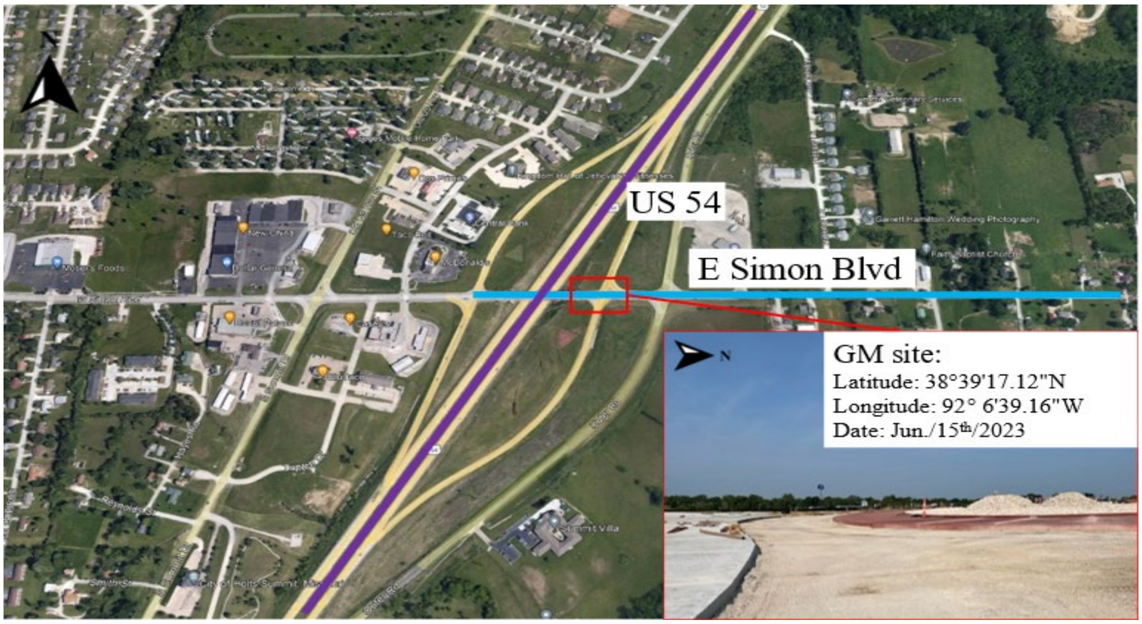
Implementing the LWD for MoDOT Construction Acceptance of Unbound Material Layers: Phase II



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16. Abstract
This Phase II project aimed to accumulate more field test data to improve the standards for the implementation of the Zorn lightweight deflectometer (LWD) for the acceptance of unbound materials layers. Five more different soils, including New Florence CL, Holts Summit GM, Sikeston SM, Rolla CL, and Rolla GM, were collected from different project sites in Missouri for this project, and a series of laboratory and field tests were conducted. In addition, a disturbance isolation unit was devised for accurate field moisture measurement, ensuring reliable data collection. Field LWD tests were conducted across four project sites, evaluating moisture content and modulus ratios against specified criteria for compaction acceptance. Results indicated varying degrees of compliance across soil types and testing points. Comparisons of test results obtained from different LWD devices and with traditional density-based methods revealed LWD's effectiveness for fine-grained soils but limitations for coarse-grained soils. Consistency between LWD devices was generally good, though discrepancies were noted at certain sites. Overall, the project advances LWD implementation for unbound materials acceptance, offering insights into soil behavior under different conditions and refining testing methodologies for improved accuracy and efficiency.

17. Key Words
Unbound materials; Construction acceptance; LWD implementation; Moisture content analyzer

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Final Report

Disclaimer

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List of Abbreviations and Acronyms

AASHTO .... American Association of State Highway and Transportation Officials
CL .... lean clay
COV .... coefficient of variation
DOT .... department of transportation
GM .... silty gravel
I-270 ....Interstate 270
I-44 ....Interstate 44
LWD .... lightweight deflectometer
MC .... moisture content
MDD .... maximum dry density
MO .... Missouri
MoDOT .... Missouri Department of Transportation
OMC .... optimum moisture content
PC .... percent compaction
QA .... quality assurance
QC .... quality control
R^2 ....coefficients of determination
RC .... relative compaction, also known as percent compaction
RLTT .... repeated load triaxial test
SM .... silty sand
SWCC .... soil water characteristic curve
USCS .... Unified Soil Classification System

Executive Summary

This Phase II project aimed to accumulate more field test data to improve the standards for the implementation of the Zorn lightweight deflectometer (LWD) for the acceptance of unbound materials layers. Five more different soils were selected and collected from different project sites in Missouri for this project, and a series of laboratory and field tests were conducted. In addition, a field moisture analyzer system was designed and validated for accurate and effective moisture measurement in the field.

The four project sites were from New Florence Intersection Enhancement project, Holts Summit Roundabout project, Sikeston Overpass over US 60 project, and Rolla Interstate-44 (I-44) Improvement project, where three soil types including lean clay (CL), silty gravel (GM), and silty sand (SM) were tested (one from each of the first three projects and two from Rolla I-44 project). Soils were named with their source sites and types, for example, the CL collected from New Florence was named New Florence CL.

Laboratory tests were conducted to determine basic properties of the five collected soils, including sieve analysis, Atterberg limits, and modified Proctor test. With maximum dry densities (MDDs) and optimum dry densities (OMCs) determined by modified Proctor tests, all collected soils were prepared at a relative compaction (RC) of 95% and various moisture contents for LWD tests on Proctor mold and repeated load triaxial tests (RLTTs).

In lab LWD tests, also known as the LWD test on Proctor mold, each soil was tested at five moisture contents and seven stress levels. The five moisture contents included two moisture contents lower than the OMC, two moisture contents higher than the OMC, and the OMC, respectively. The seven stress levels were 11 psi, 15 psi, 19 psi, 22 psi, 24 psi, 29 psi, and 38 psi, respectively. Except for New Florence CL, the rest three types of soils (i.e., Holts Summit GM, Sikeston SM, and Rolla CL) showed an increasing trend in deflection and a decreasing trend in LWD modulus with the increase of moisture content. In lab LWD tests conducted on Holts Summit GM, Sikeston SM, and Rolla CL, the increase of deflection became more significant as the moisture content increased beyond the OMC though dry densities were comparable. Moreover, the deflection was found to increase with the increase of applied stress. The LWD modulus generally decreased as the moisture content increased, with a steeper gradient at moisture contents higher than the OMC, and the LWD modulus also increased with the increase of applied stress. It was observed that for New Florence CL, the deflection and the LWD modulus increased with the increase of applied stress but varied insignificantly with the increase of moisture content.

In resilient modulus tests, known as RLTTs, each soil was tested at the identical five moisture contents used in their LWD tests on Proctor mold. Testing sequences for base/subbase soils recommended in the specification were used for facilitating the comparison between different types of soils. Stress dependency was noticed during the tests. The resilient modulus was found to increase as the applied stress increased at all stress levels on the two coarse-grained soils (i.e., Holts Summit GM and Sikeston SM) and low stress levels on the two fine-grained soils (i.e., New Florence CL and Rolla CL). The resilient modulus decreased with the increase of applied stress at high stress levels on these two fine-grained soils. For all tested soils, their peak resilient moduli at each tested moisture content were found to decline gradually as the moisture content increased.

A disturbance isolation unit was designed to accommodate Ohaus MB 120 to be used in the field with adequate accuracy and effectiveness. The disturbance isolation unit included a 1000 W power invertor, four vibration isolation elements, a leveling platform, and a covering hood for Ohaus MB 120. The

system was examined with a series of field tests. It was found that the four isolation elements were sufficient to isolate the vibration from surroundings, and a hood was effective to isolate the wind disturbance that made the device fail to tare and meet the switch-off criterion for automatically ending the drying process. In addition, lab tests were designed and performed to develop a proper operation procedure, with recommendations of the sample weight and switch-off criterion. According to lab drying testing results, a drying weight of 10 gram was suggested for soils having mostly small particles, such as Rolla CL and Sikeston SM, and 30 gram was recommended for gravel materials. As for the selection of switch-off criterion, the reduction of sample weight became not noticeable as the drying duration extended. Thus, a moderate switch-off criterion, such as 1mg/60s indicating no more than one milligram change within 60 seconds, was recommended. In addition, with results of drying tests obtained from Ohaus MB 120 and Oven, calibration coefficients of 1.20 and 1.06 are recommended for non-gravel and gravel materials, respectively.

Field LWD tests were conducted with three LWD devices, including LWDs #3878, #3879, and #4421, at all four sites abovementioned. 162, 126, 132, 81, and 81 tests were conducted at New Florence CL, Holts Summit GM, Sikeston SM, Rolla CL, and Rolla GM sites, respectively. A series of contours were plotted to visually illustrate the distribution of field moisture content and LWD modulus at testing sites. Colors in contours showing LWD moduli measured with different LWDs generally matched well, indicating good consistencies among these three LWD devices. Good correlations, indicated by the match of colors in contours of moisture content and LWD modulus, were observed at most points at two fine-grained soil sites (i.e., New Florence CL and Rolla CL). For the remaining three coarse-grained soil sites, including Sikeston SM, Holts Summit GM, and Rolla GM, the good correlation occurred at half number of points at Sikeston SM site but barely could be perceived at the other two GM sites.

With measured field moisture contents and target LWD moduli predicted based on characteristics of LWD tests on Proctor mold, testing points at all sites were evaluated according to the moisture content and modulus ratio criteria. The first evaluation was to check if the moisture content of a testing point is within the acceptable range (OMC-3% ~ OMC). If test points passed the first evaluation, the modulus ration evaluation would be performed to assess if the ratio of measured field LWD modulus to predicted target LWD modulus was greater than or equal to one. Only the soil that met both criteria was considered acceptable for the compaction. In summary, New Florence CL site had 20 out of 72 with acceptable moisture contents, however, among them none was considered acceptable for any LWD. Holts Summit GM site had 25 out of 42 points having acceptable moisture contents, and 24, 22, and 24 out of these 25 points were evaluated as acceptable for LWDs #3878, #3879, and #4421, respectively. Among the 44 points tested at Sikeston SM site, 38 of them were found acceptable in terms of their moisture contents. Out of these 38 points, 30 and 35 points were found acceptable eventually for LWDs #3878 and #3879, respectively, while only 10 points had modulus ratios no less than one for LWD #4421. At Rolla site, 27 points were tested for each of the CL and the GM. Among these, the CL had only three points with acceptable moisture contents, while the GM had four. For Rolla CL, only one point was considered acceptable for LWD #3878. On the other hand, for Rolla GM, only LWD #3879 rejected one point while the other two LWDs accepted all the four points that met the moisture content criterion. Overall, the three coarse-grained soils (i.e., Holts Summit GM, Sikeston SM, and Rolla GM) showed better evaluation results than the two fine-grained soils (i.e., New Florence CL and Rolla CL), which primarily resulted from the excessively high moisture contents in the two fine-grained soils. The consistencies between LWD devices in terms of compaction acceptance were found good for all sites, except for Sikeston site where LWD #4421 qualified less points than the other two LWDs.

When compared with the NDG density-based evaluation method, LWD performed reasonably well for fine-grained soils such as clay but poorly for coarse-grained soils. Among the three different LWD devices, results from LWD#3878 and #3879 were more consistent with the NDG density-based evaluation method than those from LWD#4421.

Chapter 1. Introduction

1.1 Problem Statement

Conventional density-based methods of compaction quality assurance (QA) using nuclear density gauges (NDG) have been the practice for many years. However, NDG testing becomes less desirable because of safety, regulatory, and cost concerns. In addition, density is not a direct input to the structural design of the pavements and is not directly linked to pavement performance. In recent years, modulus-based compaction QA of unbound materials using the lightweight deflectometer (LWD) is gaining attention, as it can not only result in a better constructed product but also provide the engineering properties critical for better understanding of the connection between pavement design and long-term pavement performance. Moisture content is one of the main factors influencing soil modulus and should also be performed concurrent with field modulus measurement. However, existing LWDs do not have the function to measure moisture content.

In 2020, Missouri Department of Transportation (MoDOT) funded Missouri University of Science and Technology (S&T) a project entitled “Implementing the LWD for MoDOT Construction Acceptance of Unbound Material Layers,” which is referred to as “Phase I project” hereafter. In this study, a national survey on acceptance of LWD and a substantial literature review were first carried out to study the status of LWD application. Then, four types of representative soils from two projects sites provided by MoDOT were selected to investigate the implementation of LWD for construction acceptance of unbound materials. Four LWD devices including three Zorn ZFG 2000 and one Zorn ZFG lab 3.0, were used in laboratory and field tests. Furthermore, two moisture content analyzers including Aggrameter and Ohaus MB 120 were chosen to evaluate their practicability of quick moisture content measurement in the field.

In Phase I project, it was concluded that the LWD is a promising tool for construction acceptance evaluation of unbound material layers such as well graded sands and clay soils. The LWDs successfully captured the LWD modulus changes with variations in moisture content in the soil. Among the four soils, only the two coarse-grained soils (i.e., SGB sand and base aggregate) had acceptable moisture contents, while the two clayey soils had field moisture contents much higher than their optimum moisture contents (OMC) and cannot be used to evaluate the LWD performance and develop specifications for future usage. Therefore, there is a great need to test more types of soils from different sites to have more meaningful and representative specifications.

In addition, in Phase I project, results indicate that neither the Aggrameter nor the Ohaus MB 120 moisture analyzer performed well in the field. The Aggrameter worked well only on the SGB sand, while gave constant readings on the two clayey soils, regardless of actual moisture content in soils. It was also very difficult to insert the Aggrameter into granular soils. On the other hand, compared with laboratory oven-drying method, the Ohaus MB 120 had excellent performance in the vibration-free laboratory environment after proper calibrations. However, when being used in the field, the Ohaus MB 120 was very sensitive to vibrations and disturbances and stopped working. Since the working mechanism of Ohaus MB 120 was the same as that of oven-drying method, the Ohaus MB 120 should be able to generate accurate results in the field if methods are used to eliminate vibrations.

In Phase I project, a two-step construction acceptance evaluation method was proposed to qualify the compaction quality of unbound materials, where the first step is the moisture content evaluation, and the second one is the LWD modulus ratio evaluation. However, the method was developed based upon limited data and soil types. More data are needed to enrich and validate the proposed method which can cover a larger range of soil types and applications. In addition, the procedures should be simplified so that the proposed specifications can be easily used by MoDOT engineers with minimum training.

1.2 Research Objectives

The principal objective of this Phase II project is to accumulate more field test data to improve standards for the implementation of the Zorn LWD for acceptance of unbound material layers. This includes following elements:

- Identify/develop vibration isolation solutions for the Ohaus MB 120 moisture analyzer so that it can be used in the field together with LWDs for QA purposes,
- Perform laboratory LWD tests on samples of various soil types prepared at different moisture contents, and determine target modulus ranges for field LWD tests,
- Perform field LWD tests and evaluate impacts of moisture, stress states, and time and spatial variability on measured LWD modulus,
- Compare target and measured field LWD modulus and verify the proposed LWD modulus-based QA approach under field conditions, and
- Simplify the LWD modulus-based QA specifications so it can be easily used by MoDOT engineers with minimal training.

1.1 Research Methodology

The following major tasks were accomplished to meet the objectives of this study:

- Task 1: Project site and soil selections
- Task 2: Laboratory testing
- Task 3: Field testing
- Task 4: Data reduction and analysis
- Task 5: Refine and simplify the draft specification

Task 1: Project Site and Soil Selections
In consultation with the Technical Assistance Committee with the intention of spanning a range of embankment, subgrade, and base geo-materials, four construction sites from four projects were selected in Missouri, as described in section 2.1. From the four sites, five different unbound geo-materials covering applications of subgrade, embankment, and base course were selected and collected.

Task 2: Laboratory Testing
A comprehensive laboratory testing program was conducted on soil samples collected from construction sites. Laboratory tests are listed as follows, and more experimental details are presented in Chapter 2. In addition, in Chapter 3, a unit was designed to overcome the disturbance hindering the field moisture analyzer, Ohaus MB 120, from working properly, which was validated with field drying tests. Moreover, optimization in drying accuracy and efficiency with considerations of sample weight and switch-off criterion was conducted with lab drying tests.

- Fundamental material properties including gradation (ASTM D6913, 2021), Atterberg limits (ASTM D4318, 2018), and specific gravity (ASTM C127, 2016; ASTM D854, 2016);
- Soil classification based upon both Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) soil classification system (AASHTO M 145, 1991; ASTM D2487, 2020);
- Modified Proctor tests (ASTM D1557, 2021) to obtain OMCs and maximum dry densities (MDD);
- LWD tests on Proctor mold at five different moisture contents and seven stress levels with Zorn Lab 3.0 LWD;
- Repeated loaded triaxial tests (AASHTO T 307, 1999) at the moisture contents identical to those in LWD tests on Proctor mold; and
- Drying tests with Ohaus MB 120.

Task 3: Field Testing
A total of five field-testing campaigns were performed in this project, in addition to the other five trips made to the field for collecting samples. These five different unbound geo-materials were from the subgrade, embankment, and base course. Details of field-testing activities and analysis of test results are provided in Chapter 4, as well as the evaluation of moisture content and field to target LWD modulus ratio acceptance for each material.

Task 4: Data Reduction and Analysis
All testing data from lab and field tests was summarized and analyzed. A comprehensive data analysis was conducted including:

- Determining coefficients in mechanistic-empirical pavement design guide (MEPDG) model by means of regression.
- Characterizing relations between LWD modulus, applied stress, and moisture content for prediction of target LWD modulus.
- Further optimizing the operation of Ohaus MB 120 with considerations of sample weight and switch-off criterion.
- Evaluating Zorn 2000 LWDs in the field by means of calculating, summarizing, and analyzing Zorn LWD moduli measurements at different sites.
- Correlating field LWD moduli with laboratory LWD moduli, in terms of field to target modulus ratios (E_{field}/E_{target}), for compaction acceptance.

Task 5: Refine and Simplify the Draft Specification
The draft *Modulus-based Construction Acceptance Testing of Unbound Material Layers with a Lightweight Deflectometer* developed in Phase I project are used as references for lab and field testing in Tasks 2 and 3. Therefore, the research team used this document as the basis, and revised and refined the document to incorporate findings from this study including the new developed rapid field moisture measurement system including the Ohaus MB120, as well as recommended sample weights and switch-off criterion that meet both accuracy and efficiency requirements. The guideline was drafted in the format of MoDOT's Engineering Policy Guide. An Excel calculation spreadsheet was developed to simplify the data analysis for DOT engineers.

Chapter 2. Laboratory Tests

This chapter mainly involves descriptions of laboratory testing plan, equipment, and testing result analysis. Firstly, sampling locations of different types of soils are introduced, as well as their classifications according to both USCS and AASHTO soil classification system. In addition, methods of modified Proctor compaction tests for each soil are presented, following which results including MDD and OMC are shown. The relationship between water content and suction for each soil is characterized by the soil water characteristic curve (SWCC). Besides, testing plans of LWD tests on Proctor mold, such as applied stresses, moisture contents, and the relative compaction (RC) are presented, and results including in-mold moisture content, deflection, and LWD modulus are analyzed. Finally, to evaluate the collected materials' stress dependency properties, the testing method, and results of repeated load triaxial tests (RLTT) are discussed.

2.1 Soil Sources and Classifications

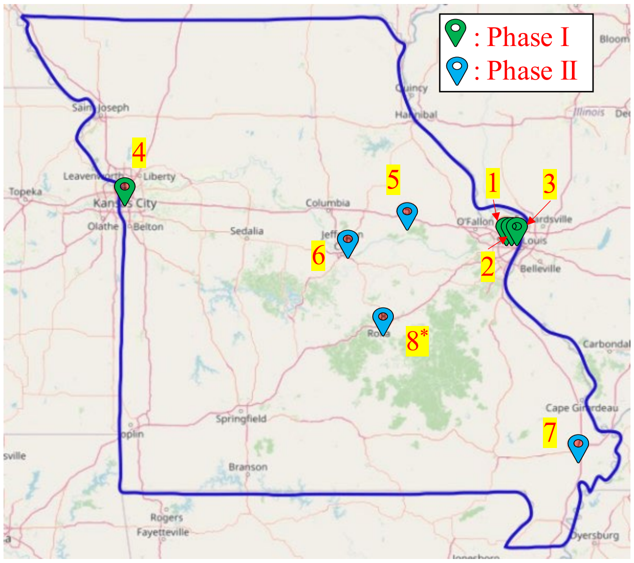
2.1.1 Soil Sources and Applications

A total of eight construction sites were selected in projects including Phases I and II, as shown in Table 2.1, covering a wide range of soil sources in Missouri. In the Phase I project, construction sites were mainly from two projects, as indicated with green map pins, with first three sites from Interstate 270 (I-270) North project in St. Louis and the fourth site from Buck O'Neil Bridge Design-Build project in Kansas city (Zhang et al., 2022). The four constructions sites involved in the Phase II project came from four different projects, which are indicated with blue map pins. The fifth site was from Missouri Route 19 Bridge Replacement and Interchange Improvement over I-70 project in New Florence, New Florence project hereafter. Soil samples were collected from the borrow site for project, which was compacted as pavement subgrade. The sixth site was a roundabout construction site in U.S. Route 54 and OO Roundabout Construction in Callaway project, Holts Summit project hereafter. The soil compacted as base course was sampled from the quarry where it was produced, as no spare sample was available in the field. A type of sandy soil was compacted as an overpass approach (embankment) at the seventh site in Sikeston for Route 60 in New Madrid County Reduced for Ingram Overpass Construction project. For the eighth site, it was a part of Interstate 44 (I-44) Phelps/Crawford County Improvements project, in which over 50 miles of I-44 in Phelps and Crawford counties underwent several improvements. Soils compacted as both subgrade and base course were sampled from the field.

2.1.2 Soil Classifications

Basic soil properties including gradation, liquid limit (LL), plastic limit (PL), and plasticity index (PI) were determined for the soil classification based on the USCS and AASHTO soil classification systems. Soils were named after their sources and USCS classifications. For example, the soil sampled from New Florence was named New Florence CL, where New Florence was its source and CL was its classification based on USCS.

Table 2-1 Soil sources.



No.	Location	Soil	Application
1	St. Louis	CL	Subgrade
2	St. Louis	SW	MSE wall backfill
3	St. Louis	GW	Base course
4	Kansas City	CL	Bridge approach foundation
5	New Florence	CL	Subgrade
6	Holts Summit	GM	Base course
7	Sikeston	SM	Overpass approach
8*	Rolla	CL	Subgrade
8*	Rolla	GM	Base course

* Sites worked for the intelligent compaction (IC) project

As shown in Figure 2-1, three out of the five soils (i.e., Holts Summit GM, Sikeston SM, and Rolla GM) were coarse-grained soils with passing rates at #200 (0.075 mm) less than 50%, while the rest two were fine-grained soils including New Florence CL and Rolla CL with more than 50% particle passing #200. Hydrometer tests were conducted on the two fine-grained soils to investigate particle distribution under #10 sieve. For the two fine-grained soils, Atterberg limits (i.e., LL, PL, and PI) were evaluated for with samples passing #40 according to ASTM D4318 (ASTM D4318, 2018), while those of the three coarse-grained soils were not measured. Results of Atterberg limits are shown in Table 2-2, in which specific gravities, G_s, evaluated according to ASTM D854 (ASTM D854, 2016) are included, as well as soil classifications. The five collected soils were classified according to USCS and AASHTO soil classification system (AASHTO M 145, 1991; ASTM D2487, 2020) based on Atterberg limits and sieve analysis results. The soil compacted as a subgrade in New Florence was classified as lean clay with sand (CL), the soil used in a base course in Holts Summit was classified as silty gravel with sand (GM), the soil sampled from the overpass approach in Sikeston is classified as silty sand (SM), and the two soils compacted as a subgrade and base course in Rolla were categorized into sandy lean clay (CL) and silty gravel with sand (GM), respectively.

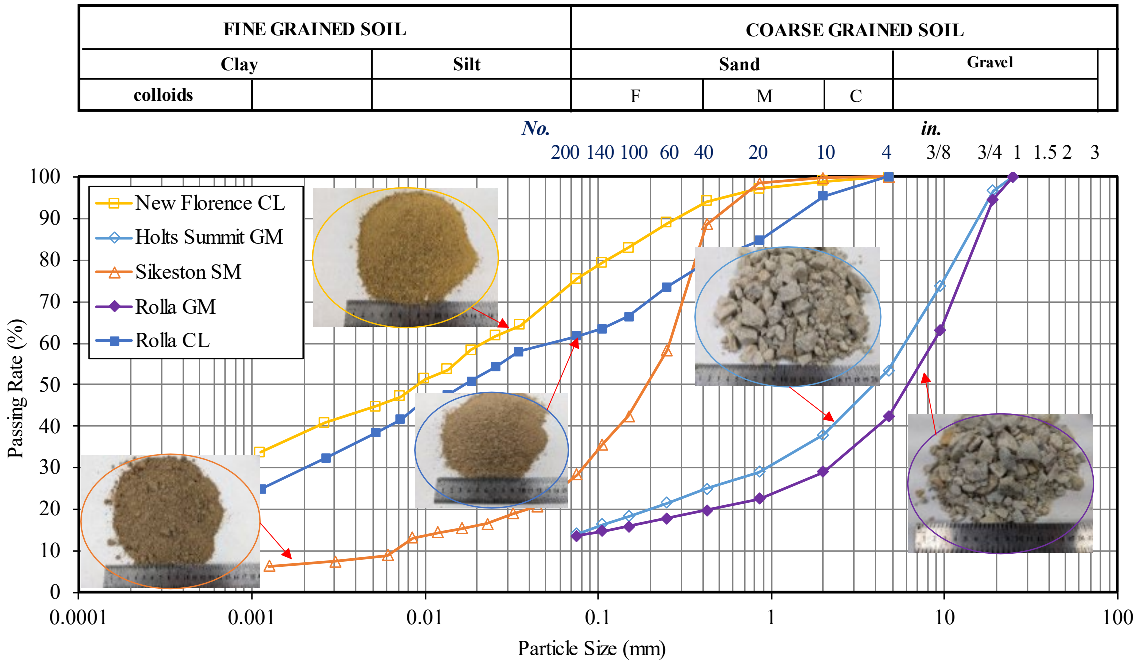


Figure 2-1 Gradations of the five soils.

Table 2-2 Fundamental soil properties.

Soil	P_{200}[1]	LL	PL	PI	G_s	Classification	
						AASHTO	USCS
-	%	%	%	%	-	-	-
New Florence CL	75.4	41	15	26	2.742	A-7-5	CL with sand
Holts Summit GM	14.1	-	-	-	2.789	A-1-a	GM with sand
Sikeston SM	28.4	-	-	-	2.623	A-2-4	SM
Rolla CL	61.6	31	15	16	2.697	A-6	Sandy CL
Rolla GM	13.6	-	-	-	2.617	A-1-a	GM with sand

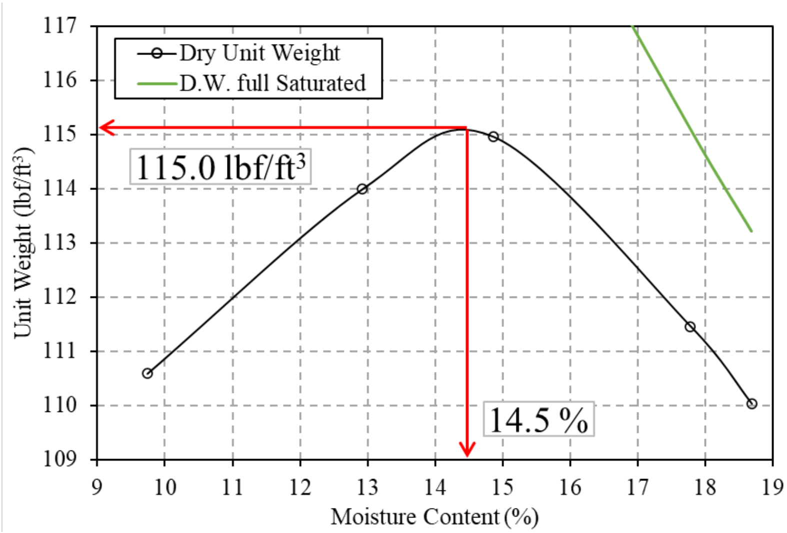
1. P_{200}, percent passing sieve #200.

2.2 Modified Proctor Test

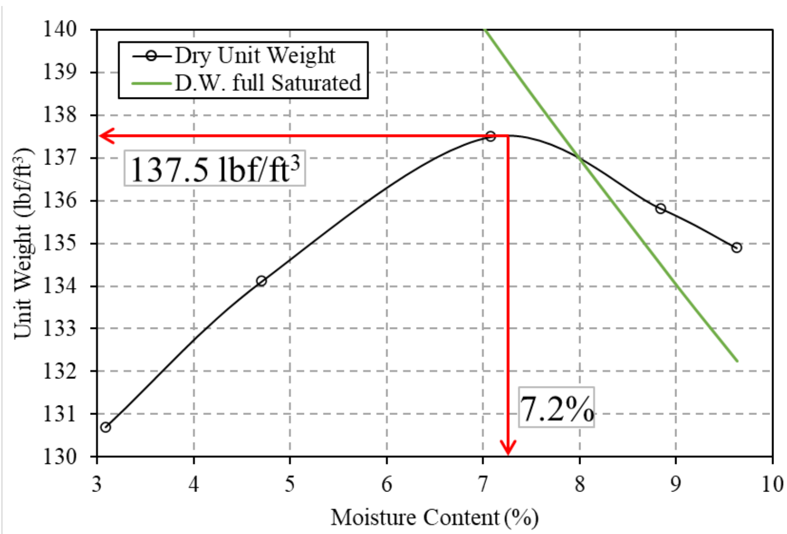
Modified compaction tests were conducted on the five soils according to ASTM D1557 (ASTM D1557, 2021) to determine their OMCs and MDDs, as their percentages retained on 3/4 in. (19 mm) were all lower than 30%. The two fine-grained soils (i.e., New Florence CL and Rolla CL) and Sikeston SM were compacted using the method A, in which specimens were compacted in a 4 in (101.6 mm) mold in 5 layers, and each layer was subjected to 25 blows with a 10-lbm (4.5-kg) hammer dropping at a height of 18 in (457 mm). GMs collected from Holts Summit and Rolla were compacted following the method C, as they had more than 60% particle retained on 3/8 in. (9.5 mm) sieve. GM specimens were compacted in a 6 in (152.4 mm) mold in 5 layers, and each layer was subjected to 56 blows with a 10-lbm (4.5g) hammer falling at 18-in (457-mm) height. A summary of methods and results of modified Proctor compaction tests for the five soils is shown in Table 2-3, and Figure 2-2 presents their moisture-density curves.

Table 2-3 OMCs and MDDs for the five collected soils.

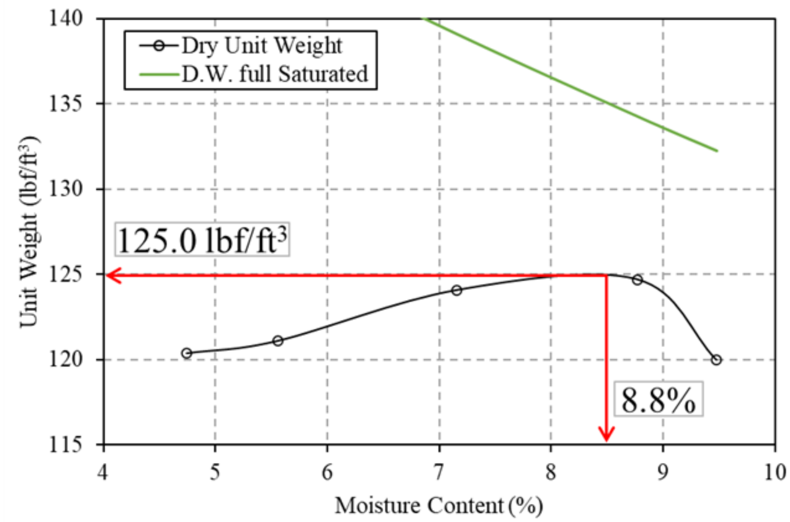
Soil types	Method	Mold dia.	Layers * Blows per layer	MDD	OMC
-	-	in	-	lbf/ft^3	%
New Florence CL	A	4	5 * 25	115.0	14.5%
Holts Summit GM	C	6	5 * 56	137.5	7.2%
Sikeston SM	A	4	5 * 25	125.0	8.8%
Rolla CL	A	4	5 * 25	122.0	11%
Rolla GM	C	6	5 * 56	137.8	7.9%



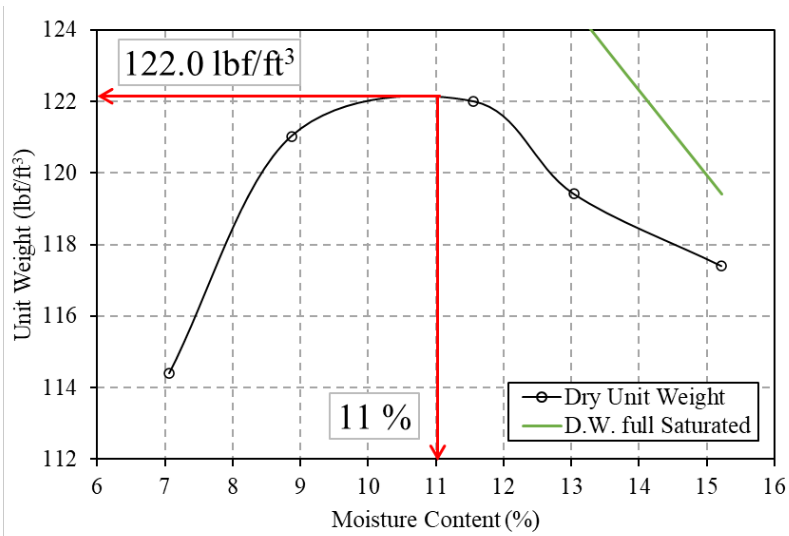
(a) New Florence CL



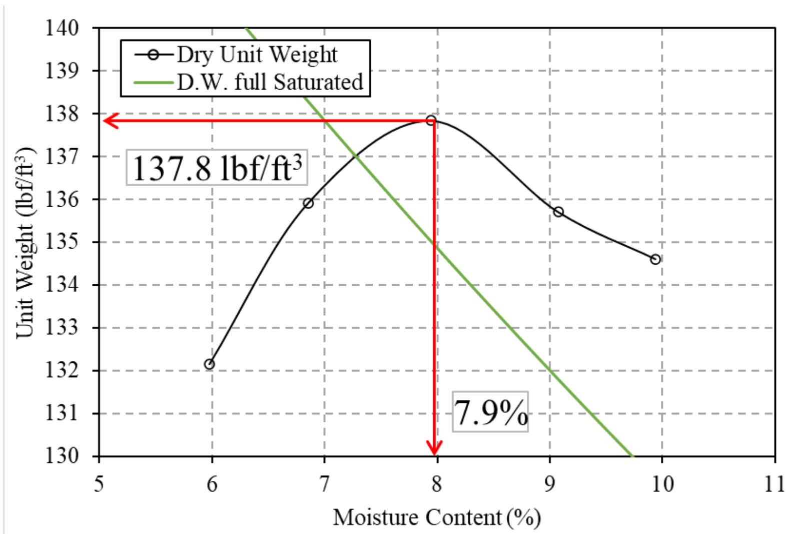
(b) Holts Summit GM



(c) Sikeston SM



(d) Rolla CL



(e) Rolla GM

Figure 2-2 Moisture-density relationships of the four soils.

2.3 Soil Water Characteristics Curve Test

Tensiometer and salt concentration tests were performed to determine the ability of soils to hold water under unsaturated conditions, which is characterized by the soil water characteristics curve (SWCC), also known as water retention curve. The tensiometer test was responsible to capture the curve at a suction lower than 145 psi, while the suction measurement by means of salt concentration test ranged from 87 psi to 4753.8 psi.

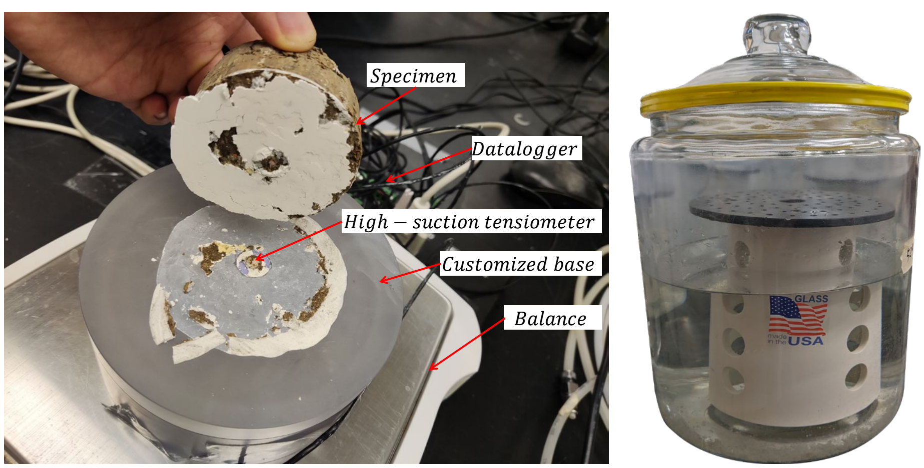


Figure 2-3 Tensiometer test (left) and one of jars used for salt concentration test (right).

The tensiometer test has been used in the field of unsaturated soils to measure the suction (Li & Zhang, 2014). In the tensiometer test, as shown in Figure 2-3, a customized base installed with a calibrated high-suction tensiometer on top was set on a balance, and a saturated specimen was positioned upon the tensiometer with a thin layer of saturated Kaolinite applied between them for ensuring a good contact. Readings of tensiometer and balance were recorded throughout testing by dataloggers. With the dry mass of specimen determined after completion of tensiometer test and the mass change recorded during the test, the moisture content change could be derived.

The salt concentration test, a thermodynamics-based technique, is usually conducted in a series of jars containing different concentrations of solutions (Figure 2-3). The variation in concentrations of solutions led to different relative humidity levels in jars, which corresponded to various suction levels as summarized in Table 2-4. In each of jar, a saturated specimen was first set on the platform, and gradually the moisture content of specimen and the relative humidity came to an equilibrium after two to four weeks. Then the specimen was retrieved to determine the moisture content.

Table 2-4 Solution concentrations and corresponding suction levels.

Mg Cl_2 (oz/gal)	Suction (psi)
1.21	93.3
2.54	189.0
5.09	397.3
6.36	511.0
8.90	760.6
12.72	1196.4
19.08	2110.9
38.72	4753.8

With moisture contents and suction values measured in the two tests, SWCCs of four soils were characterized and formulated as a nonlinear sigmoid function using two four-parameter equations (Equation 2-1) proposed by van Genuchten (1980) and Fredlund and Xing (1994), respectively.

$$w_w = w_r + \frac{w_s - w_r}{[1 + (\alpha\psi)^n]^m}$$

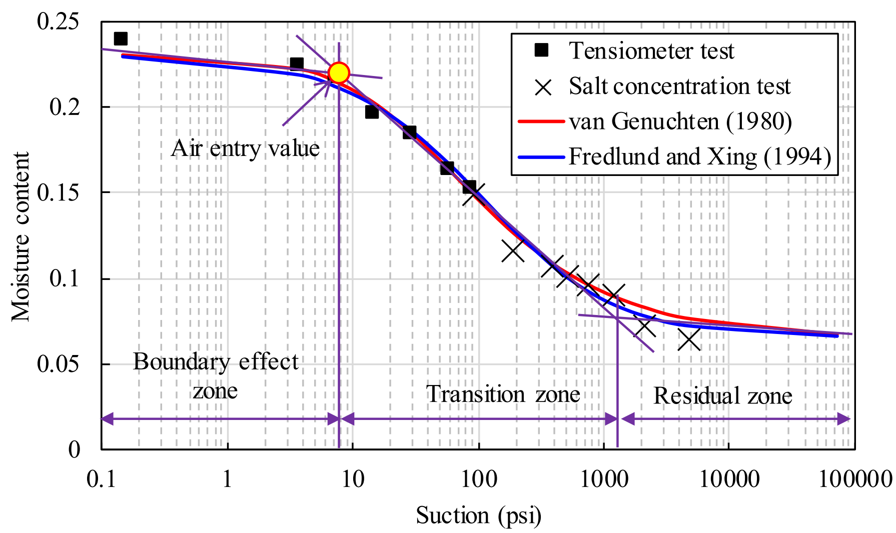
$$w_w = w_r + \frac{w_s - w_r}{\left\{ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m}$$

where

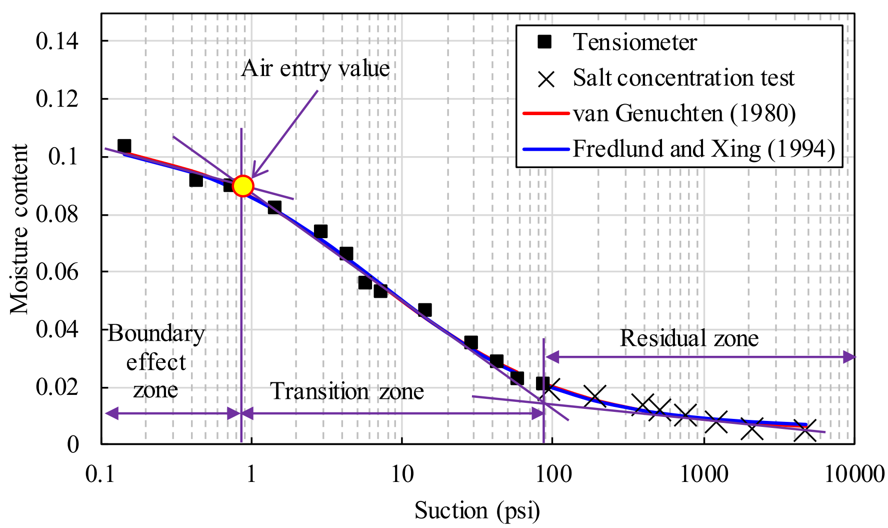
w_w = moisture content,
w_r = residual moisture content,
w_s = saturation moisture content,
ψ = the suction,
e = Euler's number, and
α, n, m = fitting parameters.

Equation 2-1 SWCC formulars by van Genuchten (first), and Fredlund and Xing (second).

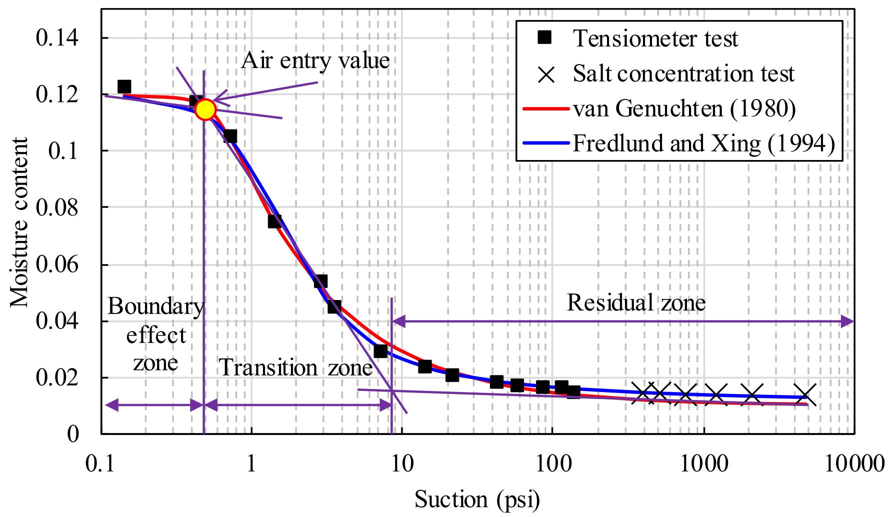
Figure 2-4 shows SWCCs of the four collected materials based on results of two laboratory tests. Results indicate that the two clay soils (i.e., New Florence CL and Rolla CL) had much higher moisture contents at the same suction values compared with the two coarse-grained soils including Holts Summit GM and Sikeston SM. A SWCC consists of three zones separated by two key transition points including the air-entry value and the residual value (Fredlund et al., 2012). The first zone, known as the boundary effect zone, has low suction, and the soil is in an entirely saturated condition. A decrement in moisture content does not generate a substantial increase in suction until a point at which some air bubbles start to appear in the soil skeleton, and the suction corresponding to this point is known as the air entry value. Air entry values were approximately 8.50 psi, 0.85 psi, 0.50 psi, and 10 psi for New Florence CL, Holts Summit GM, Sikeston SM, and Rolla CL, respectively. The second part of SWCC is known as the transition zone starting with the air-entry value and ends with the residual value, in which a significant reduction in moisture content is required for any further suction increase. Residual values were around 1200 psi, 90 psi, 8.50 psi, and 400 psi for New Florence CL, Holts Summit GM, Sikeston SM, and Rolla CL, respectively. In the third part, known as the residual zone starting with the residual value, the suction of the soil considerably increases with any decrement of moisture content. In addition, parameters in Equation 2-1 determined for the four soils are listed in Table 2-5.



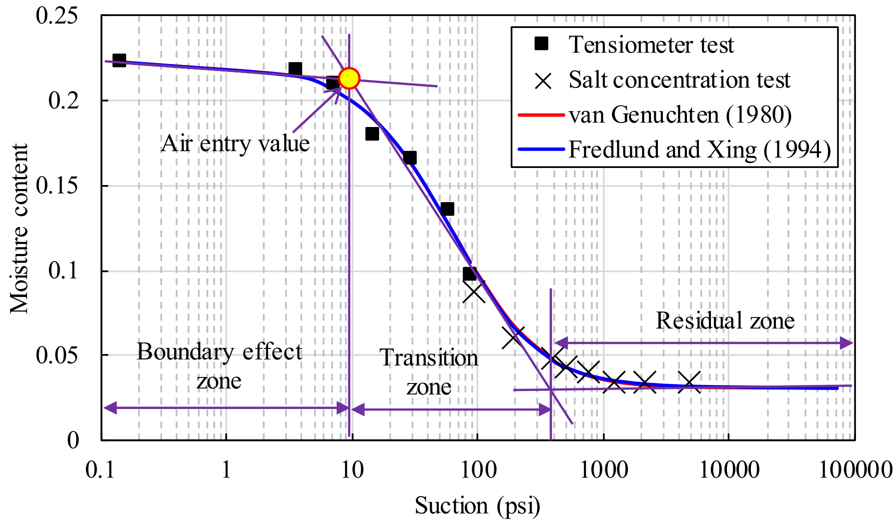
(a) New Florence CL



(b) Holts Summit GM



(c) Sikeston SM



(d) Rolla CL

Figure 2-4 SWCC for the four soils.

Table 2-5 Fitting parameters and R^2 of two SWCC models for the four soils.

Models	Para.	New Florence CL	Holts Summit GM	Sikeston SM	Rolla CL
van Genuchten (1980)	w_s	0.231	0.109	0.120	0.223
	w_r	0.065	0.005	0.010	0.031
	m	0.539	0.877	0.133	1.333
	n	0.991	0.698	4.719	1.073
	α	0.028	0.193	1.610	0.012
	R^2	0.993	0.996	0.997	0.993
Fredlund and Xing (1994)	w_s	0.231	0.109	0.120	0.223
	w_r	0.065	0.005	0.010	0.031
	m	3.046	2.716	1.286	3.419
	n	0.732	0.636	2.034	1.050
	α	145.104	7.939	1.194	84.368
	R^2	0.991	0.996	0.9982	0.994

2.4 LWD Test on Proctor Mold

The applied stress and moisture content have significant influence on mechanical behavior of soil, which is the LWD modulus in the project. The relationship between them, characterized by a quadratic equation with two variables (applied stress and moisture content) as later shown in Section 2.4.3, is utilized to provide a reference, the target LWD modulus, for the field soil compaction evaluation using an LWD. Therefore, in this section, LWD tests on Proctor mold were conducted at various applied stresses and moisture contents for different soils to generate dataset for characterizing the relationship.

The procedure of conducting a LWD test on Proctor mold is straightforward (ASTM E3331, 2022). With a trimmed specimen prepared in a Proctor mold, the collar was reattached to the mold to help keep the bearing plate in place and minimize its lateral movement during successive drops. Next, a 6-in bearing plate was carefully positioned on top of the specimen and rotated 45 degrees clockwise and counterclockwise to ensure a proper contact between plate and specimen. Then the guide rod with the falling weight was gently placed on top of the bearing plate, and a total of six drops were applied — three seating drops followed by three measurement drops — by raising the falling weight to a designated falling height and allowing the weight to fall freely without lateral movement. Readings of deflection (s_{lab}) for the six drops from the device, along with the applied stress (σ_{lab}), specimen height (H), and type of soil, were recorded for calculating laboratory LWD modulus (E_{lab}). With the assumption that the soil tested in the laboratory and field is homogeneous, isotropic, and linear elastic, the modulus of elasticity of soil in LWD test on Proctor mold can be solved using the Equation 2-2 derived from calculation of constrained modulus of elasticity of soil with inputs of applied stress and deflection.

$$E_{lab} = H\frac{\sigma_{lab}}{s_{lab}}\left(1-\frac{2v^2}{1-v}\right)$$

where:

E_{lab} = lab LWD modulus (psi)
H = height of specimen (in.)

σ_{lab} = applied stress in lab LWD test (psi)
s_{lab} = deflection in lab LWD test (psi), and
v = Poisson's ratio (Table 2-6)

Equation 2-2 Lab LWD modulus.

Table 2-6 Typical Poisson's ratio values for different geomaterials from MEPDG.

Material	Range of values	Typical value
Untreated granular materials	0.30-0.40	0.35
Cement-treated granular materials	0.10-0.20	0.15
Cement-treated fine-grained soils	0.15-0.35	0.25
Lime-stabilized materials	0.10-0.25	0.20
Loose sand or silty sand	0.20-0.40	0.30
Dense sand	0.30-0.45	0.35
Saturated soft clays	0.40-0.50	0.45
Silt	0.30-0.35	0.32
Clay (unsaturated)	0.10-0.30	0.20
Sandy clay	0.20-0.30	0.25
Coarse-grained sand	0.15	0.15
Fine-grained sand	0.25	0.25

As mentioned previously, a quadratic equation consisting of the modulus of elasticity of soil, the applied stress, the moisture content, and five regression coefficients is used to characterize the relationship between the first three. The characterization or calibration is performed by regressing results of LWD test on Proctor mold, at the completion of which five regression coefficients are obtained. With this calibrated equation, a target value of modulus of elasticity of soil can be calculated with the applied stress and moisture content in field LWD tests, and thus a modulus ratio of field modulus of elasticity of soil to target modulus of elasticity of soil. This modulus ratio is then used to evaluate compaction quality of soil in the field. In the evaluation, a testing spot with modulus ratio no less than 100% shows comparable mechanical behavior with the well compacted soil tested in the lab, while modulus ratios significantly lower than 100% at some testing spots indicate obviously under compaction.

2.4.1 Testing Plan

Given that the two GMs had similar gradations, MDDs (i.e., 137.8 lbf/ft^3 vs. 137.5 lbf/ft^3) and OMCs (i.e., 7.9% vs. 7.2%), data of lab LWD tests conducted on Holts Summit GM was used for predicting field moduli for both Holts Summit and Rolla GMs.

With the fact that the MoDOT is currently using an RC of 95% in field compaction QA, the same RC was used to prepare specimens for LWD tests on Proctor mold, so that the relationship obtained from the test represented the mechanical behavior of soil with an RC of 95% (Missouri highways and transportation commission, 2022). Besides, various moisture contents and stress levels were used in this project, as shown in Table 2-7. Moisture contents were controlled at OMC±4%, OMC±2%, and OMC except for Holts Summit GM, as it would be too dry or too wet at two ends. Instead, moisture contents of OMC±3%, OMC±1%, and OMC were used for Holts Summit GM. In addition, seven stress levels that were identical as stresses used in the Phase I project were used in this project, which were achieved by adjusting the falling height of LWDs. The first six stress levels were achieved by adjusting the falling height of LWD Lab 3.0 at 2.1 in, 4.1 in, 6.2 in, 8.3 in, 10.3 in, and 14.8 in, respectively. While the last stress level of 38 psi was applied by combining the falling weight of LWD 2000 at a height of 12.2 in with the bearing plate of ZFG Lab 3.0. Three replicates were conducted at each combination of factors, and thus 105 specimens were prepared and tested for each soil.

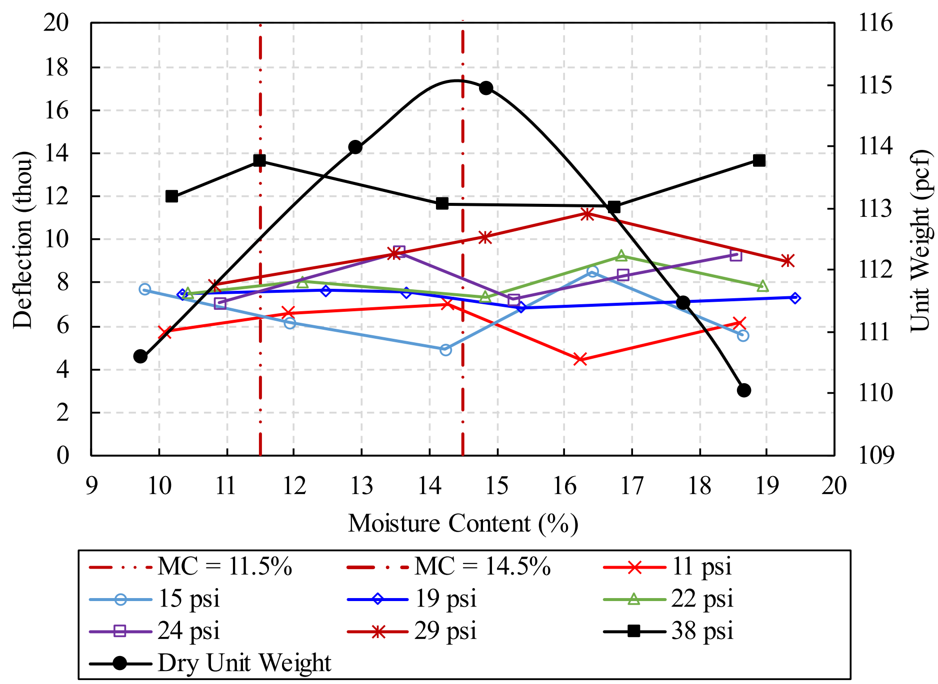
Table 2-7 Moisture contents and stress levels.

Soil	Moisture Content (%)	Stresses (psi)
New Florence CL	10.5, 12.5, 14.5 (OMC), 16.5, 18.5	11, 15, 19, 22, 24, 29, 38
Holts Summit GM	4.5, 6.5, 7.2 (OMC), 8.5, 10.5	
Sikeston SM	4.8, 6.8, 8.8 (OMC), 10.8, 12.8	
Rolla CL	7, 9, 11 (OMC), 13, 15	

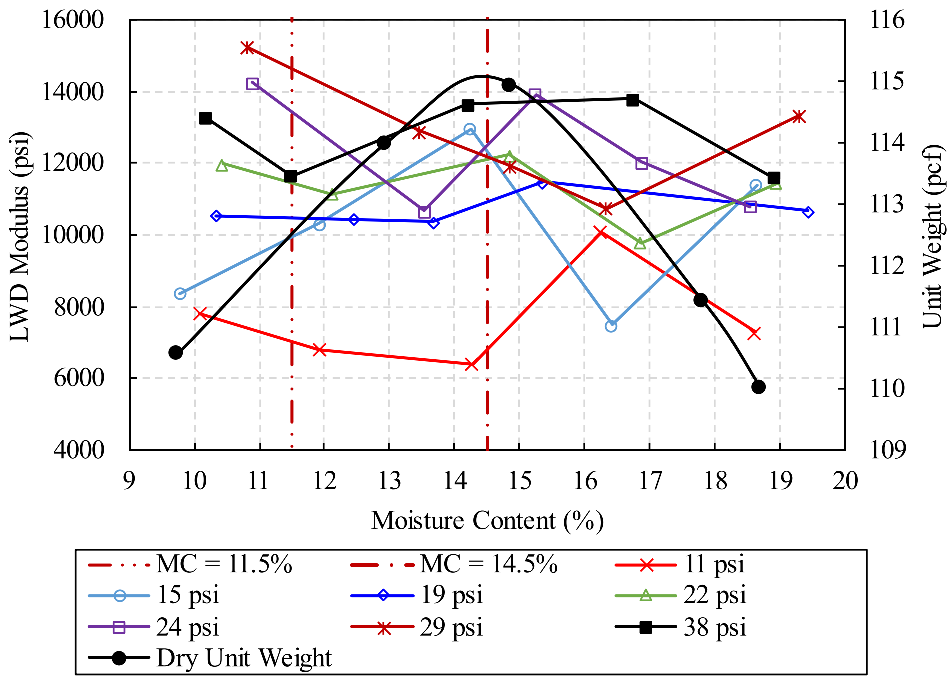
2.4.2 Testing Results

Figures 2-5 to 2-8 show results of LWD tests on Proctor mold for New Florence CL, Holts Summit GM, Sikeston SM, and Rolla CL, respectively. These results consist of deflection and LWD modulus measured at various moisture contents and applied stresses, which are ordered by the dates they were collected in the field.

Figure 2-5 illustrates testing results of New Florence CL tested at five moisture contents and seven stress levels. In Figure 2-5 (a), the deflection showed a response of increase as the stress level increased from low to high; however, with the increase in moisture content, the deflection fluctuated irregularly and remained within a span of 4 thou to 14 thou. The LWD modulus depicted in Figure 2-5 (b) showed a similar, but less apparent, pattern to the deflection. The difference in the LWD moduli between neighboring stress levels is not significant, while a relatively noticeable alteration can be observed only in LWD moduli at stress levels that significantly varied (e.g., 11 psi, 22 psi, and 38 psi).



(a) Deflection versus moisture content

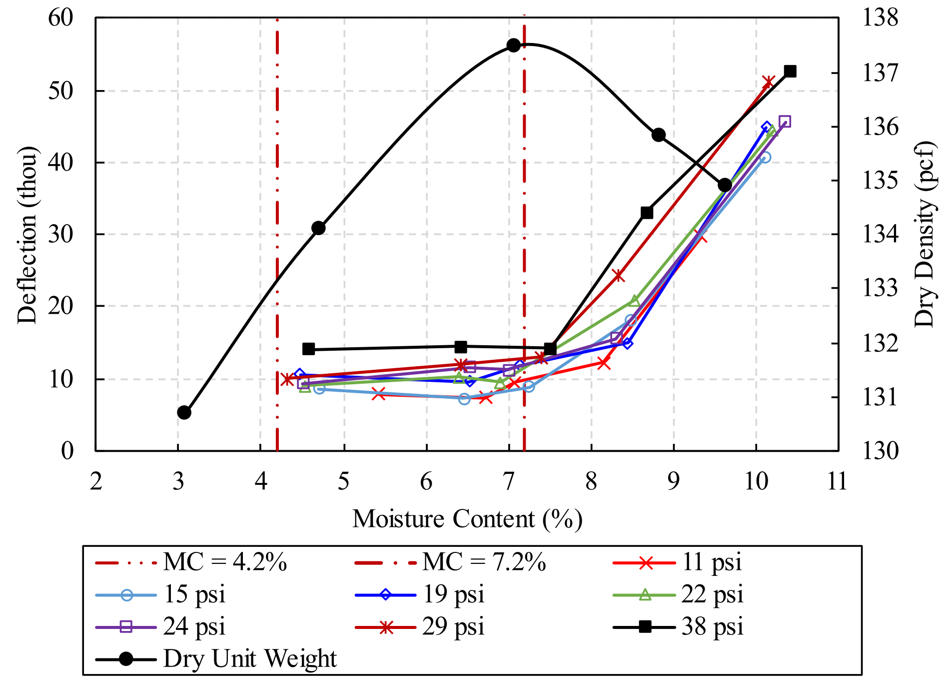


(b) Modulus versus moisture content

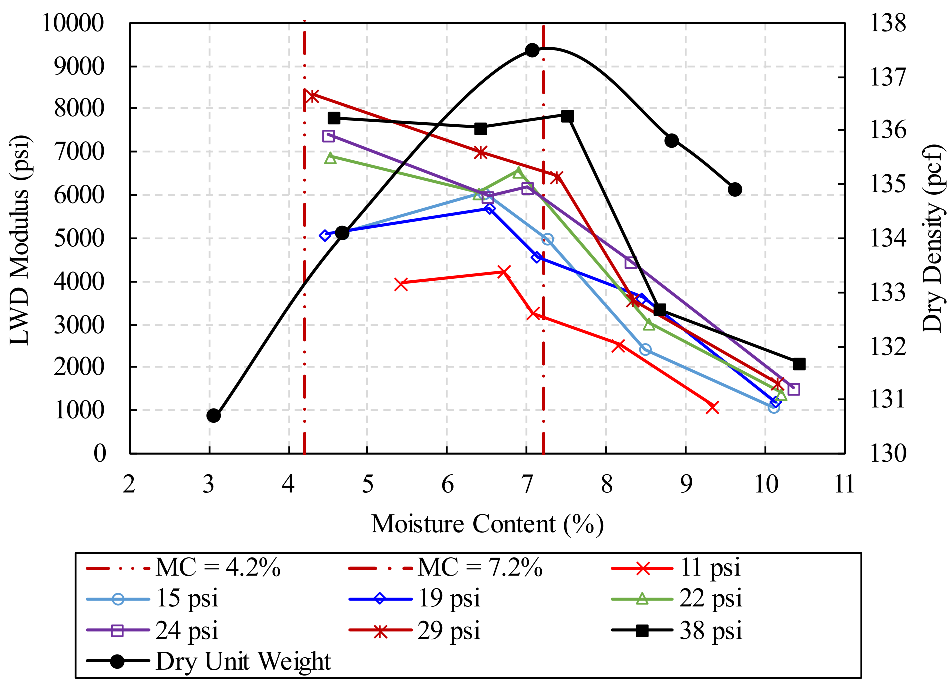
Figure 2-5 Lab LWD test results for New Florence CL.

In Figure 2-6 (a), it can be observed that deflections of Holts Summit GM remained relatively unchanged at two lower moisture levels, which did not start changing until the moisture content rose beyond its OMC (7.2%). The deflection developed exponentially as the moisture content continued to rise from 7.2% to 8.2% and then to 10.2%, indicating the deflection developed significantly more at moisture contents higher than the OMC than those lower though dry densities were controlled comparable. Comparing trend lines of deflections measured at different stress levels, lines scatter and overlap each other in the diagram, indicating deflections induced by neighboring stress levels were close. However, the trend that deflections increase with the increase of applied stresses appears clear when comparing deflections occurred at disparate stresses. For example, at stress levels of 11 psi, 22 psi, and 38 psi, the three increasing stresses induced three increasing deflections of 8 thou, 10 thou, and 14 thou, respectively, at moisture levels around 6.2%.

In Figure 2-6 (b), the LWD modulus of Holts Summit GM showed an opposite trend compared with the deflection, which generally decreased as the moisture content increased. At moisture contents lower than the OMC, LWD moduli at low stress levels (i.e., 11 psi, 15 psi, and 19 psi) showed peak LWD moduli at moisture contents around OMC instead of the lowest tested moisture content. Similarly, the LWD modulus declined much more at moisture content higher than the OMC than those lower though dry densities were close. Likewise, less overlap between LWD modulus trend lines of different stresses was observed as the difference between stresses increased, indicating a trend that LWD moduli increased with the increase of applied stresses.



(a) Deflection versus moisture content

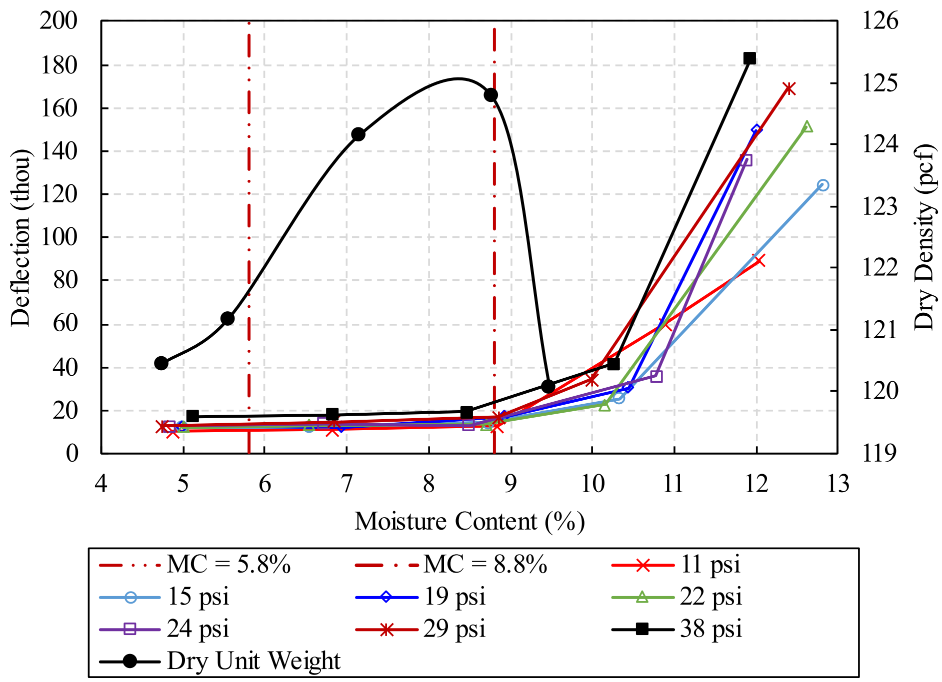


(b) Modulus versus moisture content

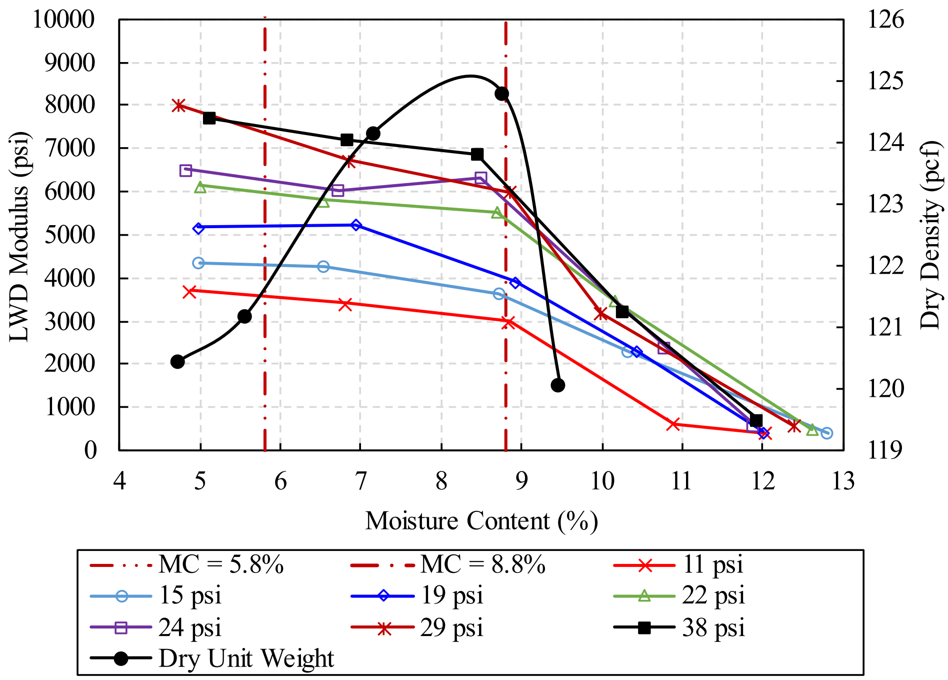
Figure 2-6 Lab LWD test results for Holts Summit GM.

Figure 2-7 (a) shows the development of deflections at various stress levels regarding changes of moisture contents for Sikeston SM, which is similar to that for Holts Summit GM. The deflection remained relatively unchanged at moisture contents lower than the OMC (8.8%) and started increasing when the moisture content increased beyond the OMC. The increase of deflection was more rapid as the moisture content increased from 10.8% to 12.8%. On the other hand, the trend that Sikeston SM deflected more with higher stress applied did not appear clear until the testing moisture content increased to around 12%.

It can be seen from Figure 2-7(b) that the LWD moduli generally decreased with the increase of moisture content. The development trend of LWD moduli regarding changes of moisture contents shown in Figure 2-7 (b) is more apparent. However, at moisture contents lower than the OMC, LWD moduli kept increasing from lowest applied stress 11 psi to the highest applied stress 38 psi; while at moisture contents higher than the OMC, LWD moduli at seven stress levels showed consistent trend at moisture contents around 10.5% and declined to comparably low levels when moisture contents increased beyond 12%. LWD moduli at moisture contents higher than the OMC showed more intense reduction compared with those at moisture contents lower than the OMC.



(a) Deflection versus moisture content

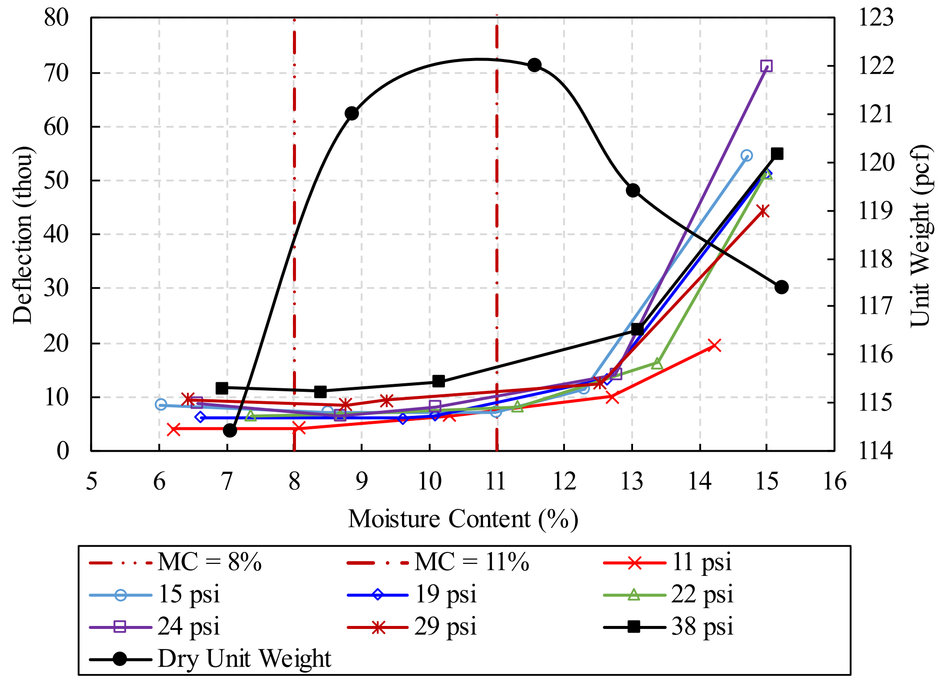


(b) Modulus versus moisture content

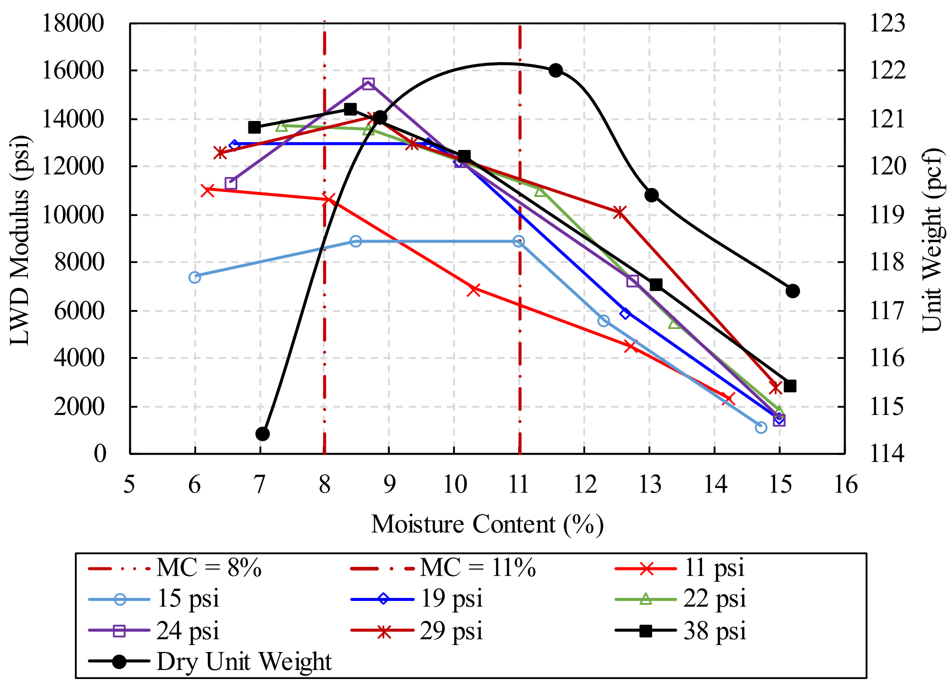
Figure 2-7 Lab LWD test results for Sikeston SM.

Different from what New Florence CL demonstrated in Figure 2-5, Rolla CL produced results indicating a different trend, though they both were classified as lean clay. Instead, Rolla CL showed alike trends in deflection and LWD modulus as Holts Summit GM and Sikeston SM did. Figure 2-8 (a) illustrates impacts of moisture content and applied stress on deflection. The development of deflection at moisture contents lower than the OMC (11%) increased slightly as the soil became wetter, a moderate increase followed by a steep one occurred as the moisture content went up beyond the OMC to 13% and then to 15%. The general trend that a higher stress level leads to more deflection appeared on Rolla CL as well, though there are some scattered points at other stresses due to various factors, such as slight differences in operation of LWD device, in relative compaction, and in pore water pressure buildup.

Figure 2-8 (b) depicts the relationship between LWD modulus, moisture content, and applied stress for Rolla CL. Similar to observations on Holts Summit GM and Sikeston SM, the Rolla CL showed a decreasing trend in LWD modulus in response to the increase of moisture contents. However, with the fact that LWD moduli obtained at similar moisture contents and different stress levels fell close to each other in the plotting, it is not confident to conclude that the LWD modulus generally increased with the increase of applied stress. This trend was consistent with the stress dependency property of clay soils, which included the stress hardening and the stress softening. The stress hardening usually occurs at low stress levels while the stress softening usually happens at high stress levels for clay soils.



(a) Deflection versus moisture content



(b) Modulus versus moisture content

Figure 2-8 Lab LWD test results for Rolla CL.

2.4.3 Determination of Regression Coefficients

A quadratic equation comprising soil modulus of elasticity, applied stress, moisture content, and five regression coefficients was used to correlate the relation between first three variables. The characterization or calibration was performed by regressing results of LWD test on Proctor mold with Equation 2-3 as follows:

$$E_{lab} = a_0 + a_1 \times MC_{lab} + a_2 \times MC_{lab}^2 + a_3 \times P_{lab} + a_4 \times P_{lab}^2$$

where:

a_i (i = 0, 1, 2, 3, and 4) = regression coefficients

MC_{lab} = lab moisture content (%)

Equation 2-3 Characterization of lab LWD modulus, applied stress, and moisture content.

The regression analysis was conducted using the least square method in Microsoft Excel, in which coefficients a_i were set as changing variables and the sum of squares of differences between actual and predicted LWD moduli was set to be minimum. Iterations continued until a series of stable values were obtained for a_i and coefficients of determination (R^2). At the completion of regression, five regression coefficients a_i (i = 0, 1, 2, 3, and 4), are obtained. With these coefficients plugged into Equation 2-4, a target value of modulus of elasticity of soil can be calculated with the applied stress and moisture content in a field LWD test, and thus a modulus ratio of field to target moduli of elasticity of soil.

$$E_{target} = a_0 + a_1 \times MC_{field} + a_2 \times MC_{field}^2 + a_3 \times P_{field} + a_4 \times P_{field}^2$$

where:

E_{target} = target LWD modulus (psi)

MC_{field} = field moisture content (%)

σ_{field} = field applied stress (psi)

Equation 2-4 Characterization of target LWD modulus, applied stress, and moisture content.

Figures 2-9 to 2-12 illustrate regression fitting diagrams for the four soils (i.e., New Florence CL, Holts Summit GM, Sikeston SM, and Rolla CL). In each diagram, data points including moisture contents and LWD moduli of 15 psi and 29 psi are plotted, given that the LWDs used in the field LWD tests applied these two stress levels. Outliers are presented with different styles of marker, which are excluded prior to regression analysis. The data reduction was conducted in light of the moisture content and LWD modulus, if points having similar moisture contents showed dissimilar LWD moduli, the point differed from the other two was discarded from the regression analyses. In addition, a coefficient of variation (COV) of 10% was used to assess the last three deflections in an LWD test on Proctor mold. The test having a COV greater than 10% for its last three deflections was discarded. Along with the testing data, prediction lines for the two stress levels are also plotted grounded on the calibrated equation, as well as their R^2 values.

Figure 2-9 illustrates the fittings on data of LWD tests on Proctor mold conducted on New Florence CL. Five data points and four data point were excluded from data analyses for stresses of 15 psi and 29 psi, respectively, due to the obvious deviations in data. With remaining solid marked left in the plotting, the regressions for the two stress levels were performed, which produced R^2 of 0.1 and 0.72 for stresses of 15 psi and 29 psi, respectively. While an R^2 of 0.72 is still statistically acceptable for 29-psi, 0.1 for 15 psi is not acceptable. Further investigation of LWD tests on the New Florence CL is needed to explain how this disparately different observation happened.

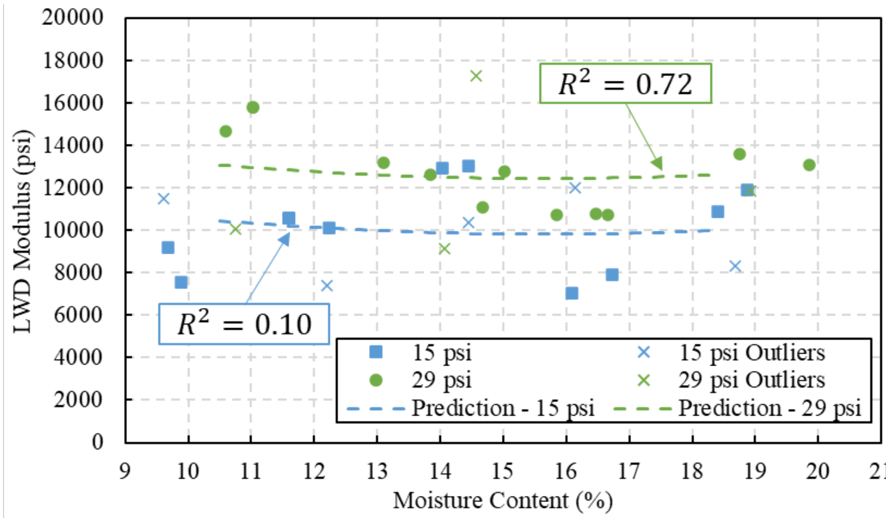


Figure 2-9 Regression fitting for New Florence CL.

Figure 2-10 shows how the data of LWD tests on Proctor mold conducted on Holts Summit GM fitted the quadratic equation. Given that R^2 values of 0.85 and 0.91 were obtained from fittings of stresses 15 psi and 29 psi, respectively, the regression fitting of Holts Summit GM was good.

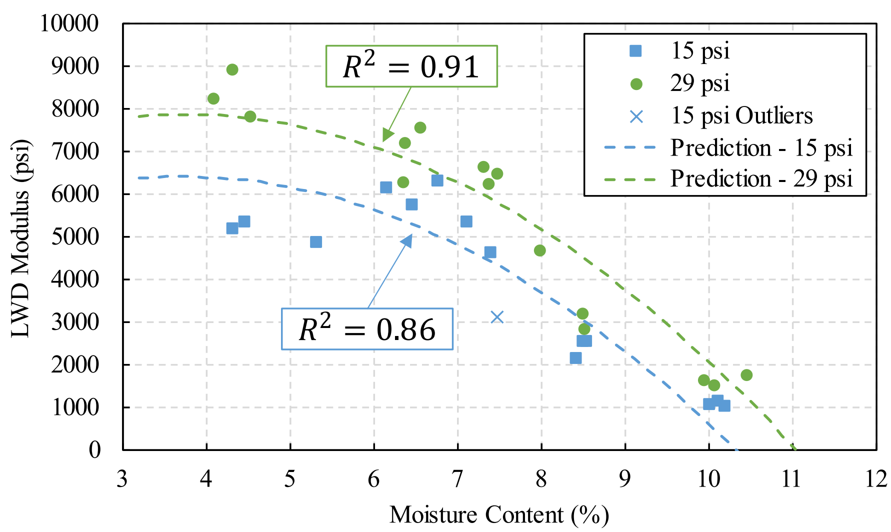


Figure 2-10 Regression fitting for Holts Summit GM.

In the regression fitting of Sikeston SM shown in Figure 2-11, only one outlier was excluded from the analyses of 15 psi stress. Regressions on 15-psi and 29-psi stresses produced R^2 of 0.93, which indicated that the quadratic equation well characterized the relationship between LWD modulus, moisture content, and applied stress for Sikeston SM.

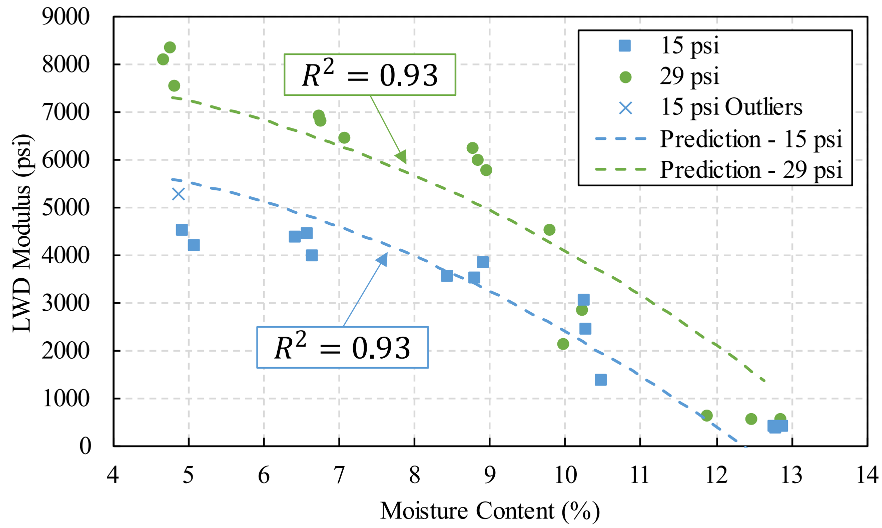


Figure 2-11 Regression fitting for Sikeston SM.

Figure 2-12 illustrates the fitting of the quadratic equation on Rolla CL, from which R^2 values of 0.95 and 0.93 were obtained. Very few points were excluded. Overall, the regression on the Rolla CL yielded the best R^2 among the four tested soils.

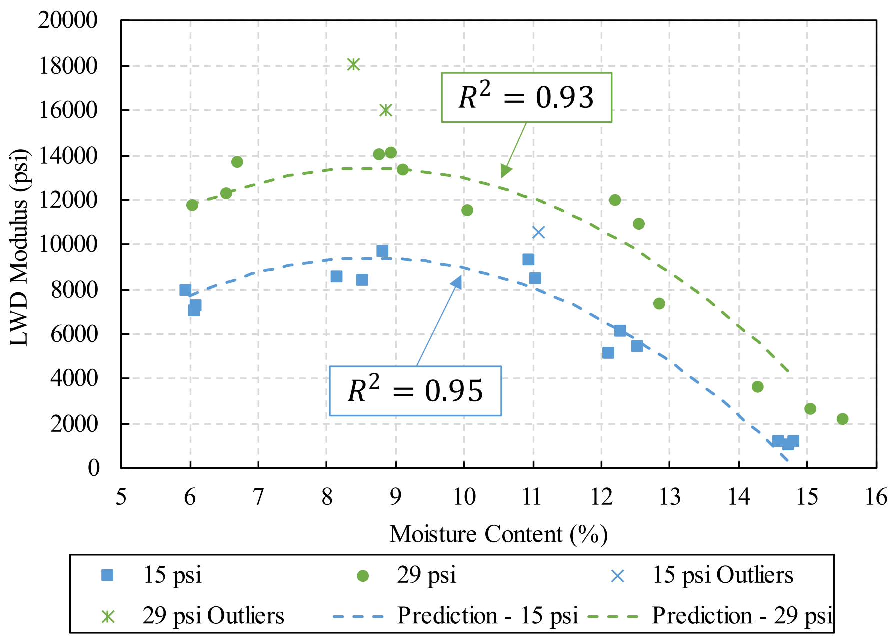


Figure 2-12 Regression fitting for Rolla CL.

Regression coefficients for the four soils are summarized in Table 2-8. Except for New Florence CL, R^2 values around or over 0.9 for the other three soils strongly indicated that the quadratic equation, Equation 2-3, could characterize the relationship between LWD modulus, moisture content, and applied stress.

Table 2-8 Regression coefficients in the prediction model for four soils.

Soil	a_0	a_1	a_2	a_3	a_4	R^2
New Florence CL	149.676	-753.406	24.076	1476.990	-29.307	0.41
Holts Summit GM	59.338	1076.781	-145.601	385.800	-6.393	0.88
Sikeston SM	53.293	171.495	-53.142	537.799	-9.457	0.93
Rolla CL	47.671	4239.685	-245.172	-1055.342	30.494	0.94

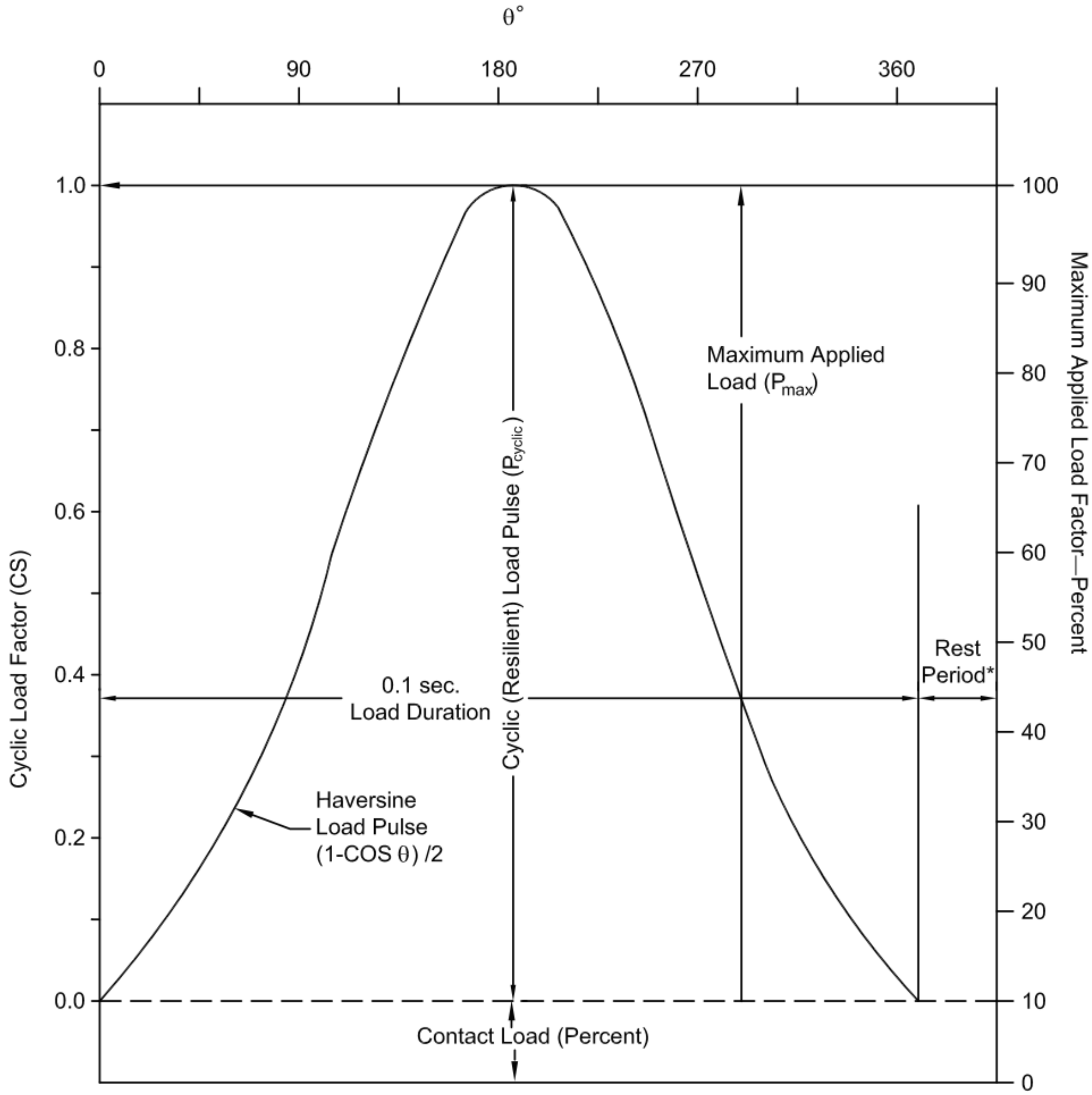
2.5 Resilient Modulus Test

2.5.1 Testing Plan

According to the MEPDG, the resilient modulus (M_R) is an essential material input in the pavement design for unbound materials used in pavement layers including subgrade and base course (American Association of State Highway and Transportation Officials, 2020). The M_R for an individual soil can significantly vary with changes in the density, moisture content, gradation, plasticity index, and stress level (Vanapalli et al., 1999). The M_R of unbound materials is determined in the laboratory by the RLTT according to the procedure in AASHTO T 307 (2006). Typically, 15 combinations of different axial loads and confining pressures are applied during the test in addition to the preconditioning phase. Loading sequences for base/subbase soils, depicted in Table 2-9, was used for all soils to compare their M_R results, though they were used at different locations in the field. The loading of each cycle consists of a 0.1-s haversine loading pulse and a 0.9-s rest period, as shown in Figure 2-13.

Table 2-9 Testing sequence for base/subbase soils (AASHTO T 307, 1999).

Sequence No.	Confining Pressure, σ_3		Max. Axial Stress, σ_{max}		Cyclic Stress, σ_{cyclic}		Constant Stress, 0.1 σ_{max}		No. of Load Applications
-	kPa	psi	kPa	psi	kPa	psi	kPa	psi	-
0	103.4	15	103.4	15	93.1	13.5	10.3	1.5	500–1000
1	20.7	3	20.7	3	18.6	2.7	2.1	0.3	100
2	20.7	3	41.4	6	37.3	5.4	4.1	0.6	100
3	20.7	3	62.1	9	55.9	8.1	6.2	0.9	100
4	34.5	5	34.5	5	31.0	4.5	3.5	0.5	100
5	34.5	5	68.9	10	62.0	9.0	6.9	1.0	100
6	34.5	5	103.4	15	93.1	13.5	10.3	1.5	100
7	68.9	10	68.9	10	62.0	9.0	6.9	1.0	100
8	68.9	10	137.9	20	124.1	18.0	13.8	2.0	100
9	68.9	10	206.8	30	186.1	27.0	20.7	3.0	100
10	103.4	15	68.9	10	62.0	9.0	6.9	1.0	100
11	103.4	15	103.4	15	93.1	13.5	10.3	1.5	100
12	103.4	15	206.8	30	186.1	27.0	20.7	3.0	100
13	137.9	20	103.4	15	93.1	13.5	10.3	1.5	100
14	137.9	20	137.9	20	124.1	18.0	13.8	2.0	100
15	137.9	20	275.8	40	248.2	36.0	27.6	4.0	100



* The rest period will be 0.9 s for hydraulic loading devices
and 0.9 to 3.0 s for pneumatic loading devices.

Figure 2-13 RLTT loading profile (AASHTO T 307, 1999).

The RLTT apparatus is a computer-controlled closed-loop hydraulic system with programmed loading sequences and data acquisition rates. Figure 2-14 shows the MTS 858 load frame and a 4-inch specimen triaxial cell for M_R tests in this project. All four soils were tested in the same specimen with a diameter of four inches and a height to diameter ratio more than two.

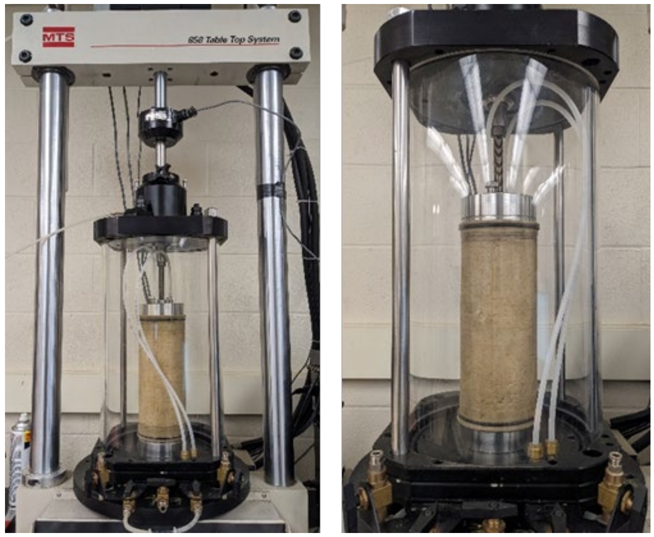


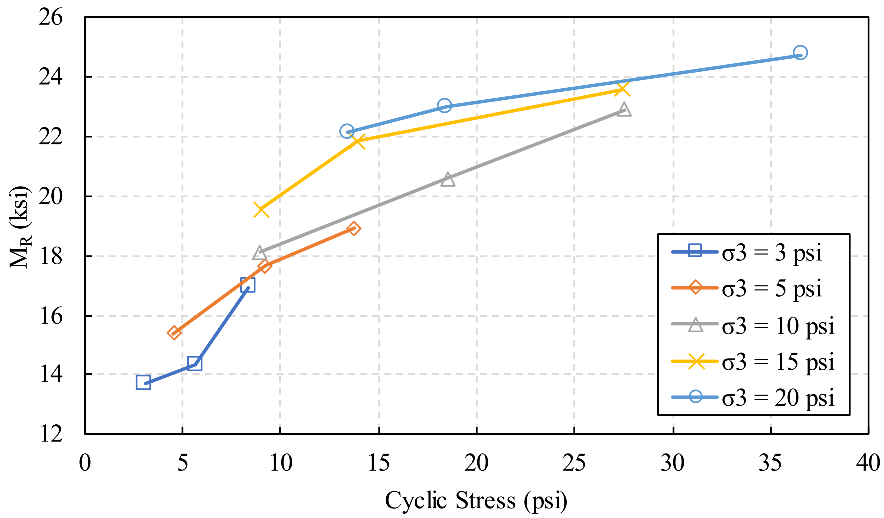
Figure 2-14 MTS 858 load frame (left) and 4-in specimen cells (right) for RLTT.

The RLTTs were performed at targeted moisture contents identical to those selected in the LWD tests on Proctor mold, as shown in Table 2-7. Relative compaction was controlled around 95% for the consistency with LWD tests on Proctor mold. RLTT samples were prepared in molds with a height to diameter ratio of two using the Proctor hammer. The number of layers and drops per layer were adjusted for different soils and moisture contents.

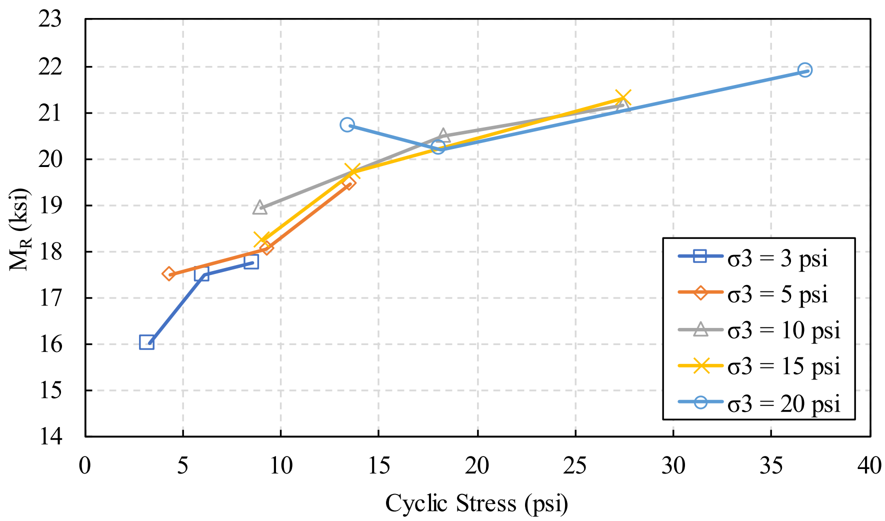
2.5.2 Testing Results

The results of M_R versus applied cyclic stresses at different confining pressures and moisture contents for all soils are shown in Figures 2-15 through 2-18. Five levels of confining pressures are plotted into five series in each figure, such that relationship between the M_R, cyclic stress, and confining pressure are presented comprehensively.

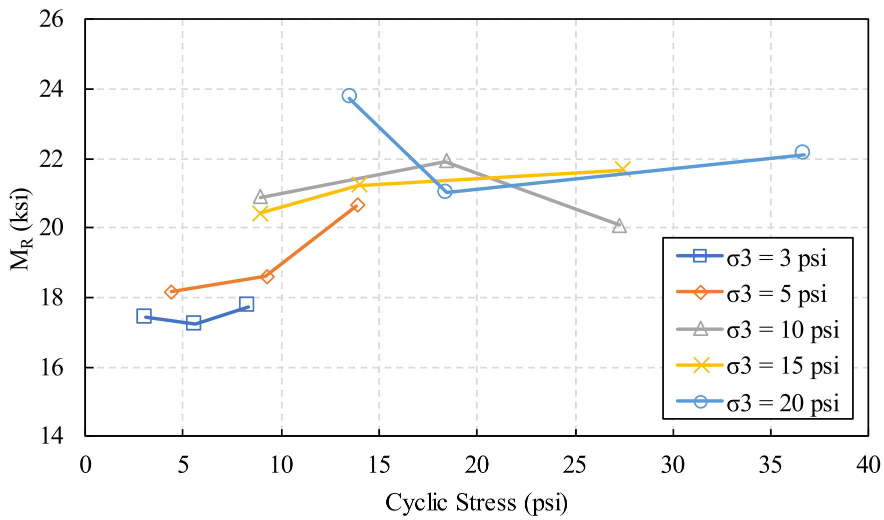
As shown in Figures 2-15 (a) and (b), with New Florence CL specimens compacted at moisture contents of 10.5% and 12.5%, the M_R increased with the increase of cyclic stress levels at each confining pressure level with an exception at the shift from sequences 13^{th} to 14^{th} at 12.5% moisture content; in the meantime, higher confining pressure levels led to higher M_R values. However, when the compaction moisture content increased to and beyond the OMC (14.5%) as shown in Figures 2-15 (c), (d), and (e), the increasing trend of M_R only occurred at low stress levels, and decreasing trends were observed at high stress levels.



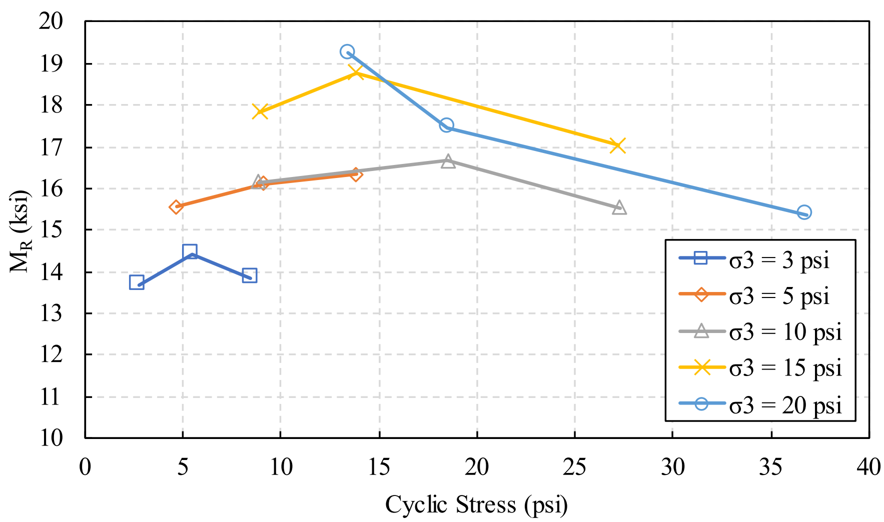
(a) Moisture content = 10.5%



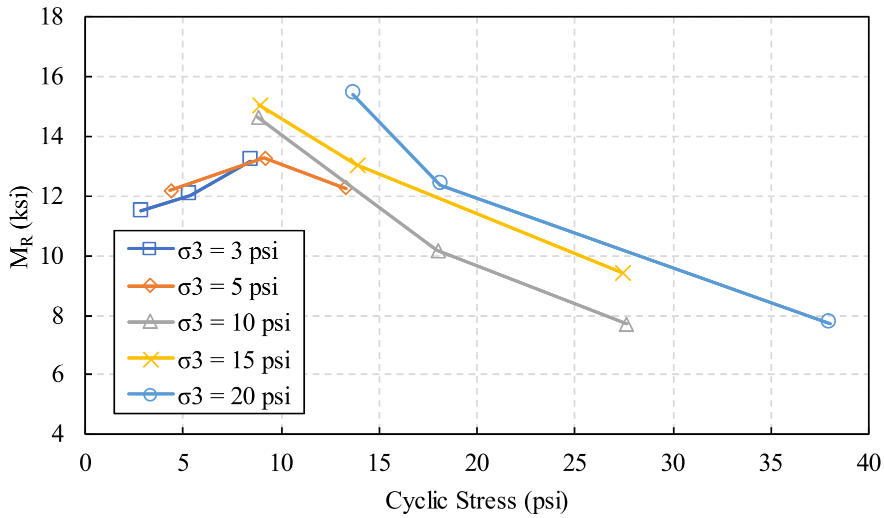
(b) Moisture content = 12.5%



(c) Moisture content = 14.5%



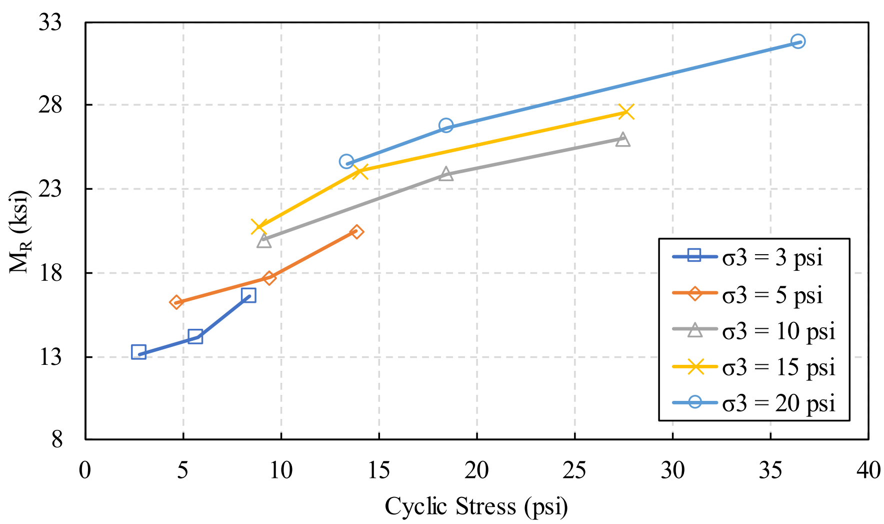
(d) Moisture content = 16.5%



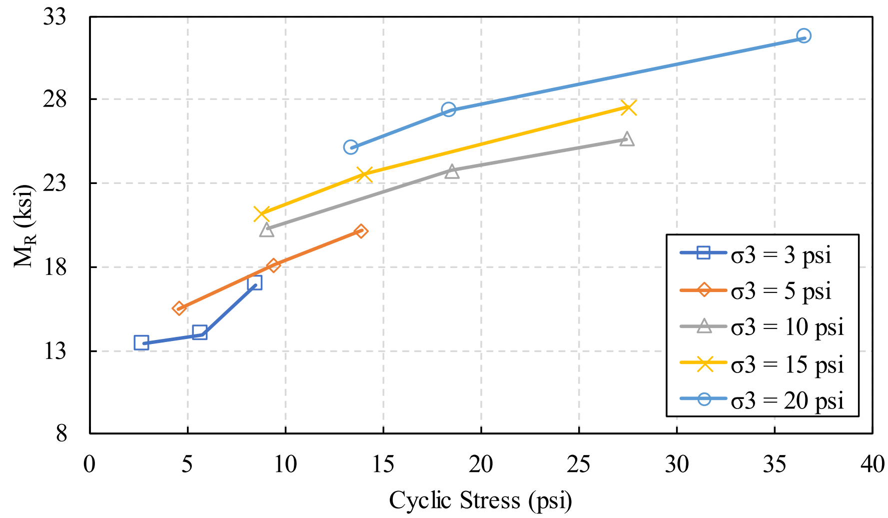
(e) Moisture content = 18.5%

Figure 2-15 M_R test results for New Florence CL.

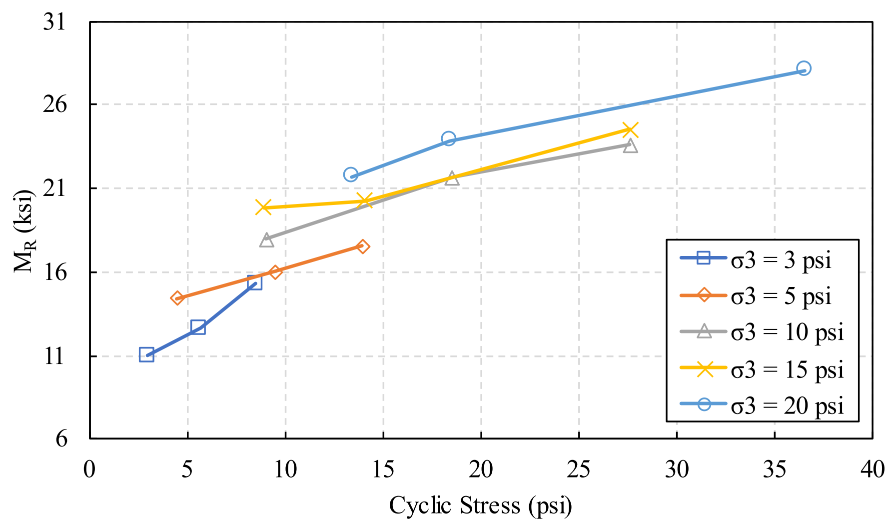
Figure 2-16 shows the M_R of Holts Summit GM, at different moisture contents. The M_R increased as the cyclic stresses and confining pressure levels increased, indicating the occurrence of stress dependency. Therefore, peak values of M_R for all moisture contents were obtained at the 15th sequence where a combination of the highest cyclic stress and the maximum confining pressure was applied. The maximum M_R for five moisture contents were 31.8 ksi, 31.7 ksi, 28.1 ksi, 29.3 ksi, and 20.0 ksi, respectively.



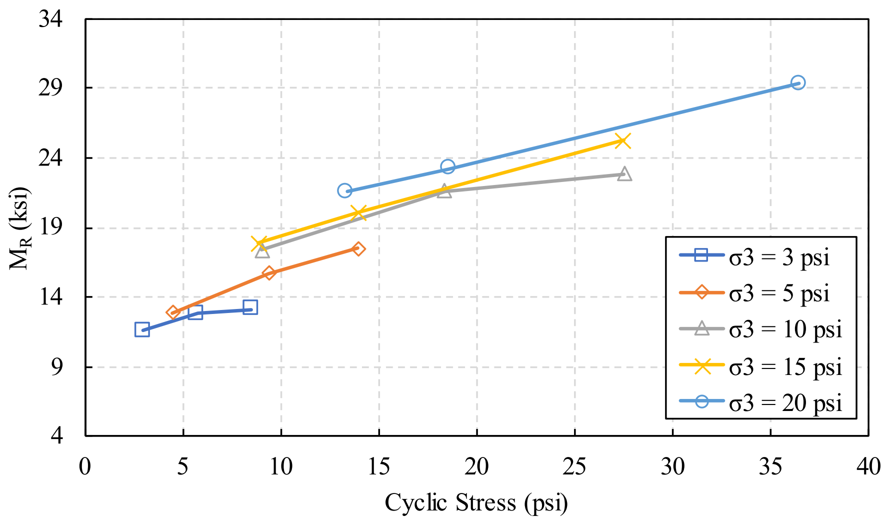
(a) Moisture content = 4.5%



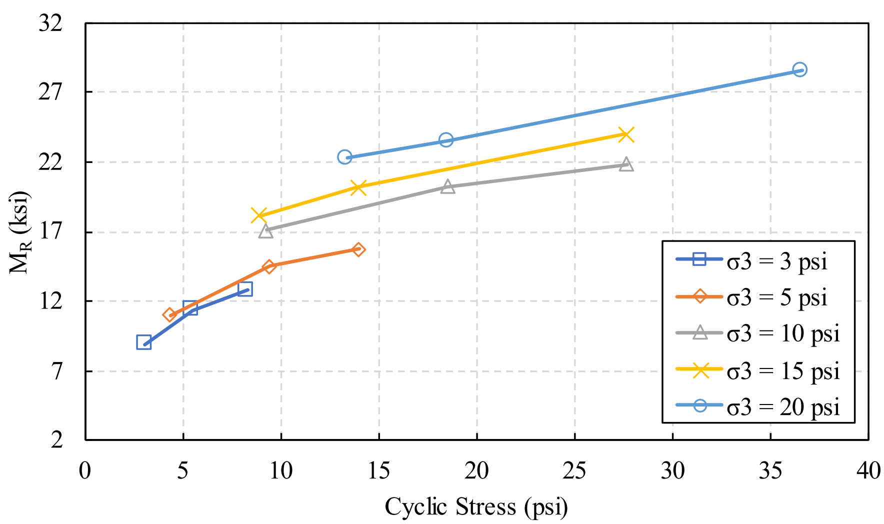
(b) Moisture content = 6.5%



(c) Moisture content = 7.2%



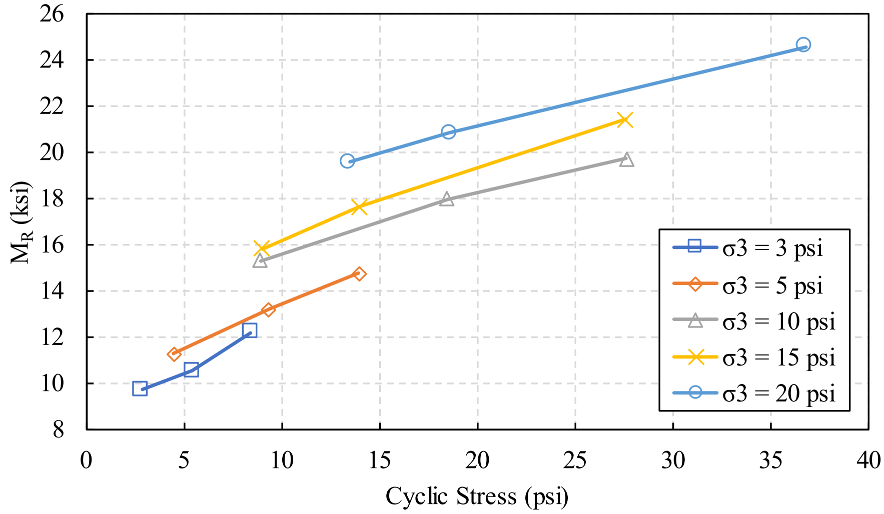
(d) Moisture content = 8.5%



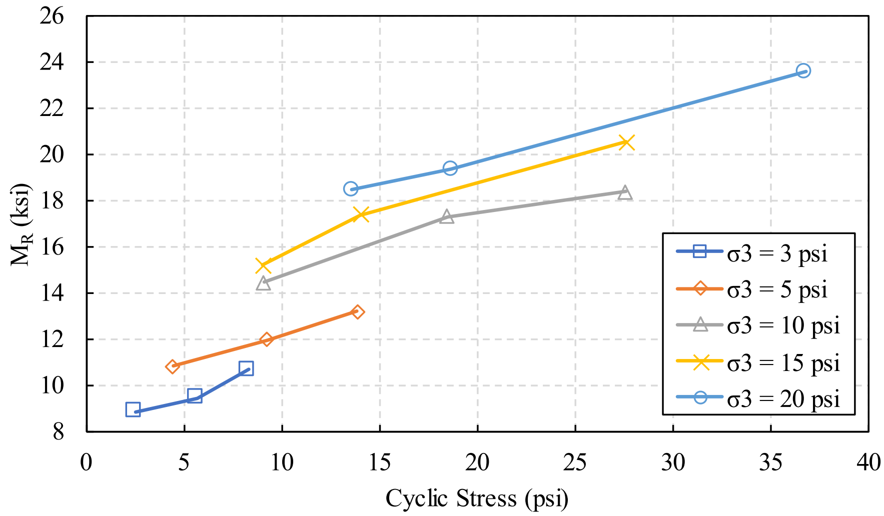
(e) Moisture content = 10.5%

Figure 2-16 M_R test results for Holts Summit GM.

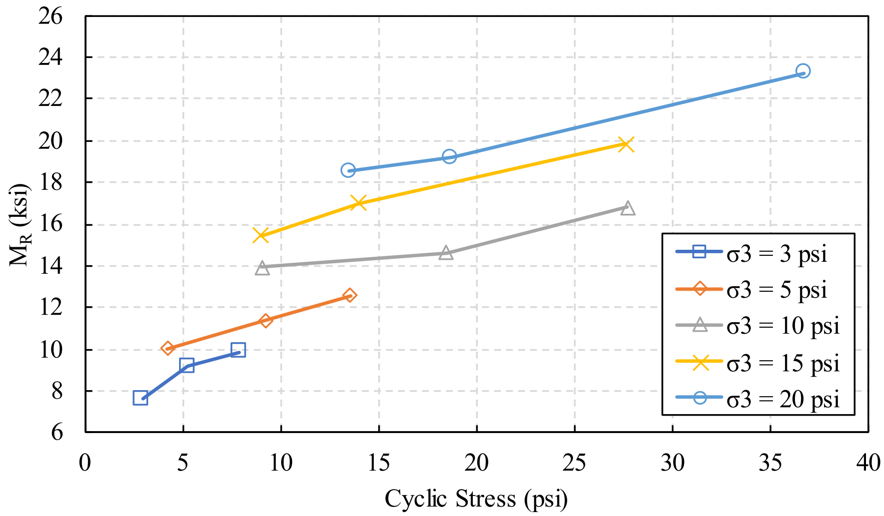
Figure 2-17 illustrates M_R of Sikeston SM tested at various moisture contents. Sikeston SM showed a similar trend to Holts Summit GM, including the stress dependency phenomenon. M_R monotonically increased as the cyclic stresses and confining pressure levels increased, and peak values of M_R for all moisture contents were obtained at the last sequence where the highest cyclic stress and the highest confining pressure were applied. The maximum M_R for five moisture contents were 24.5 ksi, 23.5 ksi, 23.2 ksi, 20.4 ksi, and 19.4 ksi, respectively, which decreased as moisture contents increased.



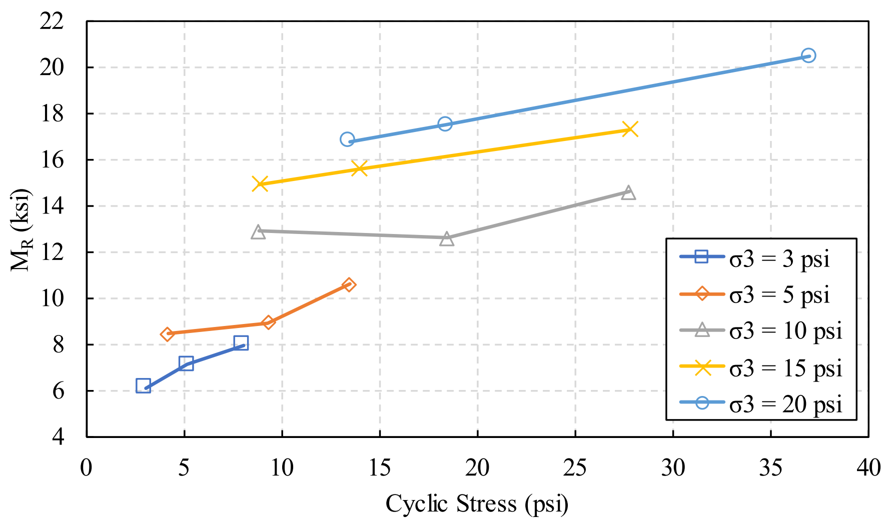
(a) Moisture content = 4.8%



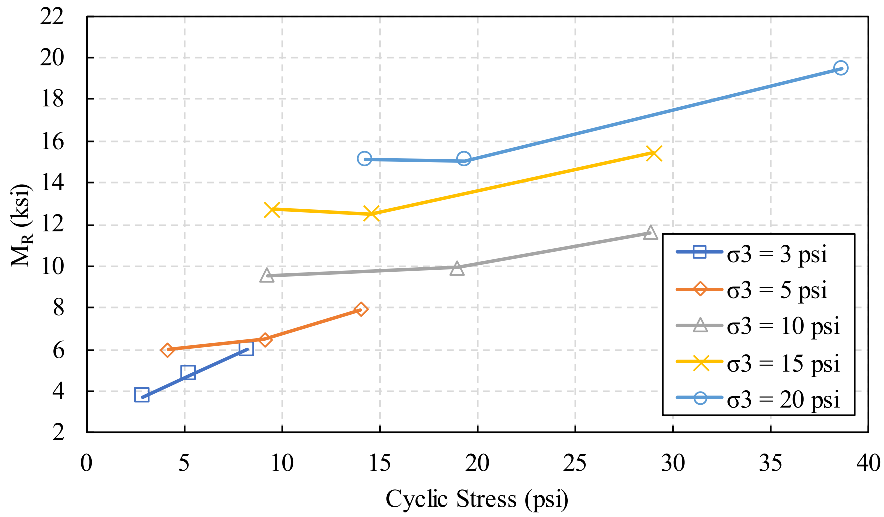
(b) Moisture content = 6.8%



(c) Moisture content = 8.8%



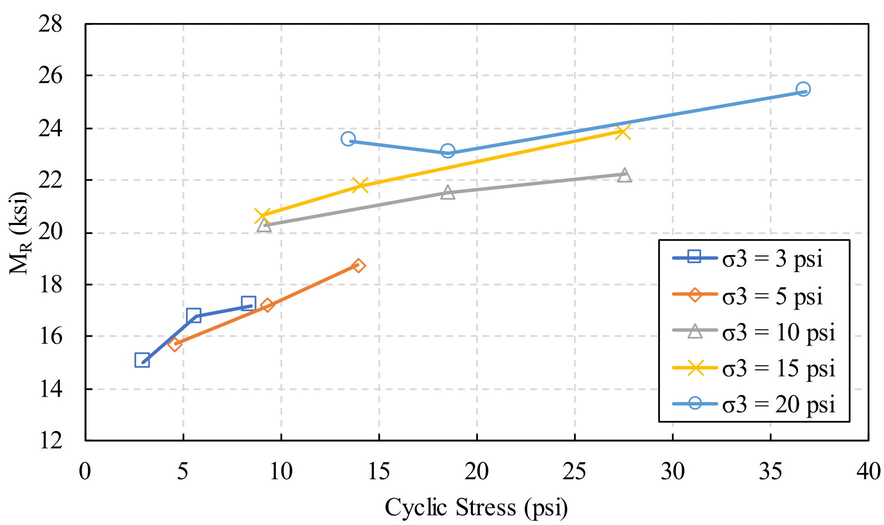
(d) Moisture content = 10.8%



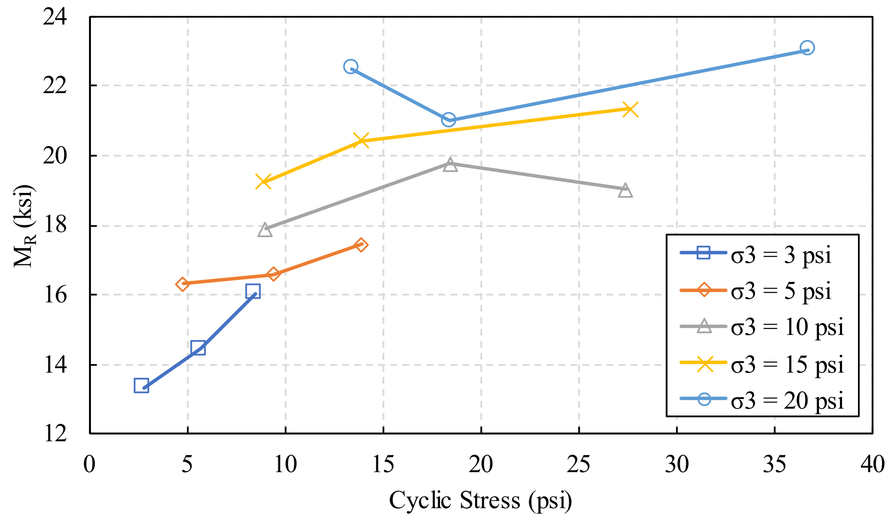
(e) Moisture content = 12.8%

Figure 2-17 M_R test results for Sikeston SM.

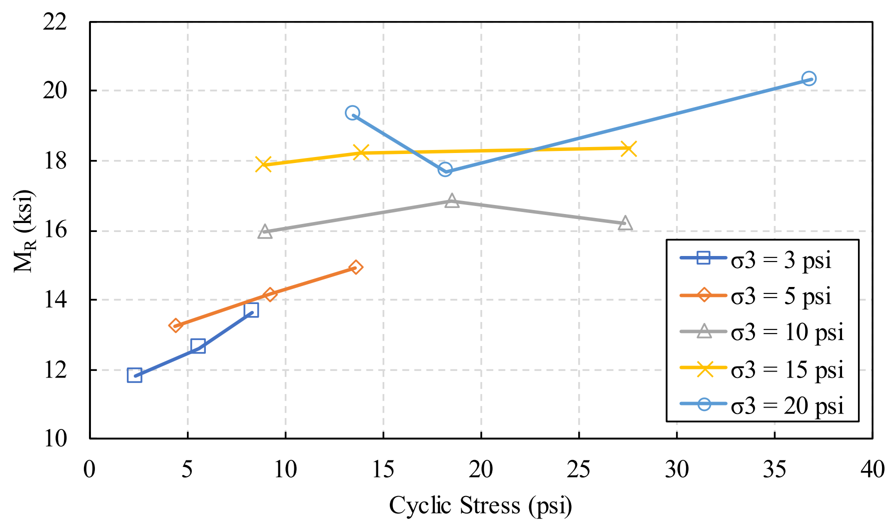
Rolla CL is a fine-grained soil similar to New Florence CL. As shown in Figure 2-18 (a), with exceptions at the shift from confining pressures of 3 psi to 5 psi and the shift from 13th sequence to 14th, the M_R increased with the increases of cyclic stress and confining pressure. At the shift from 13th sequence to 14th, the M_R decreased with the increase of cyclic stress. With moisture contents went higher, Rolla CL showed more decrease than increase the M_R. For example, as shown in Figures 2-18 (a) to (e), the M_R decreased with the increase of cyclic stress only at shifts from sequences 8th to 9th, and 13th to 14th at moisture contents of 9% and 11%. At moisture content of 13%, Rolla CL showed the decreasing M_R with the increase of cyclic stress in all sequences except the 1st one; and the M_R decreased in all sequences as the cyclic stress increased at a moisture content of 15%. In addition, the maximum M_R for five moisture contents were 25.4 ksi, 23.0 ksi, 20.3 ksi, 20.2 ksi, and 17.5 ksi, respectively, which decreased as moisture contents increased.



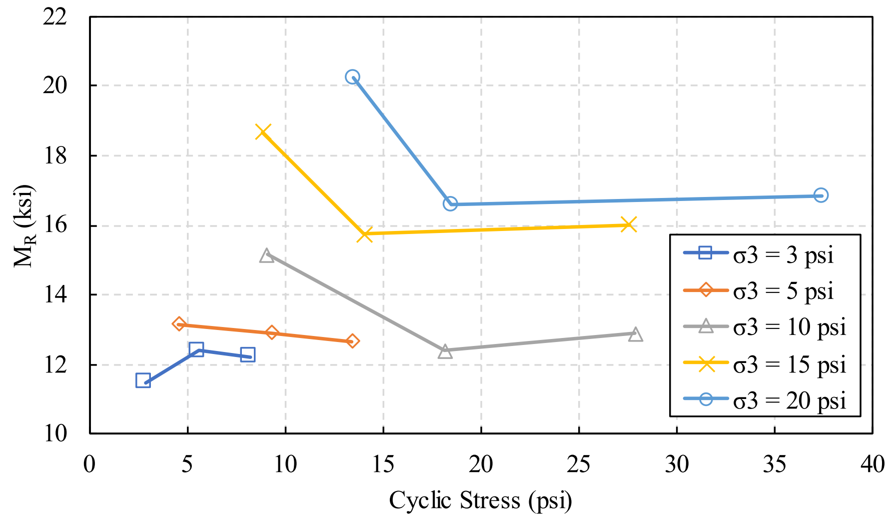
(a) Moisture content = 7%



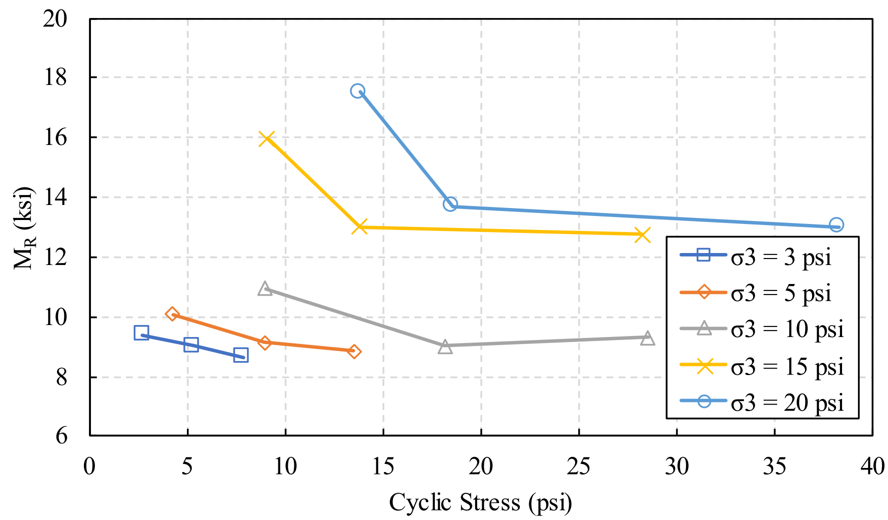
(b) Moisture content = 9%



(c) Moisture content = 11%



(d) Moisture content = 13%



(e) Moisture content = 15%

Figure 2-18 M_R test results for Rolla CL.

Among the four tested geomaterials, the two coarse-grained soils, Sikeston SM and Holts Summit GM, showed the increasing M_R with the increase of stress level. The two fine-grained soils (i.e., New Florence CL and Rolla CL) showed the increasing M_R with the increase of stress level at low moisture contents and the decreasing M_R with the increase of stress level at high moisture contents. In addition, Holts Summit GM had the highest M_R, due to the largest nominal maximum particle size (NMPS) among the four soils. The effective stress inside the soil was supported mainly by large particles for Holts Summit GM, which have higher stiffness and stability than smaller particles and fines that bear effective stresses in the rest three soils.

2.5.3 Regression of MEPDG Model

Regression analyses were performed to best fit the MEPDG universal constitutive model using the experimental results. It is worth noting that the MEPDG model considers the effect of applied mechanical stresses only as follows:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

where:

M_R = resilient modulus, (psi),

$\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ = bulk stress, (psi),

$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} = \frac{\sqrt{2}}{3}(\sigma_1 - \sigma_2)$ = octahedral shear stress, (psi),

p_a = atmospheric pressure used to normalize the equation, 15.0 psi (101.3 kPa), and

k_1, k_2, k_3 = regression constants calibrated from experimental results.

Equation 2-5 Resilient modulus.

Tables 2-10 through 2-13 summarize the average test results and coefficients of the M_R universal model for New Florence CL, Holts Summit GM, Sikeston SM, and Rolla CL. As mentioned earlier, the model does not account the effect of moisture content on M_R results. Therefore, independent sets of regression parameters were calibrated for each moisture content. Besides, R^2 values, a statistic parameter measuring correlation between model predictions and experimental results, were listed. For the two coarse-grained soils, Holts Summit GM, and Sikeston SM, had overall best fitting correlation with R^2 ranging from 0.98 to 0.99. While the two fine-grained soil, New Florence CL, and Rolla CL, had R^2 ranging from 0.78 to 0.96, with a trend that the R^2 decreased as the moisture content increased.

Table 2-10 Regression parameters k_i for New Florence CL.

MC	%	10.5	12.5	14.5	16.5	18.5
p_a	psi	14.5	14.5	14.5	14.5	14.5
k_1	-	984.08	1136.32	1234.30	1068.42	1084.82
k_2	-	0.20	0.06	0.15	0.22	0.30
k_3	-	0.29	0.25	-0.09	-0.46	-1.59
R^2	%	0.96	0.92	0.83	0.82	0.84

Table 2-11 Regression parameters k_i for Holts Summit GM.

MC	%	4.5	6.5	7.2	8.5	10.5
p_a	psi	14.5	14.5	14.5	14.5	14.5
k_1	-	940.12	946.40	835.32	783.82	695.44
k_2	-	0.26	0.27	0.28	0.25	0.38
k_3	-	0.48	0.43	0.44	0.61	0.43
R^2	%	0.99	0.99	0.98	0.99	0.98

Table 2-12 Regression parameters k_i for Sikeston SM.

MC	%	4.8	6.8	8.8	10.8	12.8
p_a	psi	14.5	14.5	14.5	14.5	14.5
k_1	-	689.92	633.10	591.54	493.96	327.30
k_2	-	0.29	0.34	0.42	0.56	0.71
k_3	-	0.45	0.38	0.22	-0.06	-0.03
R^2	%	0.99	0.99	0.99	0.99	0.98

Table 2-13 Regression parameters k_i for Rolla CL.

MC	%	7	9	11	13	15
p_a	psi	14.5	14.5	14.5	14.5	14.5
k_1	-	1066.38	1010.86	881.27	897.78	686.37
k_2	-	0.20	0.24	0.26	0.37	0.49
k_3	-	0.16	-0.01	-0.09	-0.69	-1.01
R^2	%	0.97	0.96	0.96	0.82	0.78

Chapter 3. Development of a Field Moisture Measurement System

Although the modulus-based compaction acceptance evaluation method using LWDs was found promising, an LWD is not able to determine the moisture content – a key property must be monitored during unbound geomaterials' compaction. Therefore, a field moisture analyzer is needed to assist engineers in determining soil compaction quality. In this chapter, given Ohaus MB 120 demonstrated compatibility with various types of soils in the Phase I project, influential factors that affect the performance of the device in the field were analyzed. Subsequently, a field moisture determination system composed of several parts was designed. Moreover, parameters of equipment setup, including sample weight and switch-off criterion, were investigated for the designed system, followed by the recommendations of these parameters.

3.1 Introduction

The Ohaus MB 120 is a promising moisture determination device among the two devices (Figure 3-1) used in the Phase I project, while the other device, the Aggrameter, only worked well with sandy soil (Zhang et al., 2022). The Ohaus MB 120 is a device combining functions of a balance and an oven, which continuously monitors the mass change of the sample during the drying process and switches off automatically. The number 120 is the mass capacity of the integrated balance in gram, and the balance has a readability of 0.001 g. The integrated halogen heating element in Ohaus MB 120 is able to heat up to 230 °F (110 °C) from room temperature within 60 seconds, which dries more efficient compared with a conventional oven. Nevertheless, since there are some factors preventing Ohaus MB 120 from working properly when it was used in the field, modifications are needed to solve the problems before implementing the device as a moisture analyzer that assists in the modulus-based QA/QC method with an LWD in the field. Therefore, the main objective of this chapter is to find feasible solutions to resolve those problems.

Figure 3-1 Ohaus MB 120 (left) and Aggrameter (right).

3.2 Field Moisture Measurement System

The Ohaus MB 120 is a moisture measuring device that needs a calm and controlled lab to work well. But when it is placed on a truck outside in the field, where quality control engineers often do, it doesn't work as well. The research team found that things like not having electricity, windy weather, and vibrations from nearby construction and traffic make it hard for Ohaus MB 120 to do its job properly.

They also discovered that the device needs a quiet and stable environment to measure accurately before putting in samples. If there's too much going on around it, it takes longer to get ready, and if it keeps happening, it might not work at all.

To fix the problems as mentioned above, a special setup, as shown in Figure 3-2, was made, which included the Ohaus MB 120, a 1000 W power invertor, four vibration isolation elements, a leveling platform, and a hood to protect the Ohaus MB 120.

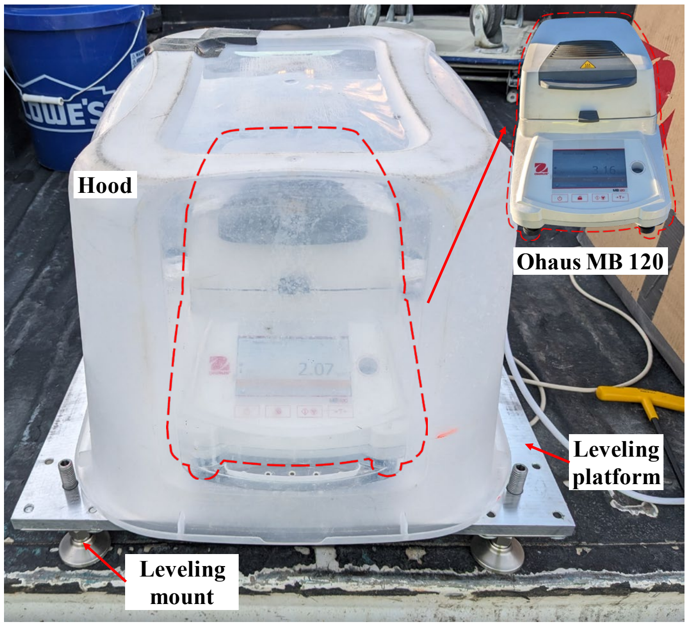


Figure 3-2 Field moisture measurement system.

3.2.1 Power Invertor

The Ohaus MB 120 needs 500 watts of power, and to use it in the field, one can either use a generator or another type of power source. Using a generator means dealing with storing and filling gasoline, which is difficult and not ideal. Instead, it was found that connecting a 1000-watt power converter to a vehicle's battery while the engine is idling can reliably power the device. Figure 3-3 shows how the vehicle's battery is connected to the power converter in the project.

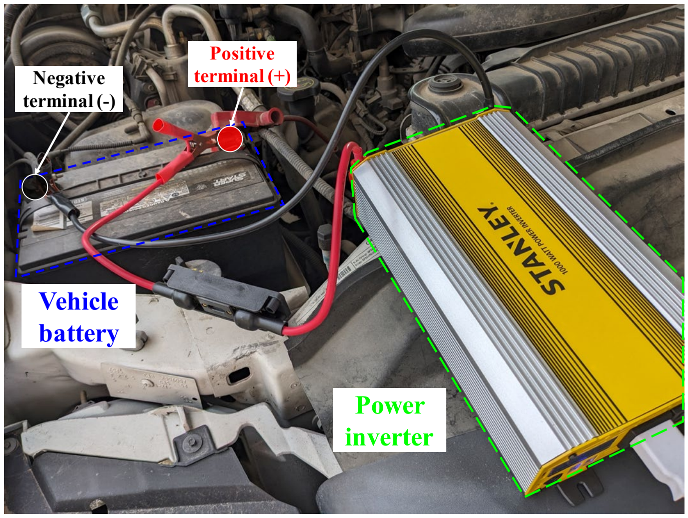


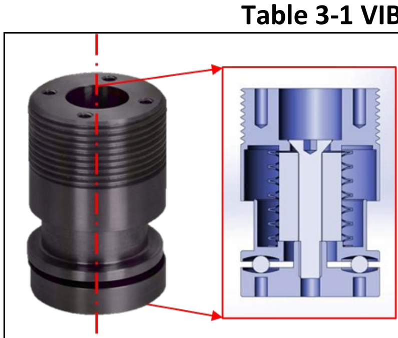
Figure 3-3 The power inverter connected with a vehicle battery.

3.2.2 Vibration Isolation Elements

A convenient way to use the Ohaus MB 120 in the field was to put it on the pickup truck bed for moisture measurement. However, doing so often causes constant vibrations from the idling engine and passing construction vehicles make it less stable.

However, isolating vibration from vibration-sensitive apparatus is not new in the laboratory. Vibration-free table is a common solution to assist the apparatus, such as optical equipment and balances, in reducing or suppressing unwanted vibrations. Therefore, four vibration isolation elements (isolator hereafter) were used to test their feasibility of isolating vibration for Ohaus MB 120, as shown in Table 3-1. The specifications for the vibration isolation elements are also listed in Table 3-1. The model of the isolator is VIB100-0205, which was selected so that the mass of the Ohaus MB 120, 11.5 lbm (5.23 kg), stays within the load range of four isolators, 7.9 lbm ~ 20.3 lbm (3.6 kg ~ 9.2 kg). Four isolators are installed at the bottom of the device via the screw holes to secure the four isolators onto Ohaus MB 120 and provide good vibration isolation, as shown in Figure 3-4.

Table 3-1 VIB100-0205 isolator specifications.

	Parameters	Values
	Load capacity	5 lbm (2.3 kg)
	Minimum isolator load	2 lbm (0.9 kg)
	Horizontal isolation, Resonance	5.8 Hz
	Horizontal Amplification at Resonance	12 dB
	Vertical Isolation, Resonance	7.8 Hz
	Vertical Amplification at Resonance	20 dB
	Weight	7 oz (200 g)

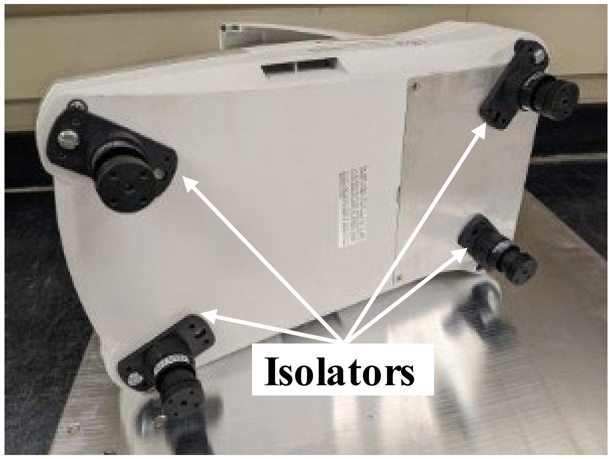


Figure 3-4 Installation of four isolators.

3.2.3 Leveling Platform and Hood

Since the four adjustable feet used for leveling the Ohaus MB 120 are replaced with four vibration isolators, a new method is needed to provide the device with a leveled platform. Figure 3-5 illustrates a possible solution, which is a new leveling platform consisting of a piece of cast aluminum and four leveling mounts. The four leveling mounts, with an adjusting range of 0 to 3 inches (0 to 7.6 cm), were bolted at the four corners on the bottom side of the cast aluminum. The hexagonal-shaped recessed hole on tip of each leveling mount is designed for easily adjusting the height with a hex key.

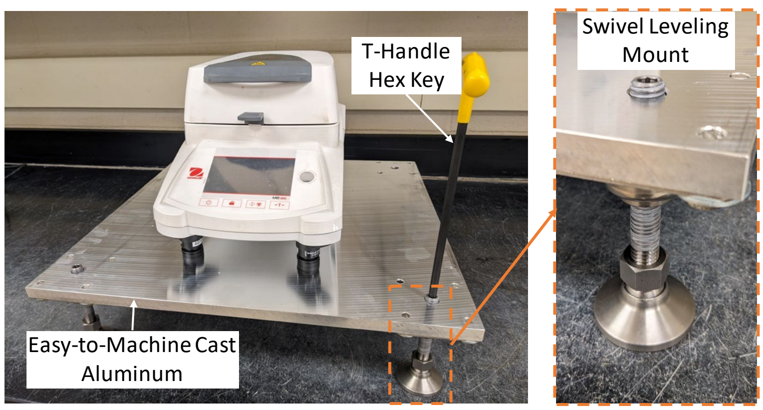


Figure 3-5 Leveling platform.

A covering hood was used to isolate the Ohaus MB 120 from the wind in the field. A clear plastic storage box was found to fit the device and leveling platform well, and thus was used as a hood to isolate wind disturbance in the field.

3.2.4 Effectiveness Validation

Both the isolators and the hood are meant to protect the Ohaus MB 120 device from vibrations and wind when it's out in the field, where vibrations can come from things like construction vehicles, the pickup truck it's on, and nearby traffic. Validation tests in the field were needed to verify if these isolators and hood could help cancel out these disturbances. Two types of soils (Rolla CL and Sikeston SM) were tested at three different moisture levels (i.e., OMC+3%, OMC, and OMC-3%) both with and without the isolators and hood to evaluate the effectiveness of new design. OMCs of Rolla CL and

Sikeston SM were 11% and 8.8%, respectively. Drying sample weight of 10 g and the switch-off criterion 1mg/60s were used in the testing.

Table 3-2 Experiment matrix for assessing isolators and hood.

Factor	Level
Soil type	Rolla CL, Sikeston SM
Moisture content	OMC+3%, OMC, OMC-3%
Isolator	With and without
Hood	With and without

Despite several attempts to perform moisture determination using the Ohaus MB 120 with isolators attached underneath but without the hood covering it, the device struggled to complete the taring process due to continuous wind blowing. This was especially challenging because the Ohaus MB 120 was left exposed to the wind without any protection. Therefore, it became necessary to temporarily use a hood for taring before starting the drying process, regardless of whether a hood was used during drying. After taring, the hood was removed, but it was carefully put back onto the leveling platform after loading the sample for testing when a hood was required.

Figure 3-6 displays the drying times for Sikeston SM and Rolla CL soils tested at different moisture levels, both with and without the hood. In tests without the hood, indicated by vertical arrows in the graph, the drying process seemed to never end due to the wind constantly disturbing the Ohaus MB 120 readings. The device couldn't meet the requirement of having no more than one milligram of mass change within 60 seconds, so the drying had to be stopped manually. On the other hand, tests conducted with the hood showed that the drying time increased as the soil moisture level went up. Furthermore, when attempting to run the drying test without isolators, it was observed that the Ohaus MB 120 placed directly on the pickup truck bed often failed to tare properly, even with a hood. This indicated that the vibrations from the pickup truck were interfering with the device's operation. However, with the four isolators installed underneath, the Ohaus MB 120 was effectively isolated from these vibrations.

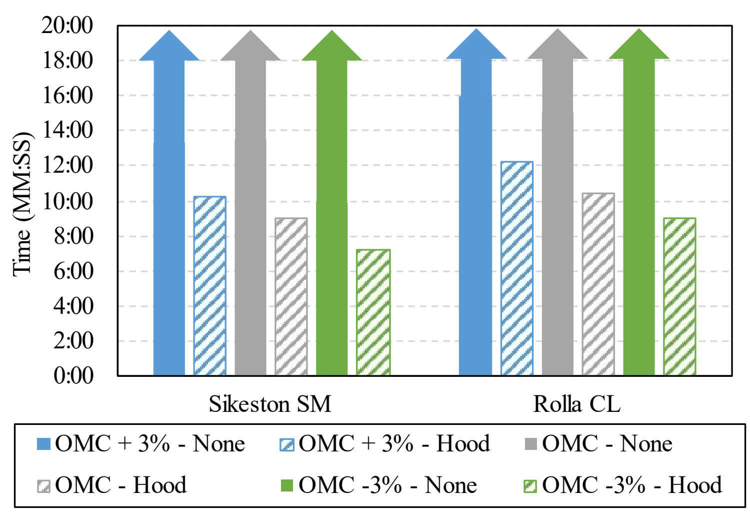


Figure 3-6 Drying durations of the Sikeston SM and Rolla CL with and without hood.

3.3 Ohaus MB 120 Setup Parameters

Now that the three main challenges in the field (electricity supply, constant vibration, and wind disturbance) have been addressed, the field moisture measurement system can effectively determine soil moisture content right in the field. However, to further improve the accuracy and efficiency of moisture measurement, two influential factors (i.e., sample weight and switch-off criterion) related to accuracy and efficiency of drying process were investigated. Some recommendations for further optimization were also made based upon the test results.

3.3.1 Influential Factors

Sample weight

The starting weight of a sample strongly affects how long it takes to dry. For a certain material at a specific moisture content, the more the sample weighs, the more moisture it has, it will take longer to dry completely. Sample weight is also crucial for accurate moisture determination. Materials with a wide range of particle sizes, like Holts Summit and Rolla GMs in this project, need a larger sample size to ensure that the sampling is representative. While for soils with narrower gradation ranges, like New Florence and Rolla CLs, and Sikeston SM, smaller sample can be used. Therefore, it is important to use proper sample weight to make sure the sample is representative, and the moisture measurement is accurate without making the drying process significantly longer, especially for materials with broad gradations.

Switch-off criterion

Due to the need of rapid moisture content measurement, the Ohaus MB 120 is not designed to dry a sample till a constant mass as what a conventional oven does. Instead, it has different ways to decide when to stop drying. These are called switch-off criteria. Even though the sample's mass might not be constant when drying stops, any errors can be fixed by calibrating the device with a simple linear function. This way, the device can be fast and still give reasonably accurate results. The switch-off criteria come in three types: time-based, mass-based, and moisture content-based. Table 3-3 shows the six preset options in the Ohaus MB 120. The first criterion, Time (MM:SS), is based on time. It stops drying after a set number of minutes and seconds. Criteria two to five are four criteria based on mass. They stop drying when the sample's mass changes by less than a certain amount in a set time. The first three time-based criteria have a mass limit of 1 mg and time limits of 30 s, 60 s, and 90 s respectively. The last time-based criterion can be customized by users with their preferred mass change and time values. The sixth option is based on moisture content. It works like the mass-based criteria, but instead of mass change, it looks at how much the moisture content changes. Like the last time-based criterion, the sixth one can also be customized with preferred moisture content change and duration values. The effects of different switch-off criteria on moisture determination should be investigated, based on which the selection of a switch-off criterion can be confirmed.

Furthermore, there are three factors temperature, surface area, and air movement that affecting how quickly water evaporates during the drying process. Among them, surface area is the easiest to manage, while keeping the temperature constant at 230 °F is required and controlling air movement can be more challenging. Having a larger surface area means more of the sample is exposed to the air, which speeds up evaporation. So, it's important to grind or cut drying samples into small pieces without breaking the particles to increase their surface area.

Table 3-3 Switch-off criteria of Ohaus MB 120.

No.	Switch-off criterion	Explanation
1	Time (MM:SS)	Drying process ends in a certain duration defined with minutes and seconds.
2	A30 (1 mg / 30s)	Drying process ends when sample mass changes less than 1 mg within 30 seconds.
3	A60 (1 mg / 60s)	Drying process ends when sample mass changes less than 1 mg within 60 seconds.
4	A90 (1 mg / 90s)	Drying process ends when sample mass changes less than 1 mg within 90 seconds.
5	Free (mg / s)	Drying process ends when sample mass changes less than certain mg within certain seconds.
6	Free (% / s)	Drying process ends when moisture content changes less than certain percent within certain seconds.

3.3.2 Testing Method

Sample weight

The first factor examined in the laboratory was the sample weight, aiming to establish a confident and appropriate weight for subsequent tests. An experimental matrix, incorporating three factors (soil type, sample weight, and moisture content), was devised and detailed in Table 3-4. As previously mentioned, three distinct soils gathered from the field—Rolla CL, Sikeston SM, and Holts Summit GM—were chosen to encompass various soil types. These soils represent the three levels of the soil type factor. The sample weight factor comprised four levels. Notably, due to the larger nominal maximum particle size (NMPS) of 3/4 in. (19 mm) in Holts Summit GM compared to the #10 (2 mm) in Rolla CL and Sikeston SM, Holts Summit GM necessitated larger sample weights. Sample weights of 30 g, 40 g, 50 g, and 60 g were selected for Holts Summit GM, while Rolla CL and Sikeston SM were used weights of 5 g, 10 g, 20 g, and 30 g.

Figure 3-7 shows the sample pan covered by evenly spread samples for different sample weights of Rolla CL and Holts Summit GM. Since MoDOT requires the compaction moisture content to lie between OMC-3% and OMC, three levels for the factor moisture content were set starting from OMC-3% with an increment of 3%, which were OMC-3%, OMC, and OMC+3%. OMCs of Rolla CL, Sikeston SM, and Holts Summit GM were 11%, 8.8%, and 7.2%, respectively. The switch-off criterion 1mg/60s was used in the testing.

Table 3-4 Experiment matrix for assessing sample weight.

Factor	Level
Soil type	Rolla CL, Sikeston SM, Holts Summit GM
Sample weight (g)	5, 10, 20, 30; 30*, 40*, 50*, 60*
Moisture content	OMC-3%, OMC, OMC+3%

* Sample weight for Holts Summit GM.

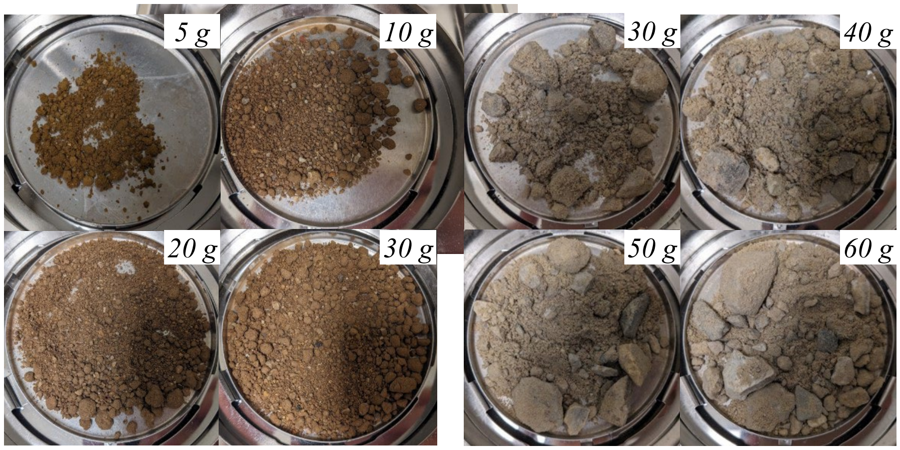


Figure 3-7 Sample weights for the Rolla CL (left) and Holts Summit GM (right).

Switch-off criterion

As mentioned previously, three sorts of switch-off criteria (i.e., time change-, mass change -, and moisture content percent change - based) are programmed in the Ohaus MB 120 for users, and either one could signal the device to terminate the drying process. However, it is not clear yet that which criterion works best without inducing significant error or longer duration. In order to investigate their impact on shortening drying duration and improving their accuracy, Sikeston SM samples, at moisture contents of OMC (8.8%) and OMC-3% (5.8%), were tested at various switch-off criteria listed in Table 3-5. Three different switch-off criteria were used for the three sorts of switch-off criteria. For example, criteria based on the time change included 6 min, 8 min, and 10 min; the mass change switch-off criteria consisted of 1mg/30s, 1mg/60s, and 1mg/90s; and 0.2%, 0.1%, and 0.01% per 60 seconds criteria were tested for the moisture content percent change switch-off criterion. Three replicates were conducted for each combination of factors. Drying sample weight of 10 g was used for the testing in light of the conclusion, obtained in the investigation of proper drying sample weight, that 10 g of drying sample weight ensured both efficiency and accuracy.

Table 3-5 Experiment matrix for assessing switch-off criteria.

Factor	Level
Switch-off criterion	1mg/30s, 1mg/60s, 1mg/90s; 6 min, 8 min, 10 min; 0.2%/60s, 0.1%/60s, 0.01%/60s
Moisture content	OMC, OMC-3%

3.3.3 Testing Results

Sample weight

Figure 3-8 shows the moisture content measurement results for the three soils (i.e., Sikeston SM, Rolla CL, and Holts Summit GM) at three different moisture contents and four different sample weights. A clear trend was observed that the drying duration almost linearly increased as the increase of sample weight in the drying pan of Ohaus MB 120. A linear function, $y = 27.11\,x + c$, was found able to approximate the development in drying duration with respect to the change in sample weight, where y is the drying duration in second, x is the sample weight in gram, and c is the intercept that differs for different moisture contents and soil types. It should be noted that this function was obtained from results measured with the switch-off criterion of no more than one-milligram mass change within 60 seconds (1mg/60s), which may not be valid with other switch-off criteria. In addition, the two coarse-grained soils, Sikeston SM and Holts Summit GM, tended to fit in a linear equation with the same intercept c at the two similar testing moisture contents lower than the OMC. For example, at the moisture content around 5% and 8%, the drying duration trend of Sikeston SM tested at weights of 5 g, 10 g, 15 g, and 30 g approximately fitted into the same line as that of Holts Summit tested at weights of 30 g, 40 g, 50 g, and 60 g. Comparing drying durations of Sikeston SM with those of Rolla CL, it was found that the two soils shared a similar increasing trend at moisture contents around 8.5% and 11.3%. On the other hand, the increasing trend of Rolla CL at moisture content of 14.6% tended to match that of Holts Summit GM at 10.2% moisture content, though their moisture contents were not close to each other. The consistency and continuity showed in drying durations of Rolla CL and Sikeston SM suggests that the type of soil may make no significant difference in the drying duration as long as soils are well grinded, at similar moisture levels, and dried at close weights.

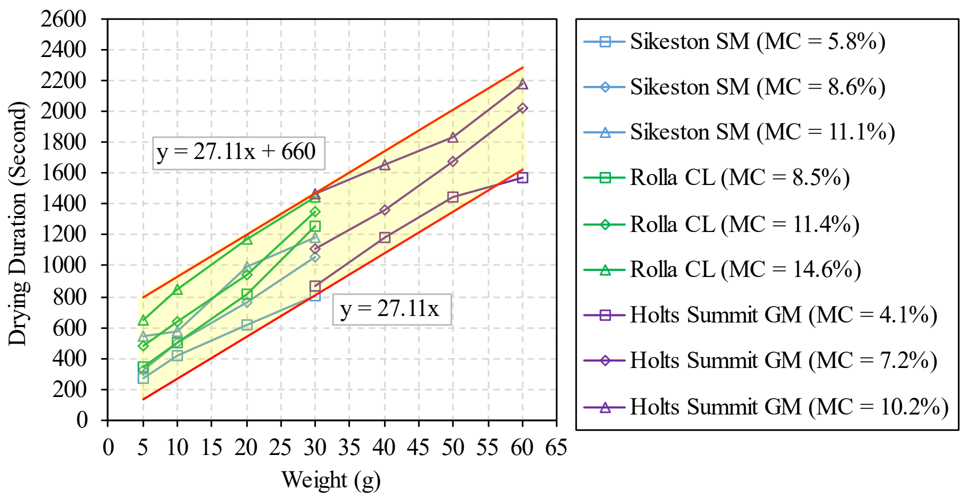


Figure 3-8 Drying sample weights and their durations.

Figure 3-9 compares results of moisture content measurements for the three soils made by the conventional oven-drying method and the Ohaus MB 120. A line of equality was also shown which was denoted by a red solid line in Figure 3-9. As a rule of thumb, the closer a point is to the line of equality, the more accurate the measurement. It can be seen that data points of Holts Summit GM fell closer to the line of equality than those of the other two, though points offset from the line slightly with the increase in the moisture content. For Sikeston SM and Rolla CL, their deviation from line of equality was comparable, and the deviation from the line of equality grew higher as the moisture content increased. The highest deviation shown in the graph occurred at data points of Rolla CL with moisture content of 14.6%, that less moisture was dried out than expected explains why its drying duration was shorter than expected as shown in Figure 3-8. Moreover, calibrations with linear functions crossing the origin were performed and illustrated in the figure. Calibration coefficients for Rolla CL, Sikeston SM, and Holts Summit GM were determined as 1.1967, 1.206, and 1.0631, respectively, with R^2 values higher than 0.998. This means that with proper calibration, the moisture contents measured by the Ohaus MB were almost the same as those obtained by the conventional oven-drying method.

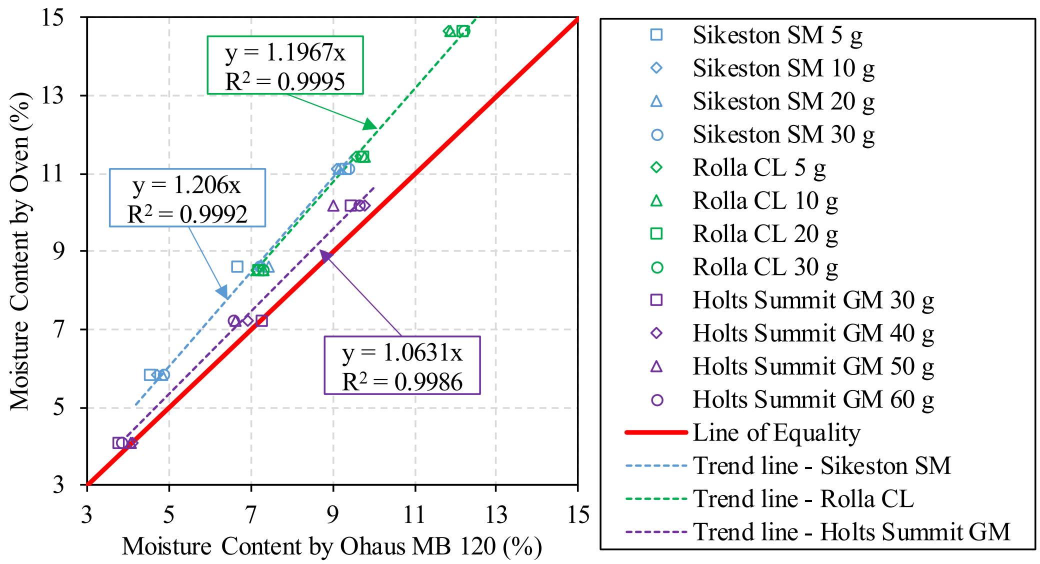


Figure 3-9 Drying sample weights and their moisture content results.

Switch-off criterion

Dry soils of Sikeston SM were ground and mixed with water to achieve two target moisture contents: 5.8% and 8.8%. The actual moisture contents of the two mixes were determined using the oven-drying method, and it was found that actual moisture contents for the mixes were 5.97% and 8.81% respectively. A total of 18 samples were then taken from the two mixes (9 from each), and their moisture contents were measured using the Ohaus MB 120 with 9 different switch-off criteria, categorized into three groups. Figure 3-10 illustrates the measured moisture contents for Sikeston SM at the two targeted moisture levels, utilizing the nine switch-off criteria. Figure 3-11 shows the dry duration for the 18 soil samples as shown in Figure 3-10.

Figure 3-10 indicated that all moisture measurements measured by the Ohaus MB 120 were lower than moisture contents of either 5.97% or 8.81% measured by the oven, which was reasonable since the Ohaus MB 120 was designed not to completely dry the soil sample. It was also found that generally, when a stricter criterion was used, the resulted moisture contents approached closer to the targeted moisture content. For example, for the targeted moisture content of 8.81%, when the moisture content-based switch-off criteria changed from 0.2%/60s to 0.1%/60s, and then to 0.01%/60s, the resulted moisture contents changed from 7.52% to 7.67% to 7.89%. The same trend was observed when the time-based criterion changed from 6 min to 8 min to 10 min, the resulted moisture contents changed from 7.82% to 7.87% to 7.91%. This trend was not seen for the mass-based criterion since when the mass changed from 1mg/30s to 1mg/60s to 1mg/90s, the moisture contents first decreased from 7.82% to 7.69% and then increased to 7.78%. This abnormality mostly was caused by the non-uniformity of the soil specimen since normally a stricter criterion often meant longer duration and subsequently dryer soil which is closer to the full completion of the moisture content tests. This can be supported by the results in Figure 3-11, in which when the moisture content-based switch-off criteria changed from 0.2%/60s to 0.1%/60s to 0.01%/60s for the targeted moisture content of 8.81%, the test durations increased from 330s to 360s to 510s.

Combining results in Figures 3-10 and 3-11, it is apparent that applying stricter parameters in the three sorts of criteria would definitely and obviously extend the drying duration, but the accuracy improvement induced by the extension would be limited after a certain point. Therefore, one may not want to stick on pursuing a better accuracy by using stricter criteria without keeping an eye on the increase in drying duration, as the accuracy and efficiency may not benefit from a change in switch-off criterion to the same degree.

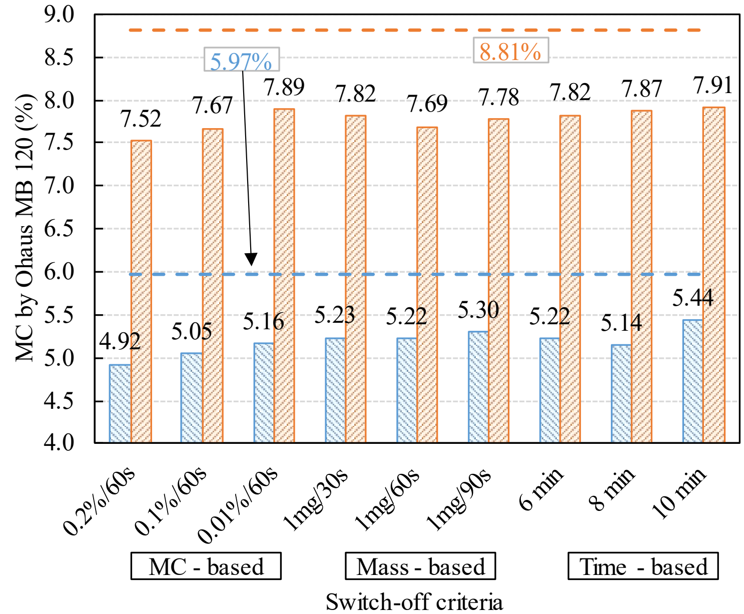


Figure 3-10 Switch-off criteria and their moisture content results.

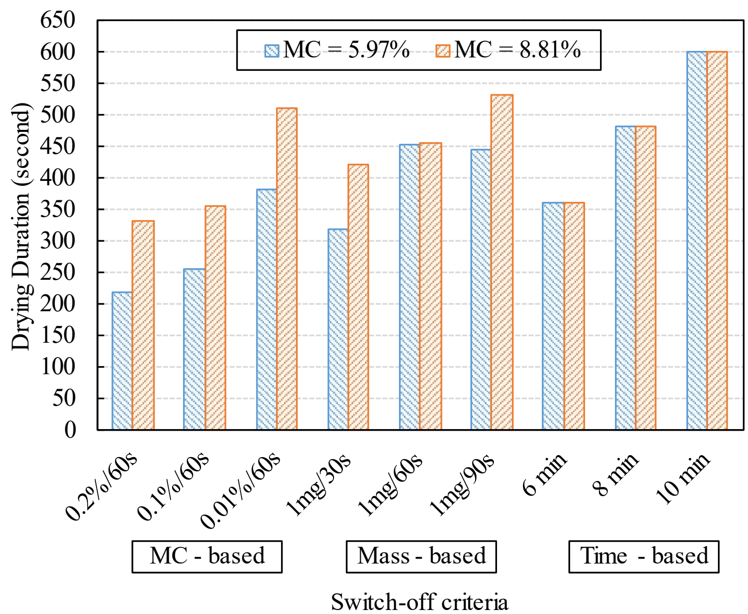


Figure 3-11 Switch-off criteria and their durations.

3.4 Conclusion and Recommendations

A field moisture measurement system, consisting of the Ohaus MB 120, a power inverter, a leveling platform, isolation elements, and a hood, was designed to overcome the three field challenges (i.e., electricity supply, consistent vibration, and wind disturbance) in field moisture determination. A series of field drying tests validated the feasibility of isolation solutions.

In field tests for validating the designed unit, Rolla CL and Sikeston SM were tested at three different moisture content for factor combinations of with/without hood and with/without isolators. The selected isolators were found effective in protecting the equipment from being disturbed by truck, and the Ohaus MB 120 hardly went through the taring process successfully because of the continuous wind blow in the field unless a hood covered on top of the equipment. Therefore, the design of drying system was successful in resolving the three challenges in moisture content measurement with Ohaus MB 120. However, some improvements, such as a more convenient hood, may need to be made for the further wide deployment.

Due to the necessity of obtaining the moisture content with a balance of accuracy and efficiency on Ohaus MB 120, the duration and accuracy of moisture determination was investigated for different sample weights and switch-off criteria, with a series of lab tests on three different sorts of soils including Rolla CL, Sikeston SM, and Holts Summit GM at various moisture contents. As Rolla CL and Sikeston SM has smaller particle distribution than Holts Summit GM, sample weights of 5 g, 10 g, 20 g, and 30 g were used for Rolla CL and Sikeston SM, while Holts Summit was dried at levels of 30 g, 40 g, 50 g, and 60 g. Compared with the sample moisture content, the drying sample weight had less impact on the drying accuracy. The deviation of moisture contents measured with Ohaus MB 120 apparently increased as the sample moisture content grew. Conservatively speaking, a sample weight of 10 grams should be reliable for soils without big particles, while soils with big particles requires at least 30 grams.

As for switch-off criteria, three categories of criteria based on time change, sample weight change, and moisture content change were tested at three levels. For example, 0.01%/60s, 0.1%/60s, and 0.2%/60s for the moisture content change criterion; 1mg/30s, 1mg/60s, and 1mg/90s for the mass change criterion; and 6min, 8min, and 10min for the time change criterion. Conclusions were drawn that applying stricter parameters in the three sorts of criteria would expand the drying duration, but the accuracy improvement resulted from which would be limited after a certain point. Therefore, one should keep an eye on the rise in drying duration when pursuing a better accuracy by unlimitedly using strict criteria, as the accuracy and efficiency may not benefit from a change in switch-off criterion to the same degree. Based on the experience in a series of drying test in present project, the criteria 1mg/60s that was used most of time was found good for all drying tests.

Chapter 4. Field Tests and Findings

In this chapter, a brief introduction of the four visited field sites, testing method, equipment, and acceptance evaluation method was first given. Details, including testing plan, results, and evaluation outcome for each soil were then described. Lastly, a comparison of moisture content measurement results between NDG and oven was presented.

4.1 Introduction

In order to evaluate the application of Zorn 2000 LWDs on more soils in Missouri, the research team performed six field-testing campaigns at four construction sites in collaborating with MoDOT personnel and contractors. Table 4-1 listed information of each field trip made for field LWD testing, which includes date, project name, soil type, and the number of field LWD tests conducted. In each trip for field testing, a series of LWD field tests were conducted, after which soil samples from each testing spot were collected for moisture determination in the laboratory. Besides trips made for field testing, another five trips were made for sample collection. In each trip for sample collection, 35 five-gallon buckets of soil were collected from either a field site or a quarry, where collected soils were ensured identical with those tested in the field.

Table 4-1 Site visit dates and in-situ soils.

Date	Project (Location)	Soil type	Testing quantity
May/04th/2023 & May/31st/2023	New Florence Intersection Enhancement project (New Florence, MO)	CL	162
Jun./15th/2023	Holts Summit Roundabout project (Holts Summit, MO)	GM	126
Sep./14th/2023	Sikeston Overpass over US 60 (Sikeston, MO)	SM	132
Oct./10th/2023	Rolla I-44 Improvement (Rolla, MO)	CL	81
Oct./11th/2023	Rolla I-44 Improvement (Rolla, MO)	GM	81

4.1.1 LWD Tests in the Field

The testing procedure of field LWD tests is similar to that of LWD tests on Proctor mold, except for steps before setting the bearing plate. In the field test, the only step for specimen preparation is smoothening the surface of testing spot, to ensure a good contact between the soil and the bearing plate. Especially for clay soils, site surface compacted by a sheepsfoot roller is rough and far away from the requirement of field LWD tests. At New Florence site, a thin layer was trimmed off from the surface testing area by a bulldozer with favors of field engineers, while the evenness at Rolla CL site was acceptable as a bulldozer was used to do compaction.

Following the same steps as those in laboratory LWD tests, a bearing plate was positioned onto the marked testing spot, and a slight twist was made clockwise and counterclockwise by 45 degrees to further ensure a good contact. Then, six drop were made by allowing the falling weight to fall freely from a certain fixed height and to rebound upon its hitting on the spring buffer. Data including testing spot, LWD model, and deflection was collected for all six drops, though the first and second three were for conditioning and measurement, respectively.

As shown in Table 4-2, three field-version LWDs, identified by model numbers #3878, #3879, and #4421, were utilized for the field testing, mirroring the LWD devices employed in the Phase I project. Notably, the first two LWDs share the same model, indicating identical dimensions for their bearing plates and guiding rods, as well as matching mass for their falling weights. In contrast, the LWD #4421 has a shorter guiding road and a smaller bearing plate. Consequently, these differences led to the difference in the resultant applied stress, with LWDs #3878 and #3879 applying a stress of 14.5 psi, while LWD #4421 exerts 24.5 psi.

Table 4-2 Properties of LWD devices used in the field.

				
LWD	#	3878	3879	4421
Drop height	in	28	28	22
Plate diameter	in	12	12	8
Hammer weight	lbm	22.0	22.0	22.0
Loading force	lbf	1590	1590	1416
Resultant stress	psi	14.5	14.5	29.0

Although tests with different LWDs were conducted one after another, a possible interference might occur if testing positions of them overlapped each other. For example, the soil bore six drops from the previous device might show a higher modulus in the measurement with the next device. Hence, as illustrated in Figure 4-1, in order to avoid any possible interference between three LWDs and ensure consistency in the tested soil, bearing plates of the three LWDs were positioned at the testing spot so that they intersected with the circle marked in mapping but did not overlap with each other.

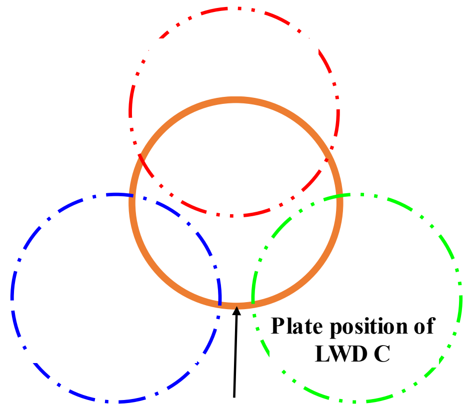


Figure 4-1 Plate positions at a testing spot.

In the calculation of modulus of LWD test on Proctor mold, assumptions were made regarding the tested soil, assuming it to be isotopically homogeneous and a linear elastic semi-finite continuum. With identical assumption, deflection of the uniformly loaded rigid bearing plate on the surface of the half-space can be derived from the original Boussinesq theory (Huang, 2004), and thus the modulus of elasticity of the tested soil beneath the bearing plate can be determined using Equation 4-1.

$$E_{field} = A\frac{2R\sigma_{field}\,(1-v^2)}{s_{field}}$$

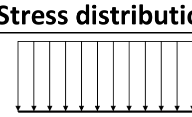
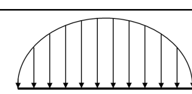
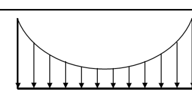
where

E_{field} = field LWD modulus (psi),
A = stress distribution factor (Table 4-3),
σ_{field} = applied stress in the field (psi),
R = radius of bearing plate (in), and
s_{field} = deflection occurred in the field (in).

Equation 4-1 Field LWD modulus

It should be noted that in the calculation of field LWD modulus, a stress distribution factor accounting for the difference of stress on different soil types was considered (Schwartz et al., 2017), as shown in Table 4-3.

Table 4-3 Stress distribution factors for different sorts of soils.

Soil type	Factor (A)	Stress distribution
Mixed soil (uniform)	1	
Granular material (parabolic)	$\frac{4}{3}$	
Cohesive (inverse-parabolic)	$\frac{\pi}{4}$	

4.1.2 Acceptance Evaluation Method

The basic concept of evaluating compaction acceptance of unbound materials using an LWD involves a three-variable model (Equation 2-3) fitted with results of LWD test on Proctor mold, where the three variables include the LWD modulus (E_{lab}), applied stress (σ_{lab}), and moisture content (MC_{lab}) in LWD test on Proctor mold. By establishing a correlation between these variables with regression coefficients a_i, a target field LWD modulus (E_{target}) can be estimated by Equation 2-4 with a moisture content (MC_{field}) and an applied stress (σ_{field}) obtained in a field test. A ratio (E_{field}/E_{target}) of measured field LWD modulus to target field LWD modulus can thus be derived.

The field test moisture content and the modulus ratio are two criteria used to assess the soil compaction acceptance. In the compaction evaluation process, the first step is to evaluate whether the field moisture content falls within the acceptable range, where a range of OMC-3% to OMC was used in accordance with MoDOT specification (Missouri highways and transportation commission, 2022). The testing point with a moisture content outside the acceptable range is considered unacceptable, while the testing point having a moisture content within the range proceeds to the next step, which is the modulus ratio evaluation. During this evaluation, the testing point with a modulus ratio greater than 100% is considered acceptable. As a rule of thumb, only the testing point that meets both moisture content and modulus ratio criteria is considered acceptable for compaction.

In addition, since the GMs at Holts Summit and Rolla sites were both a 4-in thick base course layer on top of a clay foundation and its total surface deflection under LWD plate in Equation 4-1 was the summation of both top (base aggregate) and bottom (clay) layers, the target field LWD modulus of the GM should be corrected using Equation 4-2. Field LWD moduli of 2.9 ksi and 3.9 ksi were used for the clay foundations in Holts Summit and Rolla sites, respectively, where the former is a typical value assumed and the latter is an averaged value measured in the field.

$$E_{target\ -corr} = 1/\left\{\frac{1}{E_2\left[\sqrt{1+\left(\frac{h}{R}\sqrt[3]{\frac{E_1}{E_2}}\right)}\right]} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{R}\right)^2}}\right]}{E_1}\right\}$$

where

$E_{target-corr}$ = corrected target modulus for the base material (psi),
E_2 = field LWD modulus of the bottom layer (psi),
E_1 = target modulus of the top layer (psi), and
h = top layer thickness (in).

Equation 4-2 Modulus correction for two-layer system.

4.2 New Florence CL Site

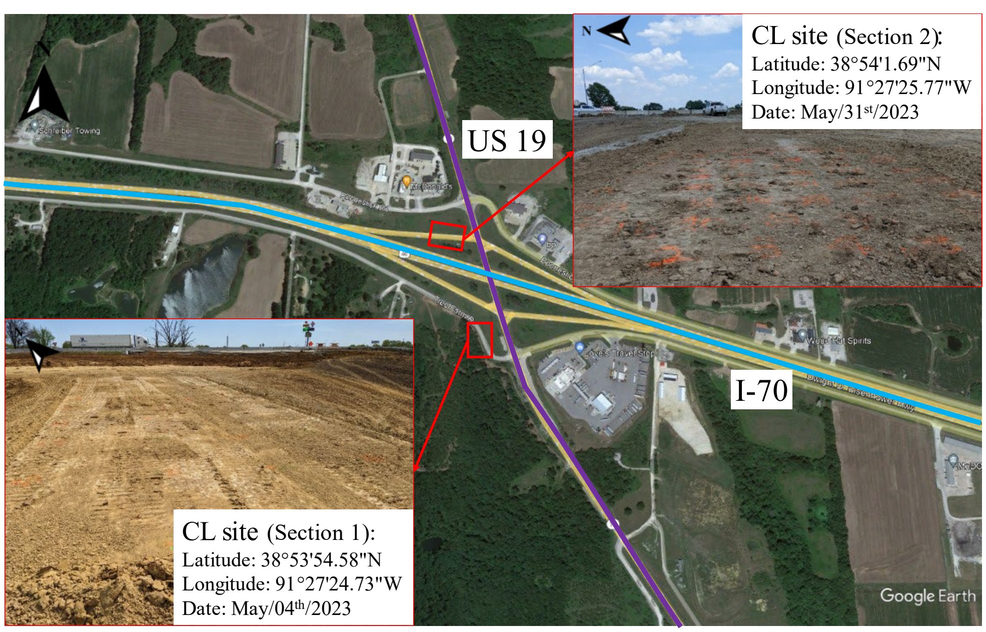
4.2.1 Testing Plan

Figure 4-2 (a) shows the location of New Florence CL site near the intersection of US highway 19 and Interstate highway 70. In order to test as many points as possible, two sections were tested at the site, with sections one and two at the southeast and northeast sides of the intersection, respectively. At the site, New Florence CL was compacted to function as the subgrade of a pavement. It is noted that the section one was tested around ten days after compaction and the section two was tested on the same day as compaction.

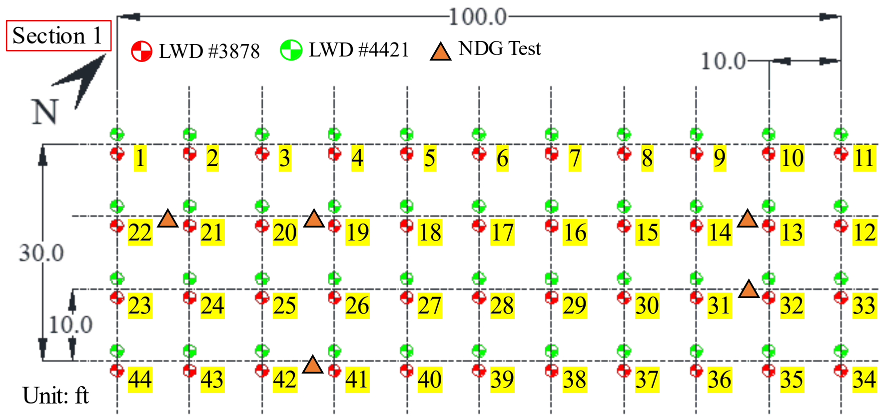
Figures 4-2 (b) and (c) show layouts of testing points in two sections, in which the section one comprised of 44 points and the section two had 40 points. Row and column spacings in two sections were 10 ft (3.1 m). In section one, only LWDs #3878 and #4421 were used to test all points, because of an unpredicted dead battery in LWD #3879. On the other hand, in section two, two rows of points at northern and southern ends were disposed because of construction disturbance in the field. In addition, to the west of section two, a slope situated three feet away from the testing area. Among those remaining points, LWD 3878 tested at all points except points 30, 31, 36, 37, and 38; LWD #3879 tested at all points excluding points 30 and 39; and LWD #4421 tested at all points.

It is worth noting that all moisture contents could have been measured on site and some of the moisture contents were measured on site using the Ohaus Moisture Analyzer as discussed in Chapter 3. However, to maximize the number of LWD test points and minimize the testing time on site and the associated interference with the field construction process, under most conditions, soil samples were taken immediately at points where the LWD tests were performed and brought back to the laboratory for moisture content determination using the oven-drying method.

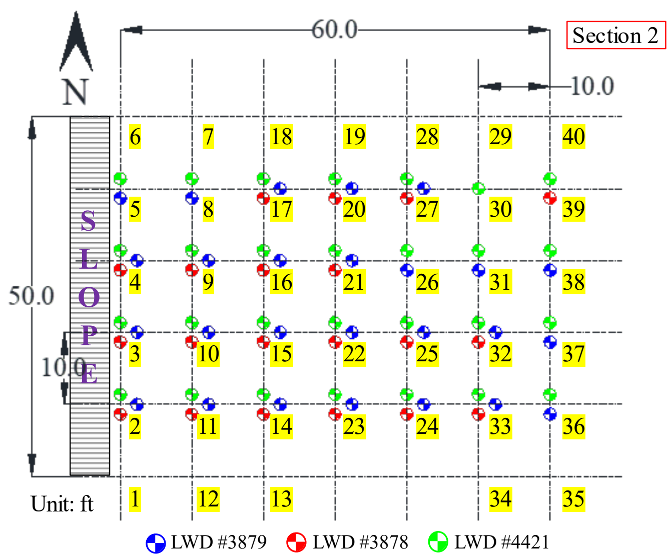
Besides field LWD tests, five points in section one, including 13, 19, 21, 32, and 41, were randomly selected to conduct NDG testing with the help of field engineers, which are noted with orange triangles in Figure 4-2 (b).



(a) Site view



(b) Testing point layout in section one



(c) Testing point layout in section two

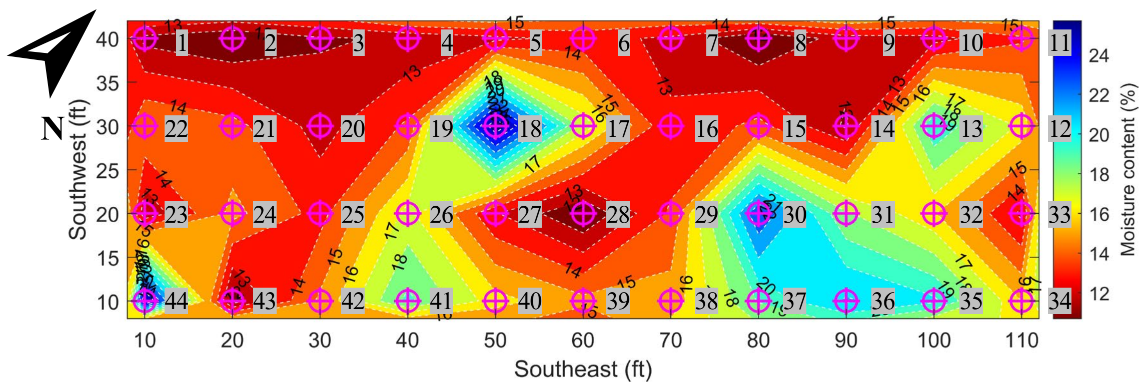
Figure 4-2 Location and testing plan of New Florence CL Site.

4.2.2 Results

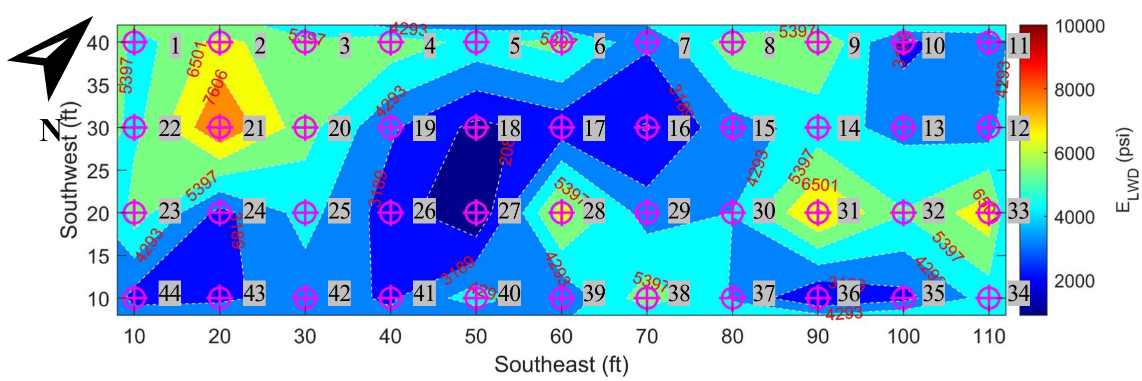
Figures 4-3 (a) to (c) illustrate distributions of moisture content and LWD moduli in section one of New Florence site. As illustrated in Figure 4-3 (a), the moisture content in this section ranged from 10% to 26%. In addition, moisture contents at the northwestern side were relatively lower than those at the southwestern side, with some exceptions such as notably low moisture content at point 28 (13%). Several points including 13, 18, 30, 35, 36, 37, and 44 showed moisture contents higher than 20%. The acceptable moisture content span ranging from 11.5% to 14.5% was determined based on the OMC of 14.5%. About one third of points fell in the acceptable moisture content span.

Figure 4-3 (b) shows the LWD modulus contour measured with LWD #3878. Its pattern correlated with that of the moisture content contour reasonably well. At locations with lower moisture contents, LWD moduli were generally high such as points 2, 8, 23,28, and 33 (5 ksi - 8 ksi). While at points 13, 18, 30, 35, 36, 37, and 44 with notably high moisture contents of more than 20%, LWD moduli were low (2 ksi - 4 ksi).

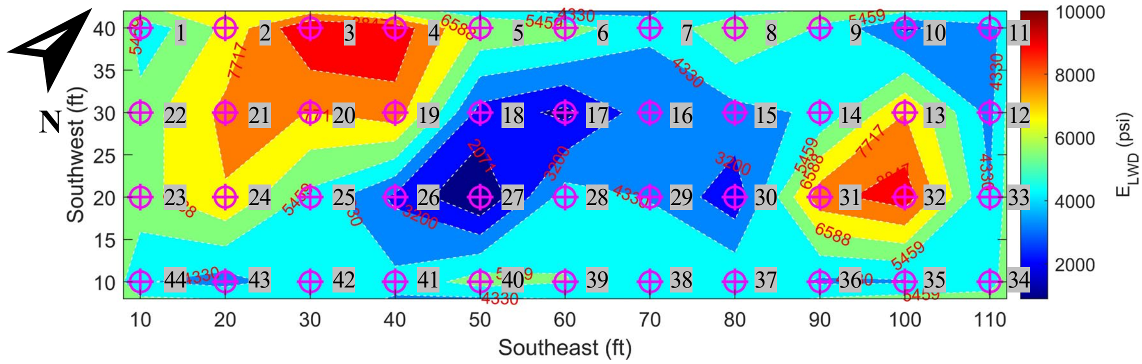
Figure 4-3 (c) shows the LWD modulus contour measured with LWD #4421. The pattern shown in the contour was similar to that measured by LWD #3878 as shown Figure 4-3 (b), and correlated with the moisture content contour (Figure 4-3 (a)) reasonably well. On the other hand, LWD moduli measured with LWD #4421 were found generally higher than those measured using LWD #3878 at the same locations. For example, at point 35, the LWD modulus in Figure 4-3 (b) was 3.2 ksi, while in Figure 4-3(c), it was 5.5 ksi. These minor disparities can be ascribed to the variations in the models for LWDs #3878, #3879, and #4421, where LWDs #3878 and #3879 share the same model. As delineated in Table 4-2, the resultant stress for LWD #4421 was 50% higher than that for LWD#3878 and #3879. Consequently, a higher stress level applied by LWD #4421 induced a higher LWD modulus, because of the stress dependency of unbound materials as underscored in Chapter 2.



(a) Moisture content contour



(b) Modulus contour of LWD #3878



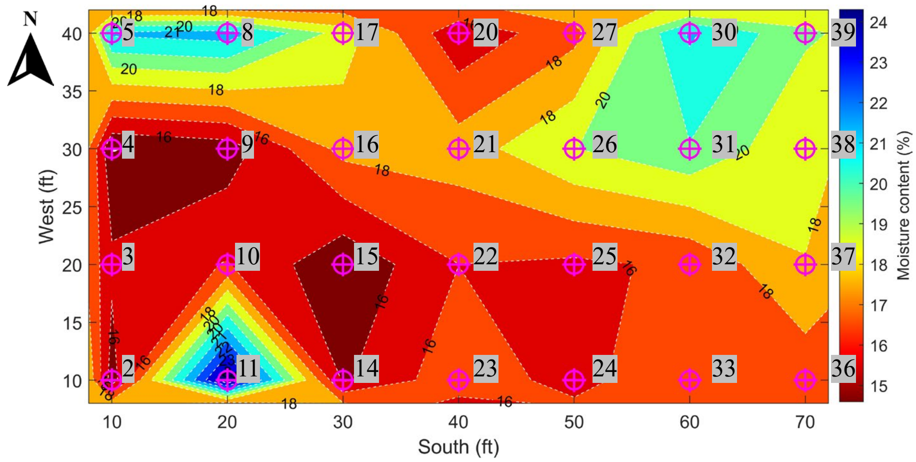
(c) Modulus contour of LWD #4421

Figure 4-3 Moisture content and LWD modulus contours of New Florence CL in section one.

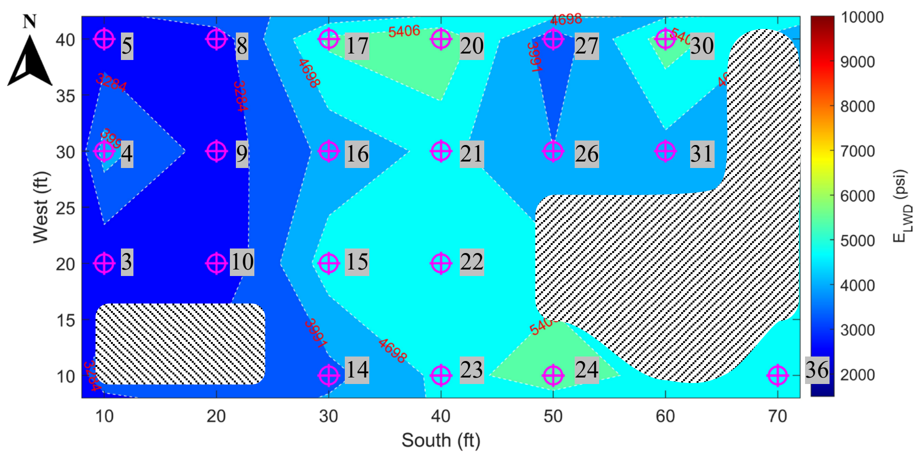
Figures 4-4 (a) to (d) show contours of moisture content and LWD moduli in section two of New Florence site. As shown in Figure 4-4 (a), the moisture content generally increased from the southwestern side to the northeastern side, with three high-moisture spots at southwest, northwest, and northeast corners, respectively. Moisture contents in this section ranged from 14.6% to 25%, indicating all testing points in this section fell out of the acceptable moisture content range (i.e., 11.5% ~ 14.5%).

Figures 4-4 (b) to (d) illustrate LWD moduli measured with LWDs #3878, #3879, and #4421, respectively. Though some points in this section were not tested with LWDs #3878 and #3879 because of construction interference, moduli measured with three LWDs generally shared a similar pattern. The LWD modulus started with consistently low values around 3 ksi in two columns at the west side and increased to a relatively higher level around 4.5 ksi in the third column connecting points 14 and 17. A vertical L-shape area with high values around 5 ksi covered the center and the southeast corner. The remaining northeast corner showed low values around 4 ksi. Similarly, except for the three western columns, LWD #4421 showed overall slightly higher LWD moduli compared to LWDs #3878 and #3879, because of the higher stress applied.

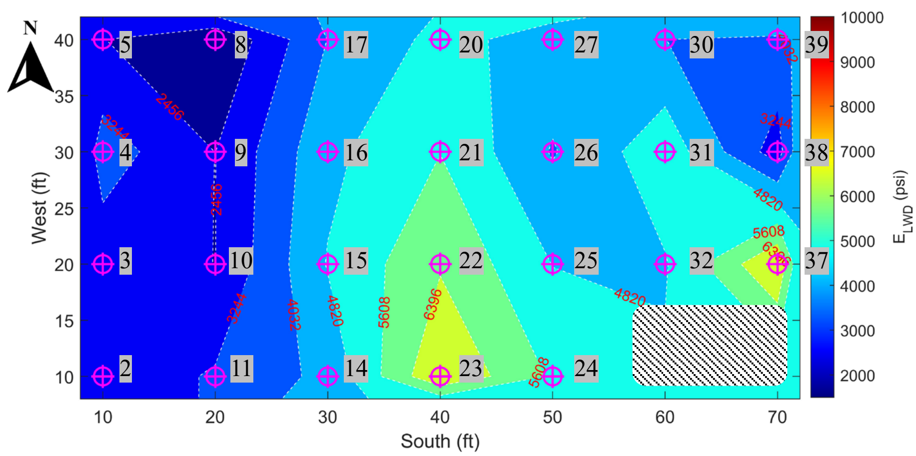
As illustrated in Figures 4-4 (a) to (d), distribution patterns of moisture content and LWD modulus generally matched, except for the area with consistently low LWD moduli that extends from the west side to the line connecting points 14 and 17. For example, the L-shape area with low moisture contents covering the center and the southeastern corner of moisture content contour matched well with the L-shape area with high LWD moduli at the same location of LWD modulus contours. Areas with relatively high moisture contents and low LWD moduli at the northeast corners of contours also matched. In addition, the subgrade slope three feet to the west of testing area could account for the consistently low LWD moduli measured in the three western columns at site, as that is where the under compaction commonly occurs.



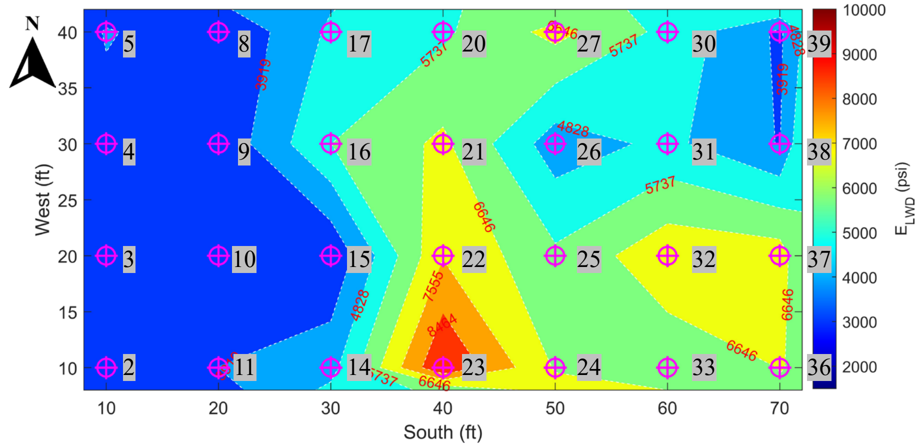
(a) Moisture content contour



(b) Modulus contour of LWD #3878



(c) Modulus contour of LWD #3879

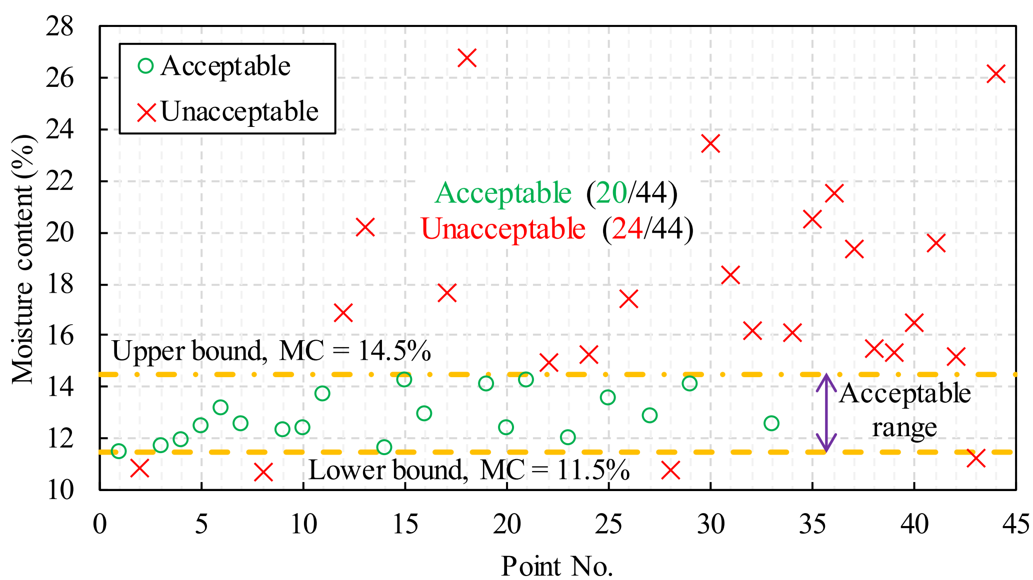


(d) Modulus contour of LWD #4421

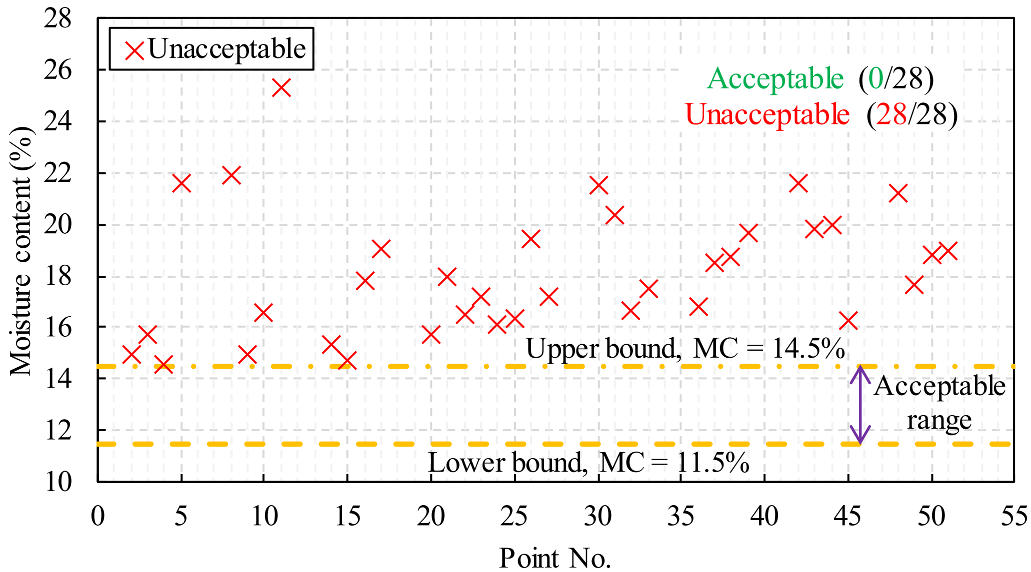
Figure 4-4 Moisture content and LWD modulus contours of New Florence CL in section two.

4.2.3 Acceptance Evaluation

Figures 4-5 (a) and (b) show moisture contents measured in sections one and two at New Florence CL site. The OMC for the soil compacted at site was 14.5%, and thus the acceptable moisture content range was determined to be 11.5% ~ 14.5%. Figure 4-5 (a) depicts the moisture content evaluation for the section one. Among the 44 points tested in this section, 20 of them had moisture contents within the acceptable range, while moisture contents at the remaining 24 points were unacceptable. However, in the section two, as illustrated in Figure 4-5 (b), none of the 28 tested points was found acceptable in terms of their moisture contents, though some of them were close to the acceptable range.



(a) Section one



(b) Section two

Figure 4-5 Moisture evaluation for New Florence CL.

Therefore, only the 20 points having acceptable moisture contents in section one will be evaluated with the modulus ratio criterion, and they will only be considered acceptable if they meet both criteria.

Figure 4-6 shows the evaluation of modulus ratio on the 20 points that met moisture content criterion for New Florence CL. All markers in the plotting fell below the acceptable ratio range, indicating that none of these points was found acceptable in terms of their modulus ratios for LWDs # 3878 and #4421. The two LWDs showed generally consistent modulus ratios in this section, which conformed to observations in their LWD modulus contours shown in Figure 4-3.

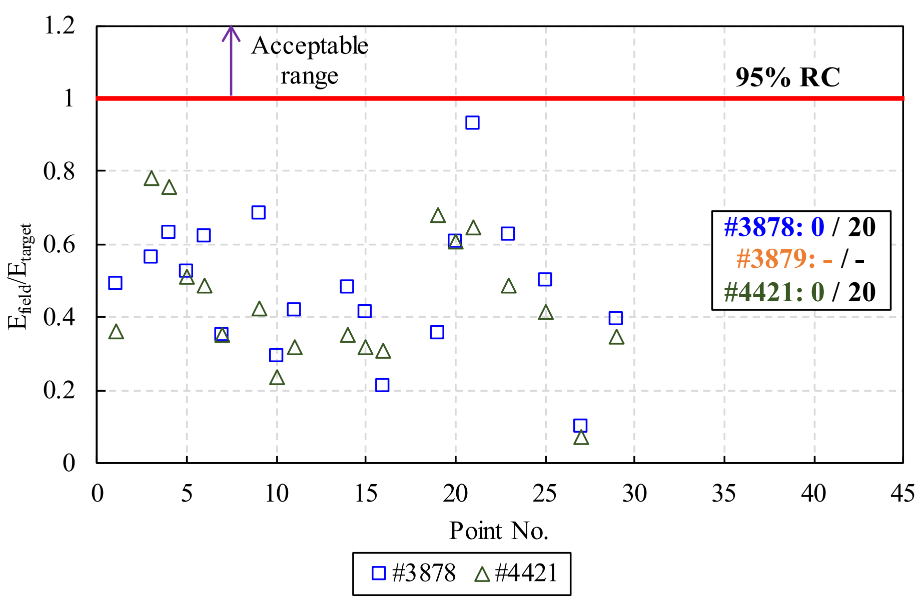


Figure 4-6 Modulus ratio evaluation for New Florence CL in section one.

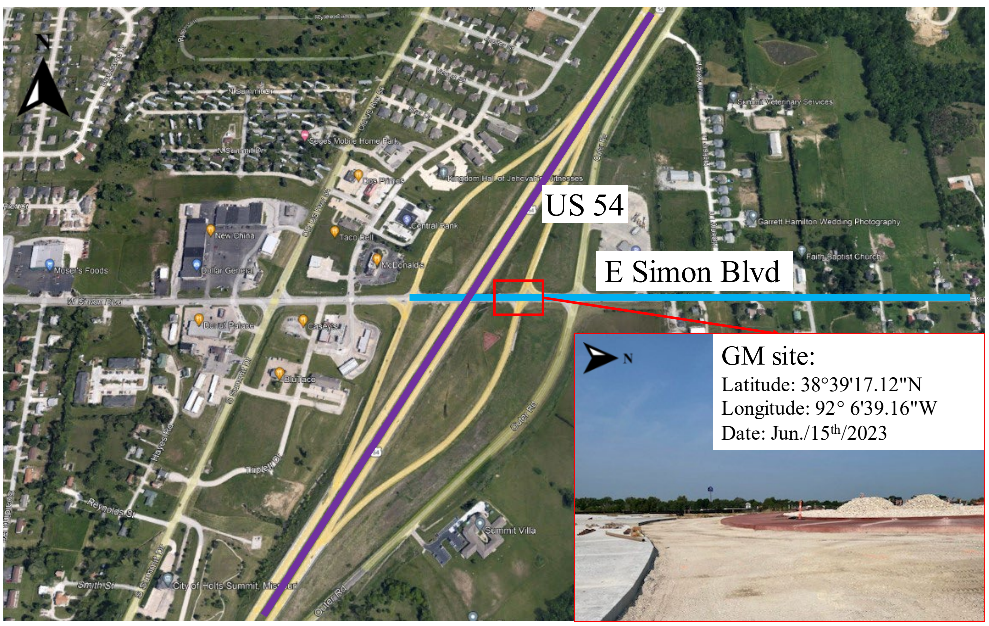
4.3 Holts Summit GM Site

4.3.1 Testing Plan

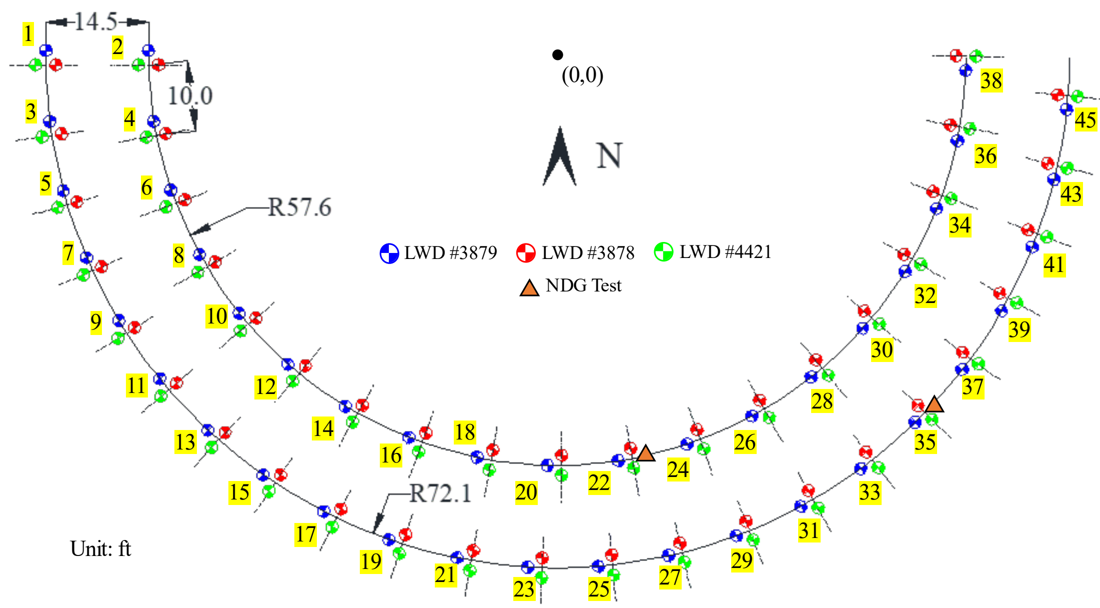
Figure 4-7 (a) depicts the location of Holts Summit site near the intersection of US highway 54 and E. Simon Boulevard. Holts Summit GM was used as the base course material for a roundabout construction. This site was tested on Jun. 15th, 2023, one day after compaction.

Figure 4-7 (b) shows the scheme of testing points at Holts Summit site. Forty-two testing points were mapped into two rows along half of the roundabout. The distance along circumference between two adjacent points in the same row was around 10 ft (3.1 m), and one row offset from the other by 14.5 ft (4.4 m). All points were tested with all the three LWDs in the field. Soil samples were taken immediately at locations where the LWD tests were performed and brought back to the laboratory for moisture content determination using the oven-drying method.

In addition to field LWD tests, NDG tests were also performed by a field engineer at two testing spots (i.e., No. 24 and 35) shown in Figure 4-7 (b), and a testing depth of 6 in was used.



(a) Site view



(b) Testing point layout

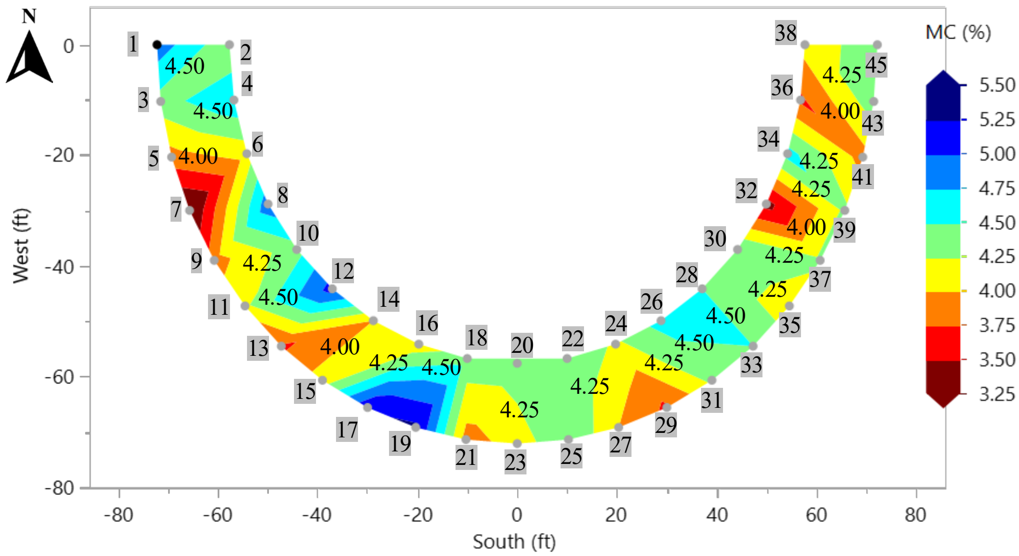
Figure 4-7 Location and testing plan of Holts Summit GM site.

4.3.2 Results

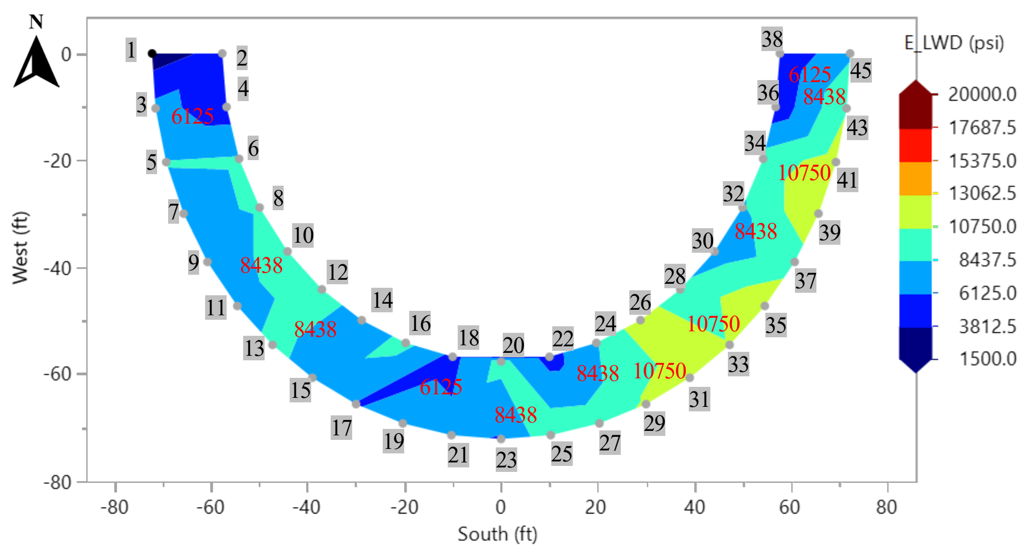
In Figures 4-8 (a) to (d), contours illustrating the distribution patterns of moisture content and LWD modulus for Holts Summit GM are shown. As depicted in Figure 4-8 (a), moisture contents at this site ranged from 3.2% to 5.5%, with majority of points having moisture contents around 4.5%. Given that the OMC of silty gravel compacted at this site was 7.2%, moisture contents at majority of points were within the acceptable range (4.2% ~ 7.2%).

Figures 4-8 (b) through (d) show LWD modulus contours measured at Holts Summit site. LWD moduli measured with three LWD devices shared a comparable distribution pattern, ranging from 1.7 ksi to 17 ksi. The LWD modulus started with low values around 3.8 ksi at starting points one to four, grew to a bit higher level around 8.4ksi at following points prior to the point 12, decreased slightly to a lower level around 6.1 ksi again at points 12 to 22, and increased to higher values around 10.8 ksi till the end of testing area. Consistencies can be observed in these contours, for example, cold colors indicating low LWD moduli at points 1~4, 14~27, 36, and 38, and warm colors implying high LWD moduli at points 10, 12, 39, 41, and 43.

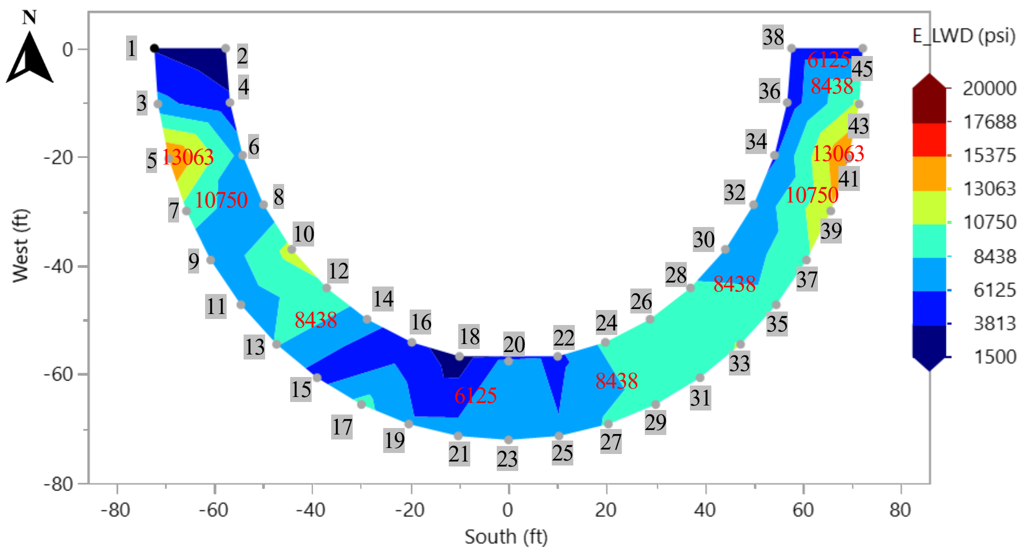
Comparing Figures 4-8 (a) through (d), however, distribution patterns of moisture content and LWD modulus did not correlate with each other as well as they did on the CL at New Florence site, and some possible correlations were observed only at several points (i.e., 37, 39, 41, and 43).



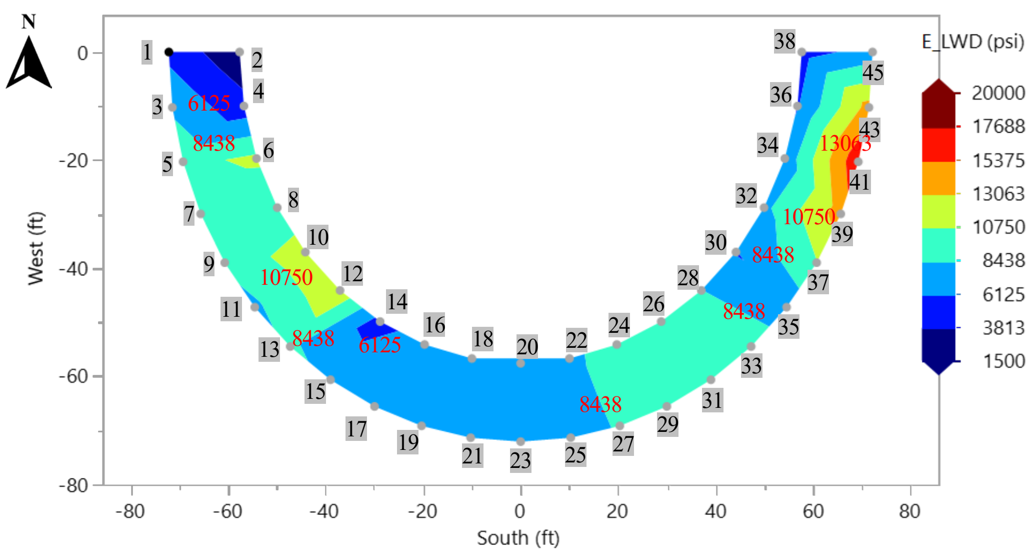
(a) Moisture content contour



(b) Modulus contour of LWD #3878



(c) Modulus contour of LWD #3879



(d) Modulus contour of LWD #4421

Figure 4-8 Moisture content and LWD modulus contours of Holts Summit GM site.

4.3.3 Acceptance Evaluation

In Figure 4-9, the evaluation of moisture contents measured at 42 points at Holts Summit GM site are shown. The OMC of Holts Summit GM was 7.2% and its acceptable range was 4.2% ~ 7.2%. Among those values in the plotting, 25 of them fell into the acceptable range, while the remaining 17 values scattered below and close to the lower bond 4.2% moisture content. It is worth noting that there was no point having a moisture content higher than the OMC. So those 25 points will continue to be evaluated in terms of modulus ratio for the final acceptance.

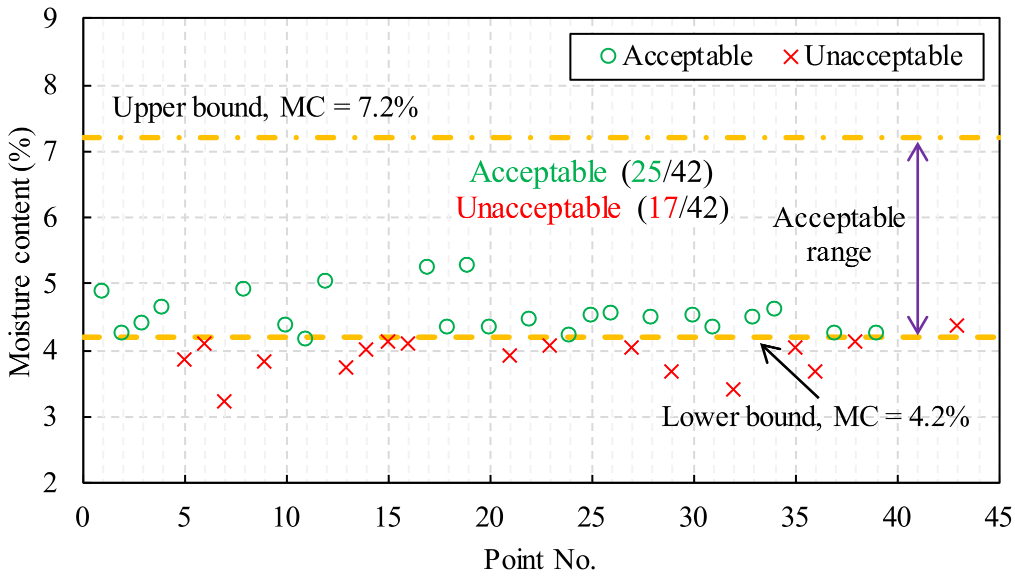


Figure 4-9 Moisture evaluation for Holts Summit GM.

Figure 4-10 depicted the evaluation of modulus ratios measured with three LWDs at Holts Summit GM site. Only five points fell out of the acceptable range, among which, one was from LWD #3878, one was from LWD #4421, and the remaining three were from LWD #3879. Therefore, 24 out of 25 points were considered acceptable for LWDs # 3878 and # 4421, while LWD #3879 had 22 out of 25 points acceptable. At this site, three LWD devices had similar numbers of acceptable points, which was in agreement with the observation in their LWD modulus contours shown in Figure 4-8. It is worth noting that some modulus ratios went up as high as 3.5, which could result from the stress-hardening feature of the material observed in both LWD tests on Proctor mold and resilient modulus tests.

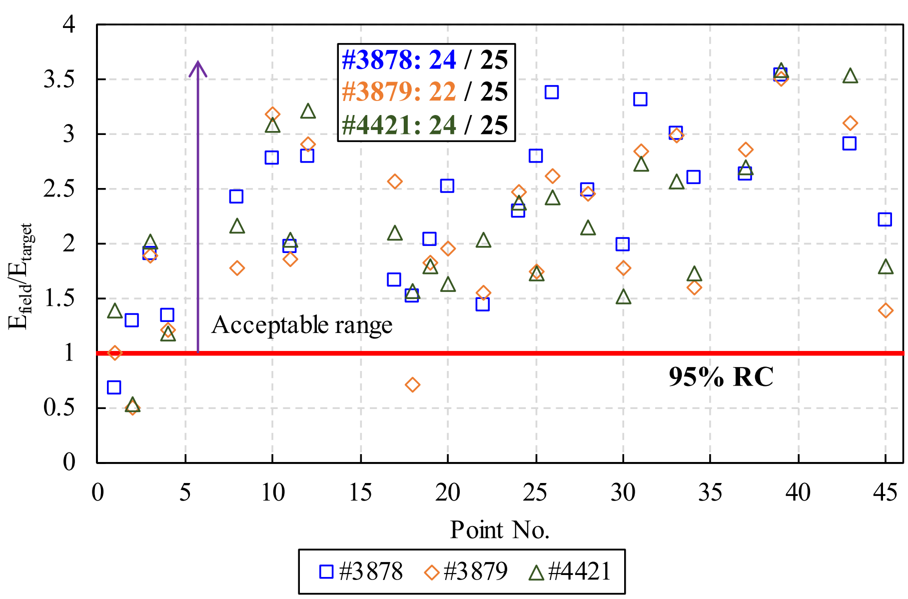


Figure 4-10 Modulus ratio evaluation for Holts Summit GM.

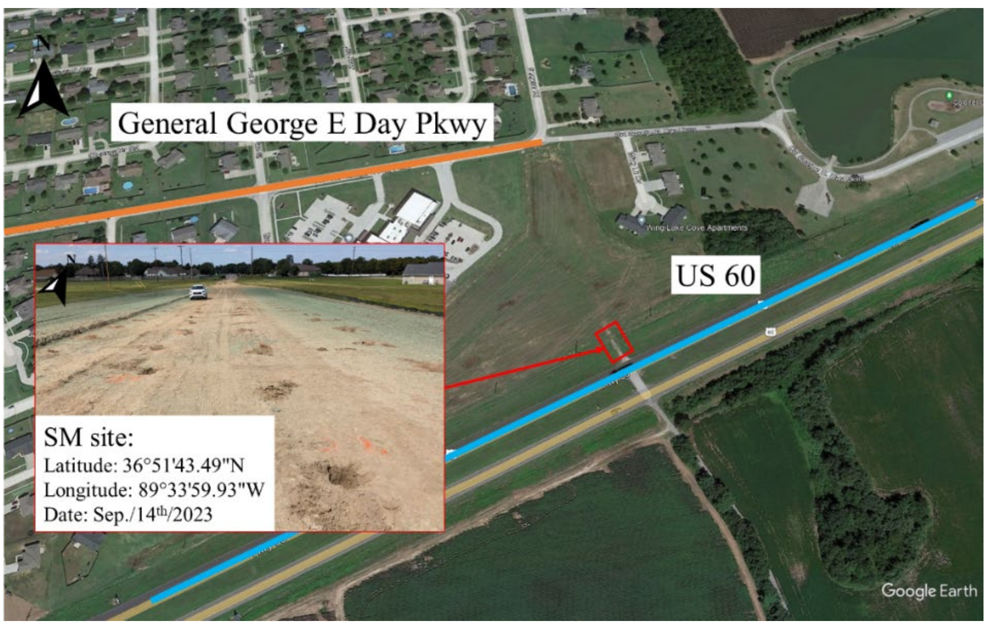
4.4 Sikeston SM Site

4.4.1 Testing Plan

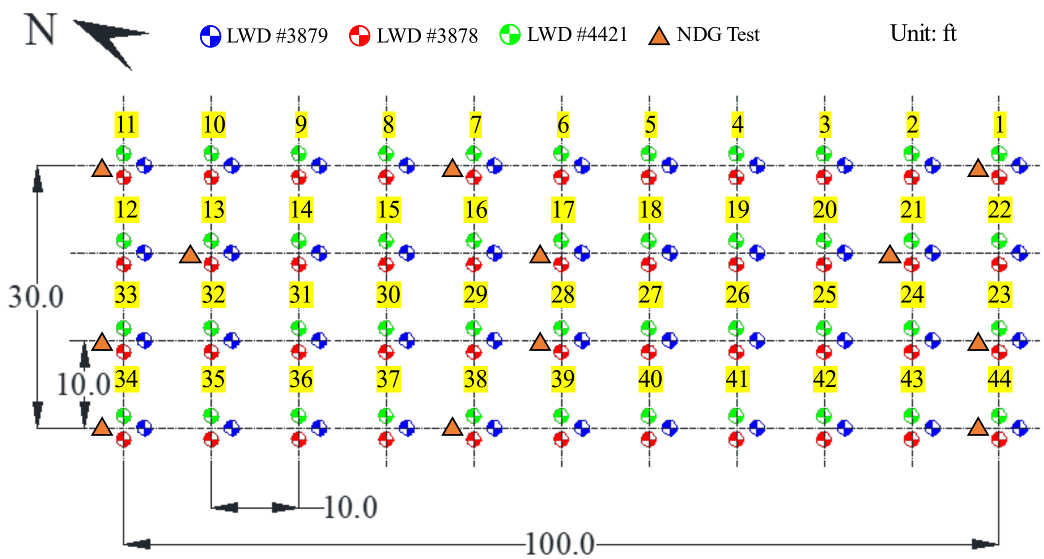
Figure 4-11 (a) illustrates the location of Sikeston SM site situating between US route 60 and General George E. Day Parkway and next to US route 60. At the site, Sikeston SM was compacted into an overpass embankment. This site was tested on Sep. 14th, 2023, prior to which the field trip was delayed several times for one week because of the continuously rainy weather then.

Figure 4-11 (b) shows the layout of testing points at Sikeston SM site. A total of 44 points were mapped into a four-by-eleven matrix, in which row and column spacings were kept by 10 ft (3.1 m). All these points were tested with three LWD devices. Soil samples at each testing spot were also collected immediately after LWD testing.

Figure 4-11 (b) also illustrates the locations of 12 points tested with NDG at Sikeston SM site, which were selected from north, middle, and south parts of the scheme so that they evenly covered the entire testing area. The 12 NDG tests were conducted with the help of a field engineer, in which a measuring depth of 10 in (25 cm) was used.



(a) Site view



(b) Testing point layout

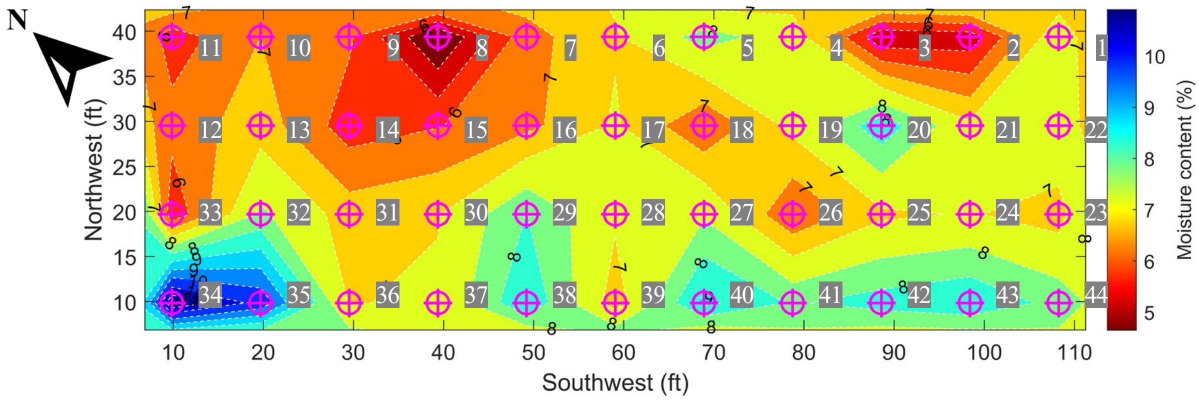
Figure 4-11 Location and testing plan of Sikeston SM site.

4.4.2 Results

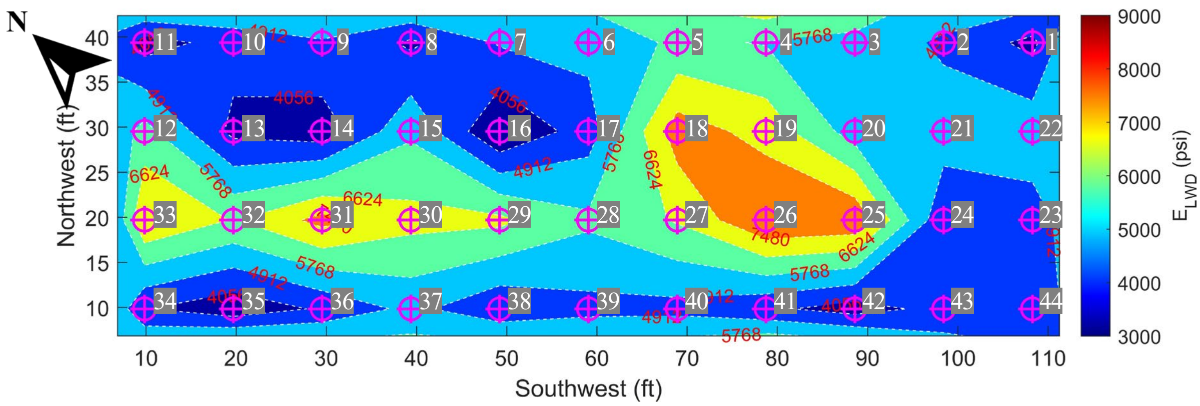
Figures 4-12 (a) to (d) illustrate distribution patterns of moisture content and LWD modulus contours at Sikeston SM site. As shown in Figure 4-12 (a), moisture contents at this site ranged from 4.6% to 11.4%, with an increasing trend from 6%-7% at the northeastern side to 8% at the southwestern side. At the southwest side, points 34 and 35 showed notably higher moisture contents around 11%, while the lowest moisture content was 4.6% at point 8.

As shown in Figures 4-12 (c) to (d), LWD moduli measured with three LWDs ranged from 3 ksi to 9 ksi, and their distributions shared a similar pattern. For example, in all three contours of LWD modulus, points on the line connecting points 26 and 33 consistently showed high LWD moduli indicated by warm colors, while the remaining points surrounding that line were illustrated with cold colors indicating low LWD modulus values.

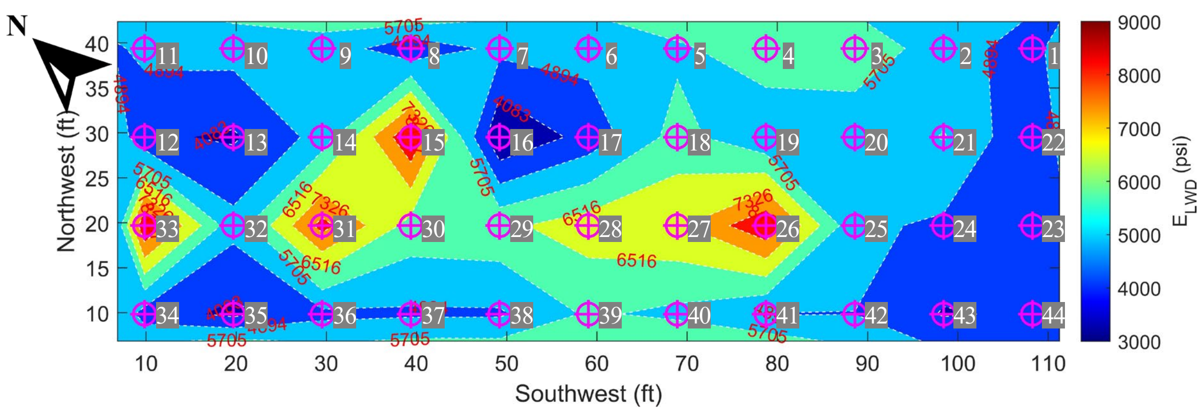
In Figures 4-12 (a) to (d), good correlations between moisture content and LWD modulus were observed in the southwestern half part of site. For example, low moisture contents in the row connecting points 25 and 33 led to high LWD moduli, and low LWD moduli in the row connecting points 34 and 44 resulted from high moisture contents. However, the two rows at northeast side having low moisture contents did not correlate with measured low LWD moduli.



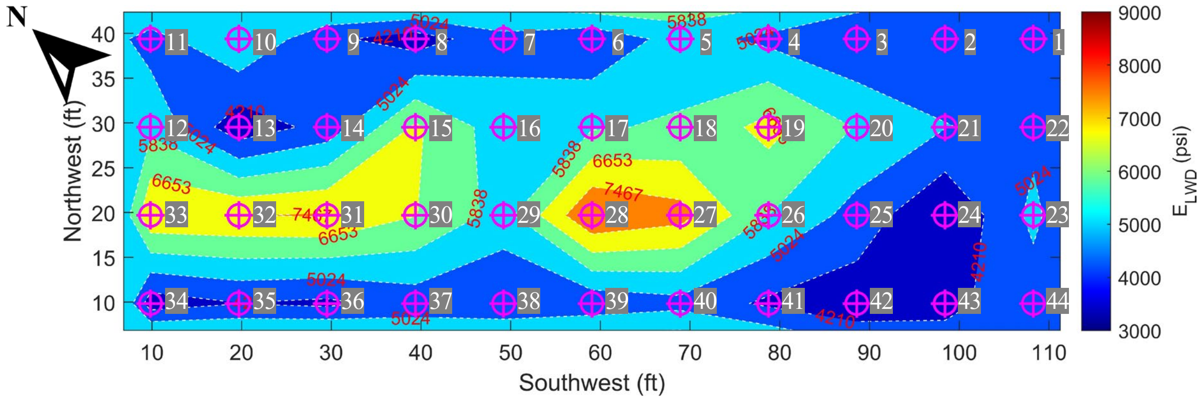
(a) Moisture content contour



(b) Modulus contour of LWD #3878



(c) Modulus contour of LWD #3879



(d) Modulus contour of LWD #4421

Figure 4-12 Moisture content and LWD modulus contours of Sikeston SM site.

4.4.3 Acceptance Evaluation

Figure 4-13 illustrates the evaluation of moisture content on Sikeston SM. With an OMC of 8.8%, the acceptable moisture content range for Sikeston SM was derived as 5.8% ~ 8.8%. Out of the 44 points test at this site, 38 points were found within the acceptable moisture content span. With these 38 points, the evaluation of modulus ratio will be conducted for the conclusion of compaction acceptance.

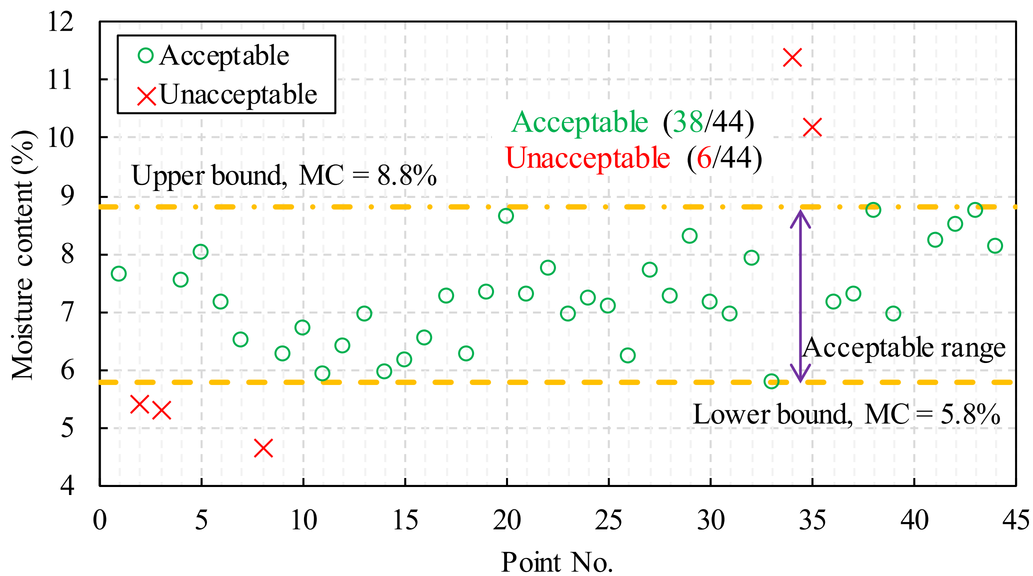


Figure 4-13 Moisture evaluation for Sikeston SM.

Figure 4-14 depicts the evaluation of modulus ratio on Sikeston SM. Most points were found in the acceptable range except for points tested with LWD #4421. Specifically, among the 38 points having acceptable moisture contents, LWDs #3878 and #3879 had 30 and 35 acceptable, respectively, while LWD #4421 had only 10 points acceptable. Though three LWDs showed similar distribution patterns in their LWD modulus contours shown in Figure 4-12, LWD #4421 had less points acceptable than the other two. It should be noted that the majority of unacceptable points for LWD #4421 had modulus ratios around 0.8, though they were less than 1.

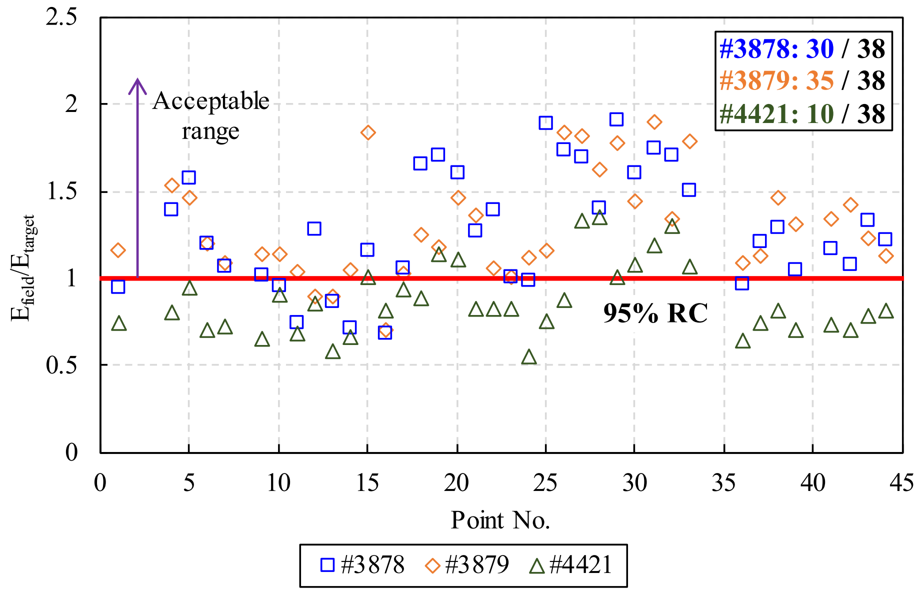


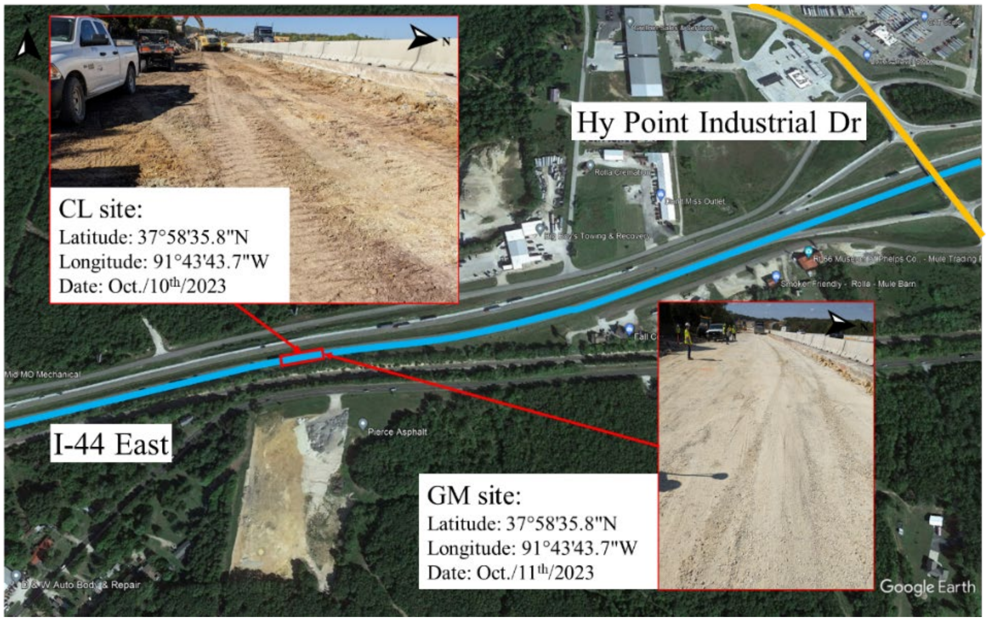
Figure 4-14 Modulus ratio evaluation for Sikeston SM.

4.5 Rolla CL and GM Sites

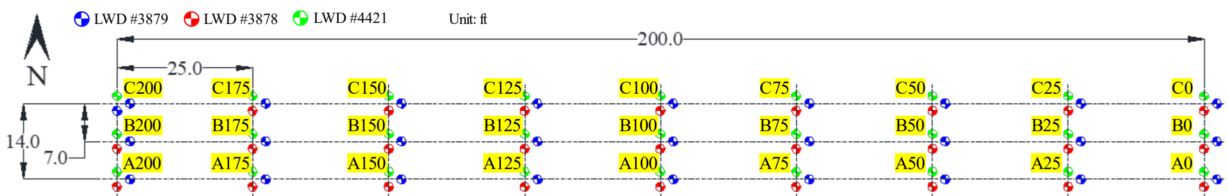
4.5.1 Testing Plan

Figure 4-15 (a) displays the locations and site perspectives of CL and GM at Rolla site, situated on the eastbound side of I-44 between Rolla and St. James, MO, at milepost 189.4. This site was a part of the I-44 rehabilitation construction project. At this site, Rolla CL and Rolla GM were sequentially compacted to serve as the subgrade and the base course, respectively. The identical site was utilized as a demonstration project for Federal Highway Administration (FHWA) intelligence compaction (IC), conducted in cooperation with Transtech company. The research team took the opportunity and collaborated with Transtech to perform field Light LWD tests on both the subgrade and base course layers, on October 10th and 11th, 2023, respectively. Compaction activities were conducted in the morning, with LWD tests performed in the afternoon of the same day for the subgrade and base course layers, respectively.

Figure 4-15 (b) outlines the layout of designated testing spots for both Rolla CL and Rolla GM, determined by engineers from Transtech company. GPS receivers were utilized to ensure that testing points on the subgrade and base course layers were positioned precisely in the vertical direction. A three-by-nine matrix comprising 27 points was marked, with 7 ft spacing between rows and 25 ft spacing between columns. All points were tested using all three LWD devices. However, no Nuclear Density Gauge (NDG) tests were conducted in the field. Additionally, samples were collected from each testing spot for moisture measurement in the laboratory using the oven-drying method.



(a) Site view



(b) Testing point layout

Figure 4-15 Location and testing plan of Rolla CL and GM sites.

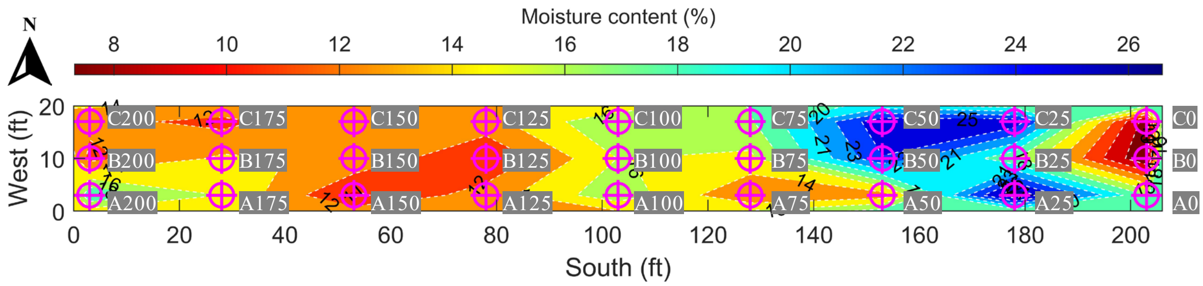
4.5.2 Results

Figures 4-16 (a) through (d) depict the moisture content and LWD modulus distribution patterns for the CL subgrade layer at the Rolla site. Generally, moisture ranged from 7.3% to 23.3%, with most points having moisture contents around 15%. As illustrated in Figure 4-16 (a), it's evident that the moisture content of Rolla CL was lower on the west side of test section (10% - 14%) and higher on the east end, with exceptions at points B0 and C0 having moisture as low as 8%. Moisture contents at the area surrounded by points A50, A75, and B75 had relatively low values about 12%.

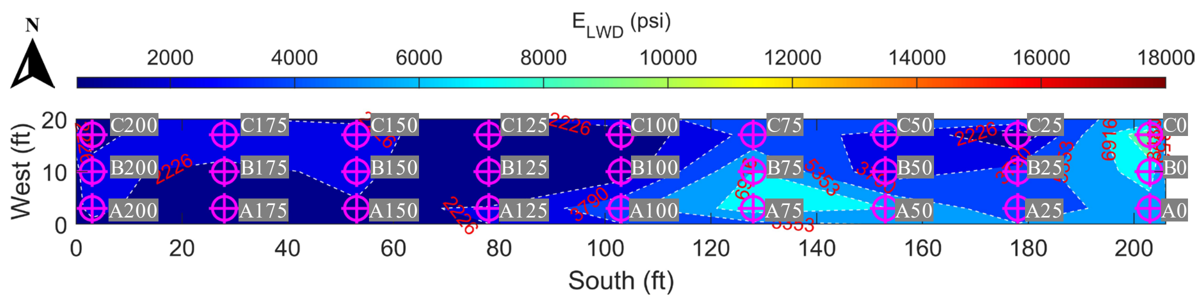
Figure 4-16 (b) shows the contour of LWD moduli measured with LWD #3878. The measured LWD moduli distribution pattern matched the moisture content contour on the east half of the test section very well. Specifically, at points B0 and C0 and the area surrounded by points A50, A75, and B75 where the moisture contents were low, LWD moduli were relatively high, while at other areas where moisture content were high such as the area bounded by points B50, C50, and C25, the measured LWD moduli were low. However, on the west half of the test section, the distribution of measured LWD moduli showed an abnormal pattern opposite to that of moisture content. It was especially clear at the area bounded by points A150, B150, and B125 where moisture contents were low, but the measure LWD moduli were low as well. This could result from the under compaction at the west half side of site.

Figure 4-16 (c) displays the contour of LWD moduli measured with LWD #3879. The measured LWD moduli distribution pattern was similar to those obtained using LWD #3878. The similarity between results from two LWDs were reasonable as they had similar specifications. The similarity also confirmed that measured results were creditable.

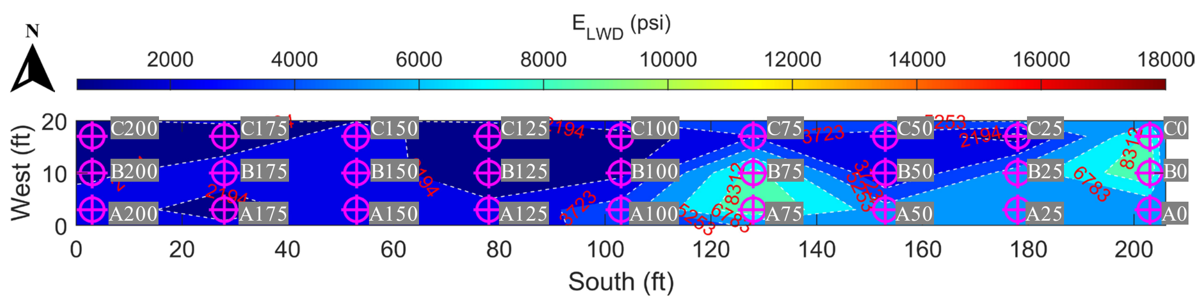
Figure 4-16 (d) displays the contour of LWD Moduli for Rolla CL utilizing LWD#4421. The distribution pattern of LWD moduli closely resembled those in Figures 4-16 (b) to (c), thereby reconfirming the reliability of the LWD moduli measurements. Similarly, at points A75, B0, and B75, LWD #4421 showed slightly higher LWD moduli compared to LWDs #3878 and #3879, because of the higher stress applied.



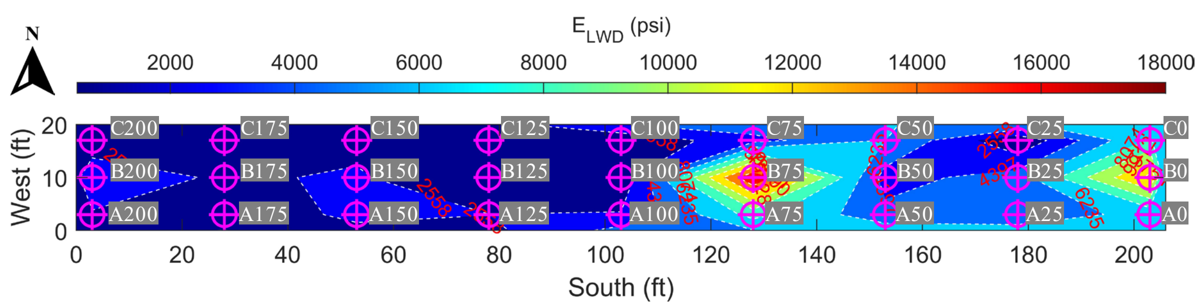
(a) Moisture content contour



(b) Modulus contour of LWD #3878



(c) Modulus contour of LWD #3879



(d) Modulus contour of LWD #4421

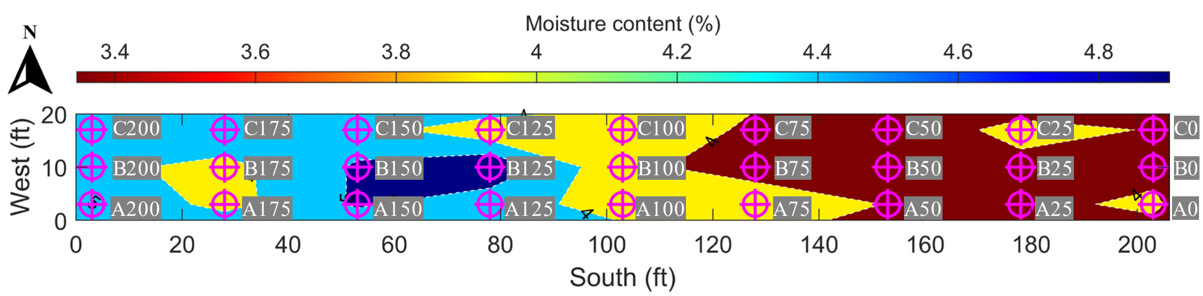
Figure 4-16 Moisture content and LWD modulus contours of CL subgrade at Rolla site.

In Figures 4-17 (a) to (d), contours of the moisture content and the LWD modulus for Rolla GM are illustrated. As shown in Figure 4-17 (a), moisture contents at Rolla GM site covered a span of 3.3% to 5.4% and gradually decreased from about 3.3% on the west end to about 4.5% on the east end. Notably, an exception occurred in the area delineated by points A150, B150, and B125 on the west side, where the moisture content was at its highest level, measuring 5.4%. The acceptable moisture content range for Rolla GM was determined to be 4.9% to 7.9%, with an OMC of 7.9%. As a result, moisture contents for most points on the east half of the test section were not in the acceptable range.

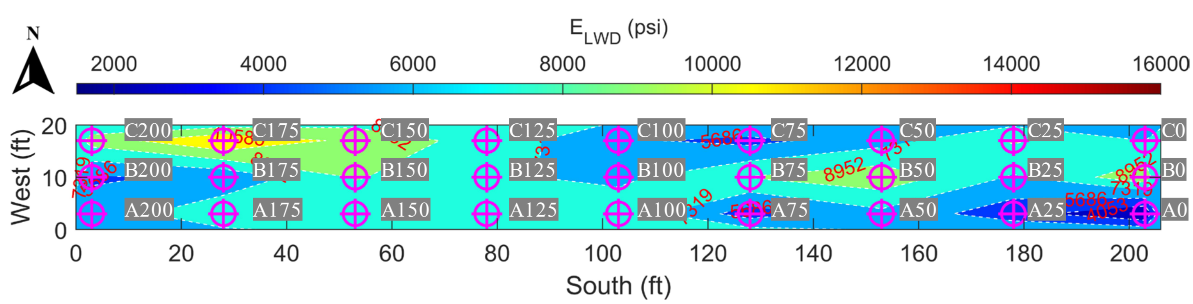
Figure 4-17 (b) displays the contour of LWD modulus measured using LWD #3878. On the strip connecting points B0, B75, A100, A150, and C200, LWD moduli were around 8 ksi and generally higher than those around 6 ksi in other areas. Notably, the distribution pattern of measured LWD moduli did not correlate with the moisture content contour. This finding aligns with observations made at the Holts Summit GM site and results from the Phase I project, indicating that the moisture content typically has a lesser impact on LWD modulus of gravel materials.

In Figure 4-17 (c), the contour of LWD modulus measured with LWD #3879 is shown. LWD moduli ranged from 1.7 ksi to 16 ksi and mostly stay around 8 ksi. Compared to Figure 4-17 (b), patterns in two contours matched well. For example, a similar strip connecting points B0, B75, A100, A150, and C200 can be observed as well, with most points on the strip having LWD moduli around 8 ksi. However, exceptions existed at points B125, B150, and C150, where lower LWD moduli were measured.

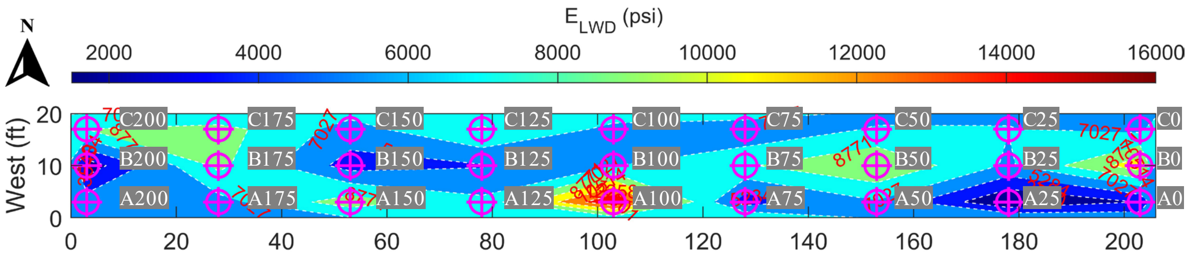
Figure 4-17 (d) displays the contour of LWD modulus measured using LWD #4421. The pattern in this contour matched well with those in Figures 4-17 (b) to (c). For instance, the strip that had LWD moduli around 8 ksi can also be found, connecting points B0, B75, A100, A150, and C200. On the other hand, LWD moduli measured at points A50, A175, A200, and C75 were slightly higher than those measured with LWDs #3878 and #3879. This could result from the higher stress applied by LWD #4421.



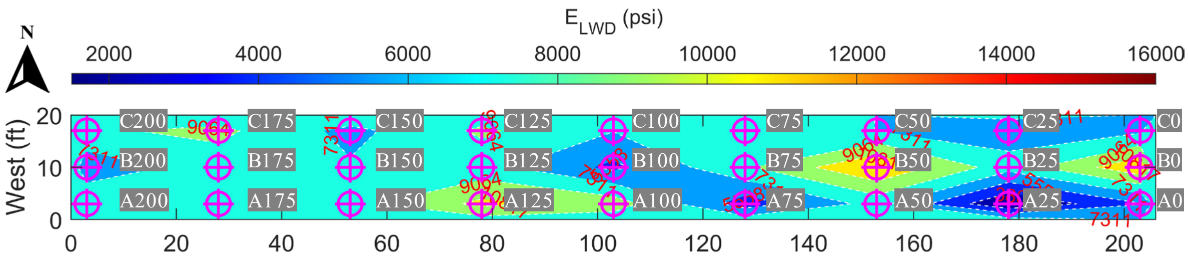
(a) Moisture content contour



(b) Modulus contour of LWD #3878



(c) Modulus contour of LWD #3879



(d) Modulus contour of LWD #4421

Figure 4-17 Moisture content and LWD modulus contours of GM base course at Rolla site.

4.5.3 Acceptance Evaluation

Figures 4-18 and 4-19 show evaluations of moisture content for the GM and the CL tested at Rolla site, respectively. In the case of Rolla CL, as illustrated in Figure 4-18, moisture contents at only three out of 27 points fell within the acceptable range. This range, determined based on the OMC of 11%, was found between 8% to 11%.

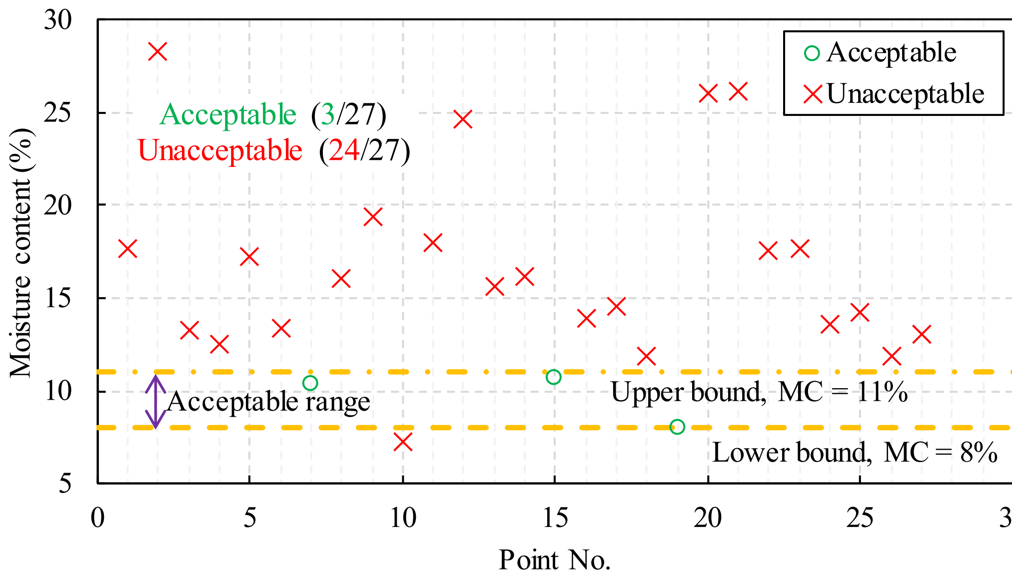


Figure 4-18 Moisture evaluation for Rolla CL.

On the other hand, as illustrated in Figure 4-19, most points of Rolla GM had moisture contents lower than its OMC (7.9%) and even lower than the lower bound (4.9%) of the acceptable range. Only four out of 27 points had moisture contents falling in the acceptable moisture content range. Hence, three points for Rolla CL and four points for Rolla GM will be evaluated with the modulus ratio criterion.

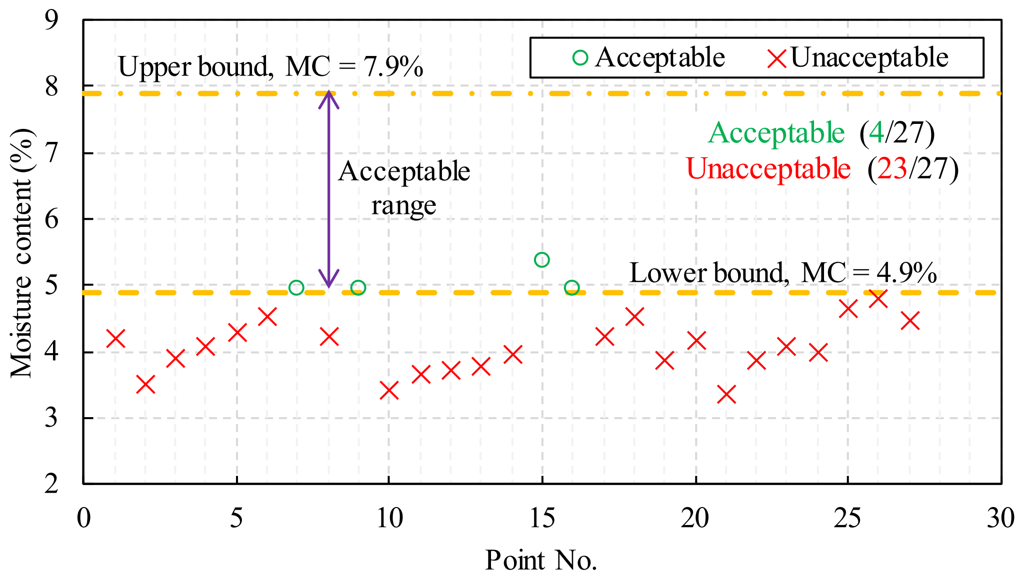


Figure 4-19 Moisture evaluation for Rolla GM.

Figures 4-20 and 4-21 show modulus ratios of Rolla CL and Rolla GM with acceptable moisture contents for three different LWDs, respectively. It should be noted that Rolla GM's modulus ratio was calculated with coefficients a_i of Holts Summit GM, given that the two soils had similar gradations, MDDs (i.e., 137.8 lbf/ft^3 vs. 137.5 lbf/ft^3), and OMCs (i.e., 7.9% vs. 7.2%). As depicted in Figure 4-20, among the three points meeting the moisture content criterion for Rolla CL, only one point tested with LWD #3878 was considered acceptable, while the other two LWDs did not have any point accepted.

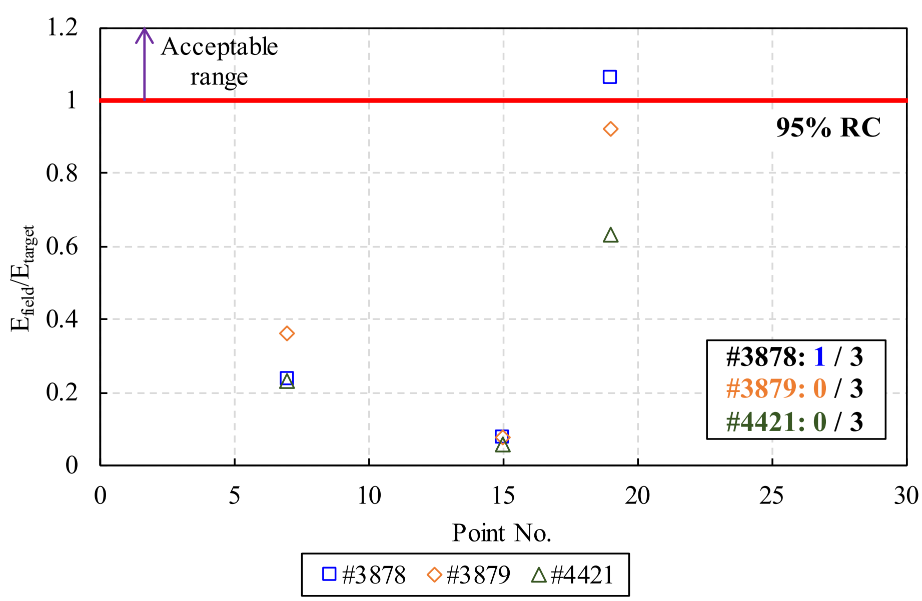


Figure 4-20 Modulus ratio evaluation for Rolla CL.

On the other hand, as illustrated in Figure 4-21, for Rolla GM, out of the four points satisfying the criterion of moisture content, LWDs #3878 and #4421 had all points acceptable, while LWD #3379 had three points meeting the modulus ratio criterion.

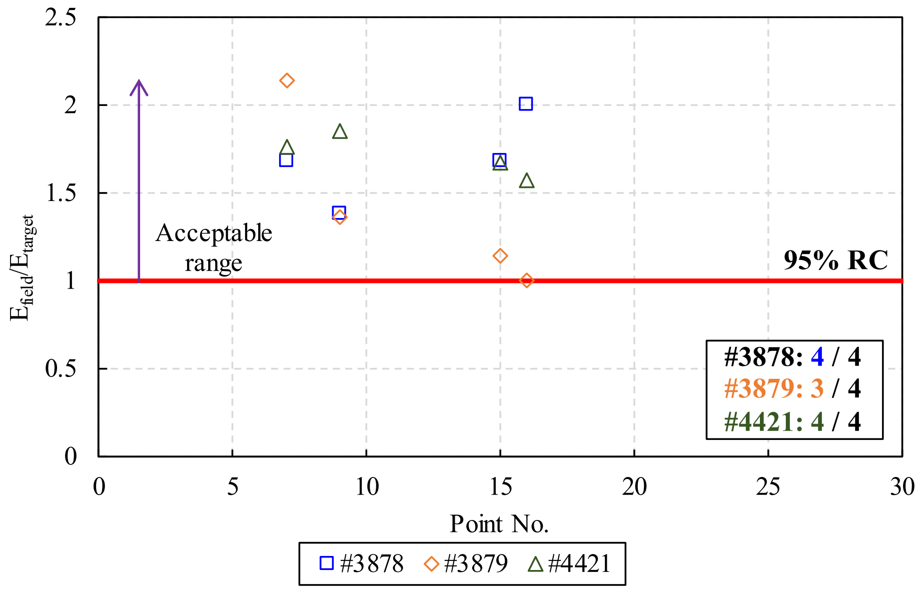


Figure 4-21 Modulus ratio evaluation for Rolla GM.

4.6 Comparison between Assessments of LWDs and NDG Tests

As mentioned previously, a limited number of NDG tests were conducted with favors of field engineers, at three distinct sites: New Florence CL site section one, Holts Summit GM site, and Sikeston SM site. Utilizing the dry density and moisture content results from these NDG tests, alongside Maximum Dry Densities (MDDs) and Optimum Moisture Contents (OMCs) determined from modified Proctor tests, density-based compaction evaluations were performed to assess relative compaction.

Table 4-4 summarizes the comparison between evaluations of LWD and NDG tests at abovementioned sites. In this table, a 0 indicates unacceptable results, while a 1 represents acceptable results. Cells with a value of 1 were filled with green color to enhance table readability.

In the section one of New Florence CL site, NDG tests were conducted at five testing points: 13, 19, 21, 32, and 41, as depicted in Figure 4-2(b). According to the NDG test results, only the result from point 21 was considered acceptable. While results from the modulus-based method using LWDs indicated that compactions at none of the five test points were acceptable.

At Holts Summit GM site, NDG tests were performed at only two points: 24 and 35, as illustrated in Figure 4-7. Interestingly, conclusions drawn from the NDG and LWD tests were contradictory. At the point 24, all LWD devices suggested acceptable compaction, while the NDG test indicated otherwise. Conversely, at the point 35, all LWDs suggested unacceptable compaction, whereas the NDG test indicated acceptable results.

For the Sikeston SM Site, a total of 12 points were tested using NDG, as shown in Figure 4-11. As indicated in Table 4-4, LWDs #3878 and #3879 produced highly consistent results, with only differences observed at points 1 and 11. In contrast, LWD #4421 yielded approximately 50% different results compared to LWDs #3878 and #3879, with only two points (28 and 31) accepted. When compared with NDG results, about two-thirds (7/12) of the results from LWDs #3878 and #3879 were consistent with the NDG density-based evaluation method, while only half (6/12) of the results from LWD #4421 matched those suggested by the NDG method.

Table 4-4 Comparison between assessments of LWD and NDG tests.

Site	Pt.	LWD #3878	LWD #3879	LWD #4421	NDG
New Florence CL site Section 1	13	0	-	0	0
	19	0	-	0	0
	21	0	-	0	1
	32	0	-	0	0
	41	0	-	0	0
Holts Summit GM site	24	1	1	1	0
	35	0	0	0	1
Sikeston SM Site	1	0	1	0	0
	7	1	1	0	1
	11	0	1	0	1
	13	0	0	0	1
	17	1	1	0	0
	21	1	1	0	1
	23	1	1	0	1
	28	1	1	1	1
	33	1	1	1	1
	34	0	0	0	0
	38	1	1	0	1
	44	1	1	0	0

Chapter 5. Conclusions

This Phase II project aimed to accumulate more field test data to improve the standards for the implementation of the Zorn LWD for the acceptance of unbound material layers. Based on Phase I project, five more different soils were selected and collected from different project sites in Missouri. These four projects included New Florence Intersection Enhancement project, Holts Summit Roundabout project, Sikeston Overpass over US 60 project, and Rolla Interstate-44 (I-44) Improvement project. A series of laboratory and field tests were conducted including materials characterization, LWD tests on proctor mold and RLTTs in the laboratory, and field LWD tests. In addition, a field moisture measurement system including Ohaus MB 120 and a disturbance isolation unit was developed. Comprehensive data analyses were performed from which the following conclusions were drawn:

1. Among five soils tested in Phase II project, the soil compacted as a subgrade in New Florence was classified as lean clay with sand (CL), the soil used in a base course in Holts Summit was classified as silty gravel with sand (GM), the soil sampled from the overpass approach in Sikeston was classified as silty sand (SM), and the two soils compacted as a subgrade and a base course in Rolla were categorized into sandy lean clay (CL) and silty gravel with sand (GM), respectively.

2. In lab LWD tests conducted on Holts Summit GM, Sikeston SM, and Rolla CL, the increase of deflection became more significant as the moisture content increased beyond the OMC though dry densities were comparable. The deflection increased with the increase of applied stress. The LWD modulus generally decreased as the moisture content increased, with a steeper gradient at moisture contents higher than the OMC, and the LWD modulus also increased with the increase of applied stress. For New Florence CL, the deflection and the LWD modulus increased with the increase of applied stress but varied insignificantly with the increase of moisture content.

3. Stress dependency was noticed during the resilient modulus tests. The resilient modulus was found to increase as the applied stress increased at all stress levels on the two coarse-grained soils (i.e., Holts Summit GM and Sikeston SM) and low stress levels on the two fine-grained soils (i.e., New Florence CL and Rolla CL). The resilient modulus decreased with the increase of applied stress at high stress levels on these two fine-grained soils. For all tested soils, their peak resilient moduli at each tested moisture content were found to decline gradually as the moisture content increased.

4. A disturbance isolation unit was designed to accommodate Ohaus MB 120 to be used in the field with adequate accuracy and effectiveness. The disturbance isolation unit included a 1000 W power invertor, four vibration isolation elements, a leveling platform, and a covering hood for Ohaus MB 120. Field tests indicated that the four isolation elements were sufficient to isolate the vibration from surroundings, and a hood was effective to isolate the wind disturbance that made the device fail to tare and meet the switch-off criterion. For this field moisture measurement system, a drying weight of 10 gram was suggested for soils having mostly small particles, such as Rolla CL and Sikeston SM, and 30 gram was recommended for gravel materials. A moderate switch-off criterion, such as 1mg/60s indicating no more than one milligram change within 60 seconds, was recommended.

5. A series of contours were plotted to visually illustrate the distribution of field moisture content and LWD modulus at testing sites. Colors in contours showing LWD moduli measured with different LWDs generally matched well, indicating good consistencies between three LWD devices. (i.e., LWD #3878, LWD #3879, and LWD #4421) in the field.

6. Good correlations between moisture content and LWD modulus were observed at most points at the two fine-grained soil sites (i.e., New Florence CL and Rolla CL sites). While for the remaining three coarse-grained soil sites, including Sikeston SM site, Holts Summit GM site, and Rolla GM site, good correlation occurred at half number of points at Sikeston SM site but barely could be perceived at the other two sites.

7. With measured field moisture contents and target LWD moduli predicted based on characteristics of LWD tests on Proctor mold, testing points at all sites were evaluated according to the moisture content and modulus ratio criteria. New Florence CL site had 20 out of 72 with acceptable moisture contents; Holts Summit GM site had 25 out of 42 points having acceptable moisture contents; 38 out of 44 points were acceptable for Sikeston SM site; and three and four points, among 27 points tested, were found acceptable for Rolla CL and Rolla GM, respectively.

8. In the evaluation of modulus ratio on those points with acceptable moisture contents, none was considered acceptable for any LWD for New Florence CL. For Holts Summit GM, 24 points were evaluated as acceptable for LWDs #3878, #3879, and #4421. At Sikeston SM site, 30 and 35 points were found acceptable eventually for LWDs #3878 and #3879, respectively, while only 10 points had modulus ratios no less than one for LWD #4421. For Rolla CL, only one point was considered acceptable for LWD #3878, while Rolla GM had four, three, and four points qualified for LWDs #3878, #3879, and #4421, respectively.

9. When compared with the NDG density-based evaluation method, LWD performed reasonably well for fine-grained soils such as clay and silt but poorly for coarse-grained soils. Among the three different LWD devices, results from LWD#3878 and #3879 were more consistent with the NDG density-based evaluation method than those from LWD#4421.

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Appendix A: Guideline of Implementing LWD devices on QC/QA for Unbound Material Layers

Modulus-based Construction Acceptance Testing of Unbound Material Layers with a Lightweight Deflectometer

1 Apparatus

- Zorn ZFG Lab 3.0 lightweight deflectometer (LWD) with a 6 in loading plate (Device No.: 9052)
- Zorn ZFG 2000 LWD with a 12-in loading plate (Device No.: 3878 and 3879)
- Ohaus MB 120 moisture analyzer with the disturbance isolation unit
- Other devices related to 6 in diameter Proctor test

2 Procedure

This test method consists of two parts of tests and data analysis:

- Determination of regression coefficients with results of LWD tests on Proctor mold
- Measurement of moisture content and LWD modulus in the field
- Acceptance evaluation of moisture content and field to target LWD modulus ratio

Determination of regression coefficients via LWD test on Proctor mold

The LWD test on Proctor mold is an add-on testing to the Proctor test of compaction characteristics of soils. The following steps shall be used for performing an LWD test on Proctor mold.

Step 1. Based on the optimum moisture content (OMC) and maximum dry density (MDD) obtained from the Proctor test, plan three moisture contents including OMC-4%, OMC-2%, and OMC, and determine their corresponding target masses at a relative compaction of 95%.

Step 2. Starting with one of the planned target moisture contents, prepare the specimen in a 6-in Proctor mold and trim it to the same height of the mold.

Step 3. Set the mold containing a specimen on a stable solid foundation. Reattach the collar to the mold to help align the LWD plate. Carefully position the 12-in bearing plate of ZFG Lab 3.0 LWD on top of the specimen and rotate approximately 45° back and forth to seat the plate.

Step 4. Adjust the falling height to 4 in. Carefully place the top part of ZFG Lab 3.0, mainly consisting of the guide rod and the falling weight, on top of the bearing plate. It should be noted that the falling height should be adjusted using Equation (1) if the target resultant force of field-version LWD is changed due to a change in either LWD model or falling height.

Step 5. Hold the rod vertically and apply six drops with the falling weight by releasing it at the designated falling height and allowing it to fall freely without lateral movement (Figure 1). The first three drops are conducted for the purpose of seating, while the second three are measurement drops. The falling weight should be caught as it rebounds from the bearing plate and before it makes its second impact on the plate. The specimen after testing is considered disturbed and should not be used for other mechanical property related tests.

Step 6. Record data including the deflection (s_{lab}) and soil type on the datasheet.

Step 7. Extrude the specimen from the mold and take three representative soil samples from the top, middle, and bottom of the specimen, respectively, to measure the moisture content of the tested specimen (MC_{lab}) by oven-drying method.

Step 8. Calculate the lab LWD modulus (E_{lab}) using Equations (1) and (2), where the Poisson's ratio for the specific soil is given in Table 1.

Step 9. Determine regression coefficients a_i for Equation (3) by plugging lab LWD moduli and moisture contents obtained from tests conducted on specimens at the three planned moisture contents. The Solver in MS Excel may be helpful in doing regression for this step.

Figure 1 LWD test on Proctor mold.

Table 1 Typical Poisson's ratio values for soils.

Material	Range of values	Typical value
Untreated granular materials	0.30-0.40	0.35
Cement-treated granular materials	0.10-0.20	0.15
Cement-treated fine-grained soils	0.15-0.35	0.25
Lime-stabilized materials	0.10-0.25	0.20
Loose sand or silty sand	0.20-0.40	0.30
Dense sand	0.30-0.45	0.35
Saturated soft clays	0.40-0.50	0.45
Silt	0.30-0.35	0.32
Clay (unsaturated)	0.10-0.30	0.20
Sandy clay	0.20-0.30	0.25
Coarse-grained sand	0.15	0.15
Fine-grained sand	0.25	0.25

$$\sigma = \frac{\sqrt{2mghC}}{\pi r^2} \tag{1}$$

$$E_{lab} = \frac{H\sigma}{s_{lab}}\left(1 - \frac{2v^2}{1-v}\right) \tag{2}$$

$$E_{lab} = a_0 + a_1 * MC_{lab} + a_2 * MC_{lab}^2 \tag{3}$$

$$E_{target} = a_0 + a_1 * MC_{field} + a_2 * MC_{field}^2 \tag{4}$$

where

σ = resultant stress of the falling weight, (psf), 15.4 psi for ZFG Lab 3.0 (falling at 4-in height) and ZFG 2000 LWDs (falling at 27.5-in height),

m = mass of falling weight, (lbm), 11 lbm for ZFG Lab 3.0, 22 lbm for ZFG 2000,

h = falling height, (ft),

g = acceleration of gravity, 32.2 ft/s^2,

C = spring constant of buffer spring, (lbf/ft), 725.2 lbf/ft for ZFG Lab 3.0, 779.2 lbf/ft for ZFG 2000,

r = radius of LWD bearing plate, (ft), 3 in for ZFG Lab 3.0, 6 in for ZFG 2000,

E_{lab} = LWD modulus determined from LWD test on Proctor mold (LWD lab test), (psf),

v = Poisson's ratio, refer to Table 1,

H = falling height, (ft), 4.5 in for ZFG Lab 3.0, 27.5 in for ZFG 2000,

s_{lab} = deflection in LWD lab test, (ft)

a_0, a_1, a_2 = regression coefficients,

MC_{lab} = moisture content of the sample in LWD lab test, (%),

E_{target} = target LWD modulus in the field, (psf), and

MC_{field} = moisture content of the sample in the field, (%).

Measurement of moisture content and LWD modulus in the field

A series of testing points should be planned and marked at the construction site, on which both moisture content and LWD modulus measurements are to be conducted by following the steps listed below.

Step 1. Arrange and mark testing points in the spacing of at least 10 ft at construction site with color spray.

Step 2. Level and smoothen an area approximately larger than that of the LWD plate at testing point.

Step 3. Adjust the falling height of ZFG 2000 LWD to 27.5 in. Carefully place the bearing plate onto the compacted soil surface and rotate approximately 45° clockwise and counterclockwise to seat the plate, then dock the top part of LWD onto its bearing plate.

Step 4. Hold the rod vertically and apply six drops with the falling weight (Figure 2), three seating drops followed by three measurement drops, by releasing the falling weight at the designated LWD height and allowing it to fall freely without lateral movement. The falling weight should be caught upon its rebounding back from the bearing plate and before its second hitting on the bearing plate.

Step 5. Record data including the numbering of testing point, deflection (s_{field}), and soil type, with which calculate the field LWD modulus (E_{field}) via Equation (5).

Step 6. Collect at least 4 oz (100 g) of soil sample for the testing point with a sealable container. The depth from where the sample is collected should be at least 4 in below the surface but no more than 12 in.

$$E_{field} = A\frac{2r\sigma_{field}(1-v^2)}{s_{field}} \tag{5}$$

where

E_{field} = LWD modulus measured in the field, (psf),

σ_{field} = applied stress in the field, (psf),

A = stress distribution factor, refer to Table 2, and

s_{field} = deflection measured in the field, (ft).

Table 2 Stress distribution factor for different sorts of soils.

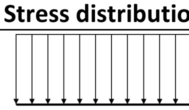
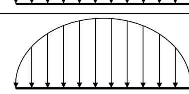
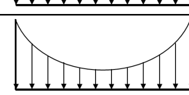
Soil type	Factor (A)	Stress distribution
Mixed soil (uniform)	1	
Granular material (parabolic)	$\frac{4}{3}$	
Cohesive (inverse-parabolic)	$\frac{\pi}{4}$	

Figure 2 LWD test in the field.

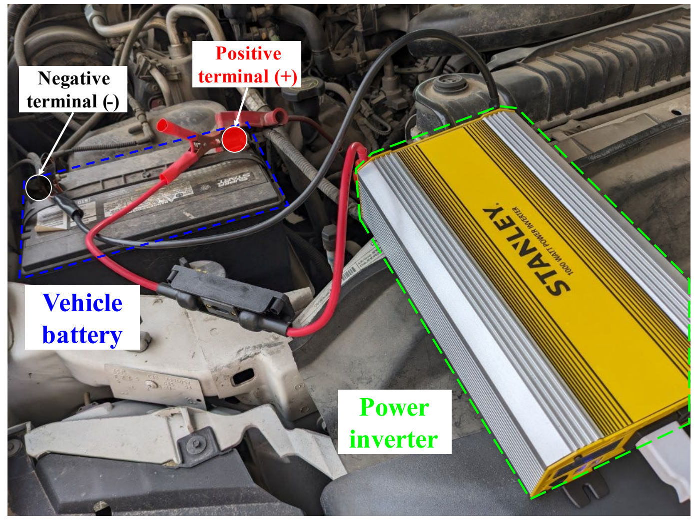


Figure 3 Power inverter.

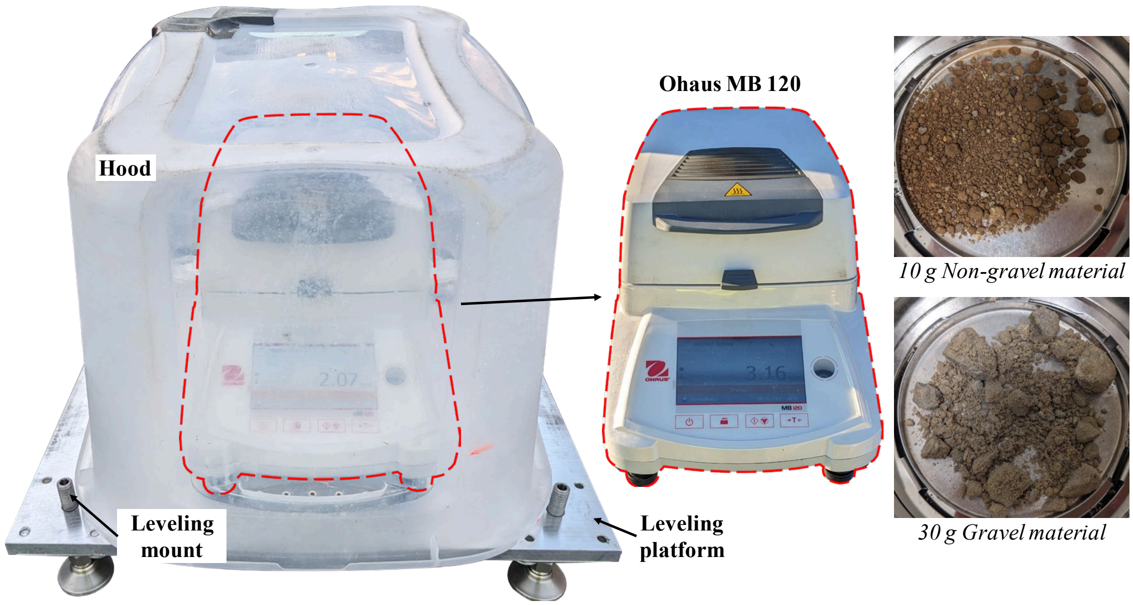


Figure 4 Field moisture analyzer unit and drying weights.

Step 7. Connect the power inverter with the battery of an idling vehicle (Figure 3) and power it on.

Step 8. Set up the field moisture analyzer unit (Figure 4), including the leveling platform, the Ohaus MB 120, and a hood. With the Ohaus MB 120 set on the leveling platform, level of the Ohaus MB 120 is adjusted via the four leveling mounts on leveling platform.

Step 9. Connect the Ohaus MB 120 with the power inverter and power on the equipment. With the Ohaus MB 120 partially covered with the hood, click on Tare and immediately fully cover the equipment with the hood. The taring process with a hood covered takes around ten seconds.

Step 10. Thoroughly crush the collected sample into small pieces (Figure 4), then load the sample into the drying pan in Ohaus MB 120 when the device is ready and close the cover to start drying. Though a maximum mass up to 120 is allowable, recommendations of sample mass for gravel and non-gravel materials are 30 g and 10 g, respectively, and drying durations for them are about 30 min and 10 min, respectively. A moderately strict switch-off criterion (i.e., 1mg/60), other than a stricter one, is recommended.

Step 11. Take the reading (MC_{field}) when the drying process ends. The reading needs to be corrected with coefficients calibrated for the specific soil, and coefficients of 1.06 and 1.20 for gravel and non-gravel materials, respectively, are recommended when those are not available.

Acceptance evaluation of moisture content and field to target LWD modulus ratio

Modulus-based acceptance evaluation starts with the moisture content evaluation and followed by the modulus ratio evaluation. Only the moisture content of soil falls into the acceptable moisture content range will the soil proceed to be evaluated with the field to target LWD modulus ratio.

Step 1. Compare moisture contents of testing points measured from the field (MC_{field}) with acceptable moisture content range. Testing points having moisture contents within acceptable moisture content range are considered qualified, while points with moisture contents beyond the range are considered unqualified.

Step 2. Calculate the target modulus (E_{target}) of qualified points in Step 1 via Equation (4). Importantly, a target modulus needs to be corrected if the soil is compacted as the top layer in a two-layer system and the thickness of the top layer is less than 12 in. The E_{target} is corrected to $E_{target-corr}$ via Equation (5), where the modulus of underlaying layer can be a measured value, or a typical value of 3.6 ksi for clay soils.

Step 3. Determine the field to target LWD modulus ratio for qualified points in Step 1 and evaluate their modulus ratios. Only the point that meets both moisture content and modulus ratio criteria is considered acceptable.

$$E_{target\ -corr} = 1/\left\{ \frac{1}{E_2\left[\sqrt{1+\left(\frac{h}{d}\sqrt[3]{\frac{E_1}{E_2}}\right)}\right]} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{d}\right)^2}}\right]}{E_1} \right\} \tag{5}$$

where

$E_{target-corr}$ = corrected target modulus of the top layer, (psf),

E_2 = LWD modulus of the bottom layer, (psf),

E_1 = target LWD modulus for the top layer, (psf),

h = top layer thickness, (ft), and

d = LWD bearing plate radius, (ft), 12 in for ZFG 2000 LWD.