**TRANSPORTATION POOLED FUND PROGRAM**
**QUARTERLY PROGRESS REPORT**

Lead Agency (FHWA or State DOT): ____Maryland Department of Transportation____________

**INSTRUCTIONS:**
*Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.*

| Transportation Pooled Fund Program Project # | Transportation Pooled Fund Program - Report Period: |
|---|---|
| *TPF-5(285)* | □Quarter 1 (January 1 – March 31, 2014)<br>□Quarter 2 (April 1 – June 30, 2014)<br>□Quarter 3 (July 1 – September 30, 2014)<br>□Quarter 4 (October 1 – December 31, 2014)<br>□Quarter 5 (January 1 – March 31, 2015)<br>□Quarter 6 (April 1 – June 30, 2015)<br>□Quarter 7 (July 1 – September 30, 2015)<br>□Quarter 8 (October 1 – December 31, 2015)<br>□Quarter 9 (January 1 – March 31, 2016)<br>■Quarter 10 (April 1 – June 31, 2016) |

Project Title:
Standardizing Lightweight Deflectometer Measurements for QA and Modulus Determination in Unbound Bases and Subgrades

| Name of Project Manager(s): | Phone Number: | E-Mail |
|---|---|---|
| Rodney Wynn | 443-572-5043 | RWynn@sha.state.md.us |
| Lead Agency Project ID:<br>TPF-5(285) | Other Project ID (i.e., contract #): | Project Start Date:<br>January/15/2014 |
| Original Project End Date:<br>December/31/2015 | Current Project End Date:<br>November/30/2016 | Number of Extensions:<br>2 |

Project schedule status:
□ On schedule ■ On revised schedule □ Ahead of schedule □ Behind schedule

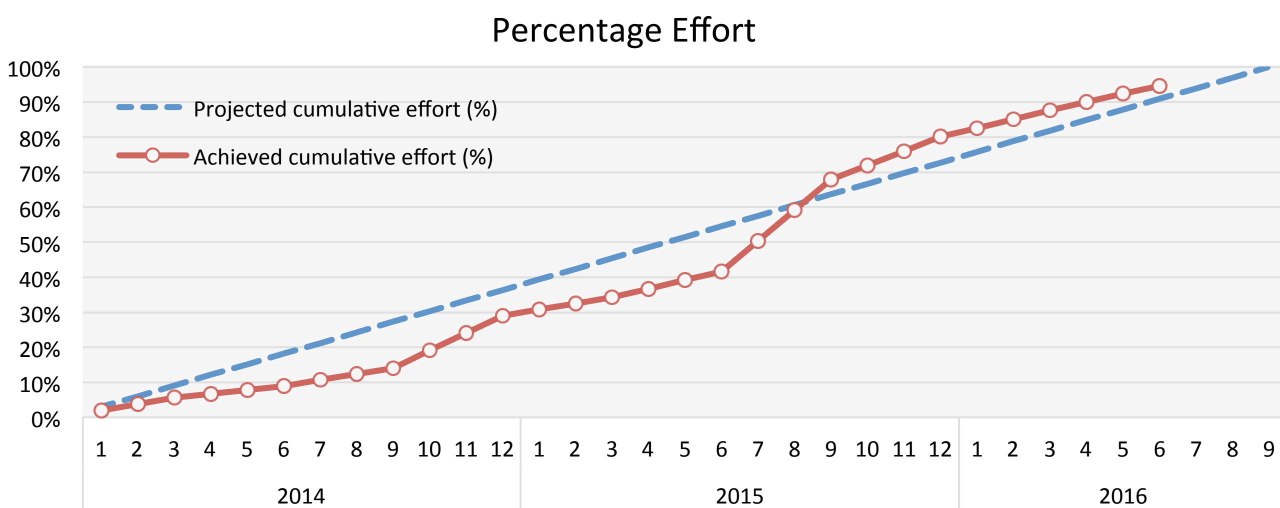
Overall Project Statistics:

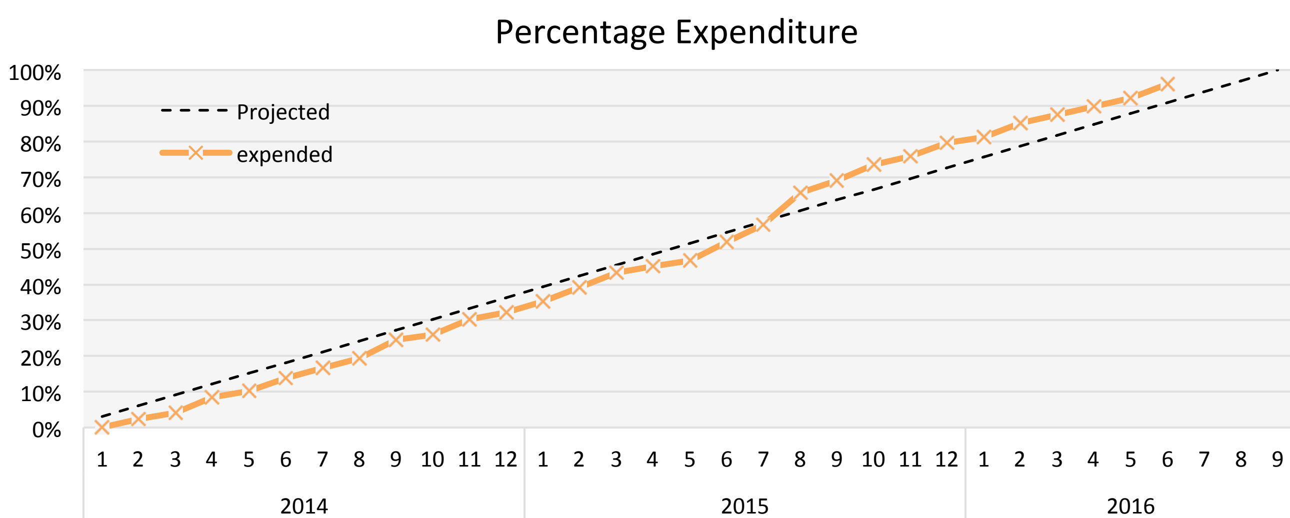
| Total Project Budget | Total Cost to Date for Project | Percentage of Work Completed to Date |
|---|---|---|
| $371,984.00 | $357,322.62 | 96.1% |

***Quarterly*** Project Statistics:

| Total Project Expenses and Percentage This Quarter | Total Amount of Funds Expended This Quarter | Total Percentage of Time Used to Date |
|---|---|---|
| $31,884.04 (8.6%) | $33,816.73 | 95% |

Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):




The progress with respect to each Task is as followed:

**Literature Review. Percent completion of Task 1: 100%**

The personnel continue the review of the current and upcoming literature when deemed necessary.

Project personnel participating in these activities: Schwartz, Khosravifar, and Afsharikia.

**Equipment Evaluation. Percent completion of Task 2: 100%**

Target moduli values from LWD drops on proctor mold were compared for different LWDs. The Dynatest LWD annular plug option was also investigated.

Project personnel participating in these activities: Schwartz, Afsharikia, and Khosravifar.

## Model Refinement/Development. Percentage completion of Task 3: 100%

Several of the models in Task 3 were refined in conjunction with laboratory efforts in Task 4, and Task 5.

Project personnel participating in these activities: Schwartz, Afsharikia, and Khosravifar.

## Controlled Trials. Percentage completion of Task 4: 100%

This task was completed during the previous quarter.

Project personnel participating in these activities: Schwartz, Khosravifar, and Afsharikia.

## Field Validation. Percentage completion of Task 5: 96%

Extensive LWD testing on Proctor molds has been performed to determine the target modulus for base material in addition to the subgrades. The effect of finite layer thickness has also been incorporated (Appendix A). Most of the data have been analyzed for base material. The target moduli were compared to the field-measured moduli to assess compaction quality. The LWD testing on Proctor mold procedure has been finalized and Improved.

Project personnel participating in these activities: Schwartz, Afsharikia, and Khosravifar.

## Draft Test Specifications. Percentage completion of Task 6: 60%

Testing on base aggregate validated the LWD testing on Proctor mold method combining Odemark's method of two layer systems, which has been adopted by AASHTO Guide for the Design of Pavement Structures. By limiting the field range of acceptable compaction moisture content, the target modulus can be derived from LWD on mold around the optimum moisture content and then translated to surface modulus (Appendix A).

Project personnel participating in these activities: Schwartz, Afsharikia, and Khosravifar.

## Workshop and Final Report. Percentage completion of Task 7: 67%

Progress was made during this period on documenting the results from LWD testing on Proctor mold for the field test sites. Final report outline has been finalized and is under compilation along with the specification.
Additionally, a paper on target modulus determination for subgrade soils based on the findings of this research has been submitted to the TRB 2017's AFP30 committee and is under review (Appendix B).

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## Anticipated work next quarter:

- Continued drafting the Final Report
- Drafting the specification in the AASHTO format

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

**Potential Implementation:**

LWDs should be implemented more widely using standardized testing procedures and data interpretation methods. LWDs are a tools for performance based construction quality assurance testing that not only result in a better product but also provide the quantitative measures critical to better understanding the connection between pavement design and long term pavement performance.  As the benefits of performance based quality assurance testing become increasingly apparent, more public agencies and private consultants are expected to acquire these tools and implement the standardized procedures.  The product of this research will allow state DOT construction specifications to be modified to include this new lightweight deflectometer (LWD) option for construction quality assurance.

# Appendix A

## LWD Testing on Proctor Mold for Base Soils

Similar to LWD on mold for subgrade soils, base material was compacted in six-inch Proctor molds at 3 to 7 different moisture contents using standard compaction energy (AASHTO T-99). Table 1 shows a summary of the project locations and soil types for this study. LWD tests were performed directly on the compacted molds resting on the laboratory's concrete floor.

Table 1- Project location, soil specification, and testing condition

| | State Location | Soil Type | AASHTO Classification | Unified Classification | | Field LWD Testing Condition |
|---|---|---|---|---|---|---|
| 1 | Maryland | MD404 Sand overlaying Subgrade | A-2-7 | SP | Poorly graded sand | 4" of dry sand has been placed on top of wet compacted local subgrade, tested right after compaction before GAB placement |
| | | MD 404 Subgrade | A-2-6 | SP | Poorly graded sand | |
| | | MD 404 GAB | A-2-7 | GP-GM | Poorly graded gravel with silt and sand | Tested right after compaction of 6"-8" base |
| 2 | Indiana | Cement modified Subgrade | A-2-4 | SW | Well graded sand with gravel | Tested a week after placement and compaction (Dried and cured SG) right before GAB placement, No NDG data available |
| | | GAB | A-1-a | GW | Well graded gravel with sand | Tested on 3" on GAB compacted on cement stablized SG right after compaction |
| 3 | Missouri | Subgrade | A-3 | SP | Poorly graded sand with gravel | No LWD data available, Testing only on compacted GAB |
| | | GAB | A-3 | GW | Well graded gravel with sand | 4" crushed lime stone was compacted on top of 1-2 pass of roller compacted SG (the road shoulder), testing right after compaction |
| 4 | Florida | Subgrade | A-2-7 | SP | Poorly graded sand | Subgrade placed and compacted 4 days before LWD testing performed (Dried SG) |
| | | Base | A-3 | SP | Poorly graded gravel with sand | Tested on 6"-8" of Lime rock base on top of dried SG right after compaction |

The modulus of the base in the mold was derived from the theory of elasticity for a cylinder of elastic material with constrained lateral movement:

$$E = (1 - \frac{2v^2}{1-v}) \frac{4H}{\pi D^2} k \qquad \text{Equation 1}$$

Where:
$v$ = Poisson's ratio
H = height of the mold
D = the diameter of the plate or mold
k = soil stiffness =F/δ as calculated by LWD device
F = maximum applied force by LWD in the last 3 drops
δ = average last three LWD drops deflection

The Florida SR-23 road base compaction project in South Jacksonville (Figure 1) is assessed in this report. Then the procedure was successively applied to the other base material. The full set of results will be presented in the final report.

Figure 1- Jacksonville SR-23 project LWD and NDG testing on the subgrade and base after compaction

The AASHTO Guide for the Design of Pavement Structures (AGDPS) approach assumes a two layer system (Figure 2) with a stiff top layer of thickness *h* (base) over subgrade of infinite depth (AASHTO 1993). This method is based on the fundamental Boussinesq solution and Odemark's method of equivalent thickness (Grasmick et. al, 2014). The AGDPS procedure gives appropriate estimations of layer moduli in a two layer systems and has been broadly implemented for the falling weight deflectometer (FWD) (Schmalzer et. al, 2007).

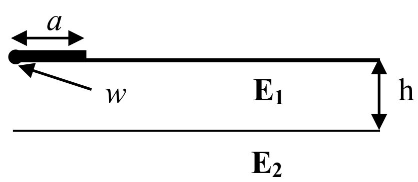


Figure 2- Two-layer system of subgrade with modulus $E_1$ overlain by base with modulus $E_2$

According to the AGDPS method, the total surface deflection *w* directly under the circular load (LWD plate) is the summation of deformation occurring in the top (base) and bottom (subgrade) layers (Grasmick et. al, 2014). The deflection/modulus ($E_2$) on top of the subgrade is measured by the LWD right before base placement on approximately the same location of base testing. The target modulus ($E_1$) is derived by the Equation 1 from LWD on mold method. The total surface deflection under the LWD is obtained in Equation 2, with known values of *h* (base layer thickness), *a* (LWD plate dimeter=300 mm), and *A* (contact stress distribution or shape factor). Subsequently, the target surface modulus can be calculated from Equation 2 and compared to the masured field surface modulus (instead of back-calculating the layer modulus) to assess the compaction quality.

$$w = \frac{A(1-v^2)F}{\pi a}\left\{\frac{1}{E_2\left[\sqrt{1+\left(\frac{h}{a}\sqrt[3]{\frac{E_1}{E_2}}\right)}\right]}+\frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{a}\right)^2}}\right]}{E_1}\right\} \qquad \text{Equation 2}$$

for all 10 tested stations. Since most of the data points are in the upper right quadrant, this well-compacted base satisfied both the density and modulus compaction requirements.

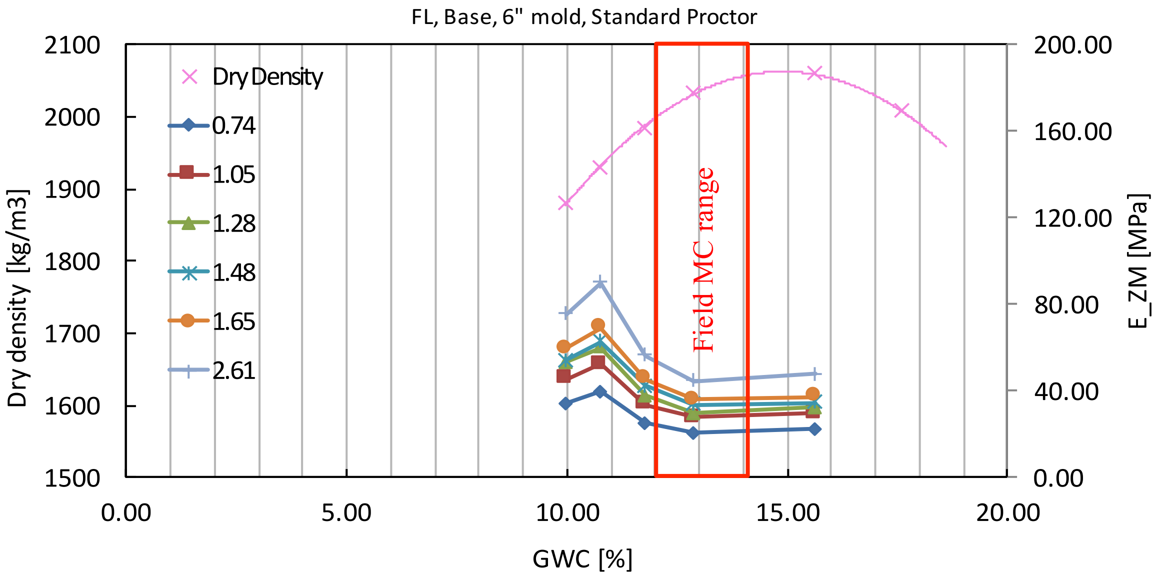


Figure 3 and Figure 5 presents the LWD modulus on mold versus gravimetric water content (GWC) superimposed by dry density for Zorn and Dynatest LWDs respectively. The legend shows the varied surface contact stress normalized to atmospheric pressure (P/Pa), caused by drops from different heights on the mold. The field moisture content ranged between one to three percent drier than the optimum. A multi-variable regression was applied to express the mold modulus as a function of MC and P/Pa. The base target modulus ($E_1$) was then determined by feeding the field MC range and P/Pa into the regression equation. Knowing the subgrade surface modulus ($E_2$) from LWD testing in the field before base placement, the total target surface deflection was calculated using Equation 2.

The field surface modulus passed the surface target in most stations for both Zorn and Dynatest LWD. Their ratio was compared to the NDG percent compaction values in

Figure 4 and Figure 6 for all 10 tested stations. Since most of the data points are in the upper right quadrant, this well-compacted base satisfied both the density and modulus compaction requirements.

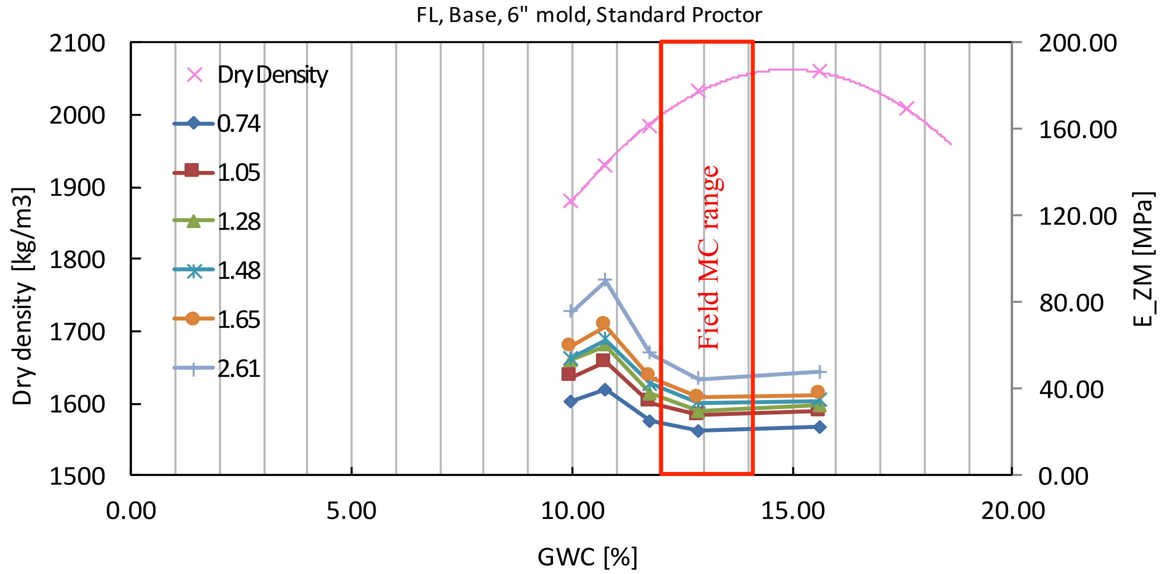


Figure 3- Zorn LWD on 6” mold, Florida base

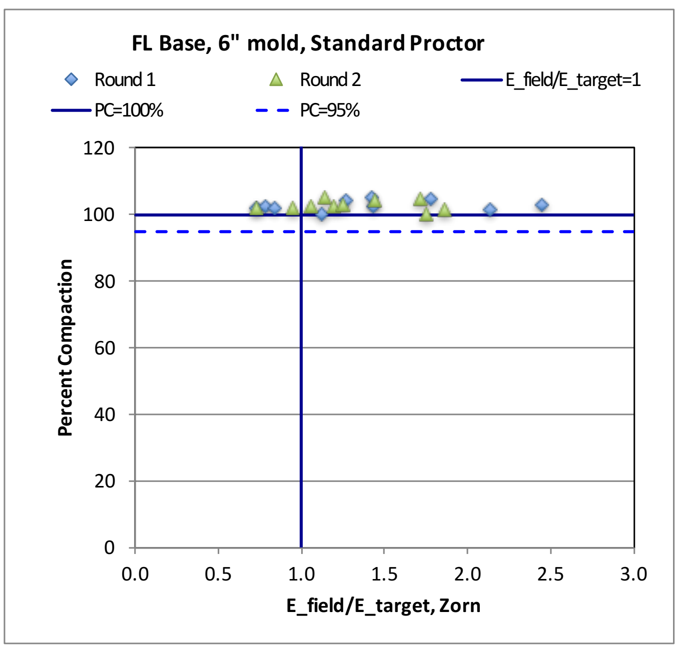


Figure 4- Zorn LWD field surface modulus to the target surface modulus ratio versus percent compaction

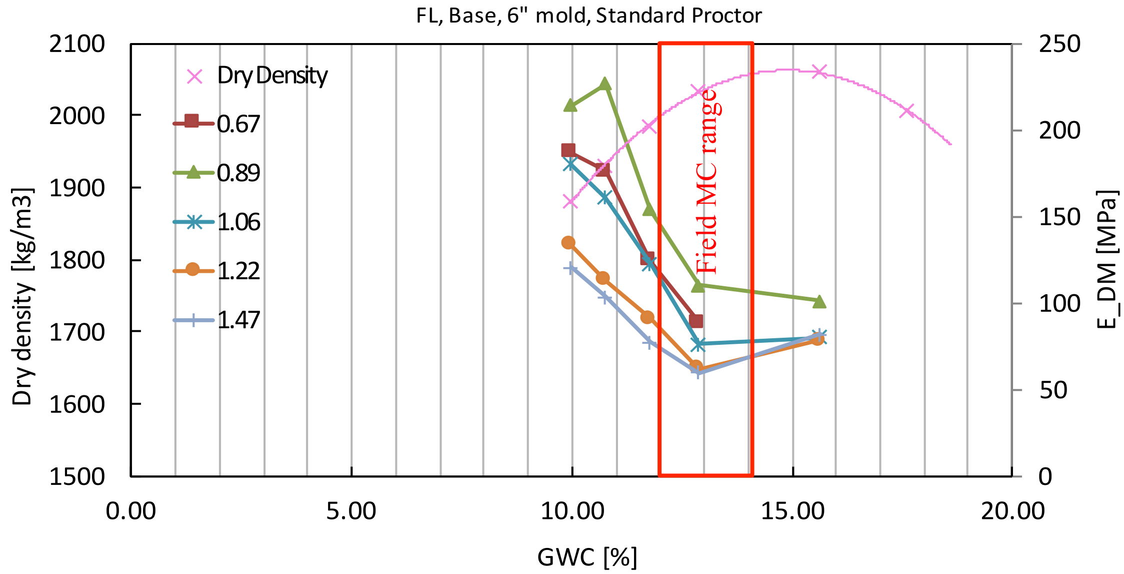


Figure 5- Dynatest LWD on 6” mold, Florida base

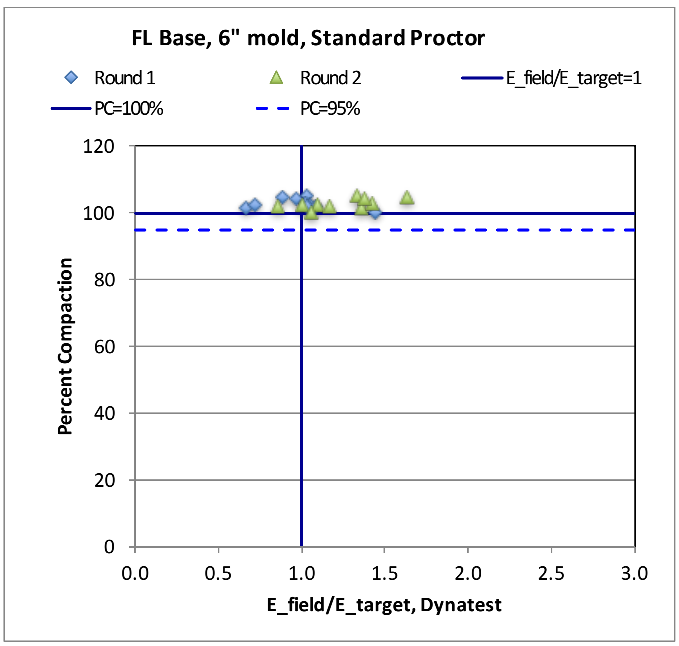


Figure 6- Dynatest LWD field surface modulus to the target surface modulus ratio versus percent compaction

## References


- Grasmick, J. G., Mooney, M. A., Surdahl, R. W., Voth, M., & Senseney, C. (2014). Capturing a Layer Response during the Curing of Stabilized Earthwork Using a Multiple Sensor Lightweight Deflectometer. *Journal of Materials in Civil Engineering*, *27*(6), 04014183.
- Schmalzer, P.N., Rada, G.R., and Miller, J.S. (2007) “Falling Weight Deflectometer (FWD) Testing and Analysis Guidelines Volume I,” Report No. FHWA-FLH-07-001, Federal Highway Administration, Federal Lands Highway Division, Washington, DC.

# Appendix B

## TRB Paper Submittal

# COMPACTION QUALITY CONTROL TARGET MODULUS DETERMINATION USING LIGHT-WEIGHT DEFLECTOMETER DROPS ON PROCTOR MOLD

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Word count: abstract (139)+ words text + 17 tables/figures x 250 words each = 7265 words

Submission Date: August 1st, 2016

**ABSTRACT**

Moving away from traditional density-based methods of compaction quality control/quality assurance towards modulus-based procedures using Light Weight Deflectometer (LWD) requires setting soil-specific target modulus values. This procedure should account for the influence of the moisture content and density at the time of compaction and testing, which may be different than the lab-determined optimum condition. A practical method to establish the target modulus based on LWD drops on compacted Proctor molds was developed, refined and compared to other existing specifications. Three types of LWDs were evaluated: Zorn ZFG 3000, Dynatest 3031, and Olson NDE360. LWD measurements along with Nuclear Density Gauge testing have been performed on the Subgrade and Base layer of several project sites in the states of Maryland, New York, and Indiana. Then the target moduli were compared to the field moduli to assess the quality of compaction.

*Keywords:* Geomaterial, Subgrade, Compaction, LWD, Modulus, Proctor

# INTRODUCTION

Conventional methods of compaction quality control (QC) using Nuclear Density Gauges (NDG) has been standard practice for many years, even though it does not reflect the true engineering properties of interest for the geomaterial. The particle arrangement in the soil structure may vary substantially without any significant change in the density (*1*). The target maximum dry density (MDD) and optimum moisture content (OMC) is derived from standard or modified Proctor test (American Association of State Highway Officials: AASHTO T-99 and T-180). It is interesting historically that back in 1948 Ralph Proctor used a Penetration Needle to find the correct soil moisture content (MC) for compaction and the Indicated Saturation Penetration Resistance as a measure of compaction (*2*).

Moreover, the density-based QC methods do not incorporate the stiffness change in unconventional material over time. Studies by Khosravifar et al. (*3,4*) showed that the final stiffness of a field-cured Foamed Asphalt Stabilized Base (FASB) was about 15 times higher than that for the Graded Aggregate Base (GAB), while the dry density (DD) remained constant.

There are several studies in the literature on stress dependency and moisture dependency of the stiffness of geomaterials (*5,6*). However, the effect of DD is found rather unpredictable and material dependent. This, in one hand makes it reasonable to move forward to modulus-based QC of geomaterials but in the other hand challenging it. In NCHRP Project 10-84, Nazarian et al. (*7*) tried to capture the effect of compaction MC, testing MC, and density on modulus. Free-free resonant column (FFRC) tests showed that the greater the difference between the MC at compaction and testing, the higher will be the seismic modulus which in turn is correlated with resilient modulus (Mr). They also found that the effect of density was negligible as compared to MC.

Recently, several state DOTs including Minnesota, Indiana, and Florida have implemented a modulus-based specification using LWDs. The target modulus/deflection is typically derived by Resilient Modulus testing (AASHTO T 307), which is unconventional for production design and difficult to adjust for field moisture conditions.

This paper attempts to develop a practical method to determine target modulus values based on LWD drops on compacted Proctor molds in the lab. Three types of LWDs were evaluated: Zorn ZFG 3000, Dynatest 3031, and Olson NDE360.

# METHOD

## LWD Testing in the Field

Depending on the project site and condition, a total of 5 to 20 stations were tested on freshly compacted subgrade or base with the three LWDs, starting right after compaction and continuing with additional rounds of testing at one-hour intervals (Figure 1).

The field modulus is calculated using the Bousinesq half-space equation assuming the layer to be a linear elastic, isotropic, homogeneous semi-infinite continuum:

$$E = \frac{2k\left(1-\upsilon^2\right)}{Ar_0} \tag{1}$$

in which δ is the maximum deformation, F is the maximum impact load, and k is the maximum peak stiffness equal to F/δ, $\upsilon$ is Poisson's ratio (assumed to be 0.35 for all soils in this paper), and $r_0$ is the plate radius. The stress distribution shape was assumed to be uniform for sandy soils with or without gravel, giving A the stress distribution factor=π. A 300mm plate size was used for all three LWDs in the field. The peak deflection and applied load were taken as the average of the last three LWD drops in the field.

The density and MC at each station were measured with a Troxler 3440 NDG in direct transmission mode to calculate the equivalent DD and Percent Compaction (%PC). Samples were also collected from below the surface to correct the NDG readings according to laboratory determined MCs (AASHTO T 265).

**LWD testing on Proctor Molds**

Using soil samples collected from the field, Proctor molds were compacted at 3 to 7 different moisture contents using standard and modified compaction energy (AASHTO T-99 and T-180). Four- and six-inch mold sizes were tested for all subgrade soils. LWD tests were performed directly on the compacted molds sitting on the laboratory's concrete floor (Figure 1). The diameter of the LWD plate is almost equal to mold diameter, so the plate clears the rim of the mold and measures the deflection on top of the compacted soil inside. Full height drops on the Proctor mold exert stress levels well in excess of conditions in the field; so reduced height drops are used to permit interpolation/extrapolation to the field stress state. Six drops at each drop heights were performed. The drop heights are: 1, 2, 3, 4, and 5 inches plus a drop from half height of each LWD.

The modulus of the soil was derived from the theory of elasticity for a cylinder of elastic material with constrained lateral movement imposed by the rigid mold (Equation 2). In this analysis it was assumed that (a) soil is an elastic material, (b) the deformation occurred in the soil material only and not in the underlying stiff concrete foundation, and (c) the impact load was static as opposed to dynamic. The corresponding equation for calculating the soil modulus is:

$$E = \left(1 - \frac{2\upsilon^2}{1-\upsilon}\right)\frac{4H}{\pi D^2}k \qquad (2)$$

in which $\nu$ = Poisson's ratio, H = height of the mold, D = the diameter of the plate or mold, and k = soil stiffness =F/δ measured by the LWD device.

For the Zorn ZFG 3000, which does not have a load cell, the magnitude of the peak load for the reduced height drops is computed using *Eq. 2-6* in reference (*8*). Each drop height corresponds to an applied plate pressure (P), which has been normalized by atmospheric pressure (Pa=101.325 kPa) in the analysis. The LWDs moduli on the mold are designated as E_ZM, E_DM, and E_OM for the Zorn, Dynatest, and Olson LWDs, respectively.

A multi-variable regression analysis was performed to express E_xM as a function of MC and P/Pa, keeping in mind that the DD and MC should remain within the acceptable range in the State's specification. Consequently, data points with a DD less than 95% of Standard MDD were excluded from the regression analyses. This would automatically happen when excluding the samples with MC outside a 2 to 4 percentage point deviation from OMC in most cases. The target modulus was then determined by feeding the field MC and P/Pa into the regression equation.

**FIGURE 1 From left to right: LWD testing in the field; NDG testing and MC sample collection; field stations locations; LWD testing on 6” Proctor mold in lab**

## RESULTS

The grain size distribution, liquid limit, and plastic limit tests were performed on the samples collected from the field projects according to AASHTO T 27, T 89, and T 90 respectively.

TABLE 1 shows a summary of the project locations and soil types for this study.

In order to validate the target values from LWD testing on the Proctor mold, target deflections were compared to other DOTs specification for similar soil types. Then compaction quality was assessed on two subgrades and a deep layer of graded aggregate base (GAB). Finally, the procedure was refined for ultimate implementation.

**TABLE 1 Project Locations and Soil Classifications**

| Project Name | Code | AASHTO | Unified | |
|---|---|---|---|---|
| Maryland route 5 Subgrade compaction over embankment | MD5_2 SG | A-2-7 | SP | Poorly graded sand with gravel |
| Albany, New York, Luther Forest Boulevard Extension | NY SG | A-3 | SP | Poorly graded sand |
| Maryland route 337 lane widening, Deep GAB | MD 337 | A-2-7 | GW-GM | Well graded gravel with silt and sand |
| Indiana Graham Road Subgrade and Base compaction | IN GAB | A-1-a | GW | Well graded gravel with sand |

### Validation

Indiana DOT sets maximum allowable deflection as an acceptance criterion as measured using a LWD with 300mm plate size, a drop load of 7.07 kN, and deflections measured using an accelerometer, similar to a Zorn LWD (*9*). Figure 2 presents the deflection target values obtained from LWD drops on Proctor molds for each station’s MC condition and Indiana DOT’s target deflection for GAB on top of cement modified subgrade. The target deflections are in the same range as the DOT target. The field MC conditions were mostly on the wet side of OMC.

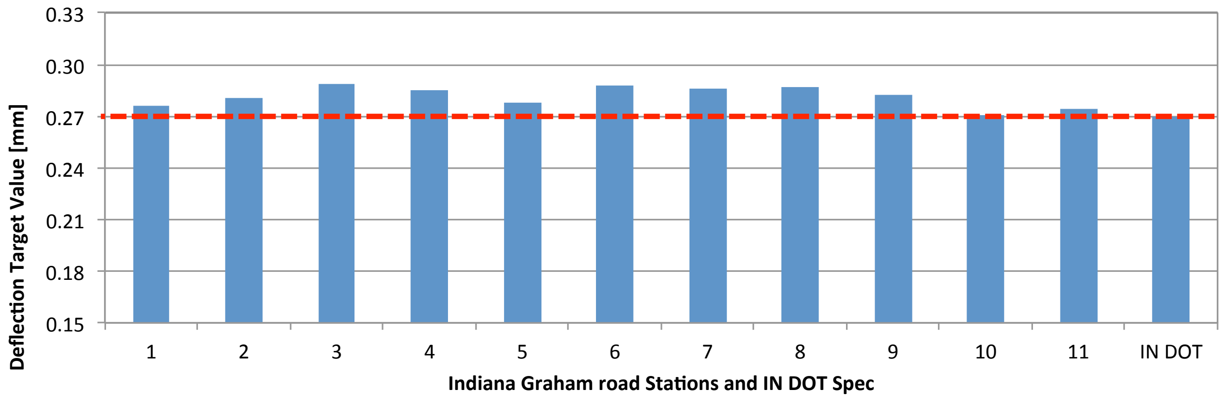



**FIGURE 2 Target deflections for each station determined from Zorn LWD on 6" Standard Proctor Mold versus IN DOT target value**

Minnesota DOT specifies a maximum deflection of 0.40 mm for an A-3 soil at MC below the optimum as determined using a Zorn LWD (*10*). The embankment in the "Luther Forest" boulevard extension project in Albany, NY, was also compacted from a poorly graded local A-3 sand. Target modulus values from the LWD on mold method are compared to MN DOT target in Figure 3. The testing was done at 10 stations on two compacted lifts of 1 foot each, with two testing rounds at one-hour intervals (Lifts designated as: L1 and L2, and Rounds as: R1 and R2 in Figure 3). The average target deflection for each lift is about 30% less than the MN DOT target. Although the soil classification was the same, other soil characteristics and compaction circumstances may have contributed to the disagreement among the target values. Additionally, some stations were drier than the acceptable range of 3 to 5 percentage point deviation from OMC.

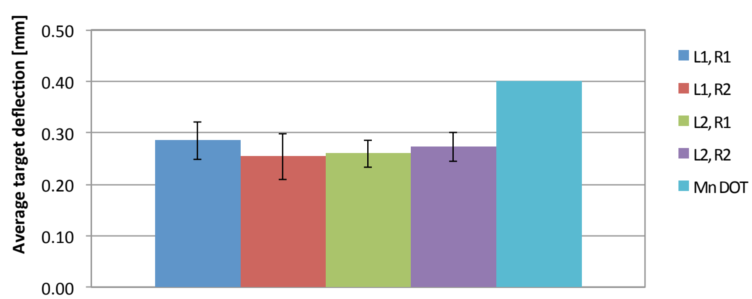



**FIGURE 3 Target deflection for NY A-3 subgrade from Zorn LWD on 6" standard Proctor mold compared to MN DOT specification for A-3 soil**

## Application

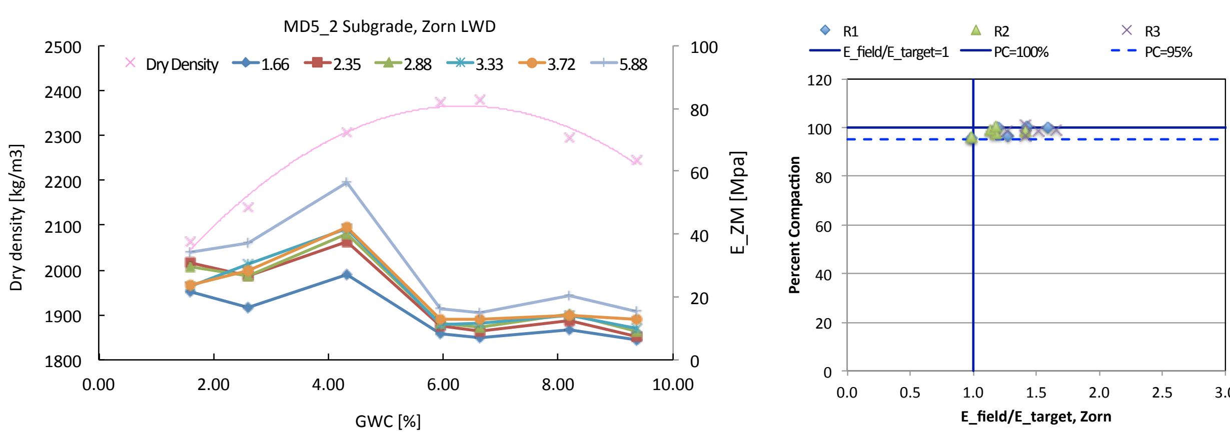
QC is required to be performed right after compaction to avoid any environmental effects such as precipitation or excessive drying. Normally, the MC at the time of compaction may not significantly exceed the OMC during a field construction. Moreover, LWD testing on molds in far wet side of OMC is simply impossible. Depending on soil type, even OMC+2% might be too wet and much permanent deformation, uneven surface deformation under the LWD plate, and water drainage from the top and bottom of mold during testing is experienced.

The compaction quality of a well-compacted subgrade and base and a poorly compacted subgrade/embankment was investigated in this study. The MD Route 5 Subgrade (MD5_2), was a well compacted, poorly graded sand with gravel, constructed on top of an embankment. Testing on this subgrade was performed immediately after compaction and at one and two hours after compaction (R1, R2, and R3). The LWD drops on Proctor molds captured the stress and moisture dependency trends in the soil behavior, as depicted on the left side of Figure 4. It should be noted that the field conditions were mostly on dry side of optimum or near optimum. For each LWD, the ratio of the field-measured modulus to the laboratory-determined target modulus (E_field/E_target) is compared to %PC as obtained from a conventional NDG, as depicted on the right side of Figure 4, where the color codes correspond to each round of testing. The field to target modulus ratio is more than 1 for almost all stations using all 3 LWD types. There is not much effect of drying observed after each round in Zorn and Olson LWD results. The Dynatest LWD measurements exhibited a slight increase in field modulus and E_field/E_target. This may be due to Dynatest's center geophone that measures deflection directly on top of the soil through an annulus in the plate, making it more sensitive to any drying occurring on the soil surface.

If the values fall in the upper right corner of the "PC vs. E_field/E_target" graph, they are in the acceptable zone for both density and stiffness. This corresponds to acceptable PC values of more than 95% (density passed) and E_field/E_target values more than 1 (modulus passed). The results in Figure 4 show that the MD Route 5 subgrade was well compacted and passed both the modulus and density compaction quality control criteria.

The same analyses were performed for the NY subgrade soil, which was a poorly compacted embankment. Figure 5 shows that all of the data points lie in the lower left quadrant, indicating that the poorly compacted NY subgrade failed to meet the target modulus and the required PC.

Maryland Route 337 natural subgrade was soft expansive clay. The upper 2 ft were therefore replaced with a well graded gravel with silt and sand to meet the proof rolling criteria. As shown in Figure 5, this well-compacted material satisfied both the density and modulus compaction requirements—i.e., all data points are in the upper right quadrant.



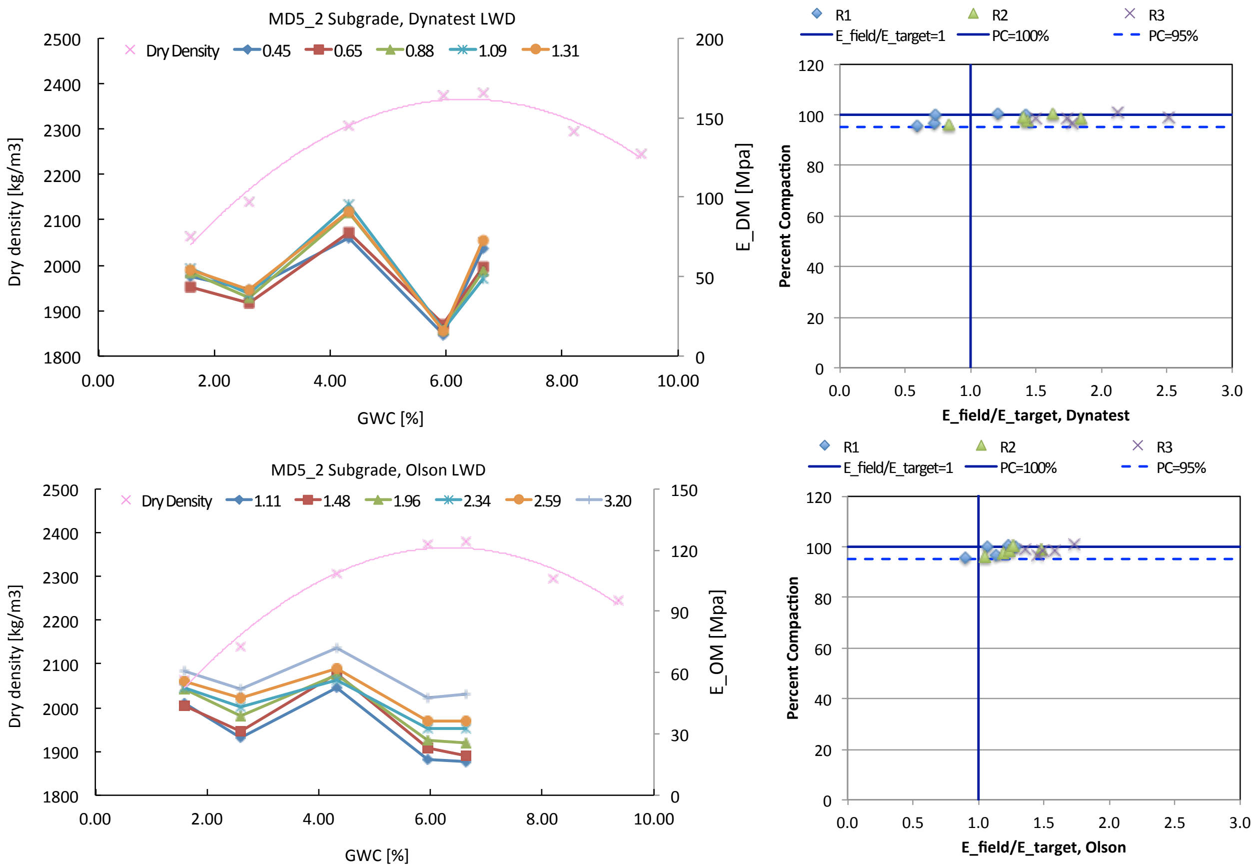
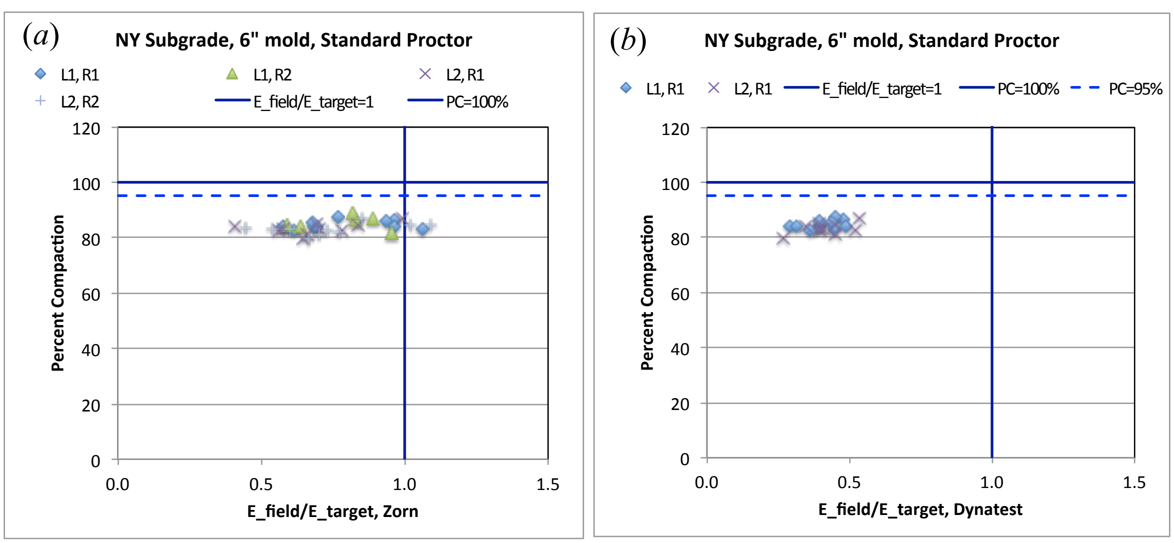



**FIGURE 4 Left side: LWD modulus on mold versus gravimetric water content (GWC) superimposed by DD versus GWC for MD5_2 subgrade soil compacted in 6"mold and standard compaction energy at variable P/Pa for Zorn, Dynatest, and Olson LWDs. Legend specifies P/Pa. Right side: field-measured modulus to the calculated target modulus ratio versus %PC**



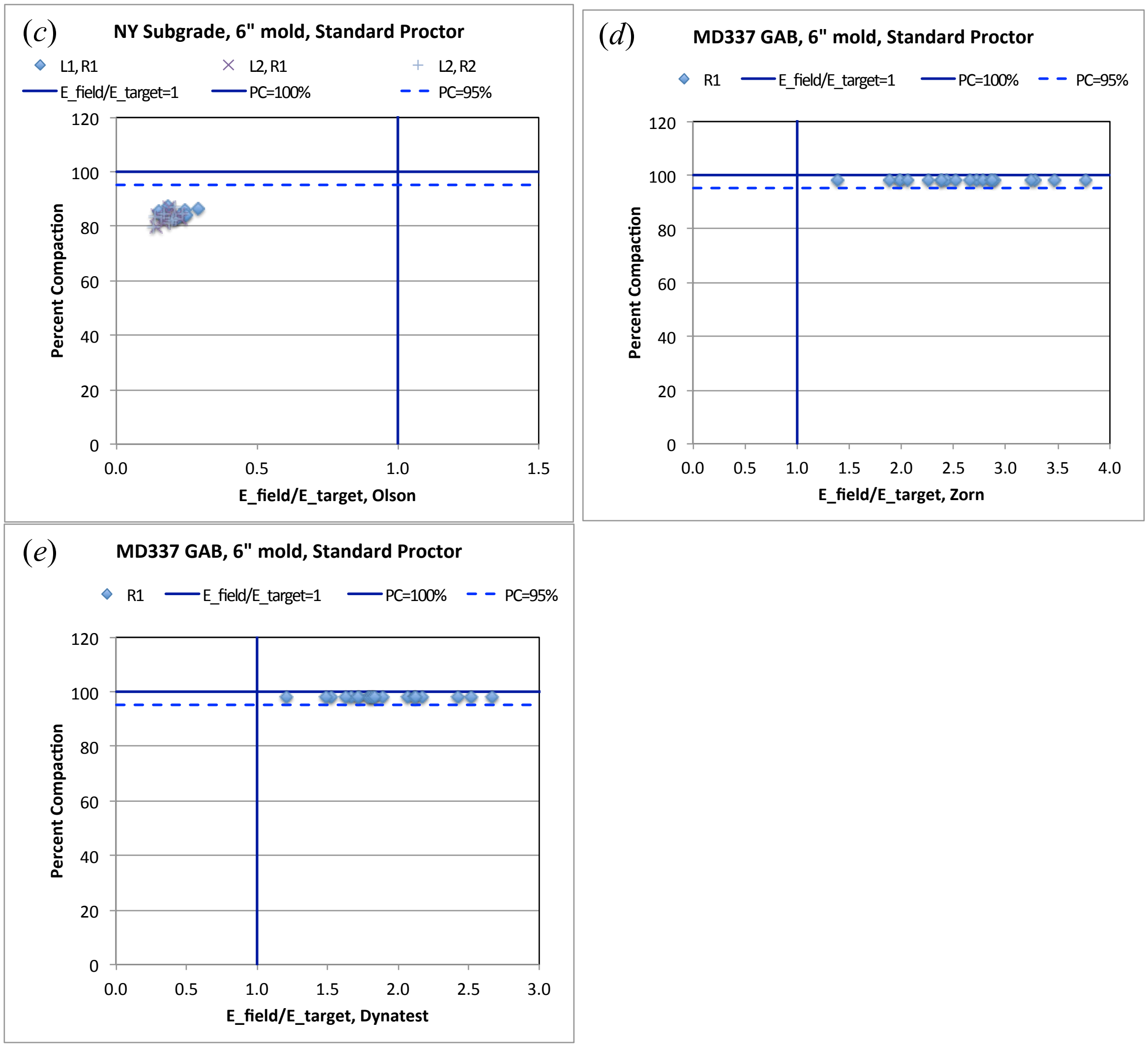



**FIGURE 5 field-measured modulus to the calculated target modulus ratio versus %PC for NY subgrade: (*a*), (*b*), and (*c*); MD 337 GAB: (*d*), and (*e*)**

## Refinement

Attempts were made to solve the instability of the LWD on top of the mold to improve data quality. The shakiness particularly occurred when dropping the load from greater drop heights using Zorn LWD, as the plate is much heavier compared to other devices. A simple collar similar to that of Proctor mold's was designed to keep the LWD plate in place and centered on the mold.

The four-inch diameter mold provided considerable confinement of the soil under the LWD drops and thus failed to duplicate the field condition. Moreover, there was more water drainage and permanent deformations as compared to the 6" diameter mold.

In addition, the Dynatest LWD results (Figure 4) on the wet side of optimum did not follow the expected trend observed with the other LWDs. The modulus is increasing with increase in GWC from 6% to 7%. This is attributed to the way that Dynatest measures deflection directly on the top of the soil through the center annulus; heaving of the soil into the annulus under load causes an underestimate of deflection and thus a higher modulus. This problem can be mitigated by measuring the plate deflection using the Dynatest LWD's Plugin optional feature. The Plugin enables the center geophone to measure plate rather than soil surface deflection.

The Percent Coefficient of Variation (%COV) of deflections for last 3 drops was used as a measure of the quality of the data obtained on the Proctor mold. Figure 6 illustrates the %COV for 4” and 6” diameter Proctor molds compacted with Standard (Std Proc) and Modified (Mod Proc) energy, with additional data for the Dynatest Plugin (LWD w/ plug) and for full height drops in the field. The 6” mold compacted with standard energy best simulates field condition using the Zorn LWD. However, the trend is not the same for Dynatest LWD.

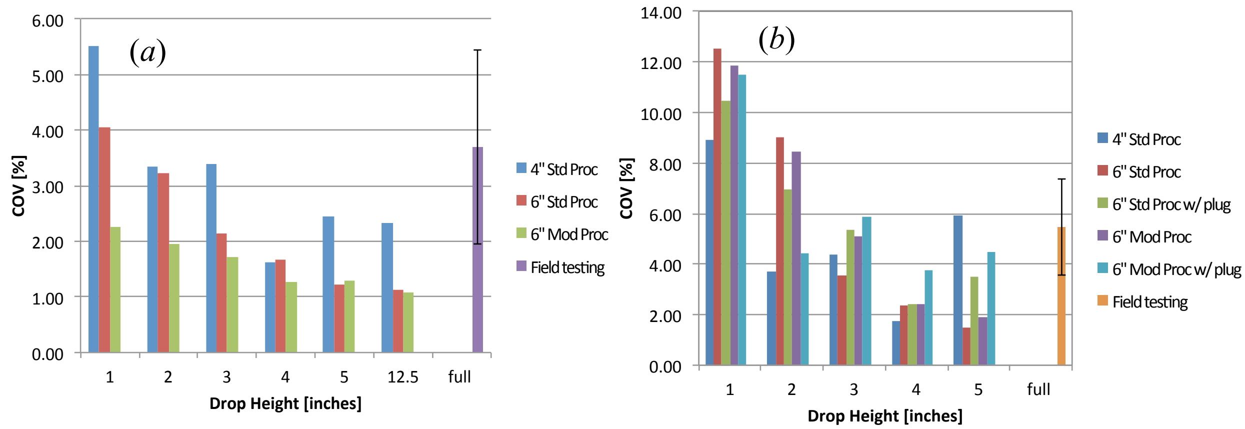



**FIGURE 6 Average Coefficient of Variation of Deflections for last 3 drops on the proctor mold and field at each drop height: (*a*) Zorn LWD, and (*b*) Dynatest LWD (NY Subgrade)**

## CONCLUSION

LWD testing on Proctor molds is an easy add-on to conventional compaction testing that can be used to establish target LWD modulus values for the field. The Proctor molds can be compacted at various moisture contents using either standard or modified compaction energies. LWD deflection and moduli from adjusted drop heights were captured on the compacted molds in the lab and compared to the field-measured LWD values. Since both the field and target moduli were determined using the same device, the measurement differences including plate size and device type largely cancel when looking at the ratio of E_field/E_target. Drops on 6” diameter Proctor mold compacted with standard energy and with MC near optimum or as expected in the field is recommended.

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