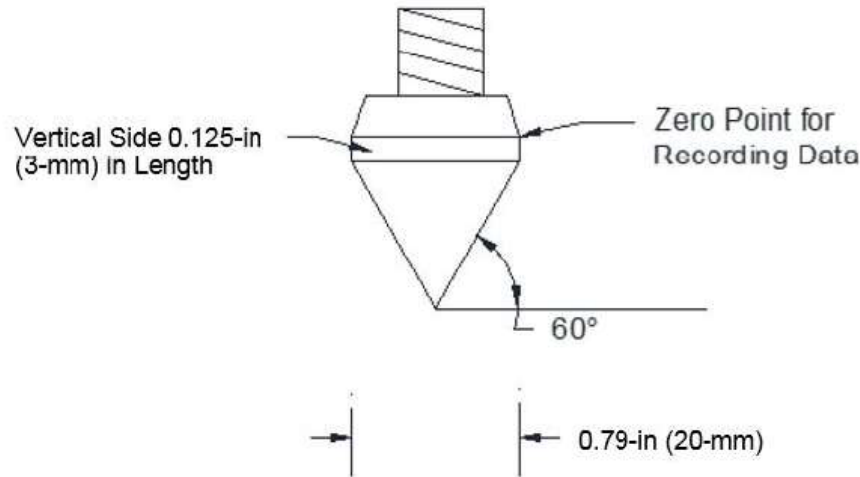


Figure 2. Replaceable Point Tip

- 2.2 The following tolerances are recommended for the apparatus: Hammer weight-measurement of 17.6-lb (8.0-kg); tolerance is 0.02-lb (0.01-kg), Drop of rammer-measurement of 22.6-in. (575-mm), tolerance is 0.04-in (1.0-mm), Tip angle measurement of 60 degrees included angle; tolerance is 1 degree, and Tip base diameter measurement of 0.79-in (20-mm); tolerance is 0.01-in (0.25-mm).
- 2.3 In addition to the DCP, the following equipment is needed: Tools for assembling the DCP, Lubricating Oil, Thread Locking Compound, and PIV Data Worksheet for recording data (See Attached).
- 2.4 Depending on the circumstances, the following equipment may also be needed or is recommended: a vertical scale graduated using increments of 0.04-in (1.0-mm), or measuring rod longer than the longest drive rod if the drive rod(s) are not graduated. An optional sliding attachment for use with a separate scale or measuring rod, and Extraction jack.
3. **Procedure:**
 - 3.1 Basic Operation
 - A. The operator holds the device by the handle in a vertical position and lifts and releases the rammer from the standard drop height. The recorder measures and records the total penetration for a given number of blows or the penetration per blow. A single operator can perform both tasks concurrently if required.
 - 3.2 Equipment Check
 - A. Before beginning a test, the DCP device shall be inspected for fatigue-damaged parts, in particular the coupler and handle, and excessive wear of the drive rod and replacement point tip. All joints must be securely tightened including the coupler assembly and the replaceable point tip (or the adapter for the disposable cone tip) to drive rod.
 - 3.3 Initial Reading and Seating for Testing Granular Materials
 - A. Locate a level, undisturbed area.
 - B. The DCP is held vertically and the tip seated such that the top of the widest part of the tip is flush with the surface of the material to be tested. Take an

initial reading and record it on the PIV Worksheet. The distance is measured to the nearest 0.04-in (1-mm). Some sliding reference attachments allow the scale/measuring rod to be set/marked at zero when the tip is at the zero point shown in Figure 2.

- C. Raise the rammer until it meets the handle, then release the rammer under its own weight and allow it to impact the anvil coupler assembly. Repeat this process one more time for a total of 2 initial drops to complete the seating process. The corresponding penetration is recorded on the PIV Data Worksheet. The distance is measured to the nearest 0.04-in (1-mm).

NOTE: The operator raises the rammer until it makes only light contact with the handle.

3.4 Testing Sequence.

- A. Carefully raise the rammer until it meets the handle, then release the rammer under its own weight. Repeat the process two more times for a total of five blows.
- B. Measure and record the final penetration measurement after 5 blows on the PIV Data Worksheet.
- C. The DCP is extracted from the test hole. An extraction jack may be used to aid in this process.
- D. Collect a representative sample from the test hole for a moisture content determination. Weigh the material to the nearest 0.1 g and dry it to a constant weight as per SD 108. Record the moisture content on the PIV Data Worksheet.

NOTE: The presence of large aggregates or rock strata will either stop further penetration or deflect the drive rod. If after 5 blows, the device has not advanced more than 0.08-in (2-mm) or the handle has deflected more than 3-in (75-mm) from the vertical position, the test shall be aborted and the device moved to another test location. The new test location shall be a minimum of 12-in (300-mm) from the prior location to minimize test error.

4. Report:

4.1 Calculations

- A. The SEAT measurement is calculated by subtracting the initial reading from the reading after 2 blows.
- B. The PIV value is the reading obtained after 5 blows minus the reading after 2 blows divided by the number of blows (3) as seen in the equation below.

$$PIV = \frac{\text{Reading after 5 blows} - \text{Reading after 2 blows}}{3}$$

4.2 Report

- A. Report the moisture content to the nearest 0.1 percentage point.
- B. Report the SEAT value to the nearest 1 mm.
- C. Report the PIV value to the nearest 1 mm.
- D. Provide required information on the DCP Penetration Index Value Worksheet.

5. References:

ASTM D6951
SD 108

Sample ID _____ DOT-## _____
 File No. _____
 PROJECT _____ COUNTY _____ PCN _____ Subbase and Base Course Granular Materials
 Date _____ of _____ Lift Thickness _____ in.

Tested By _____ Checked By _____ Notes _____

Gradation Data

Gradation Sample ID Used _____

Sieve	% Passing
1 Inch	
3/4 Inch	
3/8 Inch	
# 4	
# 8	
# 40	
# 200	
GN =	

$$(GN) = \frac{1" + \frac{3}{4}" + \frac{3}{8}" + \frac{3}{8}" + \#4 + \#8 + \#40 + \#200}{100}$$

Penetration Requirements

Grading Number	MC (% Dry)	Maximum Allowable Seating (mm)	Maximum Allowable PIV (mm/blow)	Grading Number	MC (% Dry)	Maximum Allowable Seating (mm)	Maximum Allowable PIV (mm/blow)
3.1 - 3.5	< 5.0	40	10	4.6 - 5.0	< 5.0	65	15
	5.0 - 8.0	40	12		5.0 - 8.0	75	19
	> 8.0	40	16		> 8.0	85	23
3.6 - 4.0	< 5.0	40	10	5.1 - 5.5	< 5.0	85	17
	5.0 - 8.0	45	15		5.0 - 8.0	95	21
	> 8.0	55	19		> 8.0	105	25
4.1 - 4.5	< 5.0	50	13	5.6 - 6.0	< 5.0	100	19
	5.0 - 8.0	60	17		5.0 - 8.0	115	24
	> 8.0	70	21		> 8.0	125	28

No moisture test is required when DPI is met for a given GN, for example if GN is 4.8 and DPI is 14, no moisture test is required.

DCP Data

$$PIV = \frac{\text{Reading after 5 blows} - \text{Reading after 2 blows}}{3}$$

Test Information				Requirements			DCP Data (mm)				Test Results			
Test #	Date	Station	Offset	GN	MC (%)	Maximum Allowable SEAT (mm)	Maximum Allowable PIV (mm/blow)	Initial Reading	Reading after seating (2 Blows)	Reading after 5 blows	SEAT (mm)	SEAT : Pass or Fail	PIV (mm/blow)	PIV: Pass or Fail

