JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Developing Statistical Limits for Using the Light Weight Deflectometer (LWD) in Construction Quality Assurance

Matthew Volovski

Mohammad Arman

Samuel Labi

SPR-3651 • Report Number: FHWA/IN/JTRP-2014/10 • DOI: 10.5703/1288284315504

RECOMMENDED CITATION

Volovski, M., Arman, M., & Labi, S. (2014). *Developing statistical limits for using the light weight deflectometer (LWD) in construction quality assurance* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/10). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284315504

AUTHORS

Matthew Volovski
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Mohammad Arman
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Samuel Labi, PhD
Associate Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-5926
labi@purdue.edu
Corresponding Author

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at: http://docs.lib.purdue.edu/jtrp/

NOTICE

COPYRIGHT

Print ISBN: 978-1-62260-315-2
ePUB ISBN: 978-1-62260-316-9

Cover photo used with permission of MnDOT.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2014/10		

4. Title and Subtitle	5. Report Date
Developing Statistical Limits for Using the Light Weight Deflectometer (LWD) in Construction Quality Assurance	July 2014
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Matthew Volovski, Mohammad Arman, and Samuel Labi	FHWA/IN/JTRP-2014/10
9. Performing Organization Name and Address	**10. Work Unit No.**
Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	
	11. Contract or Grant No. SPR-3651
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

The traditional methods of evaluating the compaction quality of pavement subbase and subgrade construction require considerable time and resources. Therefore, there is a need for a safe, reliable, rapid, and cost-effective field measurement technique for compaction testing of unbound pavement layers. The Light Weight Deflectometer (LWD) is one such mechanism that offers field measurement of deflections and stiffness of unbound pavement layers under a given load. The LWD is gaining increased attention for quality control and quality assurance (QC/QA) during pavement construction. The Indiana Department of Transportation (INDOT) is planning on implementing the LWD in field QA/QC for unbound layers of pavements. As such, this research investigates the feasibility of developing statistical limits for the compaction of specified combinations of subbase and subgrade materials in terms of their maximum allowable LWD deflections.

Statistical limits were developed for six of the most common subgrade, subbase, or subgrade-subbase combinations that are used for highway pavement construction in Indiana: lime modified, cement modified, natural subgrade and No. 53 crushed stone (53CS) subbase overlaying these subgrades. For the subbase layers, these statistical limits are applicable only to six inches of subbase over subgrade and may not be applicable to a different layer configuration in terms of the number of lifts or thickness of lifts. The ultimate goal is for the developed statistical limits to replace the need for site-specific LWD limits derived from the onsite test sections, ultimately saving time and money.

Due to variability in the data and data limitations, caution must be exercised when generalizing the findings published in this report. Compared to the data from the acceptance test sections, the data collected from test sections saw less variability between projects, for any given material type. The test section data yielded maximum allowable deflections that did not vary significantly between projects for cement- and lime-modified subgrade, non-modified subgrade, and six inches of #53 crushed stone over lime-modified subgrade. Generally, within any specific contract location (project site), the data indicates adequate confidence that the test pads generate control measurements that can be used reliably to check the adequacy of compaction at that contract location. However, across different contact locations, even for the same material type, so much variability was observed that it is not possible to guarantee that the control measurements generated from a limited number of test sections (pads) can be confidently transferred to another site of the same material type.

17. Key Words	18. Distribution Statement
Light Weight Deflectometer, LWD, compaction, subbase, deflection, statistical limits, quality assurance	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	54	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

DEVELOPING STATISTICAL LIMITS FOR USING THE LIGHT WEIGHT DEFLECTOMETER (LWD) IN CONSTRUCTION QUALITY ASSURANCE

Introduction

Quality control/quality assurance (QC/QA) during the compaction of a roadway's subbase and subgrade helps ensure the load-carrying capacity of the pavement system. The traditional in-situ compaction evaluation methods for unbound pavement layers are predominately based on density and moisture measurements requiring excessive time and resources, and in some cases, equipment that can be harmful to the health of the operator.

The Light Weight Deflectometer (LWD) measures the deflection and stiffness of unbound pavement layers under a given load, producing a safe, reliable, rapid, and cost-effective field measurement of compaction. Currently, INDOT determines the maximum allowable deflections for each project individually, by constructing an on-site test section and measuring the deflection values. The engineering properties of the compacted construction materials dictate how the unbound pavement layers react to different loadings.

This research investigated the feasibility of developing statistical limits for the compaction of specified combinations of subbase and subgrade materials in terms of their maximum allowable LWD deflections. The intention was to eliminate the need for establishing project site-specific test sections for purposes of compaction quality control during pavement construction.

The number of test sections with LWD deflection readings was limited to only two to five projects per combination of subgrade and subbase material. As such, the LWD acceptance test sections were identified as a second source of data. Acceptance tests are the measured deflections collected during compaction QC/QA after a project site-specific maximum allowable deflection is established.

Statistical limits were developed for six of the most common subgrade and subbase combinations used for highway pavement construction in Indiana: lime-modified, cement-modified, and natural subgrade, as well as #53 crushed stone (53CS) subbase overlaying these subgrades. Due to variability in the data and data limitations, any effort to generalize the findings published in this report must proceed with due caution.

Findings

The outcomes of this research suggest that there is consistency in LWD deflection measurements across a limited number of test sections for certain material types. Test section data yielded maximum allowable deflections that did not vary significantly between projects involving cement-modified and lime-modified subgrades, non-modified subgrade, and six inches of #53 crushed stone over lime-modified subgrade.

The research determined that the location of the LWD test, in terms of proximity to the edge of the placed material, did not vary significantly at a given test station. However, the research findings suggest that the number of acceptance tests completed at each station should be increased from three to seven. The average acceptance test deflection measured by the LWD was determined to be unequal across different projects with similar subbase and subgrade materials. Therefore, it is recommended that the acceptance test data should not be used as a basis to develop statewide statistical limits.

Implementation

The statistical limits developed from test section LWD data can be used by INDOT as a baseline for further developing statewide maximum allowable deflections for use with the LWD. The limits developed for the subbase layer are for the first six inches of placed subbase over subgrade and are not applicable to thicker subbase lifts, nor are they applicable to the second or third subbase lift.

Stiffness modulus values were developed as part of this study, and can be used by INDOT to assess the relative strength afforded by the developed statistical limits. However, without an accurate record of the nominal force applied at each LWD test, exact stiffness values cannot be calculated. Ultimately, the modulus is the parameter of concern. Therefore, it is suggested that subsequent research focus on the reliability of the modulus values provided in the LWD output. It is suggested that, as part of implementation, data be collected to confirm whether the modulus values, rather tha deflections, can serve as a better basis for establishing target values for QC/QA in unbound materials used in pavement construction.

Implementing the results of the study is expected to assist INDOT to decide if and how to eliminate the use of project site-specific test sections. At the current time, it is suggested that INDOT should not abandon the use of these test sections; the agency should continue the use of the project site-specific test sections as part of the LWD tests for pavement construction QC/QA. The minimum compaction requirements currently in use, in terms of the minimum number of passes of the vibratory roller, should be kept in place until further tests and additional data analysis suggest otherwise.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

A roadway's load-carrying capacity depends, in part, on the strength afforded by a properly compacted subbase and subgrade. The engineering properties of the compacted construction materials dictate how the unbound pavement layers react to different loadings. Among the material properties, density, moisture content, shear strength, and modulus of elasticity are particularly important for quality control and quality assurance of pavement construction (Kessler, 2009; Meehan, Tehrani, & Vahedifard, 2012). Additionally, pavement design methods, both the traditional empirical and the mechanistic-empirical (M-E) pavement design methods utilize data on the pavement material properties, especially the modulus of elasticity.

The traditional in-situ evaluation methods for road subbase and subgrade construction, which are discussed in detail in Chapter 2 of this report, are predominately based on density/moisture measurements requiring equipment that require excessive time and resources or are potentially harmful to the health of the operator. Thus, there is a need for more efficient field measurement that is both reliable and safe. The Light Weight Deflectometer (LWD) is one such equipment. The LWD measures the deflections and stiffness of unbound pavement layers under a given load, from which the degree of compaction can be derived. The LWD, which was first developed in Germany for use in pavement foundation construction, is receiving increased attention for use in quality control/quality assurance (QC/QA) during pavement construction (Nazzal, Abu-Farsakh, Alshibli, & Mohammad, 2007). The LWD has been evaluated extensively in several European countries, notably in the United Kingdom (Fleming, Frost, & Lambert, 2007). In the United States, the device has already been evaluated in several states, including Kansas, Louisiana, Minnesota, Montana, and Virginia (Davich, Camargo, Larsen, Roberson, & Siekmeier, 2006; Hosain & Apeagyei, 2010; Mooney & Miller, 2008; Nazzal et al., 2007; Puppala, 2008; Siekmeier et al., 2006). The Minnesota Department of Transportation (MnDOT) was at the forefront of adopting its use and has already developed a pilot specification for LWD testing (Davich et al., 2006).

The nuclear density gauge and the volume replacement equipment (such as the sand cone or balloon device), are typically used for field measurements of density, the material property that extensively serves as the basis for compaction QC/QA. The moisture content at the time of compaction dictates if an unbound layer is compactable to the maximum density of its constituent material. Additionally, the material's shear strength and stiffness depend on its moisture content. Different equipment or techniques such as the nuclear density gauge, direct heat method (using oven), chemical, and electrical methods are used in the field to measure the moisture content of road foundation materials. To measure the soil shear strength, the dynamic cone penetrometer (DCP) is a popular field equipment. The material stiffness (i.e., applied force/deflection), and the modulus of elasticity, (i.e., stress/strain) also can be measured in the field using a Static Plate Load Test, Falling Weight Deflectometer (FWD), and more recently, a LWD (Kessler, 2009; Rahim, 2003; Romero & Kuhnow, 2002; Vennapusa & White, 2009). The LWD is a modulus-based measurement instrument that can be used as a component of a compaction control process (Ryden & Mooney, 2009).

The Indiana Department of Transportation (INDOT) is considering implementing the LWD in field QC/QA for the unbound layers of its highway pavements. As such, this research investigates the feasibility of developing statistical limits for QC/QA in terms of the maximum allowable LWD deflection measurements. This research seeks to develop individual limits for each combination of subbase and subgrade material used by INDOT during pavement construction.

The current report begins with a description of different in-situ compaction assessment techniques, including the LWD, followed by a statement of the study objectives and methodology and a discussion of the data used. Finally, the results of the study are presented and discussed, and its conclusions and recommendations are presented.

2. REVIEW OF CURRENT PRACTICES

The current research is concerned with the compaction of the subgrade and subbase layers that comprise a pavement system. While the number and thickness of pavement layers varies generally, the typical construction is shown in Figure 2.1.

Some of the subgrades considered in the current research are chemically modified prior to compaction. Subgrades are compacted according to contract specifications and in accordance with INDOT Standard ITM 203.26. The subgrade serves two purposes; first, it provides a platform during the construction of the pavement system; and secondly, it ensures that excessive deflection of the natural soil does not negatively impact the pavement system (Christopher, Schwartz, & Boudreau, 2006). INDOT draws a distinction between chemically modified and chemically stabilized subgrades. Chemically modified subgrades are used to reduce the moisture of the subgrade

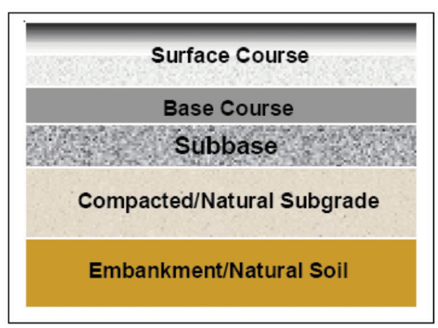


Figure 2.1 Typical pavement system (Christopher et al., 2006).

to speed up the construction process. While chemically modified subgrades add to the overall strength of the pavement system, the additional strength is not considered in the design of the pavement system. However, the additional strength afforded by chemically stabilized subgrades is taken into account in the design of the pavement system; therefore chemically stabilized subgrades require more engineering than chemically modified subgrades (INDOT, 2013). None of the subgrades included in the current research were chemically stabilized. This research is not intended to replace the subgrade compaction requirements defined in each project's contract specifications or ITM 203.26. The statistical limits developed for the various subgrade materials is intended to shed light on the interaction between subgrade and subgrade deflection.

The subbase is a material consisting of aggregates, of specific thickness placed and compacted to support the base and surface courses (Christopher et al., 2006). The strength of the subbase is considered in the design of the pavement system. Therefore, the expected bearing strength needs to be assured during construction. To this end, the current research seeks to develop statistical limits that can be used statewide for use in quality control and assurance during the construction of subbase layers.

2.1 In-Situ Assessment Techniques

For each project, a full-scale trial section, along with in-situ measurements and controlled traffic, could arguably provide the most effective approach for measuring pavement layer material properties for the purpose of QC/QA in road foundation construction. However, this approach is rather costly and may not be feasible for relatively small projects. Laboratory tests, on the other hand, are desirable in many instances for purposes of preliminary design and material selection. In addition to laboratory tests or tests under controlled conditions, quick and reliable field tests on laid material and prepared surfaces during construction are also required. The portable devices are quick to implement and have been shown to adequately mimic the transient nature of wheel load forces, qualities that make them more appropriate for practical application. Typically, these devices usually measure a single deflection on the center of a bearing plate or on the surface of the prepared material being tested. The measured deflection may relate to the influence of one or more layers of material and could be used to determine the field values of parameters relevant in quality control and quality assurance (Lambert, Fleming, & Frost, 2008).

2.1.1 Volume Replacement Devices

Volume replacement techniques include the sand cone test which determines soil density. Other examples include the water balloon technique and the steel shot replacement method which is a recent military development in volume replacement techniques. These devices do not require calibration before they are used and are relatively inexpensive; thus, they have become widely used. The volume replacement techniques measure the weight of wet in-situ soil excavated from a prepared surface and then use a known volume of reference material to fill the excavated hole in the prepared surface. The wet density of the soil is determined by dividing the wet soil weight by the excavated volume. The excavated wet soil is dried in an oven to obtain its moisture content. The dry density of the soil is found using the following formula:

$$Dry\ density/(1 + Moisture\ content\ of\ wet\ oil) \qquad (2.1)$$

The most common reference material is sand. The sand cone apparatus consists of a sand container at one end and a large metal funnel at the other end (Figure 2.2). These tests are conducted to measure the density of subgrade soil according to ASTM D 1556-07. The sand used in the test must be clean, dry, and uniform in density and gradation. The sand requires a uniformity coefficient ($C_u = D_{60}/D_{10}$) less than 2.0, all particles passing 2.0 mm (Nr. 10 sieve), and less than 3% by weight passing 250 μm (Nr. 60 sieve).

First, from the prepared surface under test, soil is excavated and carefully stored in an air-tight container (Figure 2.3 (a)). The weight of the excavated soil is

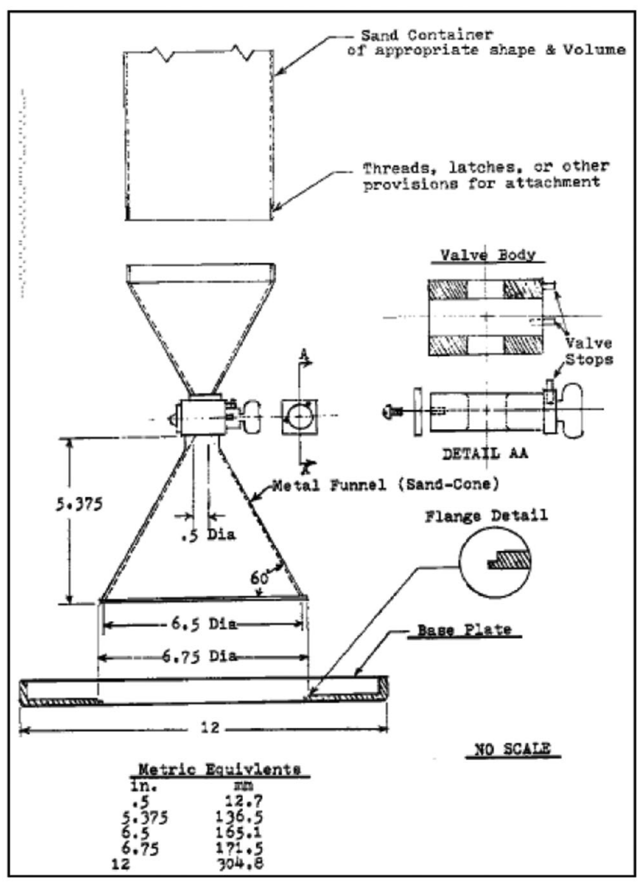


Figure 2.2 Schematic design of sand cone apparatus (ASTM D 1556-07).

Figure 2.3 Sand cone test: (a) excavation of soil; (b) pouring reference sand into test hole (Jung et al., 2009).

measured in the field and the volume of the excavated soil is measured by pouring the reference material into the test hole (Figure 2.3 (b)). Then, the moisture content of the excavated soil is measured by placing it in the oven at 110.5°C for 24 hours, as specified in ASTM D 2216-05. Thus, both the moisture content and dry density of the soil are measured (Berney & Kyzar, 2012; Jung, Jung, Bobet, & Siddiki, 2009).

2.1.2 Electrical Moisture-Density Devices

The Electrical Density Gauge (EDG) measures the electrical resistance between a series of probes embedded in subgrade soil and then the resultant resistance is compared to a set of calibrated readings of expected field moisture contents and soil densities. The Soil Density Gauge (SDG) is a plate that rests above the soil surface and computes the density as well as the moisture content of the soil by electrical impedance spectroscopy measurements (Figure 2.4). A transmitter and a receiver produce an electromagnetic field while the frequency generated falls within a radio frequency range. For each of these gauges, the device must first be calibrated to some known physical data on the unbound pavement material before it is used to measure the moisture content and wet and dry densities (Berney & Kyzar, 2012). The entire measurement takes less than a minute. These non-destructive testing devices are portable and, unlike the nuclear gauge, do not require a certified operator to perform as they are relatively safe for the operator (Wacharanon, Wachirapom, & Sawangsuriya, 2009).

2.1.3 Nuclear Gauge Test

Nuclear gauge tests measure the in-situ moisture content as well as the in-situ density of the subgrade soil as specified in ASTM D 6938-09. This is a quick non-destructive test that measures the soil density and water content. The in-situ density can be measured either by the direct transmission method or the backscatter method. The device (Figure 2.5) consists of a source and a detector; and radioactive gamma rays are emitted from the source at the end of a retractable rod. The rays/photons collide with electrons in the material and are either scattered or absorbed, and the detector inside the gauge remains on the surface to collect attenuated gamma rays (photons) from the source. As the density increases, the number of photons that are scattered back to the detectors decreases. The rays/photons reaching the detectors are counted for a selected time interval; and on the basis of this count, the density of the soil can be determined. In the direct transmission method, the source is lowered to a known depth,

Figure 2.4 Soil density gauge (SDG) (Wacharanon et al., 2009).

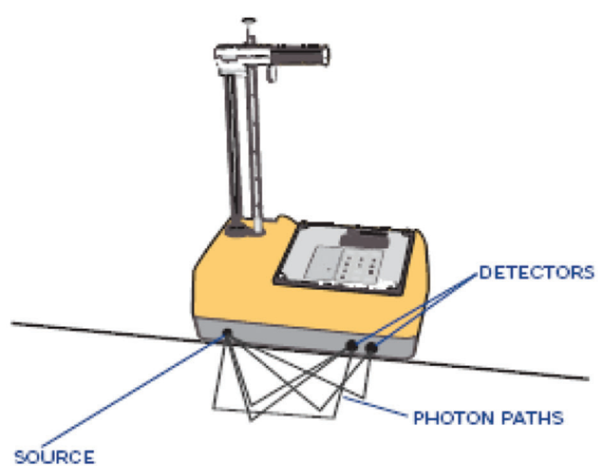


Figure 2.5 Nuclear moisture-density gauge measurements (Kim, Prezzi, & Salgado, 2010).

whereas in the backscatter method, the source remains on the surface. The gauges are calibrated before the test. However, this method involves safety risks; therefore states enforce strict safety laws and require certified operators. In addition, the test is prone to errors that exist due to variations in layer thickness and due to the effects of the underlying layers (Jung et al., 2009; Mooney et al., 2011).

2.1.4 Clegg Hammer

The Clegg Impact Hammer or Clegg hammer is another device used in the field for compaction QC/QA for compacted soils. Pictured in Figure 2.6, the Clegg hammer is a relatively simple and portable device that measures the maximum deceleration of a free falling hammer from a given height onto the surface of the test material. The hammer, typically cylindrical with a 50 mm diameter and weighs 4.5 kg, is dropped from a height of 450 mm (18 inches). The impact value (IV) reflects the changes in the near-surface strength of the compacted material. The Clegg hammer device is similar to the LWD and is used to measure the subgrade stiffness (i.e., to predict CBR values) as a function of the deceleration rate that results from dropping the mass. Soil with a higher bearing strength decelerates the mass more rapidly (Boston, Robek, & Rathom, 2012; Kim et al., 2010; Lambert et al., 2008).

2.1.5 Soil Stiffness Gauge

The soil stiffness gauge or the Geogauge is a portable device that measures the in-situ modulus of elasticity and the carrying capacity of the unbound pavement layers. The 10 kg device, manufactured by the Humboldt Manufacturing Company in Illinois, USA, is pictured in Figure 2.7. The frequencies produced by the device's mechanical shaker generate a force which will be used with the vertical displacement of the test material to determine stiffness. The Geogauge's weight is transferred to the test surface via a ring-shaped foot. The shaker produces 25 specific frequencies beginning at 100 Hz and increasing in 4 Hz increments producing a 9 N force. An accompanying computer outputs the mean and standard deviation of the stiffness (H_{SG}) for each of the 25 frequencies (Gomes-Correia, Martins, Caldeira, Marana das Neves, & Delgado, 2009). The modulus of elasticity can be calculated from the stiffness using the equation:

Figure 2.6 A 20 kg Clegg hammer (Minnesota DOT, 2007).

Figure 2.7 Humboldt geogauge/stiffness gauge (Wacharanon et al., 2009).

$$E_G = H_{SG}(1 - v2)/(1.77R) \qquad (2.2)$$

Where, E_G=elastic modulus of soil (MPa); H_{SG}= Geogauge reading (MN/m); v=Poisson's ratio; and R=radius of the Geogauge foot (57.15 mm or 2.25 in.).

The Geogauge is a relatively new device and 23 state highway agencies in the United States are reported to have participated in a verification or reliability evaluation of this equipment. The Geogauge stiffness measurements have been used to classify base courses and have also been correlated with the resilient modulus (Alshibli, Abu-Farsakh, & Seyman, 2005). The modulus of elasticity reported by the Geogauge can be influenced by a number of factors including the in-situ moisture content, the material density, the interaction between material layers, and the material properties of underlying layers (Mishra, Tutumluer, Moaveni, & Xiao, 2012).

2.1.6 Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) (Figure 2.8) was initially developed in South Africa for field evaluation of pavements, but it since has been widely used in other countries such as the United Kingdom, Australia, New Zealand, and the United States. The test is simple, fast, and economical and can provide continuous measurements of the in-situ strengths and

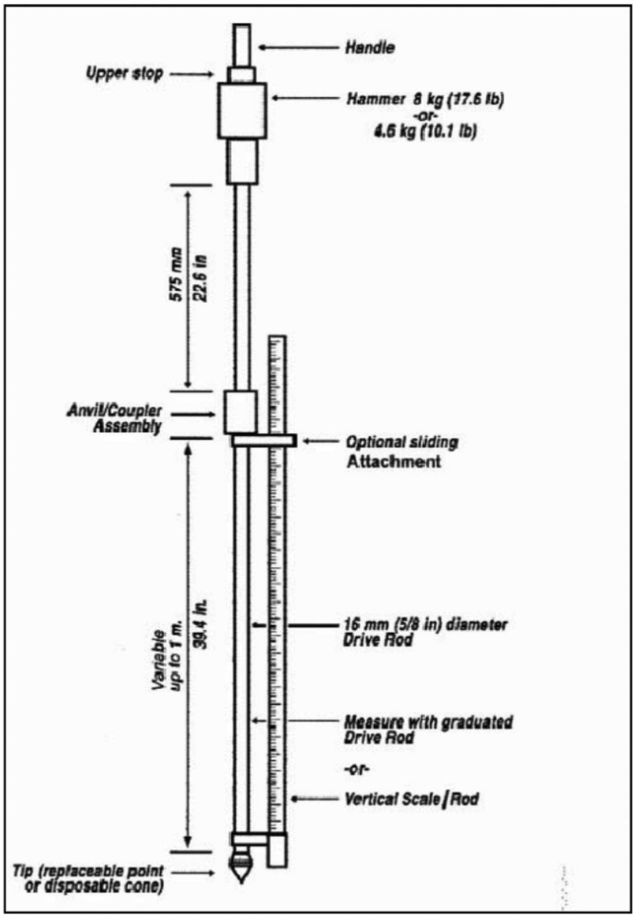


Figure 2.8 Schematic of the DCP device (ASTM D 6951-03) (Jung et al., 2009).

stiffness of the subgrade and other pavement layers. The test is conducted by dropping a weight (typically 8 kg) from a 575 mm height and recording the number of blows versus depth. The penetration rate (PR) in mm/blow is then calculated. This rate could be utilized to measure many material properties including CBR, shear strength of granular materials, subgrade resilient modulus, elastic modulus, and soil classification. These properties of foundation materials can be routinely assessed using the DCP, but it is not suitable for coarse materials due to the DCP's relatively low impact energy and small cone size (Alshibli et al., 2005; Kim et al., 2010; Lambert et al., 2008; Nazzal, Abu-Farsakh, Alshibli, & Mohammad, 2004).

2.1.7 Plate Load Test

The plate load test (Figure 2.9), which has long been used for in-situ investigations, determines soil bearing capacity and evaluates pavement strength or stiffness. A circular plate typically 305 mm (12 inches) in diameter, remains in contact with the surface and is loaded incrementally in a uniform manner. Deflections at different loading increments are measured. The static

Figure 2.9 Static plate load test (Minnesota DOT, 2007).

load is transmitted to the plate by a hydraulic jack anchored by heavy mobile equipment. The resulting load deflection curve is used to determine the elastic modulus of the tested layer using the following equation:

$$E_{PLT} = 2P(1-\nu^2)/(\pi R\delta) \tag{2.3}$$

Where, E_{PLT}=elastic modulus; P=applied load; R= radius of the plate; ν=Poisson's Ratio; and δ=deflection of the plate.

Different elastic moduli, the initial elastic modulus and the reloading modulus, can be obtained be drawing tangents on a stress-strain curve produced using data from the plate load test (Alshibli et al., 2005; Nazzal et al., 2004).

2.1.8 Falling Weight Deflectometer

The Falling Weight Deflectometer (FWD) is a popular non-destructive field test that is widely used to evaluate the properties of materials in pavement layers. The test is conducted by applying an impulse load by dropping it from a particular height to a 12-inch diameter circular loading plate that remains in contact with the surface of the pavement layers being tested. By changing the mass as well as the drop height of weight, different loadings can be simulated and load cells can measure the applied load. The resulting surface deflections are measured using seven geophone sensors positioned at various distances such as 0, 12, 18, 24, 30, 36, and 48 inches (Figure 2.10) from the center of the loading plate. The resilience modulus of pavement layers in a test section as well as the depth of the underlying layers are measured with the response of the pavement layers via geophones. The resilience moduli are then determined by a back-calculation process with the help of programs in microcomputers (Nazzal et al., 2004; Rahim, 2003; Siddharthan, Norris, & Epps, 1991; Walston & McQueen, 2000).

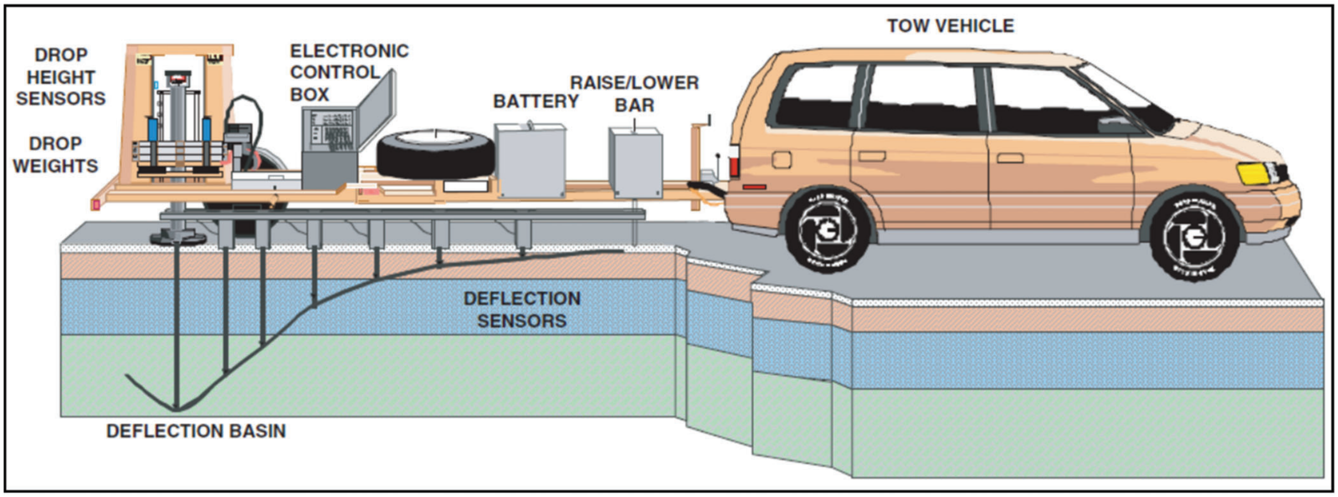


Figure 2.10 A typical setup of the Falling Weight Deflectometer (FWD) (Nazzal et al., 2004).

2.2 Light Weight Deflectometer (LWD) and Other Techniques

The various in-situ methods described so far have certain drawbacks that hinder their acceptability for use as cost-effective tools for quality assurance and quality control in earthwork construction. A number of past researchers have analyzed these methods and have concluded that the static plate load test is expensive and slow but produces replicable results and the Clegg hammer test is quick and repeatable but yields values that are extremely sensitive to moisture and hammer weight. The Geogauge has been deemed unreliable as the equipment is very sensitive to the seating conditions. The electrical devices require inserting multiple probes into the ground and have been found to be very sensitive to the presence of coarse aggregate. The DCP, which is widely used, has the following limitations: it is resource-intensive; it often requires two people to operate; and can be time consuming when testing in dense soils. Also, DCP testing at great depths in dense soil or in soil with large aggregate has been proven to be unreliable. The FWD has been found to be suitable only for finished road surfaces as the vehicle carrying the device requires a relatively hard and stable surface for the test. The FWD requires more resources than most other devices and also is not suitable for relatively soft surfaces such as subgrade layers. The traditional measurement methods for soil density and moisture to supervise earthwork construction also have their limitations. The volume replacement and oven methods require considerable time and resources. The popular nuclear gauge is considered by many to be hazardous to human health and is subject to stringent governmental regulations: also, it can produce erroneous results in soils that are non-uniform or have large aggregates. The LWD is a relatively quick and less expensive method that is reported to be a replicable test not influenced by the presence of large aggregates, proximity to metal reinforcement, and "fill end effects" (Berney & Kyzar, 2012; Mooney & Miller, 2008; Singh et al., 2010). In the next section, we discuss the LWD in greater detail.

2.3 Light Weight Deflectometer (LWD)

The limitations of existing techniques have motivated researchers to develop new devices that will be relatively more robust and more accessible to different construction sites and that can easily measure the in-situ elastic modulus of highway materials. One such device is the Light Falling Weight Deflectometer (LFWD) or Light Weight Deflectometer (LWD), which can be characterized as a portable FWD (Steinert et al., 2006). The LWD was developed in Germany as an alternative device to the PLT but it has become increasingly popular in other nations as well. In Germany, road builders are required to provide a guarantee of the quality of a road that has been built and LWD is reported to be the instrument of choice for such QC/QA (Kessler, 2009).

2.3.1 Basic Features

Lightweight, portable, and simple to apply for repeated testing, the LWD has become a device of choice for many road builders. Different types of LWD devices are available on the market and exhibit many similarities in the mechanics of their operation. However, design and operational differences remain that may lead to variations in the measured results (Livneh & Goldberg, 2001; Nazzal et al., 2004; Puppala, 2008; Ryden & Mooney, 2009; Vennapusa & White, 2009).

The schematic of a typical LWD (Figure 2.11) shows the three major elements: the drop weight, the loading plate, and the accelerometer that determines the settlement. The grip at the top of the LWD is used to hold the guide rod plumb and to limit the upward movement of the drop weight. The top fix and release mechanism holds the drop weight at a fixed height while the guide rod guides the weight to drop freely. The drop weight or the falling weight is manually raised

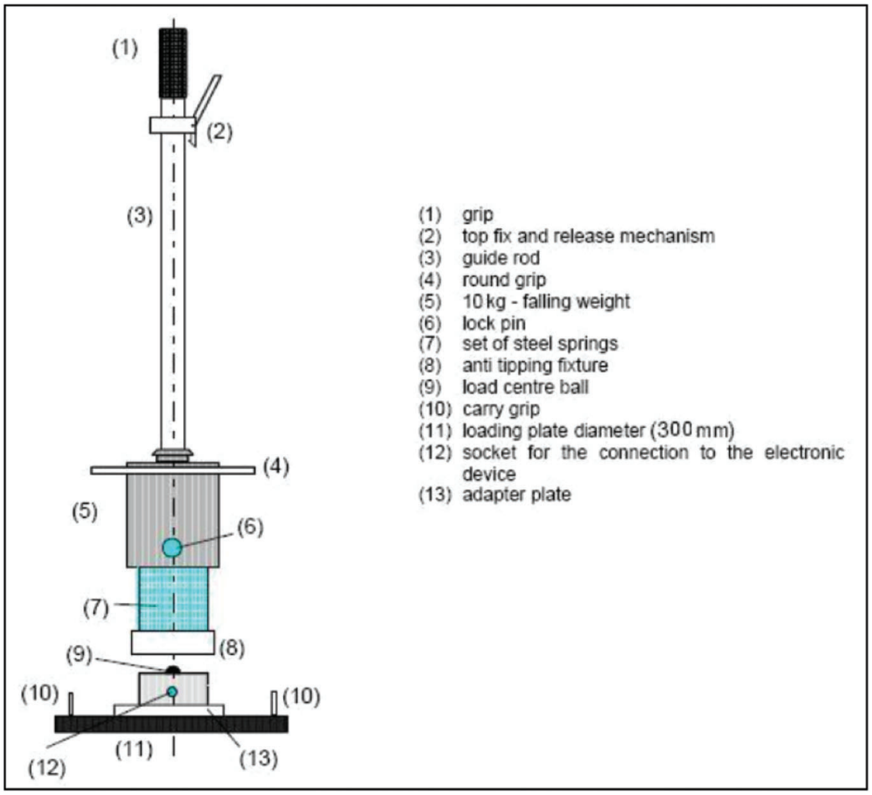


Figure 2.11 Schematic of Light Weight Deflectometer (LWD) (INDOT, 2012).

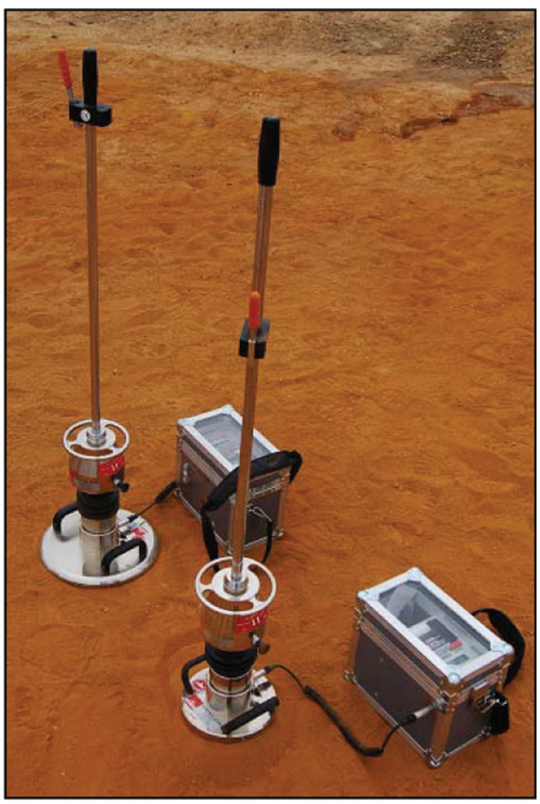


Figure 2.12 LWD with 200 mm and 300 mm diameter plates (Tehrani & Meehan, 2010).

to the bottom of the grip and is operated using the top fix and release mechanism. The lock pin can remain either in the locked or unlocked position. The set of steel rings transmits the load pulse to the plate resting on the ground. The loading plate helps in transmitting the approximate uniform distribution of the impulse load to the surface.

2.3.2 Operations

The operating principles of LWD are similar to those governing the use of FWD on bound pavements. However, the relatively lower weight of the LWD compared to the FWD makes it more suitable for use on unbound pavement layers such as subgrade and subbase. Furthermore, the LWD is relatively less expensive (Kessler, 2009). The LWD (Figure 2.12) measures the deflection of the test layer produced from a given drop weight, drop height, and load according to the American Society for Testing and Materials (ASTM) Specification 2583–07, "Standard Test Method for Measuring Deflections with a Light Weight Deflectometer." The built-in load cell and geophone measure the time history of the load pulse and soil velocity. The resulting integration provides a measure of the material displacement which can be used with a measure of the peak load to determine the modulus values (Tehrani & Meehan, 2010).

Several test dimensions can influence the LWD deflection readings, including the weight of the falling mass, the height at which it is released, the area where the load is transferred to the material, the rate at which the material is loaded, and the number and layout of the geophones. There is the possibility of misinterpretation of the peak deflection and the resulting modulus of elasticity because the reading may include not only the recoverable elastic deflection but also the permanent–plastic deflection. The peak deflection (s) of the loading plate, once measured, is used to calculate the LWD elastic modulus (E_{LWD}). The following expression, which is used to calculate the modulus, is based on Boussinesq's elastic half-space equation for the surface modulus of a layered media assuming a uniform Poisson's ratio (v) and constant loading (Vennapusa & White, 2009; Vennapusa et al., 2012):

$$E_{LWD} = A * \rho * r * (1\text{-}v^2)/s \tag{2.4}$$

Where, E=stiffness modulus (MPa or MN/m^2); A=plate rigidity factor; ρ= maximum contact pressure (kPa); r=plate radius (m); v=Poisson's ratio (usually in the range 0.3–0.45, depending on test material type); and s=peak deflection (mm).

The default value of the plate rigidity factor for a flexible plate is 2, which would simplify the expression as follows:

$$E_{LWD} = 2 * \rho * r * (1\text{-}v^2)/s \tag{2.5}$$

Furthermore, with uniformly distributed stress under the plate $\rho = P/\pi r^2$ where P is the nominal impact force (kN), which simplifies the equation further to:

$$E_{LWD} = 2 * \rho * (1\text{-}v^2)/(\pi * r * s) \tag{2.6}$$

2.3.3 Output

As stated earlier, the LWD is portable (with a weight of approximately 15 to 25 kg depending on the type and manufacturer), it can be operated by a single person, and the test takes only few minutes. First, the equipment is calibrated to deliver a maximum specified amount of impact load and impact duration. It is assumed that the plate is sufficiently rigid to move with the soil and the impact load is constant. Soil deformations are calculated by integration of the accelerometer readings. During operation, the plate is first placed directly over level ground and three initial drops are performed to ensure a close contact. Then another three drops of the weight are performed, and the data acquisition system calculates the deflection corresponding to each blow and the soil's dynamic modulus. A typical output from the data acquisition system of an LWD would show time history data (Figure 2.13) which provide important insight into the soil property (Mooney & Miller, 2009).

The typical output also provides three distinct velocities (v) and three peak deflections (s) corresponding to the three measurement drops of weight. The output also includes the mean values and corresponding standard deviation values for the velocity, v and displacement, s. These statistical values along with the value of s/v could help in quality assurance as well as quality control procedures. The dynamic elastic modulus is also reported, which can be converted into the static elastic modulus using various calibration equations found in the literature. Deflection values are readily comparable to target values and thus can easily fit into quality assurance procedures. A larger deflection in the soil is usually indicative of a weaker soil (Boston et al., 2009).

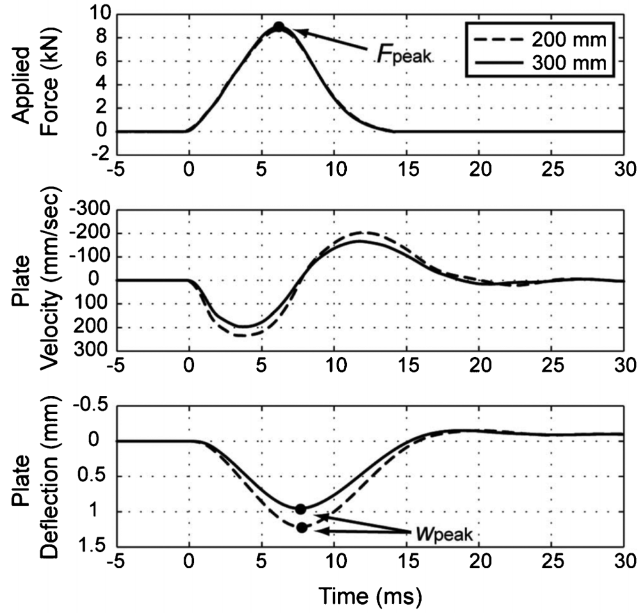


Figure 2.13 Typical time history data from a LWD test (Mooney & Miller, 2009).

2.3.4 Limitations

There are many factors that influence LWD values and these should be considered while designing a quality assurance process in any agency. These factors include, but are not limited to, the following: size of loading plate, plate contact stress, type and location of deflection transducer, plate rigidity, loading rate, and buffer stiffness. Again, the moisture content of the material being tested has been reported to significantly influence the field modulus-based measurements. There is also an inverse relationship between water content and soil moduli (Hossain & Apeagyei, 2010; Ryden & Mooney, 2009). Also, in some cases, it is reported that the actual depth of the material being tested is greater than the single layer of material under consideration and therefore is measuring a composite layer composed of the material under consideration and underlying subbase and subgrade materials. The resulting modulus is therefore a composite rather than the modulus of the single layer under consideration (Benedetto & Di Domenico, 2012).

2.4 Section Conclusions

Proper subbase and subgrade compaction is essential to ensure quality in highway construction and parameters such as the elastic modulus, density, and moisture content are important in assessing the quality of the road foundation. INDOT seeks to develop statistical limits for the LWD in the form of target values, which are expected to produce a faster, less costly, more reliable and more direct approach to ascertain acceptable compaction of unbound pavement layers for quality assurance purposes. Quality assurance (QA), unlike quality control (QC), is a proactive process that aims at preventing problems from occurring. In the context of pavement construction, QA is the establishment of design specifications and management principals aimed at ensuring the proper compaction of the various pavement layers. Currently, INDOT determines the LWD target values (i.e., peak deflection) for each project by constructing test sections (also referred to as test pads, calibration strips or control strips). The target values are then used in the QC process in which acceptance tests are conducted and the field values are compared to the established target values. It is sought to use statistical tools in selecting the target values for different combinations of materials in a manner that incorporates confidence intervals.

3. OBJECTIVES

The main objective of the current research project is to develop statistical limits, in the form of target values for the maximum allowable deflection measured by the Light Weight Deflectometer (LWD) for use in QC/QA of unbound subbase and subgrade pavement layers. The following are the layer material types that were initially considered in this research.

Subgrade

- Compacted Subgrade
- Chemically Modified Subgrade with Lime/Lime kiln dust
- Chemically Modified Subgrade with Cement
- Chemically Modified Subgrade with Fly Ash
- Geo-grid Reinforced Subgrade
- Mechanically Modified Subgrade

Subbase

- # 53 Crushed Stone (# 53 CS)
- # 53 Gravel (#53 GR)
- # 53 Slag

A LWD measures the deflection of the material below the plate to a depth approximately equal to the plate diameter (Tayabji & Lukanen, 2000). Since the LWDs used by INDOT have a plate diameter of 300 mm (11.811 inches) and the subbase material is typically placed in six-inch lifts, the LWD readings for the first six inches of subbase will be influenced by both the material properties of the subbase and the subgrade. Therefore, the current study will investigate 24 combinations of subgrade and subbase materials. The 24 combinations are composed of the 18 combinations of subbase over subgrade and six subgrade materials without an overlaying subbase. Ultimately, the scope of the current research was modified due to the availability of data from INDOT's Research Division, Geotechnical Services, and Crawfordville District Materials Management. A brief description of the two main sources of LWD data, namely the test sections and acceptance tests, along with the requisite number of test sites, is presented below:

- *Test Section*: A constructed section of the roadway used to develop maximum allowable deflection thresholds for use in the project. A test section is comprised of 10 test sites.
- *Acceptance Test*: A random station (referred to as a test station) along the roadway comprised of three test sites. The average deflection for the three sites must be less than or equal to the deflection thresholds obtained from the test section.
- *Test Site*: Each point (location) where the LWD is placed in order to obtain one complete LWD test.
- *Complete LWD Test*: The process of obtaining a measure of deflection for a given test site. The process is laid out in ITM No. 508-12T as presented in Appendix A.

Originally, the research was to include data from 30 test sections for each combination of subbase and subgrade. These 30 test sections would be evenly spread out over the six INDOT districts. However, the lack of existing contracts severely limited data availability. At the request of the research project's Study Advisory Committee (SAC), the project scope was amended to include data from acceptance testing. Acceptance testing requires a greater number of LWD test sites per contract compared to test sections, which are comprised of only 10 LWD test sites. However, even with the expansion of data to include acceptance testing results, at the current time, the data are insufficient to develop limits for all but the most commonly used combinations of subbase and subgrade.

4. METHODOLOGY

This study sought to develop LWD deflection target values for use in QC/QA of unbound pavement layers. Currently, the LWD is being used in coordination with site-specific test sections, resulting in site-specific maximum allowable deflections for each unbound pavement layer (Siddiki, 2012). However, it is believed that it is not an efficient use of construction time to conduct test sections for each contract (because the maximum allowable deflection is material-specific and therefore should not be influenced by the project's location). The following sections will discuss the current LWD practice in use in Indiana and outline the research methodology for the current study.

4.1 Current INDOT LWD Field Testing Procedures

4.1.1 Test Sections

Currently, INDOT uses the LWD in compaction QC/QA for some of its pavement construction sites.

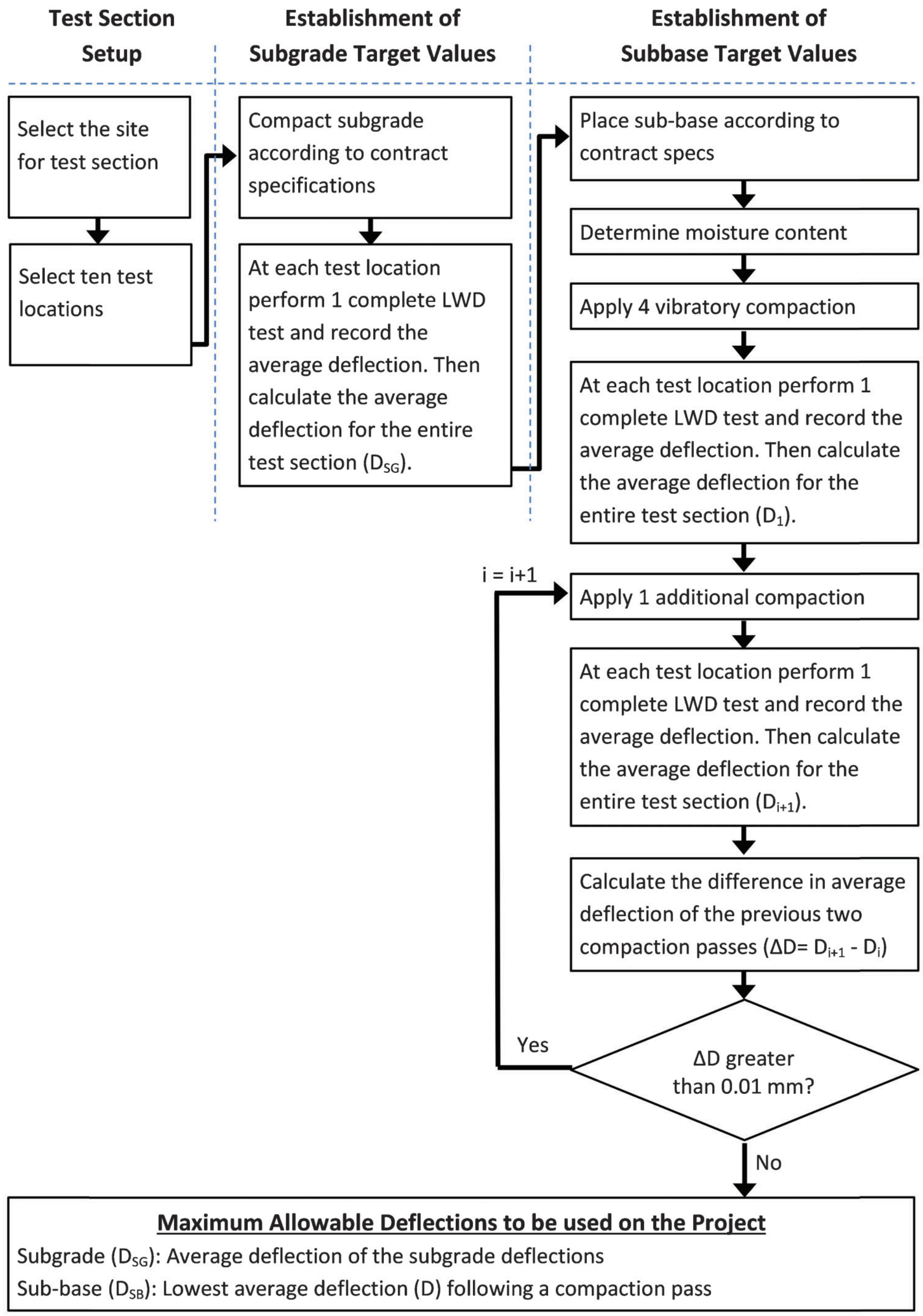


Figure 4.1 Flowchart for the current procedure for LWD test sections.

Maximum allowable deflection values are developed for each project site from values obtained from the test section. The process of completing the construction and testing of a test section is presented in Figure 4.1 and Appendix A.

The test section is approximately 100 ft in length and the full roadway width. Ten test sites are selected inside the test section in accordance with the layout shown in Figure 4.2. These ten test sites remain unchanged between compaction passes or material placement.

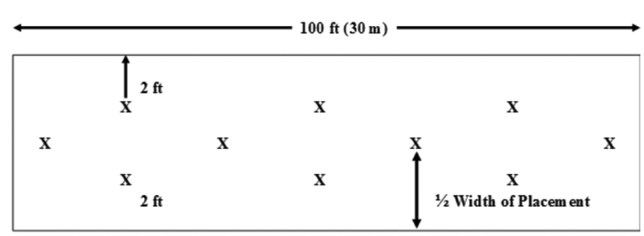


Figure 4.2 Test section layout (test sites indicated by an "X").

The subgrade is compacted according to contract specifications and in accordance with INDOT Standard ITM 203.26. One complete LWD test is conducted at each test site. The deflection values for each site are recorded, and the average value for the entire test section is calculated (see Appendix B for further details). Next, the subbase material is placed in accordance with contract specifications, at which time the moisture content of the material is determined by performing the following American Association of State and Highway Transportation Officials (AASHTO) tests on representative samples of the aggregates; AASHTO T99 Method C, AASHTO T11, and AASHTO T27. The moisture content should be within −3% and −1% of the optimum moisture content.

The aggregate is then compacted with four passes of a vibratory roller. One complete LWD test is conducted at each test site. Appendix A presents the details of the process of conducting a complete LWD test. The deflection values for each site are recorded and the average value for the entire test section is calculated. One additional compaction pass is applied and one LWD test is again conducted at each test site. The deflection at each site is recorded, and the average deflection over the entire test section is calculated. If the difference between the average deflections is less than 0.01 mm, then compaction is complete and no further compaction passes are required. Otherwise, the process of applying one additional compaction pass followed by LWD testing is repeated until two consecutive passes result in a change in average deflection of less than 0.01 mm.

The maximum allowable deflection for the subgrade is the average value from the ten test locations after the LWD test on the subgrade. The maximum allowable deflection for the subbase is the lowest average value from ten test locations after a compaction pass (minimum of four passes). An example data collection sheet is provided in Figure 4.3. Please refer to Appendix C for further details.

4.1.2 Acceptance Testing

The previous section detailed the process of completing a test section for a given roadway pavement project. The test section yields target values for maximum allowable deflections, as measured by the LWD, for the remainder of the project. Acceptance testing consists of the processes of checking the in-situ compaction of the unbound layers against the target values in accordance with ITM 502. The average deflection across a randomly chosen station along the alignment must be less than or equal to the target value otherwise additional compaction is required.

TD409 LWDt Rev10 **INDIANA DEPARTMENT OF TRANSPORTATION** ORIGINAL: PROJECT FILE

2/14/2012 **LWD TEST SECTION FOR AGGREGATE** COPY TO: GEOTECHNICAL ENGINEERING, Indianapolis

CONTRACT NO. PROJECT NO. EXAMPLE ONLY ROAD NO. DATE WEATHER

FIELD TEST NO.				**111**	**112**	**113**	**114**	**115**	**116**	**117**	**118**	**119**	**120**
SITEMANAGER TEST NO.				**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SITEMANAGER SAMPLE I.D NO. (R+12 digits)				**R123456789012**									
Test Section Site Data	Station			**112+05**	**112+20**	**112+20**	**112+35**	**112+50**	**112+50**	**112+65**	**112+80**	**112+80**	**112+95**
	Line No.		**A**										
	Ref. To Centerline			**0**	**10' Lt**	**10' Rt**	**0**	**10' Lt**	**10' Rt**	**0**	**10' Lt**	**10' Rt**	**0**
	Elevation or Lift No.		**Subbase**										
	Compacted Depth of Lift (inches)		**6**										
	Test Section Position Number		**Average**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Subgrade LWD Info	Type	LWD Assigned Test Number	**Lime**	**1255**	**1256**	**1257**	**1258**	**1259**	**1260**	**1261**	**1262**	**1263**	**1264**
	Avg.	Test Deflection(S_m)(mm)(Info)	**0.409**	**0.417**	**0.405**	**0.418**	**0.405**	**0.422**	**0.419**	**0.424**	**0.402**	**0.384**	**0.395**
LWD Test Section Data	Passes	LWD Assigned Test Number	**4**	**1265**	**1266**	**1267**	**1268**	**1269**	**1270**	**1271**	**1272**	**1273**	**1274**
	Avg.	Test Deflection (S_m) (mm)	**0.379**	**0.387**	**0.375**	**0.388**	**0.375**	**0.392**	**0.389**	**0.394**	**0.372**	**0.354**	**0.365**
	Passes	LWD Assigned Test Number	**5**	**1275**	**1276**	**1277**	**1278**	**1279**	**1280**	**1281**	**1282**	**1283**	**1284**
	Avg.	Test Deflection (S_m) (mm)	**0.349**	**0.357**	**0.345**	**0.358**	**0.345**	**0.362**	**0.359**	**0.364**	**0.342**	**0.324**	**0.335**
	Passes	LWD Assigned Test Number	**6**	**1285**	**1286**	**1287**	**1288**	**1289**	**1290**	**1291**	**1292**	**1293**	**1294**
	Avg.	Test Deflection (S_m) (mm)	**0.273**	**0.269**	**0.278**	**0.278**	**0.273**	**0.269**	**0.275**	**0.265**	**0.279**	**0.270**	**0.274**
	Passes	LWD Assigned Test Number	**7**	**1295**	**1296**	**1297**	**1298**	**1299**	**1300**	**1301**	**1302**	**1303**	**1304**
	Avg.	Test Deflection (S_m) (mm)	**0.267**	**0.266**	**0.267**	**0.275**	**0.298**	**0.268**	**0.272**	**0.269**	**0.256**	**0.244**	**0.255**
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S_m) (mm)											
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S_m) (mm)											
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S_m) (mm)											
Test Site	**Maximum Allowable Deflection (mm)**		**0.267**	**T255 DATA**									
Laboratory Report Data	Material Name and Type		**53 CS**	Test Number				**111**	**117**				
	Lab. SM ID (R+7 digits)		**R1234567**	Station				**112+05**	**112+65**				
	Lab. SM ID (Last 5 digits)		**89012**	Tested on Material Passing (No. 4 or 3/4" Sieve)				**3/4**	**3/4**				
	Optimum Moisture Content (OMC) (%)		**10**	1. Wt. of Pan & Wet Material (W1)(lb) or (g)				**2370.0**	**2389.0**				
Test Site Moisture	Determined Moisture (%)		**9**	2. Wt. of Pan & Dry Material (W2)(lb) or (g)				**2188.7**	**2193.7**				
	Difference (Sp.Prov.-3% to -1% of OMC)		**-1**	3. Wt. of Moisture (lb) **Line 1 - Line 2**				**181.3**	**195.3**	**0.0**	**0.0**	**0.0**	**0.0**
Comments	Comments 1			4. Wt. of Pan (W3)(lb) or (g)				**100.0**	**100.0**				
	Comments 2			5. Wt. of Dry Material **Line 2 - Line 4**				**2088.7**	**2093.7**	**0.0**	**0.0**	**0.0**	**0.0**
				% Moisture (0.1%) **(Line 3 / Line 5) x 100**				**8.7**	**9.3**				

REMARKS:	Example only for demonstration of this form for LWD test section for determination of Maximum Allowable Deflection for acceptance of compacted aggregate by LWD.
LWD SD Card#	12345
Compactor:	Caterpillar CS44 Vibratory Smooth Drum

LWD Serial Number 4999 RECORDED IN SITE-MANAGER: Qualified Technician:

Figure 4.3 Example of test section data collection sheet.

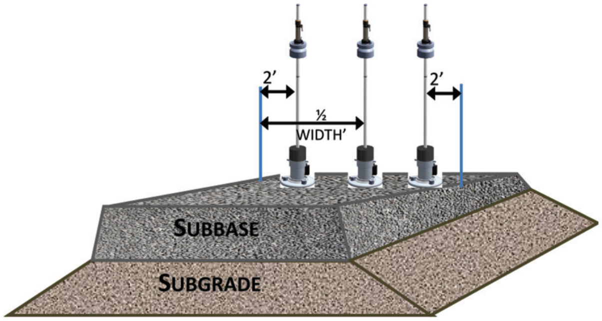


Figure 4.4 Example of LWD test station with three LWD test sites.

The random stations along the alignment are chosen in accordance with ITM 802. At each acceptance testing station, a complete LWD test is performed at three sites, one site 2 ft from the left edge, one at the center, and one 2 ft from the right edge as illustrated in Figure 4.4.

Acceptance testing is typically carried out at a rate of one station (three sites) per 800 tons of aggregate placed. This results in a much greater number of test sites per contract, and the current research therefore included this data. It is believed that the acceptance test data are appropriate because, by definition, the average deflection values at each station are required to be below the allowable threshold developed from the project's test section. An example of the data collection sheet used for acceptance testing is provided in Figure 4.5.

4.2 Research Methodology

In current practice, in order to use the LWD in compaction quality control, a test section must be constructed for each project. This control section is used to develop the maximum allowable deflection for the given project for each lift of subbase placed. As the objective of this study is to determine whether statewide threshold values could be determined (in a bid to eliminate the need to construct test sections), the research first determined whether there exist statistical differences in the mean deflection values obtained from the different projects, for the same material type and thickness. The research therefore investigated whether the deflection values obtained from the acceptance tests varied significantly across different test sites within any given project, for the same material type and thickness, depending on whether the testing was being done along

TD409 LWD Rev10 **INDIANA DEPARTMENT OF TRANSPORTATION** ORIGINAL: PROJECT FILE

2/14/2012 **LWD AND MOISTURE ACCEPTANCE TESTS** COPY TO: GEOTECHNICAL ENGINEERING, Indianapolis

CONTRACT NO. ______ PROJECT NO. EXAMPLE ONLY ROAD NO. ______ DATE ______ WEATHER ______

FIELD TEST NO.			**111**			**112**			**113**		
SITEMANAGER TEST NO.			**1**			**2**			**3**		
SITEMANAGER SAMPLE I.D NO. (R+12 digits)			**R123456789012**			**R123456789013**			**R123456789014**		
Test Site Data	Station		**444+50**			**444+50**			**444+50**		
	Line No.		**A**			**A**			**A**		
	Ref. To Centerline		**10' Lt**	**0**	**10' Rt**	**10' Lt**	**0**	**10' Rt**	**10' Lt**	**0**	**10' Rt**
	Elevation or Lift No.		**Subbase**			**Subbase**			**Subbase**		
	Compacted Depth of Lift (inches)		**6**			**6**			**6**		
	Number of Passes with Compactor		**7**			**8**			**9**		
	Chem. Modif.	LWD Assigned Test Number	**1237**	**1238**	**1239**						
		Test Deflection (S_m) (mm)	**0.223**	**0.243**	**0.210**						
		Average Deflection (mm)	**0.225**								
	Comp. Agg.	LWD Assigned Test Number	**1240**	**1241**	**1242**	**1249**	**1250**	**1251**	**1258**	**1259**	**1260**
		Test Deflection (S_m) (mm)	**0.275**	**0.285**	**0.280**	**0.275**	**0.278**	**0.271**	**0.260**	**0.255**	**0.256**
		Average Deflection (mm)	**0.280**			**0.275**			**0.257**		
Test Strip	**Maximum Allowable Deflection (mm)**		**0.267**			**0.267**			**0.267**		
Laboratory Data	Material Name and Type		**53 CS**			**53 CS**			**53 CS**		
	Lab. SM ID (R+12 digits)		**R123456789012**			**R123456789012**			**R123456789012**		
	Optimum Moisture Content (OMC) (%)		**10**			**10**			**10**		
Test Site Moisture	Determined Moisture (%)		**9**			**9**			**9**		
	Difference (Sp.Prov.-3% to -1% of OMC)		**-1**			**-1**			**-1**		
Comments	Comments 1					**Retest**			**Retest OK**		
	Comments 2		**Need Additional Compaction**			**After Additional Compaction**			**After Additional Compaction**		
PASS OR FAIL OR INFORMATION			**Fail**			**Fail**			**Pass**		

REMARKS:		**T255 DATA**			
		Test Number	**111**		
		Station	**444+50**		
Example ONLY for Demo of form for LWD Acceptance		Tested on Material Passing (No. 4 or 3/4" Sieve)	**3/4**		
		1. Wt. of Pan & Wet Material (W1)(lb) or (g)	**2376.0**		
Recurring Special Provision for LWD without nuclear gauge. LWD on chemical		2. Wt. of Pan & Dry Material (W2)(lb) or (g)	**2188.7**		
modification for information or, if DCP test strip comparison made, for acceptance.		3. Wt. of Moisture (lb) **Line 1 - Line 2**	**187.3**	**0.0**	**0.0**
		4. Wt. of Pan (W3)(lb) or (g)	**100.0**		
LWD SD Card#		5. Wt. of Dry Material **Line 2 - Line 4**	**2088.7**	**0.0**	**0.0**
Compactor:		% Moisture (0.1%) **(Line 3 / Line 5) x 100**	**9.0**		

LWD Serial Number ______ RECORDED IN SITE-MANAGER: ______ Qualified Technician: ______

Figure 4.5 Example of acceptance test data collection sheet.

the edge of the placed material or in the middle. Then, the study investigated whether the mean acceptance test deflection indicated significant variation across projects, for the same material type and thickness. After investigating the variance in the data, the maximum allowable deflection thresholds were developed. The crux of the research is to determine whether statewide limits could be generated; therefore, the subbase and subgrade combinations that were considered were those for which multiple-project data had been collected.

The test sections are constructed for the purpose of establishing the maximum allowable deflection; as such, attempts were made to ascertain whether this data could be used to create the statewide threshold values. Two approaches were used to develop statistical limits. The first defined the maximum allowable deflection as the simple mean of all projects' test section deflections for a given subgrade or subbase lift over subgrade. This approach is consistent with INDOT's current field testing methodology.

The second approach utilized both the standard deviation and mean of acceptance test deflection data along with several statistical confidence intervals. The simple mean value of the acceptance test deflections should not be used as the maximum allowable deflection because roughly half of the acceptance tests used to create the threshold, that are by definition fully compacted, would have greater deflections than would be allowed by the limit. Therefore, several confidence intervals were used to provide an upper bound on the maximum allowable deflection. In this approach, the placed material is assumed compacted unless the mean deflection of the placed material is statistically significantly greater than the average deflection value obtained in the study data.

The first approach, utilizing test section data, is considered more valid as the data upon which it is based is expected to be more consistent. In either case, the efficacy of the thresholds developed depends on the quality of the data and the variance observed between projects.

4.2.1 Analysis of Variance

In order to develop statewide statistical limits for LWD deflection measurements, the data collected at multiple locations were combined. In order to determine if the conclusions drawn from the combined data set were statistically sound, the variance in the samples was analyzed.

The analysis of variance (ANOVA) is the ratio of the between-group variability and within-group variability. The null hypothesis is that the mean values between the groups are equal, which can be written as:

$$H_o : \bar{x}_1 = \bar{x}_2 \ldots = \bar{x}_j \tag{4.1}$$

$$H_a : \bar{x}_1 \neq \bar{x}_2 \ldots \neq \bar{x}_j \tag{4.2}$$

Where, H_o=null hypotheses, H_a=alternative hypotheses, and $\bar{x}_j$=mean value for group j out of k total groups. The between-group variability can be defined as:

$$\boldsymbol{MS_{Between}}\left(\frac{\mathbf{1}}{\boldsymbol{k-1}}\right)\sum_{\mathrm{j=1}}^{k}\boldsymbol{n_j(\bar{x}_j-\bar{x})^2} \tag{4.3}$$

Where, $MS_{Between}$=the mean square for between-group variability, n_j=the number of observations in group j, and $\bar{x}$= the mean value for all observations. The within-group variability can be defined as:

$$\boldsymbol{MS_{Within}}\left(\frac{\mathbf{1}}{\boldsymbol{N-k}}\right)\sum_{i=1}^{n_j}\sum_{j=1}^{k}\boldsymbol{(\bar{x}_{ij}-\bar{x}_j)^2} \tag{4.4}$$

Where, MS_{Within}=the mean square for within group variability, N=the total number of observations, and x_{ij}=observation i in group j.

The F value is calculated as the ratio of the mean square for between-group variability to the mean square for the within-group variability ($F=MS_B/MS_W$). The F statistic is then compared to the F critical value, which is dependent on the number of groups, the total number of observations, and the selected significance level (α). A 5% significance value was chosen (α=0.05), meaning that if the probability value (p-value) is less than or equal to α, the null hypothesis is rejected and the alternative hypothesis is accepted.

4.2.2 Z-Score Calculations

Statistical limits based on acceptance test data require the mean deflection of the placed material to be statistically significantly greater than the mean acceptance test deflection value found in the current study. Several confidence intervals were used to provide an upper bound on the maximum allowable deflection. The experimental setup for the one-sided test is as follows:

$$\boldsymbol{Z_\alpha = \frac{\bar{x}-\mu}{\sigma/\sqrt{n}}} \tag{4.5}$$

Where, Z_α=Z-score for α ($Z_{0.05}$=1.645), $\bar{\boldsymbol{x}}$= the sample mean (mean of nine deflections), μ=the population mean (mean deflection for a given subgrade/subbase combination), σ=the population standard deviation, and n=the number of samples.

Solving Equation 4.5 for the sample mean yields the upper bound of the 95% confidence interval; this implies that one would need to be 95% confident in order to reject the null hypothesis. Otherwise, the alternative hypothesis is accepted. Visually, this is depicted in Figure 4.6.

For the purposes of the current study, the null hypothesis is as follows: the mean deflection of a given placement of material is less than or equal to the average deflection for the given subgrade/subbase combination.

$$H_o : \boldsymbol{\bar{x} \leq \mu} \tag{4.6}$$

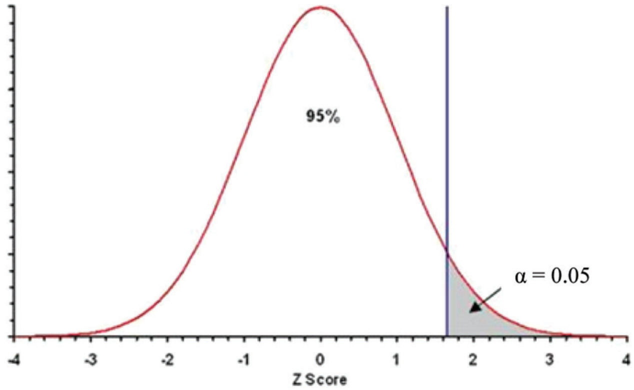


Figure 4.6 Z-scores for the normal distribution (5% level of significance).

$$H_a : \bar{x} > \mu \quad (4.7)$$

Where, H_0=null hypotheses and H_a=alternative hypotheses.

Substituting known values and solving for $\bar{x}$ yields the following equation:

$$\bar{x} = 1.645(\sigma/\sqrt{n}) - \mu \quad (4.8)$$

4.2.3 Test Section Observations

The test sections consist of 10 LWD test sites. Additional passes by the compactor typically results in a more compacted material, which corresponds to smaller deflections. As stated in an earlier section, the LWD test is repeated until two consecutive passes result in a change in average deflection of less than 0.01 mm. This can occur for any one of two reasons: (a) when two consecutive passes have nearly identical average deflections (between +0.01 mm and −0.01 mm), meaning the material did not experience further compaction and can thus be considered fully compacted; in this instance, the test section will yield 20 observations each of which is the measured deflection at a test site after each of the last two passes, (b) an additional pass results in a higher deflection than the previous pass, resulting in a negative change in average deflection (less than −0.01 mm). In this case, the test section only yields 10 observations each of which is the deflection measured at each test site after the penultimate compaction pass (the deflection measurements that yielded the lowest average deflection).

ANOVA testing was applied to the data collected from different contracts with the same subbase/subgrade material combinations to determine if the data from different contracts can be grouped to provide a statewide statistical limit. The resulting grouped data set was analyzed to determine the deflection threshold value and the required sample size.

4.2.4 Acceptance Test Observations

Recall that acceptance tests require the completion of three LWD test sites at each test station. The methodology implemented for the current study classified each LWD test site as a single observation instead of classifying each test station as a single observation. Since each complete LWD test is a single observation, a given station (cross-section) consists of three observations. There were three distinct steps to be considered. The first step was to determine if the LWD tests performed along the left edge, right edge, and center of the placed material for a given contract differ or can be grouped together. The second was to determine if the LWD tests from different contracts with the same subbase/subgrade material combinations differed or could be grouped together. Finally, the resulting grouped data set was analyzed to determine the deflection threshold value and the required sample size.

5. DATA AND ANALYSIS

The current study used data provided by INDOT Research Division, INDOT Geotechnical Services, and INDOT Crawfordville District Materials Management. Data were requested for five test sections per combination of subbase and subgrade (30) per INDOT management district (six) for a total of 900 test section results. However, each pavement contract only requires a single test section; therefore, it would have been impractical to collect all of the requested data within the study period. At the request of the study's SAC, the research scope was modified such that the results would be based on test sections and acceptance test results and would cover only the most commonly-used subbase and subgrade materials. The data sought in each test record includes:

- Type of subbase and subgrade material
- Contract identification (contract number, road number, date)
- Subbase lift number and thickness
- Number of compaction passes
- LWD test deflections for each test site
- Optimum and measured moisture content of the material

The above data requirements are crucial in proper analysis of material deflection and thus the compaction and resulting bearing capacity. As is often the case when dealing with data collected from multiple locations over the course of multiple years, several of the data sheets did not include all the required information. Some of the data used in this study were collected prior to the start of the study and therefore the INDOT field personal collecting the data were unaware of these requirements. The study subsequently used the data available to develop the statistical limits for LWD deflection values for unbound layers of pavements. It is important to note that the majority of the data reports did not include moisture content, and moisture content therefore was not considered in the development of the

TABLE 5.1
Number of test sections: subgrade only

Subgrade	Number of Test Sections
Compacted subgrade	4
Chemically modified subgrade with lime/lime kiln dust	4
Chemically modified subgrade with cement	2
Chemically modified subgrade with fly ash	0
Geo-grid reinforced subgrade	0
Mechanically modified subgrade	0

statistical limits. Previous research conducted elsewhere (discussed earlier in this report) suggest that the moisture content of the material highly influences the deflection readings. Therefore, extreme caution therefore must be taken when implementing any results from this study.

5.1 Test Section Data

The test sections are constructed for the purpose of determining allowable deflection limits for a given project; therefore, they have the potential to provide extremely high quality data. Each test section should include the deflection reading for the subgrade prior to adding the first subbase lift and the deflection readings for each subbase lift.

The number of test sections that had deflection readings for the subgrade prior to the placement of the subbase is presented in Table 5.1. Notice that there were no instances of fly ash modified, mechanically modified, or geo-grid reinforced subgrade.

The number of tests sections that yielded deflection readings for the first six-inch lift of placed subbase is presented in Table 5.2. Ten out of 11 projects used #53 crushed stone, making it the most common subbase type in the sample. There were four instances where the #53 crushed stone was placed over non-chemically modified subgrade and three instances each where it was placed over lime-modified and cement-modified subgrade.

5.1.1 Test Section ANOVA for Inter-Project Mean Deflection

For a given project, the maximum allowable deflection is the average value obtained from the test section. In order to develop statewide statistical limits for the maximum allowable deflection, data from across the state needed to be combined and analyzed. In order to draw conclusions based on multiple test sections, the variance observed within each test section and between the test sections were compared using an ANOVA test (Equations 4.1 through 4.4).

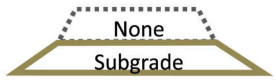
The results of the one-way ANOVA for each subgrade provided in Table 5.3 show that there was no statistical evidence to support the alternative hypothesis that the sample means are not equal. The F-factor, which is the ratio of the between-group variability to the within-group variability, was less than the F-critical value in each case. The alternative hypothesis (the mean values obtained for each test section are unequal) was statistically significant at only a 63%, 85%, and 82% level of confidence for cement modified, lime modified, and non-modified subgrades, respectively. Therefore, the alternative hypothesis was rejected and the null hypothesis (the mean values for the test sections are equal) was accepted. This allowed data from multiple projects with the same subgrade treatment to be combined. Figure 5.1 shows the normal distributions that were fit to the subgrade mean and the standard deviation for each project's test section.

While the ANOVA performed on the subgrade indicated that there was insufficient evidence to suggest the mean deflection values from different projects were statistically unequal, the ANOVA results for the first subbase lift, shown in Table 5.4, suggested otherwise. The between-group (project) variability observed in the #53 crushed stone placed over a cement modified subgrade is much greater than the variance observed within each project. The resulting P-value indicated that the mean deflection values observed in these test sections differed with over a 99% level of confidence. This holds true for #53 crushed stone placed over the non-modified subgrade as well. Only the #53 crushed stone placed over the lime modified subgrade showed consistent mean values. The alternative hypothesis of unequal test section deflection was statistically significant at only a 76% level of confidence. Therefore, the null hypothesis of the mean deflection being equal for test sections with #53 crushed stone subbase over lime modified subgrade was accepted. The variance in the test-section deflection values is illustrated in the normal distributions fit to each project's data presented in Figure 5.2.

TABLE 5.2
Number of test sections: six-inch subbase over subgrade

	Subbase		
Subgrade	53 Crushed Stone	53 Gravel	53 Slag
Compacted subgrade	4	0	0
Chemically modified subgrade with lime/lime kiln dust	3	1	0
Chemically modified subgrade with cement	3	0	0
Chemically modified subgrade with fly ash	0	0	0
Geo-grid reinforced subgrade	0	0	0
Mechanically modified subgrade	0	0	0

TABLE 5.3
Test section ANOVA results: subgrade only



Compacted Subgrade Type*	CM	CM	LM	LM	LM	LM	S	S	S	S
Road No.	I-70	US 31	US 50	US 40	I-65	US 31	SR 19	SR 10	SR 45	I-70
Contract Let	2013	2011	2012	2011	2011	2011	2011	2013	2012	2010
County	Hancock	Hamilton	Jennings	Wayne	Jackson	Hamilton	Elkhart	Newton	Monroe	Vigo
Sample Mean	0.282	0.254	0.305	0.289	0.340	0.266	1.179	1.099	0.936	1.371
Sample Standard Deviation	0.072	0.062	0.071	0.049	0.074	0.085	0.340	0.190	0.587	0.477
Sample Variance	0.005	0.004	0.005	0.002	0.005	0.007	0.115	0.036	0.344	0.228
Sample N	10	10	10	10	10	10	10	10	10	10
Group Mean	0.268		0.300				1.146			
Between-Group Variability	0.00400		0.00959				0.32543			
Within-Group Variability	0.00454		0.00505				0.18098			
Comparing Variances (F)	0.882		1.900				1.798			
alpha	0.05		0.05				0.05			
F Critical	4.414		2.866				2.866			
P-Value	0.360		0.147				0.165			

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

5.1.2 Test Section Data Grouped by Subbase/Subgrade

In the previous sections of the report, we showed how ANOVA tests were carried out for each subbase/subgrade combination collected from multiple projects (contracts) at different locations. The results indicate that the mean deflections were statistically different across all projects with #53 crushed stone subbase over a cement-modified subgrade. Likewise, the mean defections for all projects with #53 crushed stone subbase over a non-modified subgrade were proven to be statistically unequal. This result means that pooling these data to create statewide deflection thresholds could yield results that are too relaxed for purposes of compaction QA/QC. However, the data were grouped so that further analysis could proceed. Table 5.5 presents the descriptive statistics for the test section deflection values reported for each subbase/subgrade combination.

Figure 5.3 provides the relative distribution of deflection measurements for each combination of subbase and subgrade which utilized data grouped from more than one project. This includes lime-modified subgrade only and the cement-modified subgrade only (that is, prior to placing the subbase layer) and #53 crushed stone subbase over lime-modified subgrade and non-modified subgrade. The distributions were approximately normal. Normal distributions were fit to each combination; these are presented in Figure 5.4.

5.2 Acceptance Test Data

The modified research scope called for ten acceptance test stations per combination of subbase and subgrade. Each test station consisted of three LWD test sites (complete LWD test per test site), one 2 ft from the left edge of the placed material, one halfway across the placed material, and one 2 ft from the right edge of the placed material. Additional acceptance test site data were included that only consisted of a single test site at each station. The majority of this data was collected prior to the adoption of the acceptance test requirements laid out in ITM 502.

As discussed previously, data collection restrictions limited the quantity of available data. INDOT predominately uses only a few combinations of subbase and subgrade and the available data reflected this situation. There were no instances of #53 gravel or #53 slag being used for subbase material. Likewise, there were no instances of fly ash or mechanically modified subgrade. The data that were provided for analysis are presented in Table 5.6 and Table 5.7.

Each complete LWD test is considered a single observation; therefore, a given station (cross-section) consists of three observations. In order to develop statewide statistical limits, it was necessary to determine if there were statistically significant differences across the data collection locations. Differences that arise can be due to differences in the data collected within a project or between projects. Once the variance in the data was analyzed, it could be grouped so that the maximum allowable deflection and required sample size could be determined.

5.2.1 Acceptance Test ANOVA for Intra-Project Deflections

The typical acceptance test station consists of three complete LWD tests. By analyzing the variances in data (Equations 4.1 through 4.4) collected along the left edge,

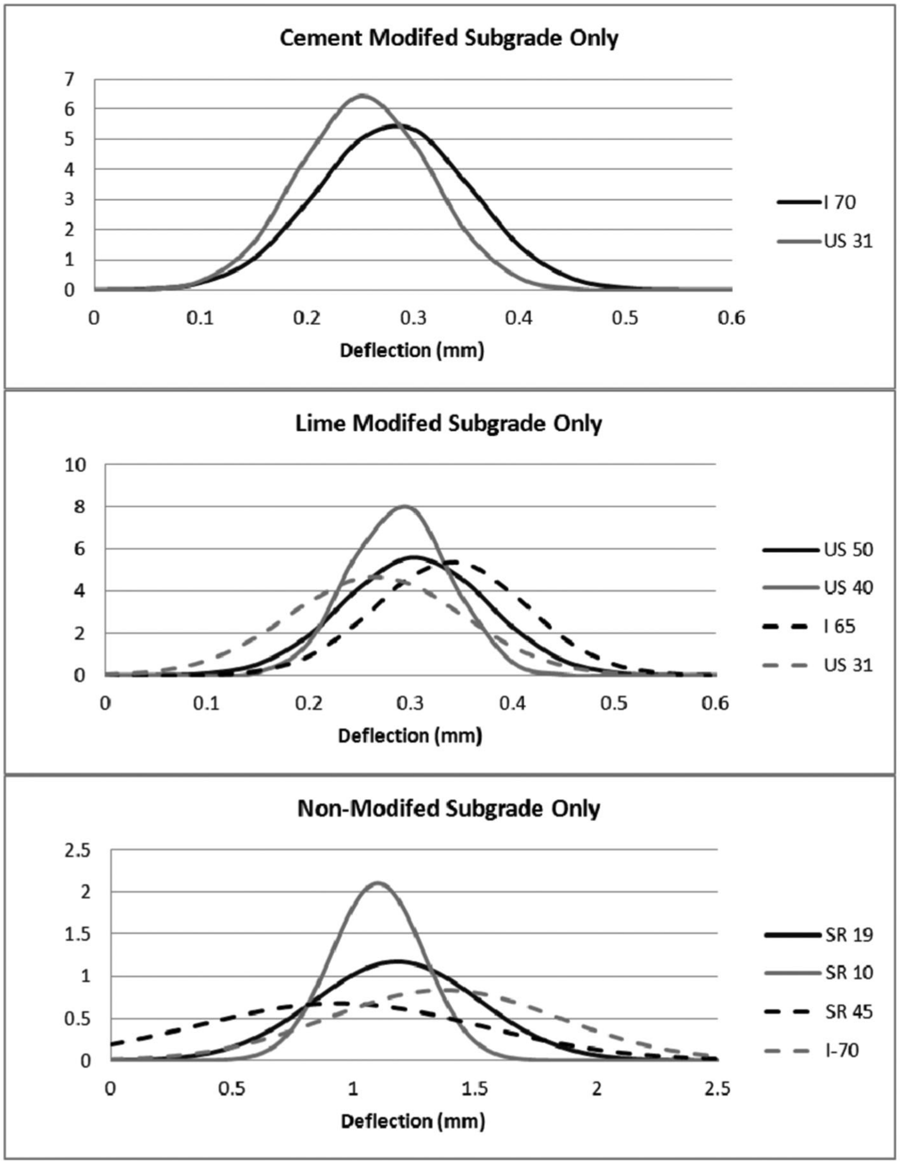


Figure 5.1 Test section normal distributions for deflections: subgrade only.

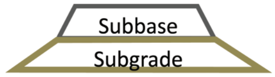
right edge, and center of the placed material, it was possible to ascertain whether the LWD deflection readings were statistically different depending on whether the LWD reading was at the center of the placed material or 2 ft from the edge as illustrated in Figure 4.4.

Table 5.8 provides an example of the ANOVA calculations for a given project. It was determined that the null hypothesis cannot be rejected, and it thus was accepted for all instances. This means that it was appropriate to group all the data for a given project regardless of the test site's proximity to the edge of the placed material.

5.2.2 Acceptance Test ANOVA for Inter-Project Deflections

After it was determined that the data from a single project (left, center, and right) could be grouped together, the next step was to determine if data with the same subbase/subgrade combination taken from different projects (and thus from different geographical locations) could be combined into a single dataset. Theoretically, the geographical location should not influence LWD deflection readings since deflection is based on the material properties and not location. However, material properties such as moisture content, and construction practices such as the time between compaction and LWD testing, can influence compaction and deflection. Data limitations prevented these factors from being included in the analysis. Therefore, it was possible that data from different contracts could result in statistically different maximum allowable deflections due to inter-project differences in attributes, including moisture content, temperature and time since material placement. ANOVA was used to investigate the appropriateness of grouping the data (Equations

TABLE 5.4
Test section ANOVA results: 6″ subbase over subgrade



Subbase over Subgrade*	CS over CM	CS over CM	CS over CM	CS over LM	CS over LM	CS over LM	CS over S	CS over S	CS over S	CS over S
Road No.	I-70	US 31	US 231	US 50	SR 25	US 31	I-70	SR 45	SR 19	US 31
Contract Let	2013	2011	2011	2012	2011	2011	2010	2012	2011	2011
County	Hancock	Hamilton	Tippecanoe	Jennings	Carroll	Hamilton	Vigo	Monroe	Elkhart	Hamilton
Sample Mean	0.331	0.280	0.302	0.278	0.298	0.269	0.734	0.434	0.527	0.514
Sample Standard Deviation	0.027	0.024	0.053	0.063	0.032	0.062	0.259	0.160	0.075	0.086
Sample Variance	0.001	0.001	0.003	0.004	0.001	0.004	0.067	0.026	0.006	0.007
Sample N	20	20	20	20	20	20	10	20	10	20
Group Mean		0.304			0.282			0.526		
Between-Group Variability		0.01327			0.00429			0.20107		
Within-Group Variability		0.00134			0.00293			0.02288		
Comparing Variances (F)		9.879			1.463			8.787		
alpha		0.05			0.05			0.05		
F Critical		3.159			3.159			2.769		
P-Value		0.000			0.240			0.000		

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*CS=#53 Crushed Stone, CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

4.1 through 4.4). Table 5.9 provides the results of the ANOVA analysis for lime-modified subgrade only (that is, prior to placement of the subbase layer). The alternative hypothesis that deflection values for different projects with lime-modified subgrade are statistically different was accepted at a 95% level of confidence (α=0.05). This means there is strong statistical evidence that the lime-modified subgrade LWD deflection readings collected from different projects are significantly different, and thus any analysis based on the grouped data could yield inaccurate results.

Figure 5.5 shows the difference between the distribution curves for the acceptance test deflections recorded at the nine projects that had lime modified subgrade without a subbase. The plotted curves are the normal distributions based on the observed sample mean and standard deviation for each project. Note that the variance in the curves for the two projects along US 421: one experienced a lower mean value and much smaller standard deviation compared to the other.

Table 5.10 provides the results of the ANOVA analysis for the first six-inch lift of #53 crushed stone subbase placed over lime-modified subgrade. The results show that there is strong statistical evidence that the mean values from different projects were unequal and therefore their data should not be grouped. Comparing variances yielded an F value of 43.0 which was greater than the F critical value of 2.40. Since the calculated F value was greater than the F critical value, we accepted the alternative hypothesis that the acceptance test deflection values for lime subgrade with #53 crushed stone were statistically different across different projects. These results are further illustrated in Figure 5.6, where the normal distributions for each project are produced from the deflection mean and standard deviations.

Table 5.11 provides the results of the ANOVA analysis for cement-modified subgrade only (that is, prior to the placement of a subbase layer). The variance F value of 45.31 is greater than the F critical value of 3.97, which implies non-rejection of the null hypothesis, thus the acceptance test deflection values for cement modified subgrade without a subbase ca ne considered statistically different across different projects. These results are further illustrated in Figure 5.7 which presents the normal distributions of acceptance test deflection values for each project.

The last subbase/subgrade combination that had data from more than one project was #53 crushed stone subbase over non-modified soil subgrade. The results from the ANOVA between the two projects are presented in Table 5.12. As was the case for the three previous within-project ANOVA results, the null hypothesis was not rejected, thus, the data suggest that the defections at the two different projects are statistically different from each other at a 95% level of confidence. The differences in the two datasets are apparent in the normal distribution diagrams presented in Figure 5.8 that illustrate the mean and standard deviation of the data from each project.

There was statistical evidence for each case where there was data from multiple contracts (lime-modified subgrade without subbase, lime-modified subgrade with #53 crushed stone subbase, cement-modified subgrade

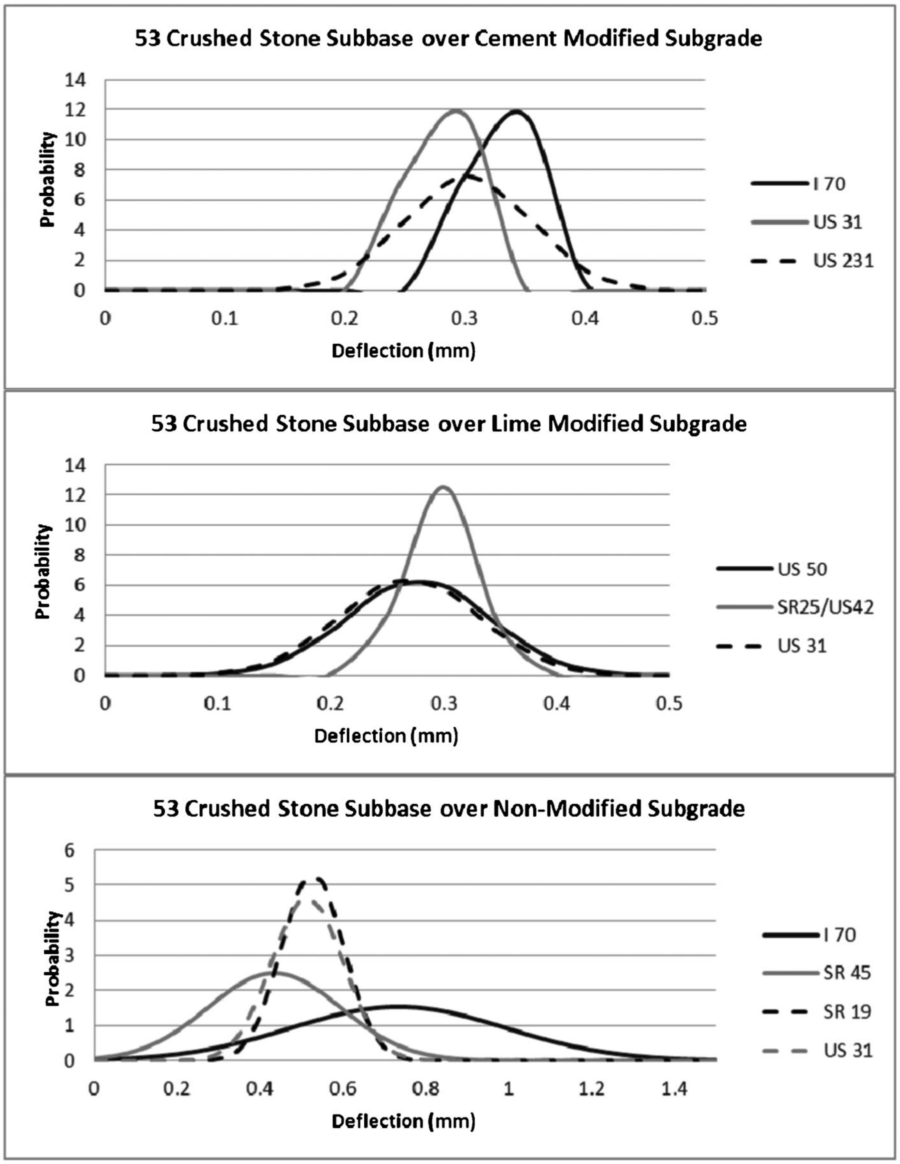


Figure 5.2 Tests section normal distributions for deflections: subbase over subgrade.

without subbase, and non-modified subgrade with #53 crushed stone subbase), which indicated that data from multiple projects are statistically different even if they have the same subbase/subgrade material combination. This was determined by calculating the between-group variability, within-group variability, and resulting F critical value for each subbase/subgrade combination and comparing it with the corresponding F critical value. In each case, the calculated F was greater than the F critical value, which means the alternative hypothesis was accepted (data for the given subbase/subgrade combinations collected at different projects were statistically different).

However, the SAC requested that statistical limits should be developed nevertheless based on all available data. For this reason, analysis continued with all data for a given subbase/subgrade combination combined in a single data set regardless of the contract from which the data originated. It is important to note that the resulting specifications derived from the data grouped by subgrade/subbase combination were expected to be relatively relaxed as the variance of the acceptance test deflection readings between contracts far exceeded that of the individual contracts.

5.2.3 Acceptance Test Data Grouped by Subbase/Subgrade

As discussed in the previous section, there was strong statistical evidence that the data should not be grouped, meaning there were significant differences in LWD deflection measurements from acceptance testing for a given subbase/subgrade combination across different pavement contracts or project locations. This could have

TABLE 5.5
Descriptive statistics for grouped test section deflections

Subbase over Subgrade*	No SB over CM	CS over CM	No SB over LM	CS Over LM	GR over LM	No SB over S	CS over S
Number of Projects	2	3	4	3	1	4	4
Sample Mean	0.268	0.304	0.300	0.282	0.339	1.146	0.526
Sample Standard Deviation	0.067	0.042	0.073	0.055	0.036	0.438	0.179
Sample Variance	0.005	0.002	0.005	0.003	0.001	0.192	0.032
Maximum	0.447	0.407	0.486	0.459	0.409	2.255	1.350
3rd Quartile	0.313	0.335	0.339	0.302	0.365	1.446	0.593
2nd Quartile	0.263	0.299	0.292	0.273	0.336	1.048	0.495
1st Quartile	0.227	0.271	0.254	0.247	0.306	0.890	0.405
Minimum	0.172	0.235	0.167	0.193	0.274	0.371	0.253
Inter-Quartile Range	0.085	0.064	0.085	0.056	0.059	0.556	0.188
Number of LWD Tests	20	60	40	60	20	40	60

Note: Measurements in millimeters.
*No SB=No Subbase, CS=#53 Crushed Stone, GR=#53 Gravel, CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

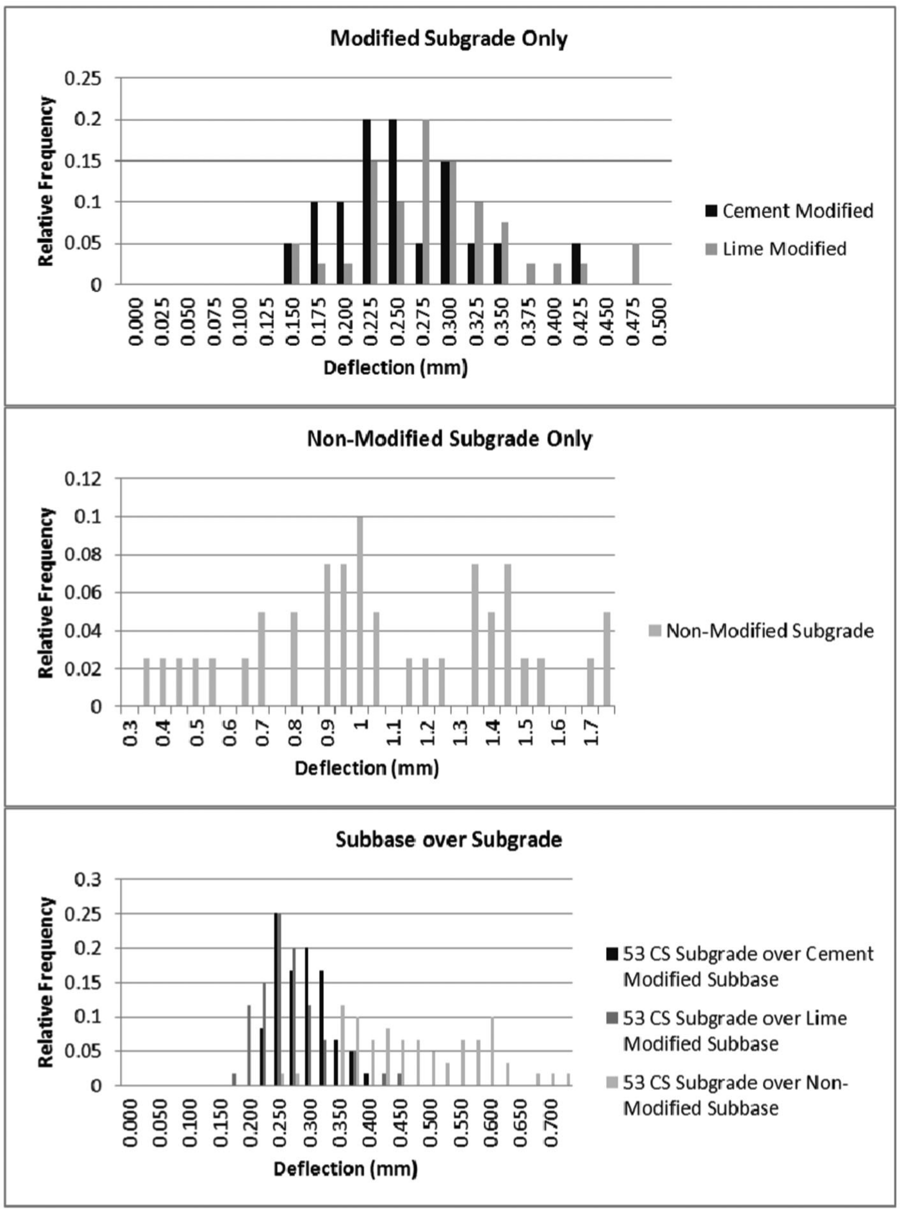


Figure 5.3 Test section relative frequency distributions of deflections.

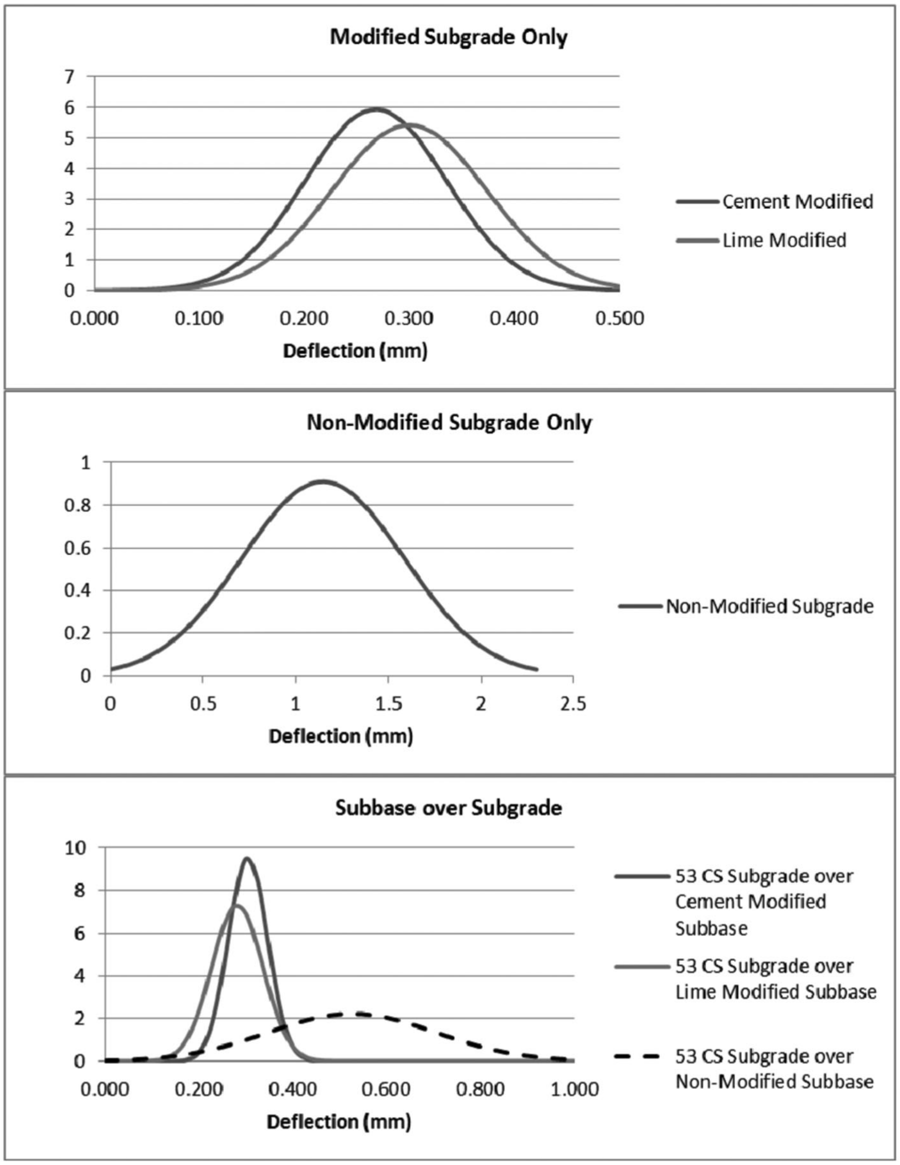


Figure 5.4 Test section fitted normal distributions of deflections.

been a result of differences in chemical modification techniques, compaction techniques, time between material placement and LWD testing, and moisture content across different contracts. Notwithstanding this, the data for each material type and configuration were placed in a single group at the request of the Study Advisory Committee, so that an average value could be developed for each subbase/subgrade combination. Table 5.13

TABLE 5.6
Number of acceptance tests: subgrade only

Subgrade	Number of Acceptance Test Sites (number of projects)
Compacted subgrade	0
Chemically modified subgrade with lime/lime kiln dust	341 (9)
Chemically modified subgrade with cement	75 (2)
Chemically modified subgrade with fly ash	0
Geo-grid reinforced subgrade	0
Mechanically modified subgrade	0

TABLE 5.7
Number of acceptance tests: 6″ subbase over subgrade

Subgrade	Subbase Number of Acceptance Test Sites (number of projects)		
	53 Crushed Stone	**53 Gravel**	**53 Slag**
Compacted subgrade	61(2)	0	0
Chemically modified subgrade with lime/lime kiln dust	312 (5)	0	0
Chemically modified subgrade with cement	30 (1)	0	0
Chemically modified subgrade with fly ash	0	0	0
Geo-grid reinforced subgrade	109 (1)	0	0
Mechanically modified subgrade	0	0	0

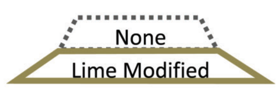
Note: 1 station is typically comprised of 3 LWD test sites; however some older records have only one or two LWD test sites per station.

TABLE 5.8
Example acceptance test ANOVA results: intra-project defleciton

Type	LWD Directly on Lime Kiln Dust Modified Soil Subgrade		
Location	**2′ from Left Shoulder**	**Center**	**2′ from Right Shoulder**
Sample Mean	0.2870	0.2911	0.2846
Sample Standard Deviation	0.1597	0.1726	0.1655
Sample Variance	0.02549	0.02978	0.02739
Sample N	21	21	21
Group Mean		0.2875	
Between-group variability		0.000229	
Within-group variability		0.027554	
Comparing Variances (F)		0.008304	
alpha		0.0500	
F Critical		3.1504	
P-value		0.9917> 0.05 thus we can't reject the null hypothesis	

Note: Measurements in millimeters.

TABLE 5.9
ANOVA results: lime modified subgrade only



Compacted Subgrade Type*	LM	LM	LM	LM	LM	LM	LM	LM	LM
Road No.	US 421	SR 641	US 421	CR 300	I-74	US 6	SR 28	SR 135	SR 25
Sample Mean	0.322	0.344	0.463	0.384	0.380	0.311	0.433	0.436	0.287
Sample Standard Deviation	0.084	0.127	0.463	0.158	0.148	0.100	0.150	0.091	0.166
Sample Variance	0.007	0.016	0.214	0.025	0.022	0.010	0.022	0.008	0.027
Sample N	28	160	23	24	6	31	34	14	21
Group Mean					0.360				
Between-group variability					0.0981				
Within-group variability					0.0297				
Comparing Variances (F)					3.3069				
alpha					0.05				
F Critical					1.9663				
P-value					0.0012				

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

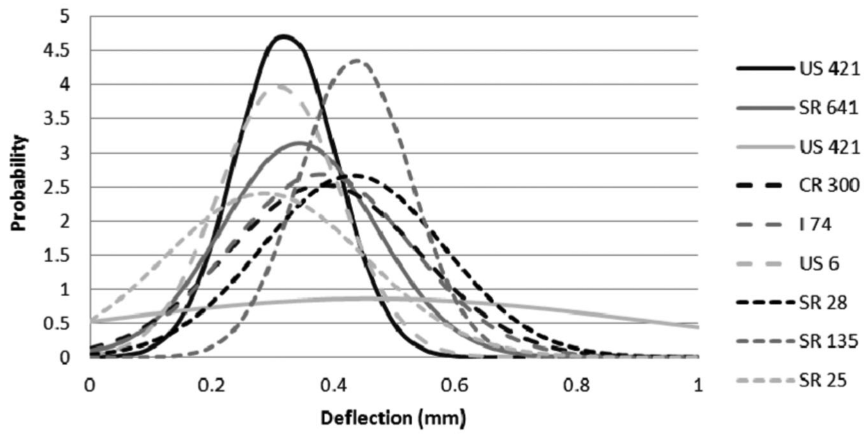


Figure 5.5 Acceptance test normal distributions: lime modified subgrade only.

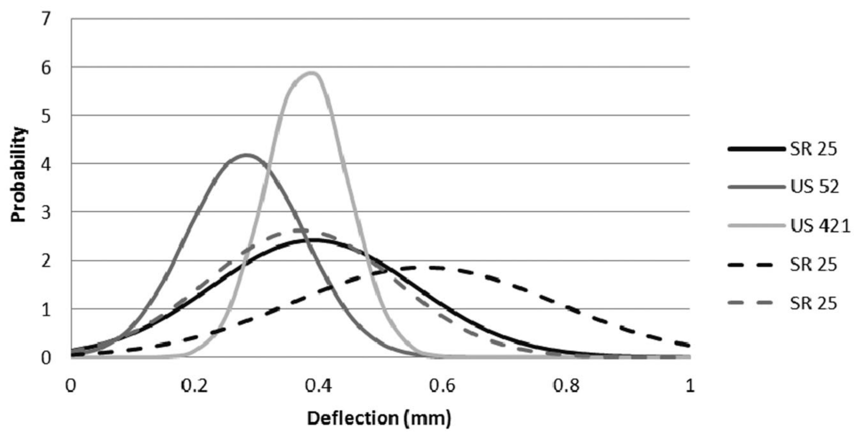
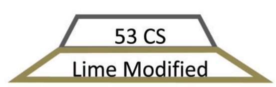


Figure 5.6 Acceptance tests normal distributions: #53 crushed stone subbase over lime modified subgrade.

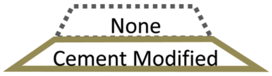
TABLE 5.10
ANOVA results: 53 CS subbase over lime modified subgrade



Subbase over Subgrade*	**CS over LM**	**CS Over LM**	**CS over LM**	**CS over LM**	**CS over LM**
Road No.	SR 25	US 52	US 421	SR 25	SR 25
Sample Mean	0.392	0.282	0.381	0.571	0.372
Sample Standard Deviation	0.164	0.095	0.066	0.214	0.152
Sample Variance	0.027	0.009	0.004	0.046	0.023
Sample N	45	114	47	67	39
Group Mean			0.386		
Between-group variability			0.8807		
Within-group variability			0.0205		
Comparing Variances (F)			43.0090		
alpha			0.05		
F Critical			2.4011		
P-value			0.0000		

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*CS=#53 Crushed Stone, CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

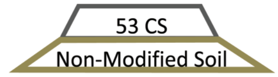
TABLE 5.11
ANOVA results: cement modified subgrade without subbase (in mm)



Compacted Subgrade Type*	CM	CM
Road No.	US 231	I-69
Sample Mean	0.152	0.295
Sample Standard Deviation	0.051	0.114
Sample Variance	0.003	0.013
Sample N	33	42
Group Mean	0.232	
Between-group variability	0.3813	
Within-group variability	0.0084	
Comparing Variances (F)	45.3097	
alpha	0.05	
F Critical	3.9720	
P-value	0.0000	

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*(CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil).

TABLE 5.12
ANOVA results: #53 crushed stone subbase over non-modified subgrade



Subbase over Subgrade Type*	CS over S	CS over S
Road No.	I-70	CR 600
Sample Mean	0.633	0.387
Sample Standard Deviation	0.148	0.121
Sample Variance	0.022	0.015
Sample N	15	46
Group Mean	0.448	
Between-group variability	0.6864	
Within-group variability	0.0163	
Comparing Variances (F)	42.0349	
alpha	0.05	
F Critical	4.0040	
P-value	0.0000	

Note 1: Each column is an individual project.
Note 2: Measurements in millimeters.
*CS=#53 Crushed Stone, CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil.

presents the descriptive statistics for the data grouped by the combination of subgrade and subbase. It is strongly suggested that the factors contributing to the large population variances need to be investigated in order to appropriately implement the research findings. The cement-modified subgrade with #53 crushed stone subbase had the lowest population variance (0.036 mm); however, it is important to note that all of this data were collected from a single contract. The combinations that had data collected from multiple contracts, such as lime-modified subgrade with #53 crushed stone subbase had much greater population variances. As may be expected, for materials with data from only one project, the population variance would increase dramatically after such data are supplemented with data from additional projects.

Figure 5.9 provides the relative distribution of deflection measurements for each combination of subbase and subgrade that has data grouped from more than one project. This includes lime-modified and cement-modified subgrades (prior to placing a subbase layer) and #53 crushed stone subbase over lime-modified subgrade and non-modified subgrade. The distributions were approximately normal. Normal distributions were fit to each combination and are presented in Figure 5.10.

TABLE 5.13
Discriptive statisitics for grouped acceptance test deflections

Subbase over Subgrade*	No SB over LM	CS over LM	No SB over CM	CS Over CM	CS over S	CS over GG
Number of Projects	9	5	2	1	2	1
Sample Mean	0.360	0.386	0.232	0.220	0.448	0.513
Sample Standard Deviation	0.177	0.178	0.116	0.036	0.166	0.169
Sample Variance	0.031	0.032	0.013	0.001	0.027	0.029
Maximum	1.873	1.533	0.653	0.311	0.947	1.494
3rd Quartile	0.416	0.463	0.282	0.239	0.532	0.578
2nd Quartile	0.327	0.337	0.215	0.22	0.399	0.469
1st Quartile	0.251	0.257	0.15	0.19	0.318	0.408
Minimum	0.112	0.129	0.055	0.167	0.207	0.268
Inter-Quartile Range	0.165	0.207	0.133	0.049	0.214	0.17
Number of LWD Tests	341	312	75	30	61	109

Note 1: Measurements in millimeters.
*No SB=No Subbase, CS=#53 Crushed Stone, CM=Cement Modified, LM=Lime Modified, S=Non-modified Soil, GG=geogrid.

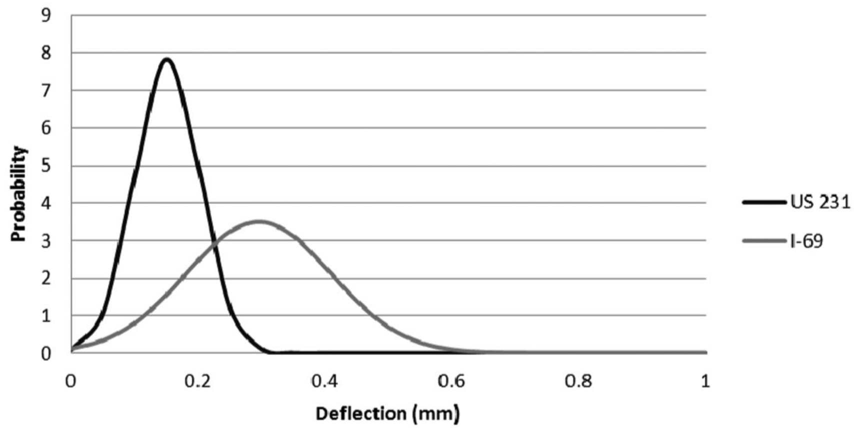


Figure 5.7 Acceptance tests normal distributions: cement-modified subgrade only.

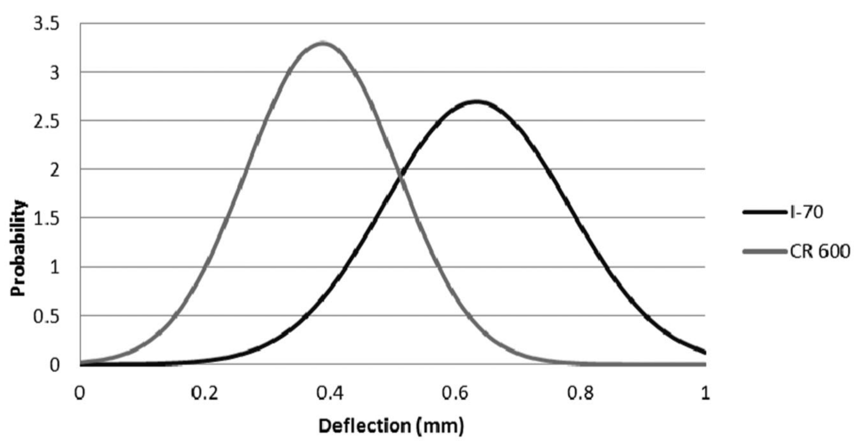


Figure 5.8 Acceptance tests normal distributions: #53 crushed stone subbase over unmodified subgrade.

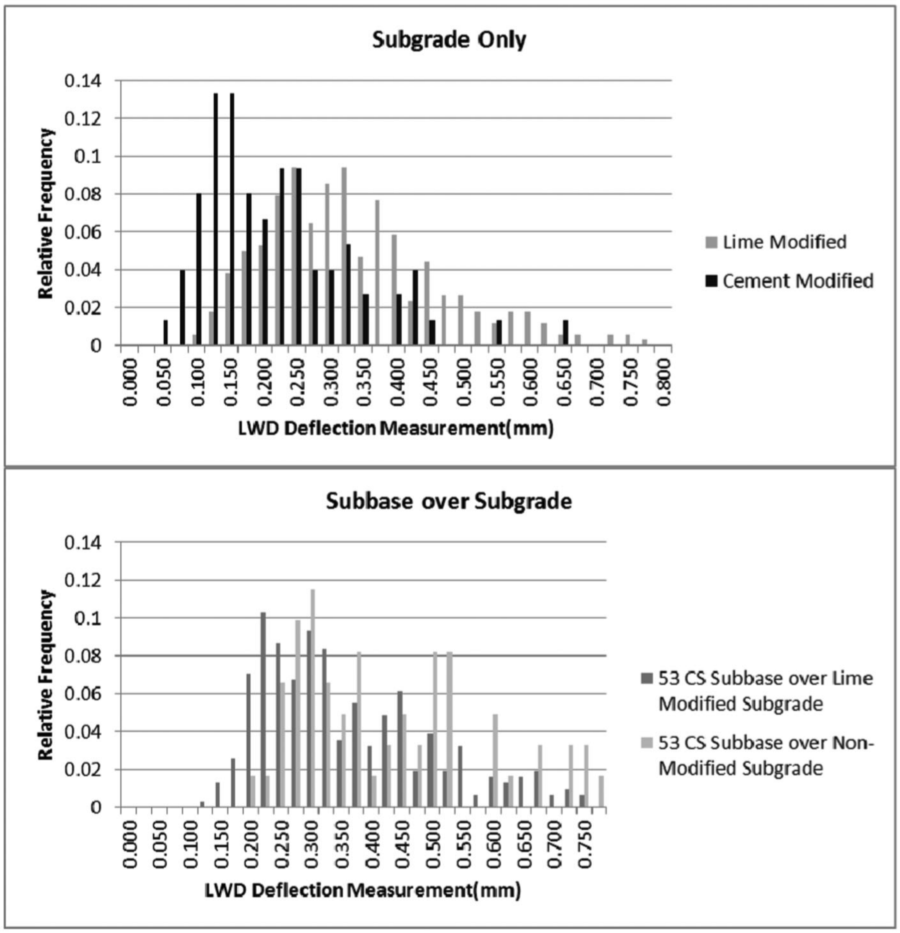


Figure 5.9 Acceptance tests distributions.

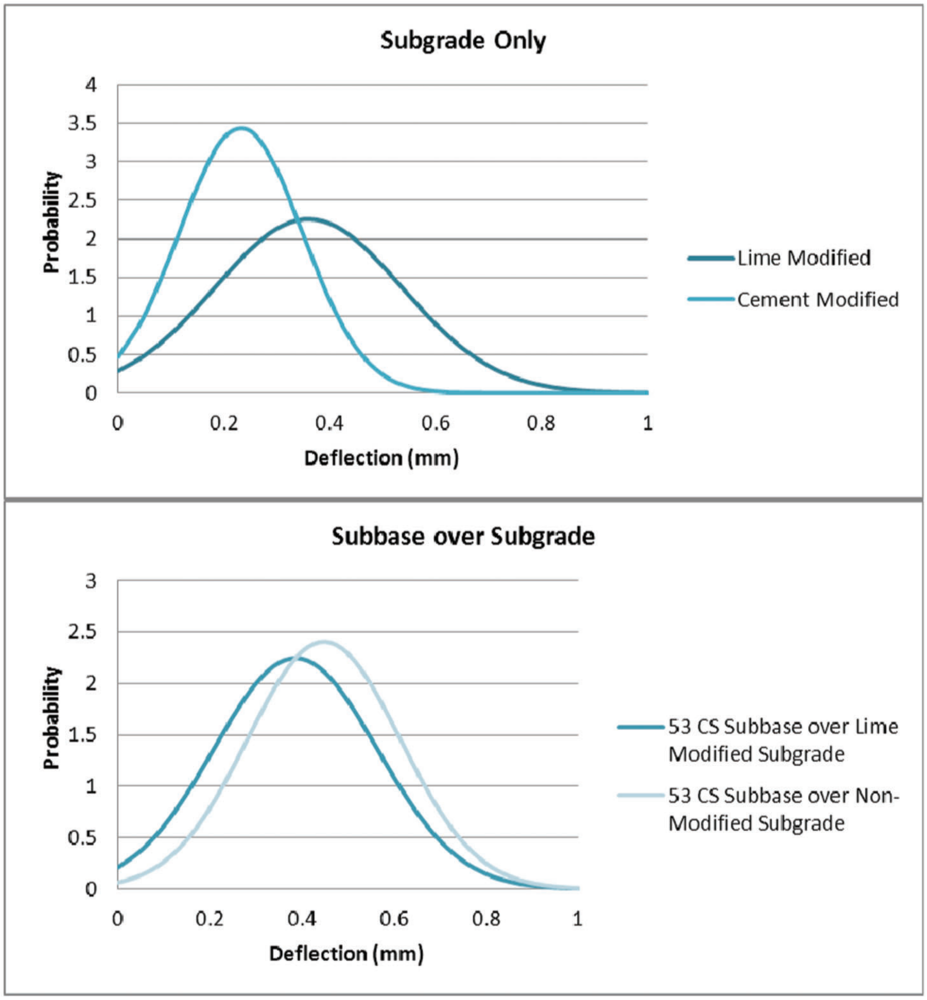


Figure 5.10 Acceptance tests normal distributions or deflections.

6. RESULTS

From the data analysis, statistical limits, in terms of the maximum allowable deflection, were developed for six combinations of subbase and subgrade materials. This chapter discusses these statistical limits for various confidence intervals. The chapter begins with an analysis of the sample size required when implementing the statistical limits.

6.1 Sample Size

For each combination of subbase and subgrade, the required number of LWD deflection readings taken at each location will depend on the subbase/subgrade population mean, the population standard deviation, the acceptable type 1 error (α), the acceptable type two error (β), and the significant change from the population mean and sample mean. The acceptable type 1 error, also known as the significance level, is set to 0.05 or 5%; and the acceptable type 2 error, equivalent to 1 – P (statistical power), is set to 0.10. The significant change from the population mean was set to 1.645 times the population standard deviation. The number of sample readings was determined using the following equation (Ott & Lognecker, 2010):

$$n = (Z_\alpha + Z_\beta)^2 (2\sigma^2)/(\mu_1 - \mu_2)^2 \tag{6.1}$$

Where, n=number of samples required, Z_α= z-score for α ($Z_{0.05}$=*1.645*), Z_β= z-score for β ($Z_{0.10}$=*1.28*), σ=population standard deviation, μ_1=population mean, and μ_2=μ_1 minus the significant change from the population mean (1.645 σ).

The required sample size for a given placement of material (number of LWD test sites) was determined to be 6.329. The required number of LWD tests was the same regardless of material types because the values of α and β were held constant and the significant change from the population mean was set as a proportion of the standard deviation (1.645 σ). Recall that the current LWD field testing procedure calls for three LWD tests at each station, one 2 ft from each edge and one in the middle. These three tests are used to represent a single placement of aggregate (800 tons). The sample size calculations show that the number of LWD tests

TABLE 6.1
Subgrade summary

Subbase	None		None		None	
	Cement Modified		Lime Modified		Non-Modified	
Subgrade	Test Section	Accept. Test	Test Section	Accept. Test	Test Section	Accept. Test
Mean	0.268	0.232	0.300	0.360	1.146	N/A
Standard Deviation	0.067	0.116	0.073	0.177	0.438	N/A
P-Value	0.360	0.000	0.147	0.001	0.165	N/A
# of LWD Test Sites	20	75	40	341	40	N/A
# of Projects	2	2	4	9	4	N/A

Note: Measurements in millimeters.

*P-Values less than 0.05 indicate acceptance of the alternative hypothesis (mean deflection across projects is unequal).

conducted at each test station should be increased from three to seven.

6.2 Statistical Limits for Maximum Allowable Deflection

The previous chapter detailed the process of analyzing the variance in test section and acceptance test LWD deflection values. This analysis is summarized in Table 6.1 and Table 6.2.

The results of the subgrade analysis strongly suggest that the test section data are better suited to develop statewide statistical limits for the maximum allowable deflection measured using the LWD. This can be seen by comparing the P-values corresponding to the test section projects and acceptance test projects for each subgrade type. In the case of the cement and lime modified subgrade, the mean deflection values obtained from different projects was accepted as statistically equal across project test sections but unequal across project acceptance tests. This is further illustrated in the larger standard deviations in the acceptance test data.

For the cement-modified subgrade, the mean of the acceptance test data is 0.036 mm lower than the test section. This is a logical result because, for a given project, the acceptance tests must be less than or equal to the test section mean value. However, since not every project's acceptance test data were accompanied by the corresponding test section data, there is the possibility that the average acceptance test deflection across all projects could be greater than the average test section deflection across all projects. This is apparent in the lime-modified subgrade datasets. The average acceptance test deflection across the nine projects was determined to be 0.360 mm whereas the average test section deflection was 0.300 mm.

In the case of the first six-inch subbase lift over subgrade, the only case of rejection of the alternative hypothesis (the mean deflection across projects is unequal) is the test section data for #53 crushed stone over lime modified subgrade. In all other instances, there was evidence that the mean deflection is statistically different across projects. Similar to the subgrade results, the #53 crushed stone over cement modified subgrade mean acceptance test deflection was less than the average test section deflection, whereas the #53 crushed stone over lime modified subgrade had the opposite relationship. It is important to note that there was only one project that had acceptance test data for #53 crushed stone over cement-modified subgrade. It is expected that the standard deviation was lower than the test section deflection for this reason, which included data from three separate projects.

The current INDOT field testing procedures for compaction acceptance testing using the LWD requires the mean acceptance test deflection be less than or equal to the mean value obtained from the project's test section.

TABLE 6.2
Six-inch lift of #53 crushed stone subbase over subgrade summary

Subbase	# 53 CS		# 53 CS		# 53 CS	
	Cement Modified		Lime Modified		Non-Modified	
Subgrade	Test Section	Accept. Test	Test Section	Accept. Test	Test Section	Accept. Test
Mean	0.304	0.220	0.282	0.386	0.526	0.513
Standard Deviation	0.042	0.036	0.055	0.178	0.179	0.169
P-Value*	0.000	N/A	0.240	0.000	0.000	0.000
# of LWD Test Sites	60	30	60	312	60	61
# of Projects	3	1	3	5	4	2

Note: Measurements in millimeters.

*P-Values less than 0.05 indicate the alternative hypothesis is accepted (mean deflection across projects is unequal).

TABLE 6.3
Maximum allowable deflection for subgrades

Subbase	None		None		None	
	Cement Modified		Lime Modified		Non-Modified	
Subgrade	Test Section	Accept. Test	Test Section	Accept. Test	Test Section	Accept. Test
Mean (mm)	0.268	0.232	0.3	0.36	1.146	N/A
Standard Deviation (mm)	0.067	0.116	0.073	0.177	0.438	N/A
Confidence	N/A	90%	N/A	90%	N/A	N/A
Number of LWD Tests Required	7	7	7	7	7	N/A
Maximum allowable deflection	0.268	0.288	0.3	0.446	1.146	N/A

6.2.1 Subgrade Maximum Allowable Deflection

In the previous section, it was stated that the number of LWD tests completed at each test station should be increased to seven. The study seeks to develop an upper limit for the average deflection of the acceptance testing. If the average deflection is greater than the limit, additional compaction is required. It may be recalled that in Chapter 4, it was stated that the statistical limits could be defined differently depending on the source of the data. If the data are obtained from test sections, then the maximum allowable deflection is defined as the mean deflection. If the data are obtained from the acceptance tests, then the maximum allowable deflection is based on the statistical distance from the mean.

The maximum allowable deflections for the subgrade are determined by applying Equations 4.5 through 4.7 to the population parameters in Table 6.3. A 90% level of confidence was used in the acceptance test approach. It must be emphasized that this does not indicate that if the average of seven LWD deflections is less than the limit, there is a 90% level of confidence that the material is compacted; rather, it means that one cannot be 90% confident the material is not compacted.

The maximum allowable deflections based on test station data and acceptance test data differ for each subgrade. The values are presented in Figure 6.1, where the distributions based on test sections and acceptance test are presented with the corresponding maximum allowable deflections.

The test sections provided lower and thus tighter values of the maximum allowable deflections. It may be recalled from Table 6.1 that only the test section data showed a lack of variance across projects. For this reason and because it is believed that the data collection at test sections is superior to that of acceptance testing (as discussed at length earlier in the report), any implementable aspect of the study results should be based on the test section data. However, extreme caution should be used when implementing any of the study's results. The original research proposal requested data from 30 projects; however, the statistical limits developed are based on as few as two projects for certain material types. Generalizing the results from such a limited number of projects to all projects involving that material type at any location in the state could result in the erroneous conclusion that an uncompacted material is adequate because it is seen to have has passed the threshold. The implications of this are somewhat limited for subgrade as INDOT does not include modified or non-modified subgrade in the calculation of the overall pavement strength. However, the strength of the subbase is included in the calculation of the pavement's strength.

6.2.2 Six-Inch Subbase Lift Over Subgrade Maximum Allowable Deflection

Unlike the subgrade data, which had multiple material types with deflections that did not vary across project test sections, only #53 crushed stone over lime modified subgrade had deflection values that did not vary across project test sections. Recall from the results presented in Table 5.4 that #53 crushed stone over cement-modified subgrade or non-modified subgrade had mean deflections that varied across projects. For this reason, extreme caution must be used when implementing the findings. The maximum allowable deflections for the first six-inch lift of subbase over subgrade are presented in Table 6.4. A 90% level of confidence was used in the acceptance test approach.

The maximum allowable deflections are presented in Figure 6.2, where the distributions based on test sections and acceptance testing are presented along with the corresponding maximum allowable deflections.

Similar to the results from the subgrade, the test sections provided lower maximum allowable deflections than the acceptance tests. In the case of the acceptance tests, it is important to note that the maximum allowable deflection would decrease with decreasing levels of confidence, meaning it is more likely to reject the null hypothesis.

Even greater care must be taken when implementing the subbase results. Unlike the subgrade, the subbase is included in the determination of pavement strength. An un-compacted subbase layer could result in lower overall pavement strength. Again, the number of projects available to include in the study was limited and great care must be taken when generalizing to a larger population.

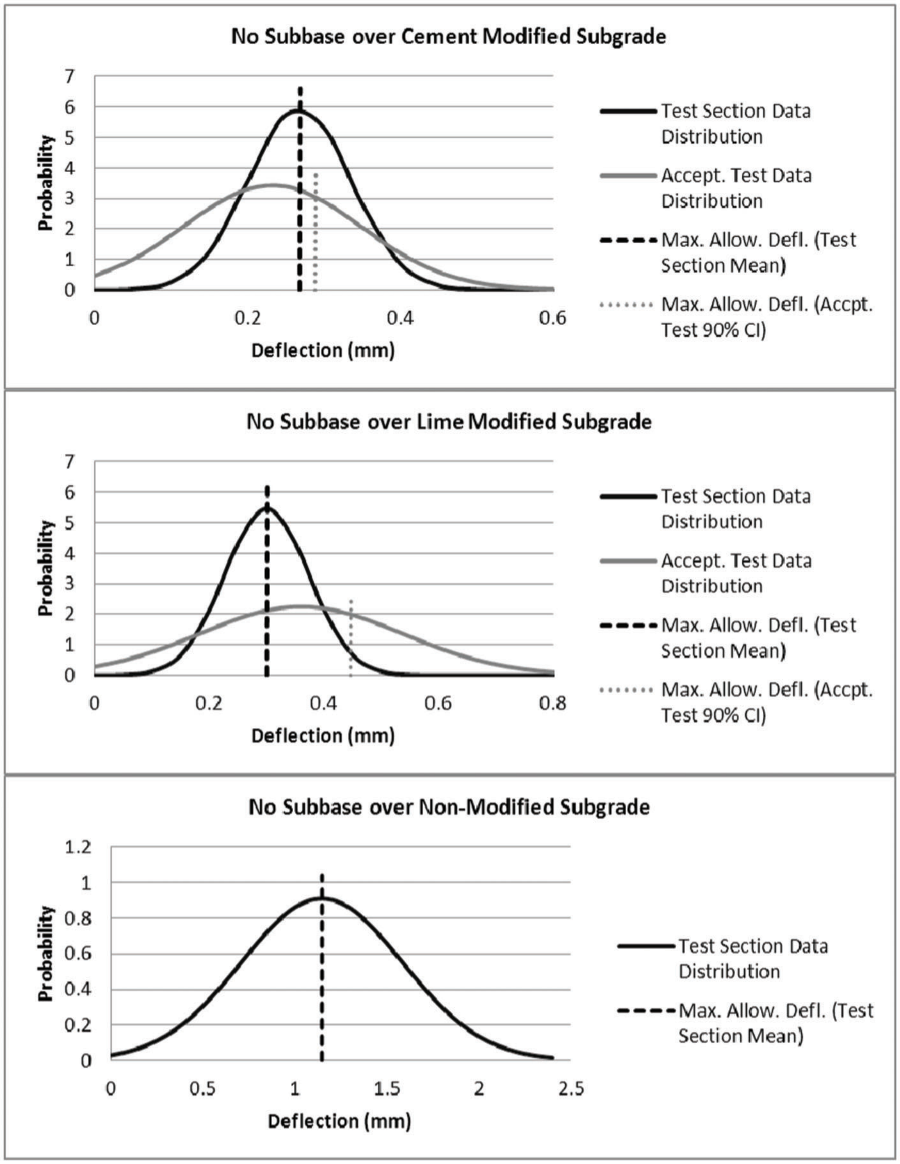


Figure 6.1 Comparison of maximum allowable deflection for different subgrade materials.

TABLE 6.4
Maximum allowable deflection for six-inch subbase lift over subgrades

Subbase	#53 Crushed Stone		#53 Crushed Stone		#53 Crushed Stone	
	Cement Modified		Lime Modified		Non-Modified	
Subgrade	Test Section	Accept. Test	Test Section	Accept. Test	Test Section	Accept. Test
Mean (mm)	0.304	N/A	0.282	0.386	0.526	0.513
Standard Deviation (mm)	0.042	N/A	0.055	0.178	0.179	0.169
Confidence	0	N/A	0.24	0	0	0
Number of LWD Tests Required	N/A	90%	N/A	90%	N/A	90%
Maximum allowable deflection	7	N/A	7	7	7	7

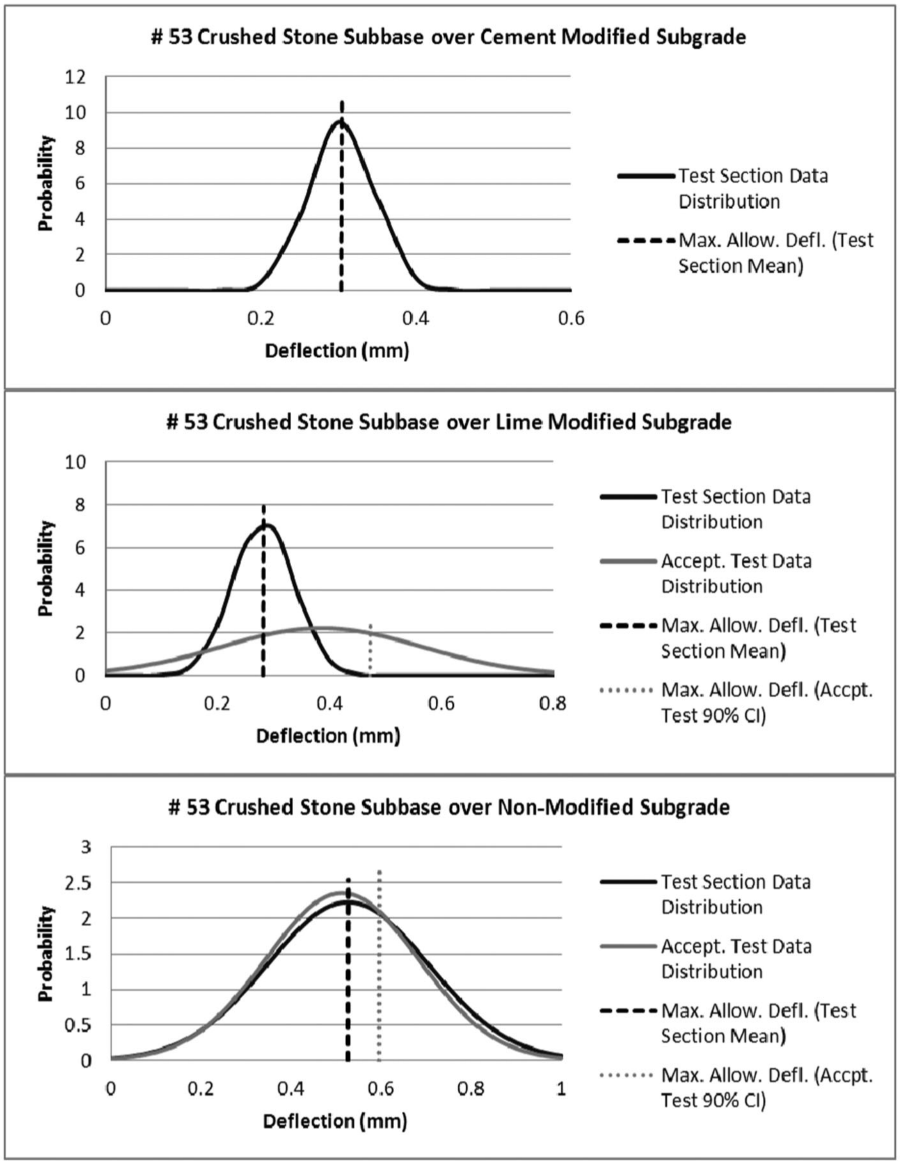


Figure 6.2 Comparison of maximum allowable deflections for six-inch subbase lift over different subgrade types.

6.2.3 Subbase Stiffness Modulus

The modulus of the subbase layer can be approximated using Boussinesq's elastic half space calculations (Equations 2.4 through 2.6). First, one must assume, for the material, a uniform Poisson ratio which can range between 0.3 and 0.45. Next, a nominal impact force needs to be calculated; however, since the velocity output for each LWD drop was not recorded, a value between 1 and 15 kN will be assumed (Nazzal et al., 2004). The calculated modulus values are presented in Table 6.5. It can be seen that the modulus values can vary greatly. For this reason, these values are for information purposes only. It is suggested that further research be conducted to determine if, compared to the deflection readings, the modulus values directly outputted from the LWD would serve better in the QC/QA of unbound pavement layers.

It is important to note that while the previous sections provided maximum allowable deflections for various subgrade/subbase combinations and the corresponding stiffness modulus, there are statistically significant differences between the different projects used in the analysis. Consequently, the statistical limits based on the resulting data set are potentially compromised. Therefore, further research should be conducted to investigate the underlying causes of the wide geospatial variation in LWD deflection values observation across multiple contracts.

TABLE 6.5
Approximate stiffness modulus for six-inch subbase lift over subgrades

	Subbase	# 53 Crushed Stone		# 53 Crushed Stone		# 53 Crushed Stone	
		Cement Modified		Lime Modified		Non-Modified	
	Subgrade	Test Section	Accept. Test	Test Section	Accept. Test	Test Section	Accept. Test
	Mean (mm)	0.304	N/A	0.282	0.386	0.526	0.513
	Standard Deviation (mm)	0.042	N/A	0.055	0.178	0.179	0.169
	P-Value	0	N/A	0.24	0	0	0
	Confidence	N/A	90%	N/A	90%	N/A	90%
	Number of LWD Tests Required	7	N/A	7	7	7	7
	Maximum allowable deflection	0.304	N/A	0.282	0.472	0.526	0.595
Average Assumptions	Assumed Nominal Impact Force	7		7	7	7	7
	Assumed Poisson Ratio	0.35		0.35	0.35	0.35	0.35
	Stiffness Modulus	**63.52**		**68.48**	**40.89**	**36.71**	**32.46**
Conservative Assumptions	Assumed Nominal Impact Force	3		3	3	3	3
	Assumed Poisson Ratio	0.45		0.45	0.45	0.45	0.45
	Stiffness Modulus	**23.04**		**24.83**	**14.83**	**13.31**	**11.77**

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Discussion and Conclusions

This study investigated the feasibility of developing statistical limits for compaction of unbound aggregate layers in roadway pavement construction in terms of the maximum allowable LWD deflection measurements for given subbase and subgrade combination. Two different data sources were investigated. The first was data obtained from test sections conducted at multiple projects. The data were from test sections that had been constructed for the purpose of determining project-specific maximum allowable deflections. For each of the three different subgrade material types (lime modified, cement modified, and non-modified) and one subbase and subgrade combination (#53 crushed stone over lime modified subgrade), it was found that the deflections do not vary significantly across different projects; therefore, statewide statistical limits could potentially be developed. However, the number of test sections available for our analysis was severely limited. In some cases, the limits were developed based on as few as two test sections so extreme caution must be used when generalizing these findings to the entire state.

The second source of data was acceptance tests which are conducted to ensure quality control during construction. These tests were determined to be appropriate to consider because, by their definition, they must be less than or equal to the maximum allowable deflection determined from the project's test section. It was determined that there were no statistically significant differences in acceptance test deflections measured at 2 ft from each edge of the construction area and at halfway across the width of the construction area within a single roadway pavement project. However, there is compelling evidence that the acceptance test deflections from different contracts using the same subbase/subgrade combinations were statistically different. The statistical test to determine compaction was set up such that the null hypothesis is that the field compaction for a given layer is satisfactory (100% field compaction) and the alternative hypothesis being tested is that the layer of material requires further compaction. The combined population of subbase/subgrade deflection data had a larger-than-expected variance, yielding a lenient statistical limit (maximum allowable deflection). The statistical limits for six combinations of subgrade and subbase material developed are presented in Table 7.1.

The overall appropriateness of the results is dependent on the quality of the data collected. Large population variances could be due to differences in compaction techniques across projects, differences in time intervals between material placement and testing, or differences in material properties (such as moisture content) that were not included in the available data and therefore were not taken into account in the study.

Generally, within a contract, there is confidence that the test pads generate control measurements that can be used reliably to check the adequacy of compaction at that site. However, across different contract locations, even for the same material type, there is so much variability that we cannot guarantee that the control measurements generated from a limited number of test sections (pads) can be confidently transferred to another site.

7.2 Recommendations

Caution must be taken when generalizing the results from this study to projects across Indiana. The current study relied on a limited number of projects to develop the statistical limits; and while the test section data did yield statistical limits for three separate subgrade types, only one statistical limit for subbase based on consistent data was determined. Furthermore, the limits developed for the subbase are for the first six inches of subbase placed over subgrade. Since the LWD measures the deflection of approximately 12 inches of material below

TABLE 7.1
Statistical limits (mm) for LWD deflections

Subgrade Only						
Subbase	**None**		**None**		**None**	
	Cement Modified		**Lime Modified**		**Non-Modified**	
Subgrade	**Test Section**	**Accept. Test**	**Test Section**	**Accept. Test**	**Test Section**	**Accept. Test**
Mean (mm)	0.268	0.232	0.3	0.36	1.146	N/A
Standard Deviation (mm)	0.067	0.116	0.073	0.177	0.438	N/A
Confidence	N/A	90%	N/A	90%	N/A	N/A
Number of LWD Tests Required	7	7	7	7	7	N/A
Maximum allowable deflection (mm)	0.268	0.288	0.3	0.446	1.146	N/A
6 Inch Lift of # 53 Crushed Stone Subbase over Subgrade						
Subbase	**# 53 Crushed Stone**		**# 53 Crushed Stone**		**# 53 Crushed Stone**	
	Cement Modified		**Lime Modified**		**Non-Modified**	
Subgrade	**Test Section**	**Accept. Test**	**Test Section**	**Accept. Test**	**Test Section**	**Accept. Test**
Mean (mm)	0.304	N/A	0.282	0.386	0.526	0.513
Standard Deviation (mm)	0.042	N/A	0.055	0.178	0.179	0.169
P-Value	0	N/A	0.24	0	0	0
Confidence	N/A	90%	N/A	90%	N/A	90%
Number of LWD Tests Required	7	N/A	7	7	7	7
Maximum allowable deflection (mm)	0.304	N/A	0.282	0.472	0.526	0.595

the device, the limits developed are not applicable to thicker subbase lifts, nor are they applicable to any additional lifts for the subbase. There was inadequate data to construct deflection limits for any further lifts for the subbase material.

It is recommended that INDOT revisit the number of acceptance tests required for each placement of material. Currently, INDOT requires three measurements across the subgrade, whereas this study suggests increasing the number of measurements to seven. This study did determine that proximity to the edge of the placed material (2 ft from the edge compared to the center) is statistically insignificant, meaning the additional four required LWD test could be spread out across the station.

The stiffness modulus values developed as a result of the test section or acceptance test data are for comparative purposes only. Without knowing the nominal force applied at each LWD test, accurate stiffness values cannot be calculated. Since the modulus is the parameter of concern, it is suggested that subsequent research focus on the reliability of the modulus values provided in the LWD output; it is quite possible that the modulus values may serve as a superior criterion for establishing target values for purposes of QC/QA during placement of unbound layers in pavement construction.

Going forward, it is suggested that INDOT continue the use of site-specific test pads for use in conjunction with LWD testing in pavement construction QC/QA. This is particularly critical for projects that require subbase lifts exceeding a single six-inch thickness. In all cases, the minimum compaction requirements currently in use, in terms of the minimum number of passes of the vibratory roller, should be kept in place.

REFERENCES

Alshibli, K., Abu-Farsakh, M., & Seyman, E. (2005). Laboratory evaluation of the geoguage and light falling weight deflectometer as construction control tools. *Journal of Materials in Civil Engineering*, *17*(5), 560–569.

Benedetto, A., & Di Domenico, F. (2012). Elliptic model for prediction of deflections induced by a light falling weight deflectometer. *Journal of Terramechanics*, *49*, 1–12.

Berney, E., & Kyzar, J. (2012). Evaluation of non-nuclear soil moisture and density devices for field quality control. *Transportation Research Record*, *2310*, 18–26. http://dx.doi.org/10.3141/2310-03

Boston, K., Robek, R., & Rathom, J. (2009). The potential use of the light drop-weight deflectometer to control subgrade compaction on forest roads. *Western Journal of Applied Forestry*, *24*(2), 83–87.

Christopher, B., Schwartz, C., & Boudreau, R. (2006). *Geotechnical aspects of pavements* (Report No. NHI-05-037). Washington, DC: National Highway Institute, Federal Highway Administration, U.S. Department of Transportation.

Davich, P., Camargo, F., Larsen, B., Roberson, R., & Siekmeier, J. (2006). *Validation of DCP and LWD moisture specifications for granular materials* (Report No. MN/RC-2006-20). St. Paul, MN: Minnesota Department of Transportation.

Fleming, P., Frost, M., & Lambert, J. (2007). Review of light weight deflectometer for routine in situ assessment of pavement material stiffness. *Transportation Research Record*, *2004*, 69–77.

Gomes-Correia, A., Martins, J., Caldeira, L., Maranha das Neves, E., & Delgado, J. (2009). Comparison of in situ performance-based tests methods to evaluate moduli of railway embankments. *Proceedings from the International Conference on the Bearing Capacity of Roads and Airfields*, *2*, 1331–1340. http://dx.doi.org/10.1201/9780203865286.ch139

Hossain, M., & Apeagyei, A. (2010). *Evaluation of the lightweight deflectometer for in-situ determination of pavement layer moduli* (Publication No. FHWA/VTRC 10-R6). Charlottesville, VA: Virginia Transportation Research Council Research.

Indiana Department of Transportation. (2012). *Field determination of deflection using light weight deflectometer* (ITM No. 508-12T). Indianapolis, IN: Author.

Indiana Department of Transportation. (2013). *Design procedures for soil modification or stabilization*. Indianapolis, IN: Author.

Jung, C., Jung, S., Bobet, A., & Siddiki, N. J. (2009). *Field investigation of subgrade lime modification* (Joint Transportation Research Program Publication No. IN/JTRP-2009/38). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284314271

Kessler, K. (2009). Use of DCP (dynamic cone penetrometer) and LWD for QC/QA on subgrade and aggregate Base.) In Chen, D.H., Estakhri, C., Zha, X., & Zeng, S. (Eds.), *Material, design, construction, maintenance, and testing of pavements* (pp. 62–67). Reston, VA: American Society of Civil Engineers.

Khattak, M., Mohammad, L., Yuan, F., & Abadie, C. (2012). Variability of in situ hma volumetric and mechanistic characteristics using non-destructive test (NDT): Case study. *International Journal of Pavement Engineering*, *13*(2), 110–125.

Kim, H., Prezzi, M., & Salgado, R. (2010). *Use of dynamic cone penetration and Clegg hammer tests for quality control of roadway compaction and construction* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2010/27). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284314246

Lambert, J., Fleming, P., & Frost, M. (2008). The assessment of coarse granular materials for performance based pavement foundation design. *International Journal of Pavement Engineering*, *9*(3), 203–214.

Livneh, M., & Goldberg, Y. (2001). Quality assessment during road formation and foundation construction: Use of falling-weight deflectometer and light drop weight. *Transportation Research Record*, *1755*, 69–77.

Meehan, C., Tehrani, F., & Vahedifard, F. (2012). A comparison of density-based and modulus-based in situ test measurements for compaction control. *Geotechnical Testing Journal*, *35*(3), 387–399.

Minnesota Department of Transportation. (2007). *Proceedings from Intelligent Compaction and Light Weight Deflectometer Technology Transfer*. Retrieved from http://www.dot.state.mn.us/materials/researchdocs/IC_LWD_Workshop_11_14_07.pdf.

Mishra, D., Tutumluer, E., Moaveni, M., & Xiao, Y. (2012). Laboratory and field measured moduli of unsurfaced pavements on weak subgrade. In Hryciw, R. D., Athanasopoulos-Zekkos, A., & Yesiller, N. (Eds.), *Proceedings from the GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering* (pp. 1381–1390). http://dx.doi.org/10.1061/9780784412121.142

Mooney, M., & Miller, P. (2008). *Analysis of light falling weight deflectometer test based on in situ stress and strain response*. Golden, CO: Colorado School of Mines.

Mooney, M., & Miller, P. (2009). Analysis of lightweight deflectometer test based on in situ stress and strain response. *Journal of Geotechnical and Geoenvironmental Engineering*, *135*(2), 199–208.

Mooney, M., Nocks, C., Seldon, K., Bee, G., & Senseney, C. (2011). *Improving quality assurance of MSE wall and bridge approach earthwork compaction* (Report No. CDOT-2008-11). Golden, CO: Colorado School of Mines.

Nazzal, M., Abu-Farsakh, M., Alshibli, K., & Mohammad, L. (2004). Evaluating the potential use of a portable LFWD for characterizing pavement layers and subgrades. In M. K. Yegian & E. Kavazanjian, *Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans 2004, July 27–31, 2004, Los Angeles, California.* Reston, VA: American Society of Civil Engineers.

Nazzal, M., Abu-Farsakh, M., Alshibli, K., & Mohammad, L. (2007). Evaluating the light falling weight deflectometer device for in situ measurement of elastic modulus of pavement layers. *Transportation Research Record*, *2016*, 13–22.

Ott, R. L., & Longnecker, M. (2010). *An introduction to statistical methods and data analysis* (6th Ed.). Belmont, CA: Brooks/Cole.

Puppala, A. (2008). *Estimating stiffness of subgrade and unbound materials for pavement design*. NCHRP Synthesis 382. Washington, DC: Transportation Research Board.

Rahim, A., & George, K. (2003). Falling weight deflectometer for estimating subgrade elastic moduli. *ASCE Journal of Transportation Engineering*, *129*, 100–107.

Romero, P., & Kuhnow, F. (2002). Evaluation of new nonnuclear pavement density gauges with data from field projects. *Transportation Research Record*, *1813*, 47–54.

Ryden, N., & Mooney, M. (2009). Analysis of surface waves from the light weight deflectometer. *Soil Dynamics and Earthquake Engineering*, *29*, 1134–1142.

Siddharthan, R., Norris, G., & Epps, J. (1991). Use of FWD data for pavement material characterization and performance. *ASCE Journal of Transportation Engineering*, *117*(6), 660–678.

Siddiki, N. (2012). Light weight deflectometer (LWD). Presented at the 98th Purdue Road School at Purdue University, IN, Mar 6–7, 2012. Retrieved from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1209&context=roadschool

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F., & Beyer, M. (2006). *Using the dynamic cone penetrometer and light weight deflectometer for construction quality assurance* (Report No. MN/RC 2009-12). Maplewood, MN: Minnesota Department of Transportation.

Singh, N., Mejia, C., Martison, T., Shah, F., Fleming, C., & Fitzpatrick, J. (2010). Use of the light weight deflectometer (LWD) at Highland Valley Copper Mine. *Proceedings from the 63rd Canadian Geotechnical Conference*, Sept. 12–16, Alberta, Canada.

Steinert, B., Humphrey, D., Kestler, M., Eaton, R., Benda, C., & Berg, L. (2006). Monitoring stiffness of gravel surfaced roads during spring thaw using a portable falling weight deflectometer. *Proceedings from the 13th International Conference on Cold Regions Engineering*, July 23–26, Orono, ME.

Tayabji, S. D., & Lukanen, E. O. (2000). *Nondestructive testing of pavements and backcalculation of moduli: Third volume*. West Conshohocken, PA: ASTM International.

Tehrani, F. and Meehan, C. (2010).The effect of water content on light weight deflectometer measurements. *Proceedings from GeoFlorida 2010: Advances in Analysis, Modeling & Design*, 930–939. http://dx.doi.org/10.1061/41095(365)92

Vennapusa, P., & White, D. (2009). Comparison of light weight deflectometer measurements for pavement foundation materials. *Geotechnical Testing Journal*, *32*(3), 1–13.

Vennapusa, P., White, D., Siekmeier, J., & Embacher, R. (2012). In situ mechanistic characterisations of granular pavement foundation layers. *International Journal of Pavement Engineering*, *13*(1), 52–67.

Wacharanon, V., Wachiraporn, S., & Sawangsuriya, A. (2009). *Innovative tools for highway construction quality control*. Retrieved from http://www.transtechsys.com/pdf/DOH%20article-english%20version.pdf

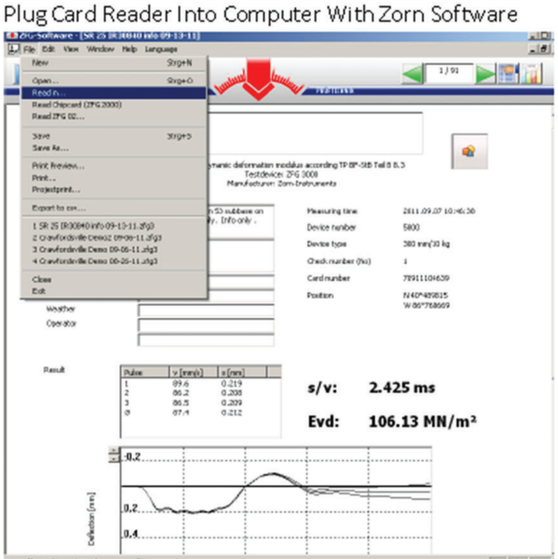
Walston, B. and McQueen, R. (2000). Development of a reliable methodology for assessing the structural performance of general aviation pavements, *Presented at the 26th International Air Transportation Conference*, June 18–21, San Francisco, CA.

LWD Field Testing Procedures
INDOT Office of Materials Management and Office of Geotechnical Engineering

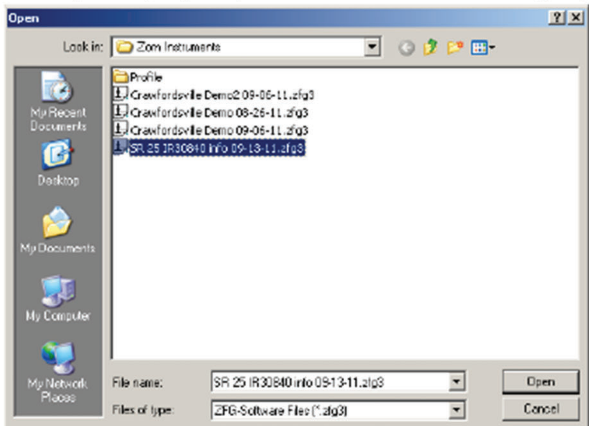
1. **References**
    a. ITM 508
    b. ITM 802
    c. Directive 501
    d. Contract Provisions And Specifications For LWD
    e. TD409 LWD In Excel
        i. Test Section
        ii. Acceptance

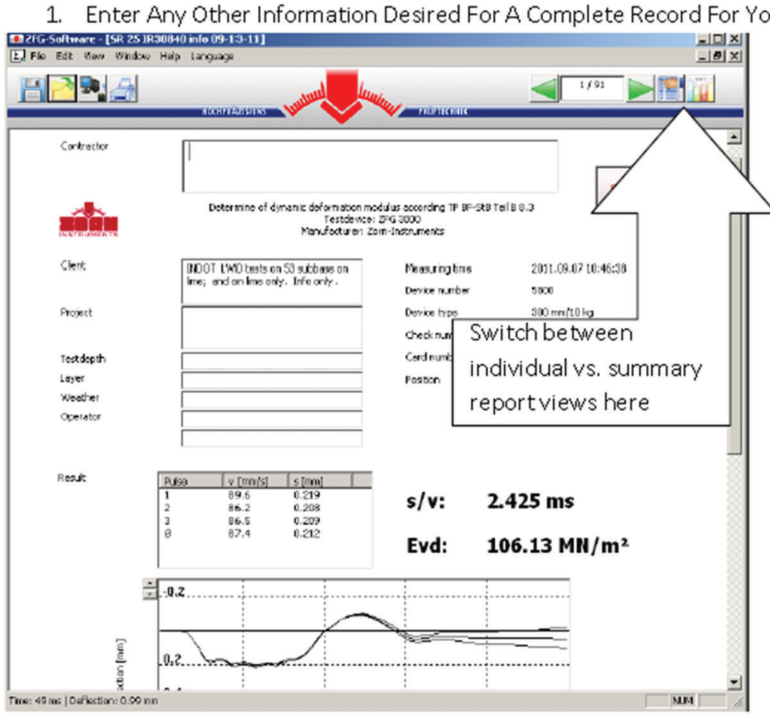
2. **LWD First Time Setup On Contract**
    a. Install Zorn Software On Local Computer
    b. CD Located In LWD Control Box

3. **LWD Practice Data Collection And Reporting**
    a. Perform At Least 3 Tests For Equipment And Software Setup
        i. Outdoors To Assure GPS Function
        ii. Any Suitable Material Or Rubber Pad On Concrete
        iii. Review ITM, Safe Operation, And Wear PPE
    b. Print To Assure Machine Printer Function
        i. Press "Print" After One Complete Test, While Test Summary Is Visible On Display Screen
    c. Transfer Data To Computer With Zorn Software. (optional)
        i. Turn Off LWD And Remove SD Memory Card
        ii. Insert SD Card Into The Provided USB Card Reader
        iii. Plug Card Reader Into Computer With Zorn Software
        iv.

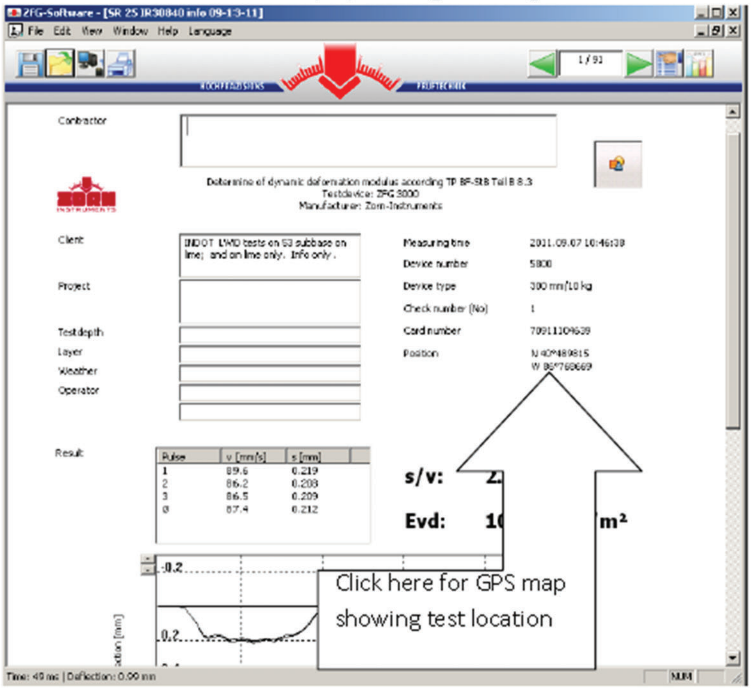


v. Select | 'File' | 'Read-In' | And Locate USB Drive Containing Data
    1. Folder: Zorn; File name: ZFG.nrz
vi. Follow Screen Prompts To Import Data
vii. SD Card Can Hold 1500 Tests.
    1. Don't Delete Unless Full And All Data Transferred to Excel CSV For Geotechnical Engineering

d. Produce Lab Report Showing Summary Of All 3 Tests (optional)
    i. Select | 'File' | 'Open' | And Locate Folder Containing Imported Data
    ii. 

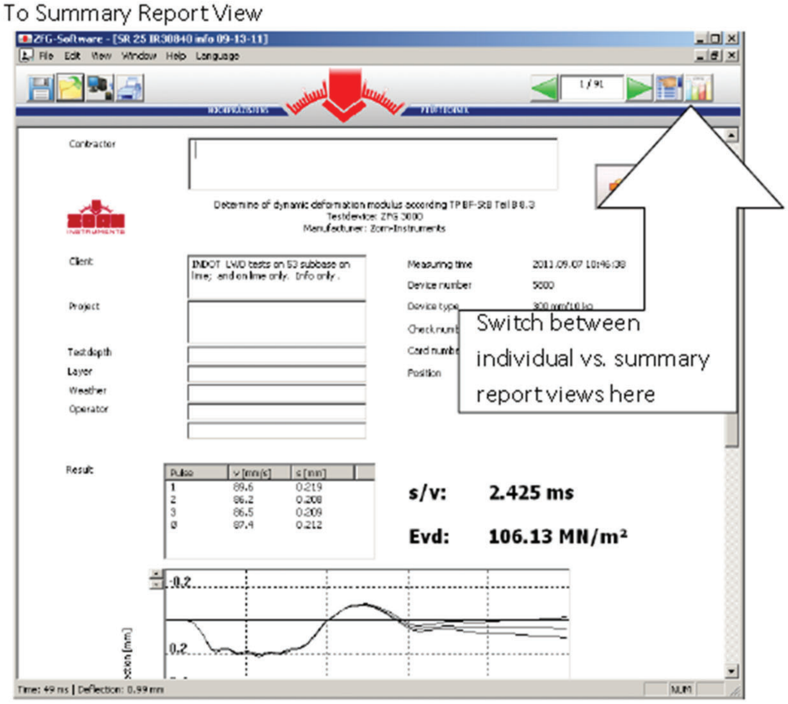
    iii. Use "Layer" Or "Remarks" Field To Enter Material Name
        1. Enter Any Other Information Desired For A Complete Record For Your Contract Files
    iv. 

v. View Test Location On GPS Map By Clicking The Longitude And Latitude On The Report



vi.

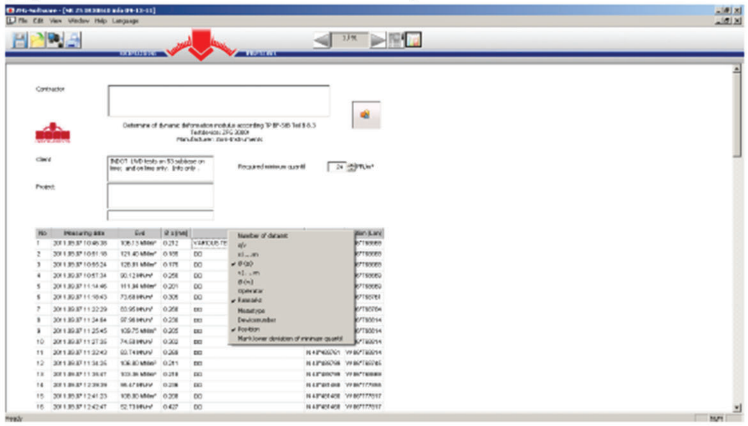
vii. Switch To Summary Report View



1.

viii. Add “s1”, “s2”, “s3”, and “Θs”; remove “v” and “s/v”

1. (Right Click On Table Header To Select Fields)

2. 

e. Print Lab Report (optional)

f. Save Data In Zorn Software (optional)

g. Use Software To Export To Excel CSV File. (optional)

   i. Save Excel File: Contract Number And Date In File Name As A Minimum;

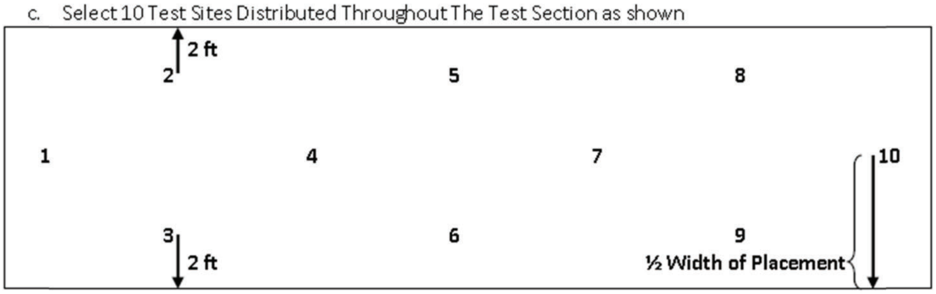
   ii. Import in Excel as “semicolon delimited”

   iii. Send To Nayyar Siddiki At Completion Of Testing For The Season For Each Contract

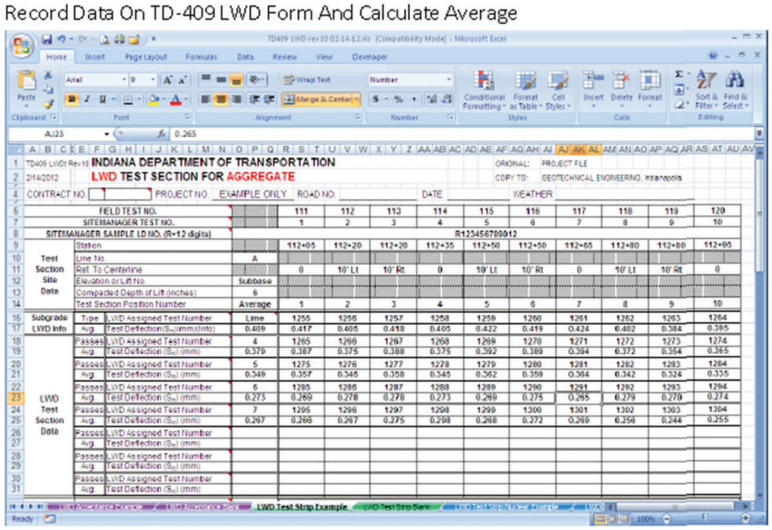
h. Troubleshoot Any Problems

i. Use Optional Printed Report As Supplement To Required TD409 As Basis For SiteManager Data Entry.

4. **LWD Test Section**
    a. After Completion Of Proofrolling And Approval Of Subgrade
    b. Select Test Section Site Per Contract Provisions (Typically 100' X Width of Material)
    c. Select 10 Test Sites Distributed Throughout The Test Section as shown



    d. Test The Approved Subgrade Prior To Placement Of The Compacted Aggregate (Optional - For Information Only – May Provide Understanding Of Stiffness Of Underlying Layer)
        1. At Each Of The 10 Test Sites, Perform 1 Complete LWD Test
        2. Record Data On TD-409 LWD Form And Calculate Average



TD409 LWDt Rev10 | INDIANA DEPARTMENT OF TRANSPORTATION | ORIGINAL: PROJECT FILE
2/14/2012 | LWD TEST SECTION FOR AGGREGATE | COPY TO: GEOTECHNICAL ENGINEERING, Indianapolis

CONTRACT NO. | PROJECT NO. EXAMPLE ONLY | ROAD NO. | DATE | WEATHER

FIELD TEST NO.				111	112	113	114	115	116	117	118	119	120
SITEMANAGER TEST NO.				1	2	3	4	5	6	7	8	9	10
SITEMANAGER SAMPLE I.D NO. (R+12 digits)				R123456789012									
Test Section Site Data	Station			112+05	112+20	112+20	112+35	112+50	112+50	112+65	112+80	112+80	112+95
	Line No.		A										
	Ref. To Centerline			0	10' Lt	10' Rt	0	10' Lt	10' Rt	0	10' Lt	10' Rt	0
	Elevation or Lift No.		Subbase										
	Compacted Depth of Lift (inches)		6										
	Test Section Position Number		Average	1	2	3	4	5	6	7	8	9	10
Subgrade LWD Info	Type	LWD Assigned Test Number	Lime	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264
	Avg.	Test Deflection (S) (mm) (Info)	0.409	0.417	0.406	0.418	0.405	0.422	0.419	0.424	0.402	0.384	0.395
LWD Test Section Data	Passes	LWD Assigned Test Number	4	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274
	Avg.	Test Deflection (S) (mm)	0.379	0.387	0.375	0.388	0.375	0.392	0.389	0.394	0.372	0.354	0.365
	Passes	LWD Assigned Test Number	5	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284
	Avg.	Test Deflection (S) (mm)	0.349	0.357	0.346	0.358	0.345	0.362	0.359	0.364	0.342	0.324	0.335
	Passes	LWD Assigned Test Number	6	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294
	Avg.	Test Deflection (S) (mm)	0.273	0.269	0.278	0.278	0.273	0.269	0.275	0.265	0.279	0.270	0.274
	Passes	LWD Assigned Test Number	7	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304
	Avg.	Test Deflection (S) (mm)	0.267	0.266	0.267	0.275	0.298	0.268	0.272	0.269	0.256	0.244	0.255
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S) (mm)											
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S) (mm)											
	Passes	LWD Assigned Test Number											
	Avg.	Test Deflection (S) (mm)											

LWD Test Strip Example | LWD Test Strip Blank

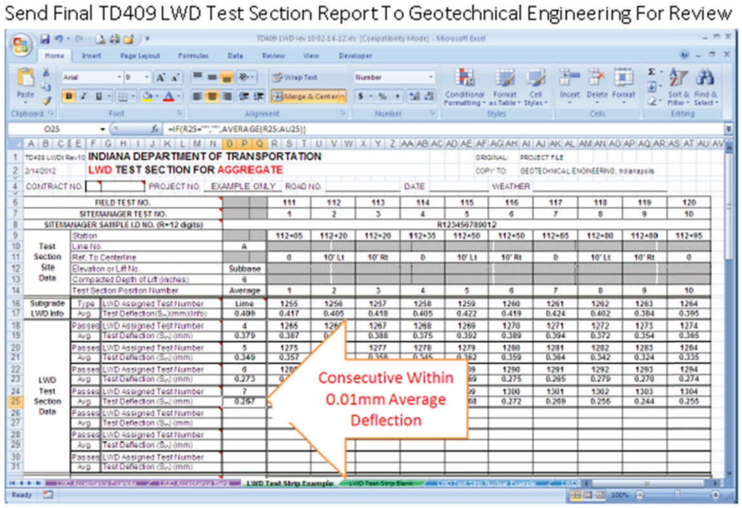
        3.
        4. For Information Only
    e. Test The Compacted Aggregate On The Test Section
        i. Determine Moisture At Time Of Placement
            1. Moisture Must Be Within -3% To -1% OMC
                a. Or As Otherwise Directed By Office Of Geotechnical Engineering
                b. Do Not Begin Compaction Until Moisture Is Correct

- ii. Apply 4 Vibratory Compaction Passes After Material Uniformly Placed and Graded
  1. LWD Tests
     - a. At Each Of The 10 Test Sites, Perform 1 Complete LWD Test
       - i. Use Same 10 Test Sites Each Time
     - b. Record Data On TD-409 LWD Form
     - c. Calculate Average Deflection For All 10 Tests
- iii. Apply 1 Additional Compaction Pass
  1. LWD Tests
     - a. At Each Of The 10 Test Sites, Perform 1 Complete LWD Test
     - b. Record Data On TD-409 LWD Form
     - c. Calculate Average Deflection For All 10 Tests
- iv. Compare Average Deflection Between Last 2 Passes
  1. If Difference > 0.01mm, Apply 1 Additional Vibratory Compaction Pass and Repeat LWD Testing and Comparison Process As Described Above
  2. If Difference $\leq$ 0.01mm, Test Section Is Complete

f. Test Section Compaction Is Complete When:

- i. At Least 5 Compaction Passes
- ii. Average LWD Deflection Changes $\leq$0.01mm (Rounded To 0.01 mm) Between Consecutive Compaction Passes At Field Moisture Within -3% To -1% OMC;
- iii. Consult INDOT Geotechnical Engineering If Unable To Achieve.

g. Maximum Allowable Deflection

- i. The Maximum Allowable Deflection Is The Lowest Average Deflection From Any Trial On The Test Section
  1. Report In mm To Three Decimals (0.001mm)
  2. Send Final TD409 LWD Test Section Report To Geotechnical Engineering For Review
  3. 

TD409 LWD rev 10-02-14-12.xls [Compatibility Mode] - Microsoft Excel

O25 =IF(R25="","",AVERAGE(R25:AU25))

TD409 LWDt Rev10 INDIANA DEPARTMENT OF TRANSPORTATION — ORIGINAL: PROJECT FILE

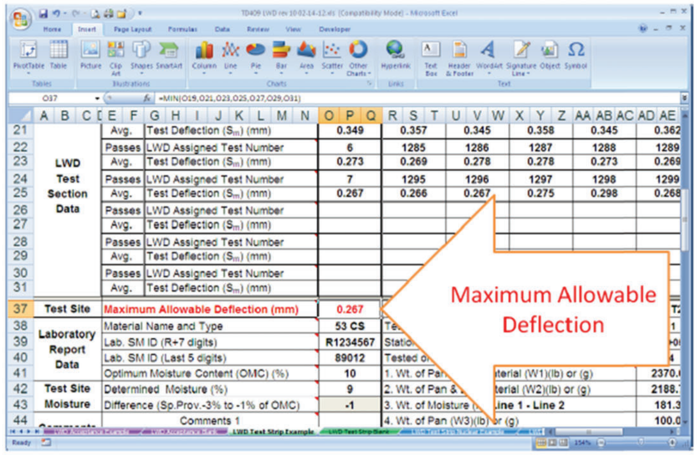
2/14/2012 LWD TEST SECTION FOR AGGREGATE — COPY TO: GEOTECHNICAL ENGINEERING, Indianapolis

CONTRACT NO. PROJECT NO. EXAMPLE ONLY ROAD NO. DATE WEATHER

FIELD TEST NO.			111	112	113	114	115	116	117	118	119	120
SITEMANAGER TEST NO.			1	2	3	4	5	6	7	8	9	10
SITEMANAGER SAMPLE I.D NO. (R+12 digits)		R123456789012										
Test Section Site Data	Station		112+05	112+20	112+20	112+35	112+50	112+50	112+65	112+80	112+80	112+95
	Line No.	A										
	Ref. To Centerline		0	10' Lt	10' Rt	0	10' Lt	10' Rt	0	10' Lt	10' Rt	0
	Elevation or Lift No.	Subbase										
	Compacted Depth of Lift (inches)	6										
	Test Section Position Number	Average	1	2	3	4	5	6	7	8	9	10
Subgrade LWD Info	Type / LWD Assigned Test Number	Lime	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264
	Avg. / Test Deflection (mm)(Info)	0.409	0.417	0.405	0.418	0.405	0.422	0.419	0.424	0.402	0.384	0.395
LWD Test Section Data	Passes / LWD Assigned Test Number	4	1265	[illegible]	1267	1268	1269	1270	1271	1272	1273	1274
	Avg. / Test Deflection (mm)	0.379	0.387	[illegible]	0.388	0.375	0.392	0.389	0.394	0.372	0.354	0.365
	Passes / LWD Assigned Test Number	5	1275	[illegible]	1277	1278	1279	1280	1281	1282	1283	1284
	Avg. / Test Deflection (mm)	0.349	0.357	[illegible]	0.358	0.345	0.362	0.359	0.364	0.342	0.324	0.335
	Passes / LWD Assigned Test Number	6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1290	1291	1292	1293	1294
	Avg. / Test Deflection (mm)	0.273	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.275	0.265	0.279	0.270	0.274
	Passes / LWD Assigned Test Number	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1300	1301	1302	1303	1304
	Avg. / Test Deflection (mm)	0.267	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.272	0.269	0.256	0.244	0.255
	Passes / LWD Assigned Test Number											
	Avg. / Test Deflection (mm)											
	Passes / LWD Assigned Test Number											
	Avg. / Test Deflection (mm)											
	Passes / LWD Assigned Test Number											
	Avg. / Test Deflection (mm)											

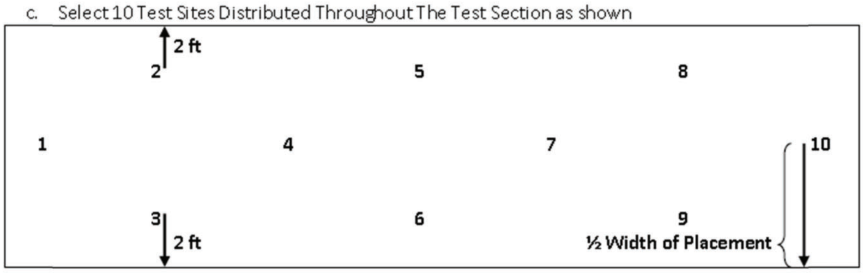
LWD Test Strip Example | LWD Test Strip Blank

LWD Field Testing Procedures
INDOT Office of Materials Management and Office of Geotechnical Engineering

4. 

5. LWD Test Section Using Nuclear Gauge

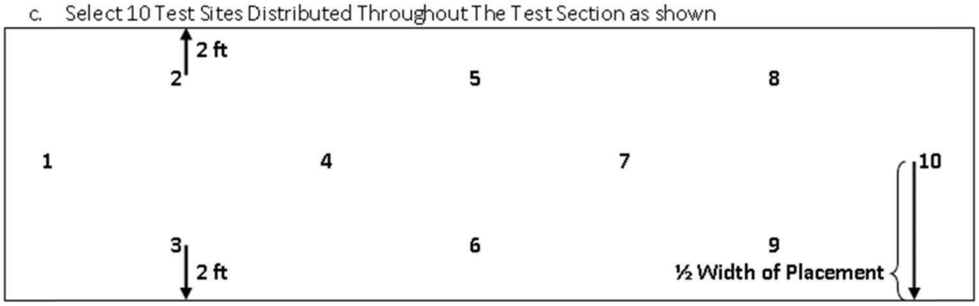
a. After Completion Of Proofrolling And Approval Of Subgrade
b. Select Test Section Site Per Contract Provisions (Typically 100' X Width of Material)
c. Select 10 Test Sites Distributed Throughout The Test Section as shown



d. Perform Density Testing In Accordance With T310
e. Compaction Is Complete When Density And Moisture Meet The Requirements Of 301.06
f. LWD Tests
   i. At Each Of The 10 Test Sites, Perform 1 Complete LWD Test
   ii. Record Data On TD-409 LWD Form
   iii. Calculate Average Deflection For All 10 Tests
g. Maximum Allowable Deflection
   i. The Maximum Allowable Deflection For Acceptance Testing Is The Average Deflection From The 10 Tests On The Test Section
      1. Report In mm To Three Decimals (0.001mm)
h. Send Final TD409 LWD Test Section Report To Geotechnical Engineering For Review

6. LWD Test Section On Chemically Modified Subgrade Using DCP

a. At Least 24 Hours After Completion Of Mixing And Compaction Of Chemically Modified Subgrade
b. Select Test Section Site Per Contract Provisions (Typically 100' X 20')
c. Select 10 Test Sites Distributed Throughout The Test Section as shown

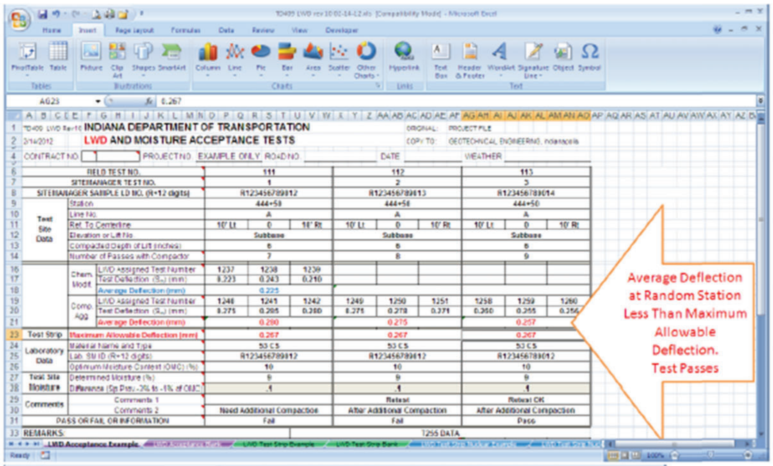


d. Perform DCP Testing In Accordance With 215.09
e. Compaction Is Complete When All DCP Tests Meet The Requirements Of 215.09
f. LWD Tests
   i. At Each Of The 10 Test Sites, Perform 1 Complete LWD Test
   ii. Record Data On TD-409 LWD Form
   iii. Calculate Average Deflection For All 10 Tests
g. Maximum Allowable Deflection
   i. The Maximum Allowable Deflection For Acceptance Testing Is The Average Deflection From The 10 Tests On The Test Section
      1. Report In mm To Three Decimals (0.001mm)
h. Send Final TD409 LWD Test Section Report To Geotechnical Engineering For Review

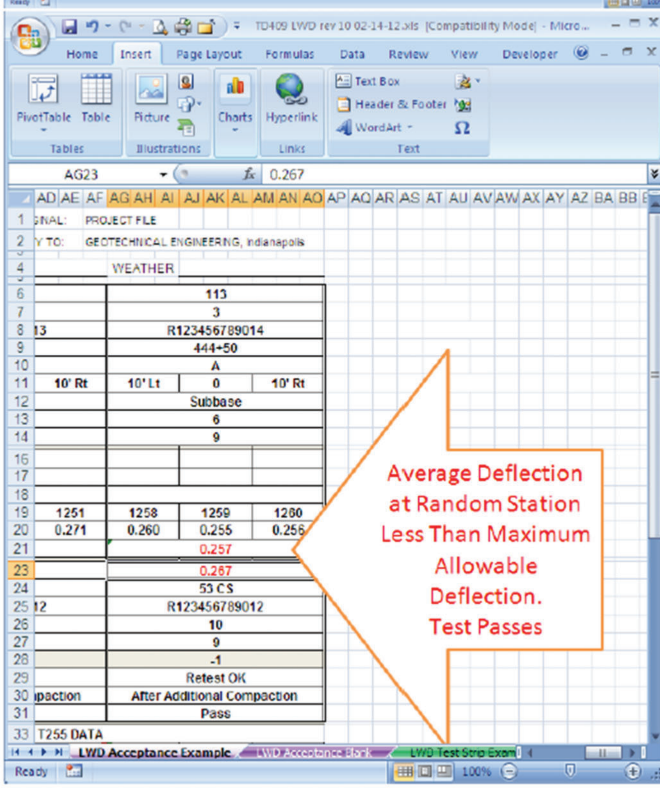
7. LWD Acceptance Testing

a. Test LWD Per Frequency Manual For Compacted Aggregate (1/800T)
   i. Select Random Station Per ITM 802
   ii. Perform 3 Complete LWD Tests At The Random Station
      1. One (1) "Complete LWD Test" per ITM 508 is defined as:
         a. 3 Seating Drops, Followed By:
         b. 3 Recorded Drops
         c. Reporting of Average Deflection "S_m" or "Θs"
   iii. Spread The 3 LWD Tests Across The Full Width Of The Material
      1. First Test Approximately 2' From Right Edge
      2. Second Test Near Centerline.
      3. Third Test Approximately 2' From Left Edge
   iv. Record Data On TD-409 LWD Acceptance Form As Average Of All 3 Tests
      1. Optionally: Use Zorn Software For Recording And Documenting Acceptance Tests As A Supplement To TD409

2. Deflection Average Of The 3 Tests Must Be ≤ Maximum Allowable Deflection From Test Section

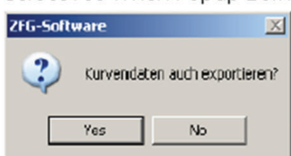


3.



4.

8. Reporting

a. Transfer Data To Computer With Zorn Software (Optional)
b. Produce Lab Report Showing Summary Of All Tests For The Day (Optional)
   i. Add GPS To Report Table (Optional)
      1. (Right Click On Table Header To Select Fields)
   ii. Use "Layer" Field To Enter Material Name
c. Print Lab Report (Optional)
d. Save Data In Zorn Software (Optional)
e. Use Software To Export To Excel CSV File (Optional Or Upon Request For Data Collection)
   i. Select | 'File' | 'Export Csv' |
   ii. Save Excel File: Contract Number And Date In File Name As A Minimum
   iii. Select Yes When Popup Box Appears In German Language
   iv. 

f. Use TD-409 (And Optional Printed Report) As Basis For SiteManager Data Entry And INDOT Acceptance
g. Email TD-409 (Required), Excel CSV File (Optional), And Related Reports (Optional), To INDOT Geotechnical Engineering At Completion
   i. Nayyar Siddiki Nsiddiki@Indot.In.Gov

APPENDIX B. ITM NO. 508-12T FIELD DETERMINATION OF DEFLECTION USING LIGHT WEIGHT DEFLECTOMETER

INDIANA DEPARTMENT OF TRANSPORTATION
OFFICE OF MATERIALS MANAGEMENT

FIELD DETERMINATION OF DEFLECTION USING
LIGHT WEIGHT DEFLECTOMETER
ITM No. 508-12T

1.0 SCOPE

1.1 This test method covers the determination of deflections of granular material with a Light Weight Deflectometer (LWD).

1.2 The LWD test relates deflection with the Dynamic Elastic Modulus and is defined as the maximum axial stress of a material in sinusoidal loading divided by the maximum axial strain during that loading.

1.3 The values stated in SI metric units are to be regarded as standard, as appropriate for a specification with which this ITM is used.

1.4 This ITM may involve hazardous materials, operations, and equipment and may not address all of the safety problems associated with the use of the test method. The user of the ITM is responsible for establishing appropriate safety and health practices and determining the applicability of regulatory limitations prior to use.

2.0 REFERENCES.

2.1 ASTM Standards.

E 2583 Measuring Deflections with a Light Weight Deflectometer (LWD)

3.0 SIGNIFICANCE AND USE. This ITM shall be used to determine the surface deflection resulting from an application of an impulse load using the LWD. The resulting deflections are used to determine the stiffness of granular materials in embankments and other applications.

4.0 APPARATUS.

4.1 Force-Generating Device (Appendix A), 10 kg ± 0.1kg falling weight with a guide system, lock pin and spring assembly. The mass of the guide rod is 5 kg ± 0.25 kg and the maximum impact force is 7.07 kN. The fixed drop height shall be in accordance with the manufacturer recommendation.

4.2 Loading Plate, made of steel, having dimensions of 300 mm in diameter and 20 mm in thickness. The plate shall have two handles and weigh 15 kg ± 0.25 kg.

4.3 Deflection Sensor, capable of measuring the maximum vertical movement with an accelerometer. The accelerometer is required to be attached to the center of the plate.

4.4 Data Processing and Storage System, capable of displaying and recording the loading data, deflection data, and the test location for each test

4.5 Miscellaneous equipment such as a spade, broom, trowel, and cotton gloves

5.0 TEST AREA PREPARATION. The test area shall be leveled so that the entire undersurface of the load plate is in contact with the material being tested. Loose and protruding material shall be removed. If required, any unevenness shall be filled with fine sand. The test shall not be conducted if the temperature is below freezing. The test area shall be at least 1.5 times larger than the loading plate.

6.0 PROCEDURE.

6.1 Rotate the loading plate approximately 45° back and forth to seat the plate. The plate should not move laterally with successive drops of the falling weight.

6.2 Place the force generating device onto the loading plate. Hold the guide rod perpendicular to the loading plate.

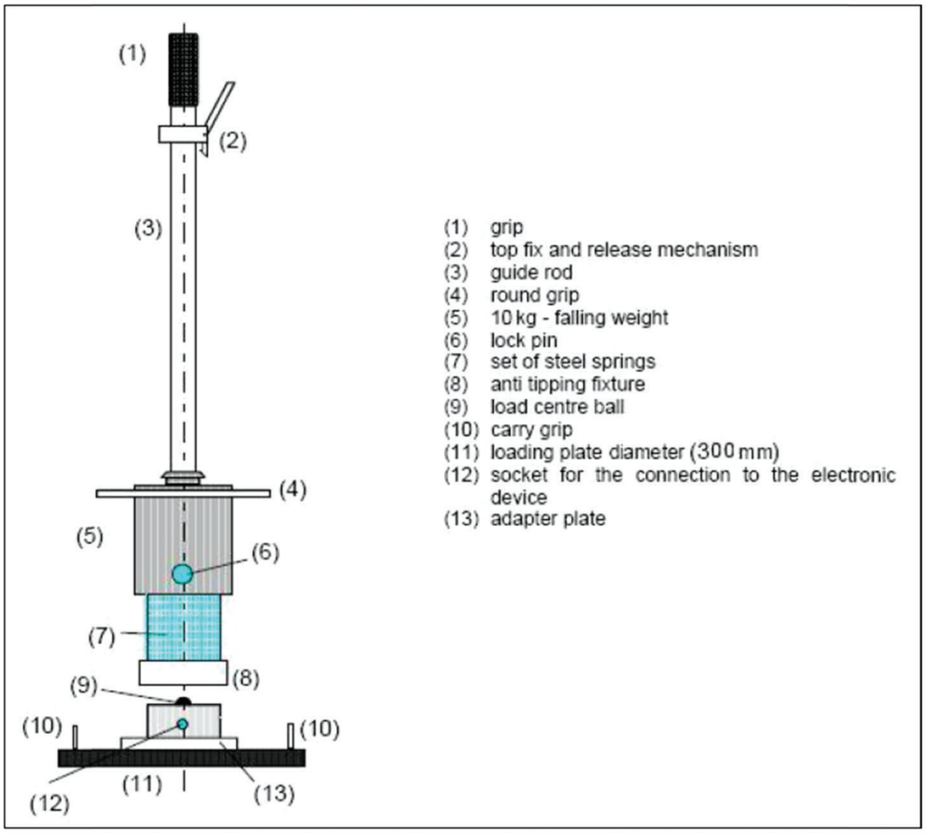
6.3 Conduct three seating drops by raising the falling weight to the release mechanism, allowing the hammer to fall freely, and catching the falling weight after the weight rebounds from striking the plate.

6.4 Following the three seating drops, conduct three drops of the falling weight and record the data for each drop. A test is considered invalid if the operator does not catch the falling weight after the weight rebounds from the load plate or the load plate moves laterally. A new test area is required at least 2 ft away from the original area of testing when the test is invalid. If the change in deflection is 10 % or greater for any two consecutive drops, the material shall require additional compaction or aeration and steps 6.1, 6.2, and 6.3 shall be repeated.

6.5 Record the smartcard number and the test drop deflection measurements on the data collection form.

7.0 CALCULATIONS. Calculate the average deflection of the three drops after the seating drops.

8.0 REPORT. Report the average deflection in mm.


(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(10)
(12)
(11)
(13)
(1) grip
(2) top fix and release mechanism
(3) guide rod
(4) round grip
(5) 10 kg - falling weight
(6) lock pin
(7) set of steel springs
(8) anti tipping fixture
(9) load centre ball
(10) carry grip
(11) loading plate diameter (300 mm)
(12) socket for the connection to the electronic device
(13) adapter plate

3/2/12

LIGHT WEIGHT DEFLECTOMETER TESTING

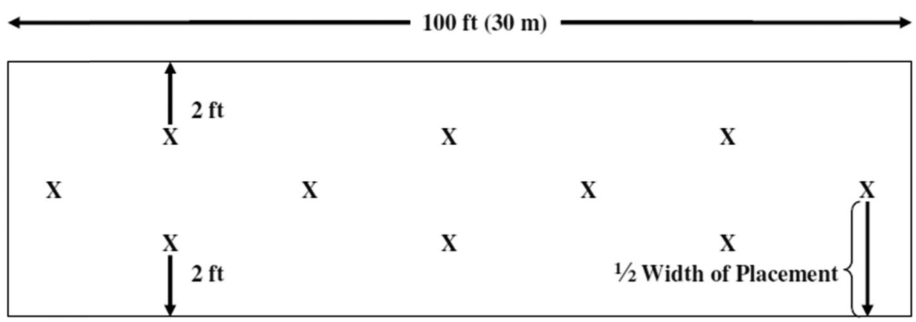
DESCRIPTION

This work shall consist of testing aggregates or chemically modified soils with a Light Weight Deflectometer, LWD. The compaction of the aggregates and chemically modified soils shall be in accordance with 301.06 and 215.09, respectively, and the requirements included herein.

TEST SECTIONS

The maximum allowable deflection will be determined based on a test section for each material type. Test sections shall be constructed in the presence of a representative of the Office of Geotechnical Services with the available equipment of the Contractor to determine the roller type, pattern, and number of passes for the maximum allowable deflection.

The Engineer will select an area approximately 100 ft (30 m) by the width of the material placed for the test section. Areas not meeting these minimum criteria will be considered. The subgrade shall be proofrolled in accordance with 203.26 prior to construction of the test section for aggregates. Chemically modified soils shall be cured at least 24 hours prior to testing of the test section. Moisture tests will be performed in accordance with AASHTO T 255 for aggregates at two random locations in the test section. The average of the two moisture content values shall be controlled within -3 and -1 percentage points of the optimum moisture content for aggregates. Ten tests will be performed on the test section at the following approximate locations:



Aggregate Test Section with LWD only

A test section shall be constructed and LWD testing will be performed to determine the maximum allowable deflection if only the LWD is used. The roller shall be operated in the vibratory mode and initially 4 passes shall be placed on the aggregate in the test section. The average deflection of the 10 random tests will be determined after completion of the 4 passes. One additional pass of the roller in the vibratory mode shall be made and 10 LWD tests will be taken at the same locations. If the difference between the average LWD test values obtained from 4 and 5 passes is equal to or less than 0.01 mm, the compaction will be considered to have peaked and the average of the 10 LWD values at 5 passes will be used as the maximum allowable deflection. If the difference between the average LWD test values is greater than 0.01mm, an additional roller pass in the vibratory mode shall be placed and 10 LWD tests will be taken at the same locations. This procedure will continue until the difference of the average of the 10 LWD tests between consecutive roller passes is equal to or less than 0.01 mm. The maximum allowable deflection will be the lowest average of the 10 LWD test values.

Aggregate Test Section with Density Control

In the aggregate test section, LWD testing will be performed concurrently with density testing performed in accordance with AASHTO T 310. The density shall meet the requirements of 301.06. The maximum allowable deflection will be the average of the 10 LWD test values.

Chemically Modified Soil Test Section with LWD and DCP

The LWD testing of the chemically modified test section will be conducted concurrently with the requirements of 215.09. The maximum allowable deflection will be the average of the 10 LWD test values.

COMPACTION ACCEPTANCE WITH LIGHT WEIGHT DEFLECTOMETER

The maximum allowable deflection will be determined from the test section. Acceptance testing with a LWD shall be in accordance with ITM 508.

The optimum moisture content and gradation will be determined by performing AASHTO T 99 Method C, AASHTO T11, and AASHTO T 27 on representative samples of the aggregates. The moisture content shall be controlled within -3 and -1 percentage points of the optimum moisture content.

Acceptance of the compaction of aggregates or chemically modified soils will be determined by averaging three LWD tests obtained at a random station determined in accordance with ITM 802. The location of the three tests will be at 2 ft from each edge of the construction area and at 1/2 of the width of the construction area. The average deflection shall be equal to or less than the maximum allowable deflection determined by the test section. The frequency of testing will be one test for each 800 t for compacted aggregate and one test for each 1400 yd^3 of chemically modified soil.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

About This Report

An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

The recommended citation for this publication is:

Volovski, M., Arman, M., & Labi, S. (2014). *Developing statistical limits for using the light weight deflectometer (LWD) in construction quality assurance* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2014/10). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284315504