# COMPACTION STUDIES ON OPEN-GRADED AGGREGATE MATERIALS: MOVING TOWARDS DEFLECTION-BASED COMPACTION CONTROL

By

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COMPACTION STUDIES ON OPEN-GRADED

AGGREGATE MATERIALS: MOVING TOWARDS

DEFLECTION-BASED COMPACTION CONTROL

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Abstract:

Compaction quality control of unbound aggregate layers in pavements has been typically based on target density values, which are defined in reference to the highest densities that can be achieved in the lab using standardized compaction tests. For Open-Graded Aggregate (OGA) base/subbase layers, however, density-based compaction control becomes difficult due to the presence of excessive voids. Due to the absence of specific compaction control protocols, a recipe-based approach is often used during compaction of these layers. This study focused on studying the compaction behavior of two different OGA materials conforming to ASTM #4 and ASTM #57 gradations, using Portable Impulse Plate Load Testing Devices such as the Light Weight Deflectometer (LWD). Deflection-based compaction control protocols can provide not only an idea about the level of compaction achieved in the field, but also a direct mechanistic design input parameter such as stiffness/modulus.

In this study, an integrated approach involving laboratory and full-scale field testing was undertaken to accomplish the research objectives. Laboratory testing included testing of the aggregates in a custom-made steel mold as well as in a large wooden box. The aggregates were compacted to different levels using different methods: Jackhammer, Vibratory Shake Table, and Vibratory Plate Compactor. LWD testing was performed on the aggregate material after different levels of compaction to measure the corresponding surface deflections. LWDs from two different manufacturers were used to ensure the developed protocol was device-agnostic. Finally, full-scale pavement test sections, comprising multiple test cells, were constructed using a combination of ASTM #4 and ASTM #57 aggregates in the subbase and base layers, respectively. Surface deflections were tracked with the LWDs after different number of vibratory steel-drum roller passes. Detailed findings from this study are discussed in this thesis and a foundation is laid for developing deflection-based compaction control protocols for OGA base/subbase layers.

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# CHAPTER I

## INTRODUCTION

Open-Graded Aggregates (OGA) are often used in unbound pavement base/subbase layers due to their superior hydraulic conductivities and lower moisture sensitivities. These unbound base/subbase layers mainly rely on aggregate-interlock for their shear strength and modulus properties. That is why the degree of compaction largely governs their behavior under loading. As in conventional flexible pavement structures, these pavement base/subbase layers act a major load-bearing layer, it has been common practice that dense-graded aggregates are preferred to construct such layers. However, mechanical properties such as shear strength and resilient modulus of dense-graded aggregate layers tend to be significantly affected under fluctuating moisture conditions. Under high moisture conditions, the shear strength of these layers may be substantially reduced which makes them prone to severe permanent deformation or even shear failures. Another problem with a well-compacted dense-graded base/subbase layer is that recurrent freeze–thaw cycles drastically reduce the stability (under loading) of these layers. On the other hand, OGA materials can have numerous benefits over their dense-graded counterparts, especially for unbound granular pavement layers. The low fines content, among many other benefits leads to better drainage characteristics Furthermore, OGA layers often have larger top-sizes, which increases the shear strength of the layers under well-compacted conditions.

Despite their numerous benefits, the overall performances including both short-term and long-term performances of OGA materials as base/subbase layers has not been investigated thoroughly. The open-graded materials may be worked with under light to moderate weathering (rain) conditions because to their moisture resistance. Open-graded aggregate materials need less compaction work amount of research and related literature on the performance of OGA materials as base/subbase materials are insignificant and few in numbers. The most reasonable explanations might be the lack of standard compaction and construction specifications for these materials. Also, the OGA materials present significant challenges when it comes to density-based compaction control. Although the compaction process is similar to those for dense-graded aggregate layers (vibratory compaction), it poses some problems such as

1. Large void-spaces in the aggregate matrix make in-situ density measurements virtually impossible
2. Conventional density verification techniques such as the nuclear density gauge are impractical
3. Setting a precise target during field compaction is quite challenging in such situations

To deal with such problems, rather than attempting to satisfy any target compaction-control criterion, the current practice is to compact these layers using recipe-based approaches. For example, some highway agency specifications require these layers to be compacted "to the engineer's satisfaction". Some others, on the other hand, specify a certain number of passes of a vibratory roller compactor before an OGA layer is considered to be 'satisfactorily compacted'. It is obvious that such compaction specifications do not ensure adequate performance of the layer under loading and needs to be updated. As a suitable alternative, deflection-based compaction control can give an indication regarding layer performance under loading.

This master's thesis research aimed to develop a deflection-based protocol for measuring the compaction level of OGA materials. The hypothesis behind this research is quite simple. As a material layer is compacted, the stiffness of that layer increases. The increased stiffness results in reduced surface deflections while the layer is subjected to loading. This thesis research involved measuring the surface deflections before & after compaction and comparing the results with field data. Surface deflections of the OGA aggregate layers were measured using Portable Impulse Plate Load Testing Devices (PIPLTDs), such as the Light Weight Deflectometer (LWD). Technically, a PIPLTD needs to have a load-cell (for direct measurement of applied loads) to be termed as an 'LWD' (per ASTM E2583). On the other hand, the PIPLTD refers to a generic equipment category, and does not have any requirement regarding direct measurement of applied load levels (see ASTM E2835). The present study uses both device types (with and without load cells). In a technical sense, the devices belong to the PIPLTD category. However, both device types have been referred to in this work as LWDs since that terminology is widely used in the technical community.

**Background and Research Needs**

Developing a deflection-based compaction control protocol for OGAs is a challenging work. The first challenge involves establishing a target or reference value to compare the field-measured surface deflection values against. For conventional density-based compaction the process is quite straight-forward. First, the material is tested in the laboratory for its compaction characteristics, and a moisture-density curve is established (either using the standard or modified compactive effort). Subsequently, field-measured density values, usually using Nuclear Density Gauges (NDGs) or other approaches such as the sand-cone method (rarely used during modern construction), are compared against these reference values to assess the level of compaction. Such density-based compaction control, however, has a number of drawbacks. For instance, the NDG uses a probe with a radioactive source and necessitates compliance with intricate safety protocols both during operation as well as storage. The sand cone method, on the other hand, is time-consuming and is not ideal for expedited construction. For OGA base/subbase layers, conventional density measurement approaches are not a suitable due to the presence of large air voids in the aggregate matrix. In light of this, there is a well-recognized need for developing alternative compaction control specifications for OGAs. Furthermore, density is not a direct input during the Mechanistic-Empirical (M-E) pavement design process. Rather, the M-E design method heavily relies on unbound layer Resilient Modulus ($M_R$) as the most critical input parameter. The $M_R$ value plays a major role in governing the stress distribution through pavement foundation layers. Even though several researchers have in the past linked higher densities to gains in unbound layer stiffness or resilient modulus (Rowshanzamir, 1995; Tutumluer and Seyhan, 1998), there is no consensus regarding the relationship between density and $M_R$. In contrast, compaction control standards created using stiffness or deflection criteria can be quite helpful. The degree of deformation (elastic or plastic) that a constructed unbound layer experiences under loading, ultimately determines its "stability."

However, when it comes to modulus/deflection-based compaction control, it is first important to establish a threshold value that can be used as a reference during field compaction. Therefore, the first challenge involves establishing a 'robust' laboratory testing method that can be used to establish target values for modulus/deflection-based compaction control of OGAs. Nazarian et al., (2014) reported that the devices used for modulus determination in field (such as the LWD) are sensitive to the moduli of underlying layers. Therefore, appropriate adjustments need be made in assigning the target modulus values. Oversize rocks, surficial cracks, uneven or rough surface texture or scaled surface may affect the measurements with the LWD. Therefore, there exists variability in LWD measured modulus for OGA layer. Steinert et al., (2005) reported poor correlation between the compaction level and LWD-measured moduli. They reported that modulus values for the same material exhibited high degrees of variability when different LWD devices were used. Vennapusa and White (2009), among others, have reported that the LWD-measured moduli are affected by the size of loading plate, plate contact stresses, type and location of deflection sensor; plate rigidity, loading rate and buffer stiffness. Therefore, although LWD-measured moduli can give a relative picture of the achieved “stiffness” in an unbound layer, comparing them against fixed threshold values can still be challenging.

Generally, the resilient modulus of unbound materials (soils and aggregates) is determined in the laboratory using Repeated Load Triaxial (RLT) testing. However, it is not common for state and local highway agencies to conduct the RLT test on a regular basis to determine the resilient modulus properties of soils and aggregates. The primary reasons behind this being: RLT tests are expensive, time-consuming, and require extensive personnel training. Most highway agencies do not have the resources to accommodate this, and end-up resorting to correlation equations or assumed values based on empirical data. Nevertheless, these correlation equations and empirical data-based assumed values are primarily for subgrade soils and/or dense-graded aggregates. When it comes to OGA materials, data related to resilient modulus properties is even more scarce. Due to the relatively coarse grain size in OGAs, RLT tests need to be conducted on considerably large samples (often greater than 150 mm or 6 in. in diameter and 300 mm or 12 in. in height), which present additional challenges for agencies. Due to all these constraints, it is not common for highway agencies to perform RLT tests on OGA materials to determine the $M_R$ properties. This means, no standard values are usually available to be used as reference values.

On the other hand, considering the devices commonly used for field-measurement of constructed pavement layer modulus, their accuracy is also greatly affected by the grain size distribution of the layer being tested. Modulus calculation in the field (using LWDs) relies on the single-layer Boussinesq’s theory. Boussinesq’s theory inherently assumes the layer to be linear elastic, isotropic, homogeneous, and behave like a semi-infinite continuum. As expected, it is not logical to assume OGA layers to meet these assumptions. Therefore, modulus calculation in the field for OGA layers using LWDs is not a trivial matter, and the results are not likely to be very precise.

Deflection-based compaction control, on the other hand, can present a suitable 'middle-ground' between these two alternatives (density-based compaction and modulus-based compaction). LWD-measured surface deflections can be used as an indicator of 'state of compaction' in a soil/aggregate layer. As the modulus values in the field and lab are not being compared, there is no need for modulus determination in the laboratory. If a standardized test method can be developed to measure the surface deflections for OGA materials under different compaction levels, these results can be used as the reference during field compaction checks. Surface deflection is closely related to the stiffness of the layer. This Master's thesis research focused on developing a deflection-based compaction protocol for OGA base/subbase layers.

**Research Objective & Tasks**

A deflection-based compaction control protocol development for open-graded aggregate base/subbase courses, such as those used under permeable pavements, is the goal of this research study. In this study, the compaction control protocols are being developed using LWDs. Extensive laboratory testing of two distinct aggregate materials and the construction and testing of full-scale pavement sections in the field are all tasks that were undertaken to accomplish the study's overall goal.

The laboratory testing involved testing OGA materials two types of LWDs. This study considered different specimen sizes (using standard and customized mold) to avoid the boundary effect. Different modes of compaction such as Jack hammer compaction and Vibratory Shake Table compaction were utilized to observe which compaction method is replicating the field compaction scenario. The surface deflection of OGAs were measured before and after different compaction efforts. To make sure the customized mold is capable of capturing the compaction behavior without any confining effect the OGA materials then further tested a wooden box using different layer configuration. In this stage vibratory plate compactor was used for compacting the materials inside the box. The depth of the layer was varied along with the use of earth pressure cell to study the pressure distribution caused by the LWD drop. Once satisfactory results were found the study moved to a full-scale field testing, constructing a test section comprised of base and subbase layer with varied layer configuration. Vibratory roller compaction was used to construct the section at different depth. Surface deflection was measured after every roller pass. Finally, the data was analyzed and compared with the lab data.

Detailed findings, from the individual tasks completed in this thesis research, are reported in Chapters III and IV of this thesis in form of two research manuscripts. Table 1 lists the individual tasks carried out under the scope of this master's thesis, and maps each of the tasks to the technical manuscripts prepared.

**Table 1: Individual Research Tasks Mapped to Respective Technical Manuscripts**

| Tasks | Manuscripts | Details |
|---|---|---|
| 1 | Manuscript-1 | Testing with LWD in customized and standard mold with varied mold configuration & compaction effort |
| 2 | | Analyze the surface deflection data based on layer thickness & compaction effort |
| 3 | Manuscript-2 | Testing with LWD & pressure cell in box with varied layer configuration & compaction effort |
| 4 | | Constructing full-scale section with varied layer configuration and testing with LWD |
| 5 | | Analyze the surface deflection data based on layer thickness & compaction effort and come up with a protocol for measuring compaction level for open graded aggregate |

## Organization of the Thesis

CHAPTER I of this thesis provides an overall introduction to this master's thesis research. This chapter focuses on the concerns and weaknesses of existing methods and lays the foundation for this research effort.

CHAPTER II presents a brief summary of available techniques used in the application of compaction control based on surface deflection. This chapter also includes a brief review on the existing research on the way to establishing a deflection-based compaction control protocol.

CHAPTER III contains results reported in the first manuscript. The title of the manuscript is, "Compaction Studies on Open-Graded Aggregates Using Portable Impulse Plate Load Test Devices". This focuses the findings from the Task-1 & 2 including detailed approach taken to make the tasks successful.

CHAPTER IV contains findings reported in manuscript # 2, titled "Use of Portable Impulse Plate Load Testing Devices in the Compaction Study of Open Graded Aggregate through Laboratory and Field Evaluation". This focuses the findings from the Task-3,4 & 5 including detailed approach taken to make the tasks successful.

CHAPTER V summarizes results and findings from the tasks completed in this thesis research, providing recommendation that can be implemented in the development of deflection-based compaction control. This chapter also discusses the limitations of this research study and provides recommendations for future research efforts.

# CHAPTER II

## LITERATURE REVIEW

Unbound pavement layers like subgrade, subbase, and base give the pavement structure strength and stability under traffic loading while also acting as a foundation during the development of the surface layer. The stability of the subgrade and base/subbase layers, which are primarily built using locally accessible soils and aggregates, heavily rely on construction techniques, notably the level of compaction. The development of unbound pavement layer quality control and quality assurance (QC/QA) procedures has historically been based on target densities. These target densities are determined as percentages of the highest densities that can be achieved for the specified materials after laboratory testing. The standard and modified compaction procedures, often known as the Proctor methods, are the most typical instances of laboratory compaction testing. Nuclear Density Gauges (NDG) or other acceptable techniques are used to determine the in-place densities of the unbound layers being built (e.g. the sand cone method). The target density values, which were determined through laboratory testing, are then compared to the in-place densities. Measuring density for OGAs is not suitable using these methods due to the presence of large air voids.

Compaction control parameters based on deflection criteria, as opposed to density-based standards, can therefore be more closely related to the performance of the pavement under loads. Deflection-based compaction control criteria will be notably helpful for the design and construction of more effective unbound pavement layers. One such tool that may measure in-place layer modulus and be used for compaction quality assurance without significantly delaying construction activities is the Light Weight Deflectometer (LWD).

**The light weight deflectometer and its Working Principle**

Germany was the first to design the Light Weight Deflectometer with the intention of making it simple to measure the in-situ modulus of roadway materials. For dense-graded aggregate base layers employing LWDs, many state Departments of Transportation (DOTs) in the US, including Florida, Indiana, and Minnesota, have approved compaction control requirements. A new specification for using LWDs to manage compaction of subgrades and dense-graded aggregate layers was recently established by Schwartz et al. (2017).

***Basic Features***

Despite minor operational and design changes, the many types of LWDs that are available show similarities in their mechanical operation. LWDs are available in the market from several manufacturers. The following models of LWDs are commercially available in the US: Zorn *(*www.kesslerdcp.com*)*, Olson *(*www.olsoninstruments.com*)*, Dynatest *(*www.dynatest.com*)*, Humboldt *(*www.humboldtmfg.com*)*, Matest *(*www.matest.com*)*, HMP *(*www.hmp-online.com*)* and Terratest *(*www.terratest-lwd.com*)*. Among these, the Zorn, Olson, and Dynatest have been used extensively by researchers and practitioners. The Olson and Dynatest LWDs have load cells to directly measure the impact load magnitudes and satisfy the ASTM E2583-07 requirements. The Zorn LWD, on the other hand, does not have a load cell and meets the ASTM 2835-11 requirements.

The LWD has become a popular tool for in-situ layer modulus assessment on soils and aggregates because to its light weight, portability, and simplicity of use. Previous studies have found that because of fundamental design and operational variances, LWD devices from various manufacturers provide somewhat varying outcomes (Puppala, 2008; Ryden and Mooney, 2009;

Vennapusa and White, 2007). Due to the LWD and PFWD's identical operating concepts, the LWD is also called as a Portable Falling Weight Deflectometer (PFWD). Figure 1 shows the schematic diagram of a typical LWD device. The fix-and-release mechanism at the top helps in stabilizing the drop mass before it is dropped. To enable uniform propagation of the stress pulse caused by the falling mass, a buffer mechanism is placed on top of the loading plate.

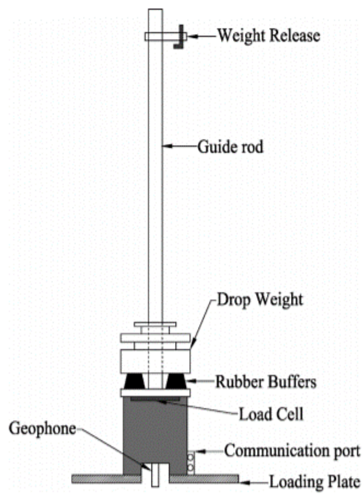



**Figure 1: Schematic of a typical LWD device (Schwartz et al., 2017)**

Several research investigated the inherent characteristics of these devices and their suitability for in-situ layer modulus assessment (Flemming et al., 2000; Mooney et al., 2009 and George, 2006). These early LWD iterations included the velocity observed on the layer-testing surface using a velocity transducer (or geophone) to determine deflection. Several different companies have begun commercially manufacturing LWD systems throughout time. Devices made by Zorn Instruments, Dynatest Corporation, or Olson Engineering are those that are widely obtainable in the US. **Table 2** lists the typical features of LWDs have been commonly used in the US by different researchers and/or practitioners. Among several differences between the devices as listed in **Table 2**, it should be noted that the Zorn does not directly measure the force being applied by the dropping mass. The Dynatest and the Olson devices, on the other hand, use load cells to measure the applied forces.

**Table 2: Features of LWDs Most Commonly Used in the United States**

| **Manufacturer** | **Dynatest** | **Olson** | **Zorn** |
|---|---|---|---|
| Plate Style | Annulus | Plate | Plate |
| Plate Dia (mm) | 150, 200, 300 | 100, 150, 200, 300 | 100, 150, 200, 300 |
| Drop Mass (kg) | 10, 15, 20 | 3.6, 10, 15, 20 | 5, 10, 15 |
| Drop Height (m) | Variable | 600mm (max) | 5 (kg) 35cm, 10 and15 (kg) 72cm and 54cm (200mm dia). All are Nominal Exact Height is Set by Calibration |
| Damper | Rubber | Steel Spring | Steel Spring |
| Force Measurement | Yes | Yes (Load cell) | No (Based on Calibration of Drop Height) |
| Plate Response Sensor | Geophone | Geophone | Accelerometer |
| Impulse time, ms | 15-30 | 16 nominal (15-20) | 15.5 (nominal) |
| Max Load (kN) | 1-25 | 1.7-13.8 | 3.5 - 10.5 |
| Contact Stress | User Defined | User Selectable | Varies by Height and Weight |
| Poisson’s Ratio | User Defined | User Selectable | Fixed -0.5 |

***LWD Working Principle***

The LWD is a dynamic plate load testing tool that may be used to calculate the modulus of unbound pavement materials like base aggregates or subgrade soils. A disk-shaped plate made of steel or aluminum in this arrangement applies a pulse load. Upon release, the drop weight strikes a spring-dashpot unit attached to the plate which applies load to the surface or ground. In a couple model that is comparable to a mass-spring-damper system with two degrees of freedom, the plate and the ground move in harmony. Figure **2** presents a schematic illustrating the mechanics of interaction between the LWD and the ground surface during impulse-based modulus measurement.

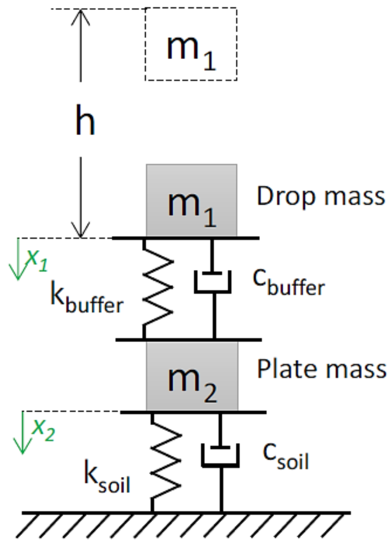



**Figure 2 : Two DOF system representing LWD-ground movement (Schwartz et al. ,2017)**

The load cell detects the load caused by the weight dropping, while the velocity sensor/geophone measures the movement of the ground. Different LWDs have various sorts of sensors in various places. The greatest displacement of the ground surface following each drop is determined using double/single acceleration/velocity integration. Some LWDs on the market (like the one made by Dynatest) come with extra velocity-based sensor (geophones) that it capable of determining the surface deflection at an offset in radial direction from the loading plate's center. Figure 3 shows example loads and deflection time histories obtained during LWD testing of geomaterials (soils or aggregates).

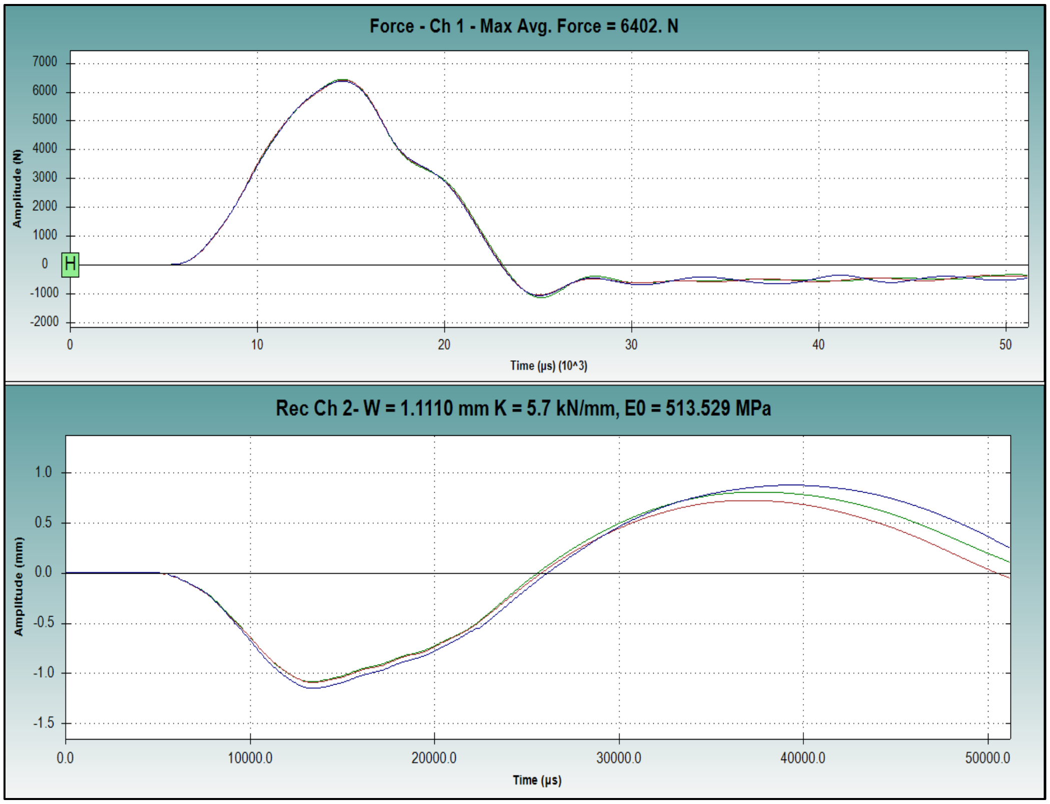
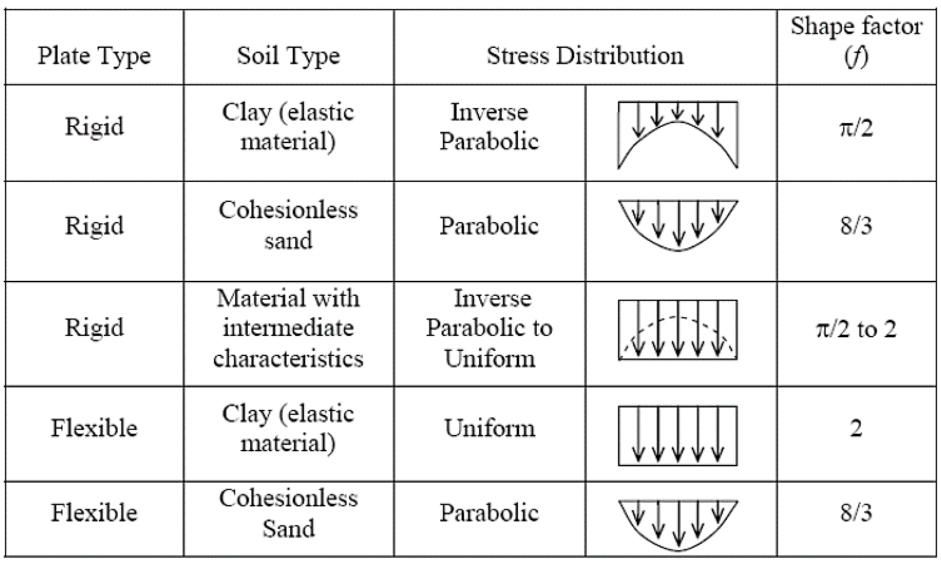



**Figure 3 Deflection time and load history obtained during LWD testing of geomaterials**

A load cell detects the load imposed on the device by the falling weight, while a velocity sensor/geophone measures the movement of the ground. Different LWDs have various sorts of sensors in various places. For example, one of the LWD types used in this study (Zorn) excludes a load cell that would allow for the precise measurement of the force exerted by the dropped weight. Instead, the force is "estimated" using a pre-determined calibration depending on the drop height. The greatest displacement of the ground surface following each drop is determined using double/single acceleration/velocity integration. The surface layer modulus is calculated using the recorded maximum surface displacement that corresponds to the maximum applied force. The formula used to calculate the modulus of the LWD tested layer is derived from the Boussinesq Equation (1):

$$E = \frac{2\times k_s \times (1-\nu^2)}{A\times r_0} \quad (1)$$

In Equation-1, A is the stress distribution factor, r is the plate radius, ν is the Poisson’s ratio, and $k_s$ is the stiffness of material which is the ratio between the peak load and peak deflection values recorded under the specific drop mass. In equation (1) it is assumed the underlying layer to be linear-elastic, isotropic, and homogeneous semi-infinite continuum media. The Poisson's ratio is predicated on the form factor to determine the contact stress distribution between the plate and soil. The relationship between soil types and plate stiffness may be used to describe the stress distribution beneath the plate (Terzaghi et al., 1996). The values of the shape factor under various situations were reported by White et al. (2007). Figure 4 shows the stress distribution factors for different types of soils and loading plates. Unfortunately, no such shape factor was found in the literature for open-graded aggregate materials.



| Plate Type | Soil Type | Stress Distribution | | Shape factor (*f*) |
|---|---|---|---|---|
| Rigid | Clay (elastic material) | Inverse Parabolic | | π/2 |
| Rigid | Cohesionless sand | Parabolic | | 8/3 |
| Rigid | Material with intermediate characteristics | Inverse Parabolic to Uniform | | π/2 to 2 |
| Flexible | Clay (elastic material) | Uniform | | 2 |
| Flexible | Cohesionless Sand | Parabolic | | 8/3 |

**Figure 4 : Stress distribution factors for estimating LWD modulus value (White et al., 2007)**

It would be extremely useful to create LWD-based compaction quality control specifications for open-graded aggregate base/subbase layers. However, accurate LWD testing on these layers is typically difficult. It is difficult to establish a flat surface for LWD testing due to the uneven nature of the surface. Point-based deflection measuring methods, such as the protruding geophone at the center of the plate for a Dynatest LWD, may not be suitable for these materials. Movement of a single aggregate particle on the layer's surface can be falsely interpreted as excessive surface deformation of the entire layer, thus presenting an erroneous picture of the state of the compaction of the aggregate matrix. To address this problem, manufacturers such as Dynatest have incorporated different ‘checking’ mechanisms into their devices. For example, a centering lever mechanism is introduced to ensure the device is seated correctly. Moreover, the Dynatest device also has a "Sensor Locking Plug" to lock the geophone to the plate and also to plug the center hole of the plate. This avoids the "protruding geophone" potential problems. Finally, the problem with localized deflection of aggregates can be checked through the deflection time history at the time of measurement; The difference between start and end deflection levels might be an indication of localized aggregate deflection. However, to avoid such confusions, it is beneficial to measure the surface deflection of the entire plate as a single unit.

**LWD Testing in a Proctor Mold**

To determine target field modulus values at a specific moisture content, Schwartz et al. (2017) conducted LWD experiments using Proctor molds. The utilized LWD plate sizes that were a little bit less than the Proctor mold's diameter. In this instance, Equation-2 illustrates how the equation for a cylinder (elastic material) with a confined lateral deflection was developed from the theory of elasticity. It was used to determine the modulus of dense-graded aggregate materials inside the mold. Afsharika (2019) presented the derivation for LWD modulus calculations in a mold, which can be expressed by the following equation:

$$E = \left(1 - \frac{2 \times \nu^2}{1-\nu}\right) \times \frac{4H}{\pi D^2} \times k \quad \text{-----(2)}$$

Here, ν is the Poisson’s ratio, H is the mold's height, D is the plate or mold diameter, k is soil stiffness (ratio of peak force to peak deflection).

Because of three factors—(a) different stress paths in the two tests (See Figure 4) ; (b) the use of the Poisson's ratio in LWD-based calculations; and (c) the different types of strain being measured—resilient strain for MR calculations vs. total strain during LWD measurements—the LWD-measured modulus values in a Proctor mold may differ from the resilient modulus test results. A steady confining pressure is provided during the resilient modulus test. After that, axial deviator stress is applied, which increases the confining pressure ($\sigma_3$) to total axial stress ($\sigma_1$). On the other hand, during LWD testing on mold, both confining pressure ($\sigma_3$) and total axial stress ($\sigma_1$) start from zero and rapidly rise to its maximum value. These differences are illustrated in Figure 5. Even though these tests are independent from one another, researchers found a correlation between Mr and LWD lab modulus for the materials used in dense-graded aggregates. (Schwartz et al., 2017, Jibon et al., 2021).

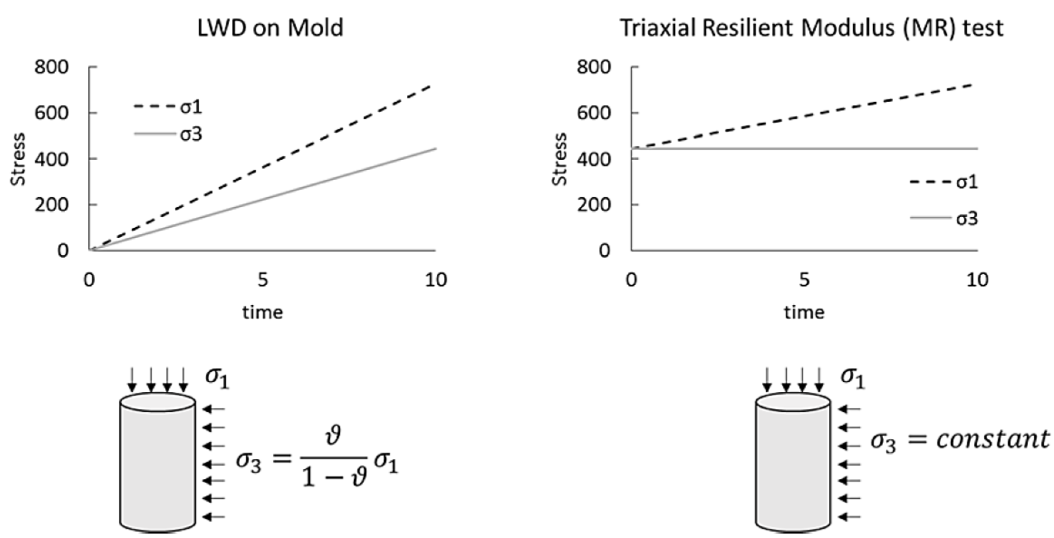



**Figure 5: Stress path difference in LWD test on mold versus $M_R$ (Schwartz et al., 2017)**

According to Schwartz et al. (2017), a target field modulus value was established in order to facilitate LWD-based compaction quality control of soil and aggregate layers. According to AASHTO T-99, they compacted specimens within a Proctor mold with a 150 mm diameter under three to six distinct moisture conditions. After compaction, LWD testing was done on the specimen, and a modulus value corresponding to each moisture content was determined. During this process, they looked at the materials' dependency on moisture and stress. The LWD testing results in Proctor molds can be plotted in a manner matching the conventional moisture-density curves (see Figure 6). The modulus vs. moisture curve closely follows a conventional moisture-density curve, as can be observed in the figure, and the LWD-measured modulus values fluctuate with compaction moisture content. This "modulus growth curve" may be used as a guide, and when evaluating the compaction quality in the field, a certain portion of the peak modulus value can be utilized as a threshold value. Notably, Schwartz et al. (2017) recommended taking caution while conducting LWD testing on Proctor molds with compaction moisture concentrations much higher than the Optimum Moisture Content (OMC).

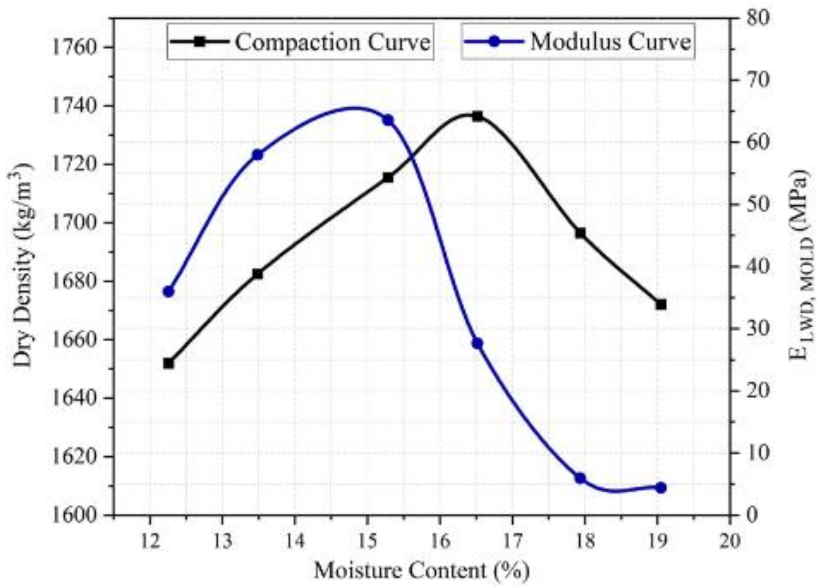



**Figure 6 : Variation of dry density and LWD modulus in mold with moisture content for a typical soil type (Jibon et al., 2021)**

**Establishing Acceptance Criteria for LWD Tests**

Each state DOT should calibrate locally to find the acceptance criteria for $E_{field}/E_{target}$ (also known as modular ratio) for their local materials. A framework was proposed by Schwartz et al. (2017) to find the acceptable limits of modular ratio. If a material's modular ratio is outside of the considerable range, that material needs to be rejected immediately. The acceptable modular ratio value also depends on different types of LWDs. For example, for the Zorn LWD, $E_{field}/E_{target} = 1$ was taken as the limiting value to differentiate well-compacted layers from less compacted layers. The corresponding threshold limits were approximately 0.8 for the Olson and 0.5 for the Dynatest. Schwartz et al. (2017) recommended the following steps to establish threshold values for $E_{field}/E_{target}$

(a) Perform LWD testing in the laboratory (in Proctor molds) to determine the $E_{target}$ value.

(b) After a few passes of the compactor measure $E_{field}$, before achieving MDD in the field.

(c) Measure $E_{field}$ after achieving MDD.

(d) Determine the $E_{field}$ /$E_{target}$ for every condition.

(e) Estimate the limit which identifies the acceptance criteria.

If the modulus ratio of the several number of test section is out of the range, the materials need to be replaced with other materials. The Percentage Within Limit (PWL) methodology can be implemented to establish acceptance criteria based on quality index Q. This quality index can be calculated using the following equation.

$$Q = \frac{\bar{X} - LSL}{s} \qquad (3)$$

Where LSL is the lower specification limit, s is the sample standard deviation for the lot/sublot and $\bar{X}$ is the sample mean for the lot/sublot. If the estimated PWL is less than the minimum number required by the agency, an appropriate remedial measure (like removal and replacement) should be adopted for the lots.

**Required Sampling Frequency for LWD Tests**

Before a given agency can develop and adopt an LWD-based compaction control specification, it is important to decide on the minimum number of LWD tests that need to be performed for a given project. Schwartz et al. (2017) proposed a methodology to decide on the minimum number of LWD tests that should be performed. They calculated the allowable error and compared with corresponding error in the NDG data. The minimum required sample size was calculated based on a t-distribution parameter as shown in the following equation:

$$n = \left(\frac{t \times s}{e}\right)^2 \text{-----} (4)$$

Where s is the sample standard deviation, t is the value from a standard Student's distribution table for each confidence level and degree of freedom, and e is the acceptable error.

**ASTM Standards Concerning LWD Testing of Soils and Aggregates**

Currently, the following two ASTM standards available concerning LWD testing on aggregates and soils:

(1) ASTM E2583-07: "*Standard Test Method for Measuring Deflection with a Light Weight Deflectometer*." This test method measures the deflection of a paved or unpaved surface with a Light Weight Deflectometer. A load cell shall be used to measure the load being applied upon each drop of the falling mass. This specification is often called a specification for a geophone-type LWD. The Olson and Dynatest LWD types have load cells to directly measure the impact load magnitudes and satisfy the ASTM E2583-07 requirements.

(2) ASTM E2835-11: "Standard Test Method for Measuring Deflection using a Portable Impulse Plate Load Test Device." This method measures the deflection of a load plate resting on a soil or aggregate layer. A velocity transducer or accelerometers is used to measure the vertical plate deflection at the center of the loading plate. As this specification does not require the device to directly measure the load being applied, the falling weight is dropped from pre-calibrated fixed heights to standardize the amount of load being applied from one test to another. The Zorn meets the ASTM 2835-11 requirements (No load-cell). Note that most of the states in the US

that have implemented LWD testing into practice, primarily follow this test method; the Zorn LWD is the device that is most commonly used by state DOTs.

The two specifications vary in several important aspects. For example, ASTM E2583 specifies that the load pulse should have a time of loading between 20 and 40 msecs. ASTM E2853, on the other hand, requires the load pulse to be between 10 and 30 msecs. It is important to note that even for the same peak load level, if the pulse durations are different, it is quite possible the surface deflections to be different because of the nature in which energy is transferred from the plate to the underlying layer. The two specifications also differ in terms of the required precision in the recorded data. ASTM E 2583 requires the precision of the deflection sensor to be within ± 2 μm (0.08 mils), whereas ASTM E 2853 requires the deflection sensor precision to be within ±40 μm (1.6 mils). Accordingly, a device meeting ASTM E 2853 can be as much as 20 times less precise than a device meeting ASTM E 2583 requirements. *These differences must be kept in mind while the two device types are being compared.*

**Available construction specifications Utilizing LWD Testing**

This section briefly summarizes currently available specifications used by state highway agencies like Department of Transportation (DOT) in the US concerning LWD testing on constructed soil and aggregate layers.

***Indiana DOT Specification***

The Indiana test method e.g. ITM No. 508-19 (www.in.gov/indot/div/mt/itm/itm.htm) describes how to use a LWD to calculate the permissible deflection of dense-graded aggregate layers. Additionally, this specification details how to conduct testing with a Dynamic Cone Penetrometer (DCP) to establish the type, pattern, and number of passes of the roller for the compaction of recycled materials. It is recommended to construct a control test section whose approximate dimensions are 100 feet by 20 feet, with a depth equal to the usual lift thickness. Before constructing the test section, the subgrade must be proof rolled in accordance with Indiana DOT guidelines. The test section's moisture content must be on the dry side and within 3% of the ideal moisture level.

Until there is longer any field indication of stiffness increase, it is necessary to aid compaction with repeated roller applications. At this point, the stiffness measurement has reached its greatest value and is regarded as peak stiffness. The following conditions should be met by the LWD device used for in-place modulus/stiffness measurement:10kg ± 0.1 kg falling weight with a 5kg ± 0.25 kg guide rod, lock pin and spring assembly. The drop height shall be fixed per manufacturer recommendations and should generate a maximum of 7.07 kN force. The loading plate should be composed of steel with a diameter of 300 mm and a thickness of 20 mm. An accelerometer should be fastened to the middle of the plate to measure the largest vertical deflection.

Zhao et al. (2018) carried out comprehensive in-situ LWD testing in Indiana and showed that whereas a wide area of compaction required at least 8 to 10 LWD tests, a small region only needed one or two. The LWD test findings' Coefficient of Variation (COV) ranged from 20% to 35%. A COV of 20% or less was minimal variance, a COV of 20% to 35% was considered to be typical variation, and a COV of more than 35% was considered to be excessive variation between test findings.

***Minnesota DOT Specification***

In order to support stiffness-based mechanistic pavement design, Embacher (2008) revealed that the Minnesota DOT (MnDOT) has been using LWDs for quality control of embankment and pavement foundation construction operations. The Zorn ZFG 2000 models are used by individual MnDOT districts for compaction quality control in accordance with the ASTM E2835-11 test standard. Development control strips are recommended by the Minnesota DOT requirements to determine the target LWD deflection values. For each type or source of soil, control strips (300 feet long by 32 feet wide; maximum thickness = 4 feet) must be constructed. At each testing site, a total of six LWD drops (three seating drops, then the average value from three measurement drops) are advised. Minimum of three locations at 25-ft. spacing should be considered for LWD testing between each compaction pass.

Once the target LWD modulus value has been established from the control strip testing, it is used as the benchmark to compare results from the actual pavement section against. The target modulus value determined during the control group testing should be met by at least 90% of the LWD-measured modulus values from the completed pavement segment. Reconstruction of the control strip is advised to restore the target modulus if the modulus determined by testing the actual pavement section exceeds 120% of the target modulus. Additionally, MnDOT suggests that the LWD devices be recalibrated once a year or every 10,000 readings. By examining the repeatability of deflection readings under distinct drops, the field may carry out on-site equipment verification. This is done on a verification pad placed on top of a concrete floor by executing three seated drops and then nine testing drops. Less than 0.04 mm should separate the maximum and minimum deflection values derived from the nine load pulses. Recalibrating the LWD should be taken into consideration if this requirement is not met.

***Nebraska DOT Specification***

Nebraska DOT standard test method designated as NDT T2835, titled "Deflection Measurement of Soils using a Light Weight Deflectometer (LWD)", is a modified version of the ASTM 2835 specification, and outlines the procedure for LWD testing on soils. The requirements for LWD are as follows: (1) 10 kg falling weight with 720 mm drop height; (2) guide rod to allow free fall of the weight; (3) a steel spring buffer system for transmitting the load to plate resting on the layer being tested; and (4) a 300-mm diameter loading plate for distributing the load imparted from the falling weight to the layer being tested. Repeatability of the LWD test results are required to be checked for newly purchased units, after a particular unit has gone through recalibration, after observing questionable test results, as well as after 10,000 test measurements. The verification is carried out by performing nine LWD drops on a test pad having a bare, sound concrete surface with a minimum thickness of 6 inches. The difference between the maximum and minimum deflection values recorded under these nine drops shall be less than 0.04 mm. The difference between mean deflection value calculated from the nine drops and the deflection recorded under an individual drop shall be less than 0.02 mm. If these criteria are not met, the LWD units is required to be submitted for recalibration.

For on-site measurements, it is recommended that LWD testing should be performed immediately after compaction when air temperature is in the range of 32 to 120 degrees Fahrenheit. Before LWD testing is performed at a particular location, a test area at least 1.5 times larger than the diameter of the loading plate should be prepared, and a smooth and level spot be prepared by removing any disturbed or additional materials from the surface. After preparation of test spot, six falling weight drops are executed, and the average deflection from the last three drops is recorded. The specification requires the tester to move approximately 1.5 ft. longitudinally from a particular test spot if any of the following conditions occur during testing: (1) sliding of load plate; (2) failing to catch the falling weight after rebound; or (3) the weight is dropped from a height that is different from the calibrated height. Cho et al. (2011) reported that the Nebraska DOT was considering the quantification and acceptance of soil compaction based on LWD-measured deflection or modulus values.

***Wisconsin DOT Study for Specification Development***

Titi (2012) evaluated the quality of the constructed foundation layers before recommending a procedure for LWD-based compaction control to the Wisconsin DOT. In-place density measurements utilizing the sand cone technique, LWD testing, and DCP testing made up the field-testing phase. LWD testing were carried out in accordance with the ASTM E 2583 test methodology on a control section that was 300 feet long and the same width as the base layer. To conduct LWD testing, 10 distinct test locations per 100 feet of the control section were chosen. The allowed deflection value was calculated using the average deflection value from 10 LWD testing. The study recommended that for QC/QA in the field, contractors should perform 10 LWD tests for each 1,000 ton of compacted aggregate with minimum of five tests per day. The average deflection from all LWD tests should be equal to or less than the maximum allowable deflection obtained from LWD tests on control section.

### Studies on open graded aggregate Layers

Smith (2017) took an initiative to conduct LWD testing on open graded base layers used in permeable interlocking concrete pavements. Compaction specification based on specific number of roller passes or minimum of 95% Proctor density do not work for open graded aggregates. Open-graded aggregates for permeable interlocking concrete pavement (PICP) have no fines (≤ 2% passing the No. 200 sieve). Porosities should be at least 30% for water storage (Smith, 2017). Jointing, bedding, base and subbase aggregates used in vehicular PICP applications should be crushed with minimum 90% fractured faces and a maximum LA abrasion values of < 40.

Performing LWD testing on these aggregates, Smith et al. (2018) observed that the deflection results were significantly affected by the depth of the subbase layer. Higher deflections were found for 300-mm thick ASTM No. 2 subbase layers compared to those where a No 57 base was constructed over the subbase.

| Havre d' Grace, Maryland | ASTM No. 2 subbase | ASTM No. 57 base |
|---|---|---|
| Test Locations | 61 | 44 |
| Subbase & Base Thickness | 300 to 600 mm | 100 mm |
| Average Deflection | 0.691 mm | 0.517 mm |
| Deflection Standard Deviation | 0.209 mm | 0.109 mm |
| Deflection Coefficient of Variance | 29.9% | 20.9% |

(a) (b)

**Figure 7: Testing at different locations at Maryland (a) & the measured surface deflection (b) (Smith et al., 2018)**

They tested with the LWD at different location, Figure 7 shows the testing done by Smith et.al at Maryland. From the figure it is observed that with increment of the aggregate size the variability increases. It was also found that the LWD-measured deflection values decreased substantially by changing the thickness of subbase layer from 300 to 600 mm. They also investigated the effect of number of drops on the LWD-measured deflections on open-graded aggregate base courses. They observed that increasing the number of drops beyond 6 further compacted the aggregate layer: drops 4 to 6 had a range of 1.362 mm deflection whereas it reduced to 0.051 mm deflection during drop 16 to 18. Note that, this test section had only a 150-mm thick subbase layer, whereas a 300-mm thick subbase layer was required to avoid the influence of soil subgrade. Smith et al. (2018) suggested to conduct further research to find the optimal number of LWD drops, the effect of saturated soil subgrade on deflection results, and also the effect of geotextile presence at the subgrade interface on the LWD-measured deflections. Li et al. (2014) found that wet conditions lead to softer subgrade conditions and higher shear stress/strength ratios on top of subgrade; accordingly, thicker subbase layers need to be constructed.

As already discussed, the railroad ballast layer is in many ways similar to open-graded base courses and presents some challenges as far as LWD testing is concerned. It is interesting to note that during the early days of LWD development in Germany in the 1980s, it was used to measure the "dynamic elastic modulus" of open graded railroad ballast along with soils and roadway base coarse aggregates. Zorn's LWD user manual lists modulus acceptance criteria for the formation layer in German railroads (Zorn 2011).

Tamrakar and Nazarian (2019) conducted LWD tests on fouled railroad ballast to characterize its permanent deformation and stiffness behavior. A container made of polyethylene pipe with 900 mm diameter, 700 mm height and 25 mm thickness were considered in this study to simulate ballast layer and subgrade in a container. The material profile consists of 100 mm pea gravel at bottom, 300 mm thick subgrade in the middle and 300 mm thick ballast layer on top. A Zorn LWD with 100 mm diameter plate was used to perform LWD tests on top of the ballast layer following the ASTM-recommended procedure.

Figure 8a shows a photograph of LWD testing on top of the ballast layer built inside the cylindrical container; Figure 8b shows typical deflection time histories obtained during the testing. Tamrakar and Nazarian (2019) reported that the LWD measurements were significantly affected by the presence of the underlying soft subgrade layer. This led to lower modulus values reported by the LWD compared to those reported by using the Portable Seismic Pavement Analyzer (PSPA). This clearly emphasizes the importance of considering the depth of influence during LWD testing, if meaningful inferences are to be drawn regarding modulus of the layer being tested.

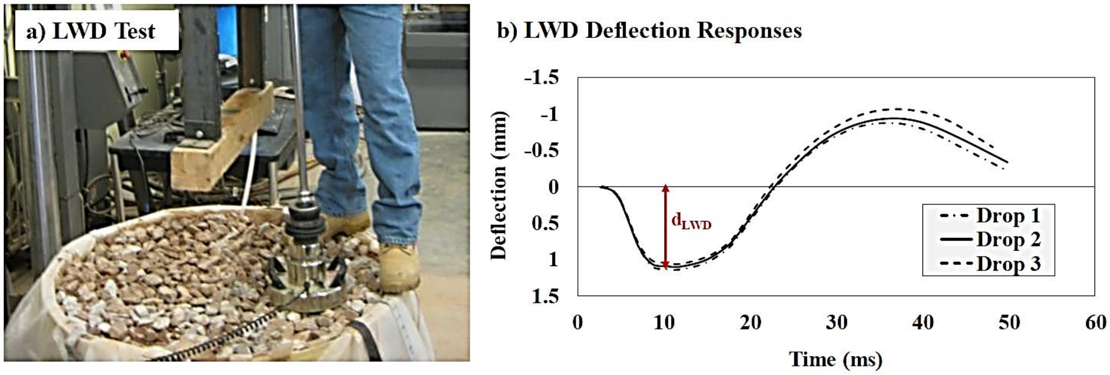



**Figure 8. (a) Photograph showing LWD testing on top of the ballast layer in the lab; (b) Typical Deflection time history obtained during the LWD testing (Tamrakar and Nazarian, 2019)**

Another device that has been used to assess the in-place modulus of constructed ballast layers, is the PANDA, a Variable Energy Dynamic Penetrometer device designed and manufactured by SolSolution in France. Several researchers have reported that both the PANDA device as well as the LWD can be used to evaluate the quality of track-bed ballast layer (Benz, 2009; Staatsministerium, 2012; Shafiee et al., 2011; Tompai, 2008 and Woodward et al., 2014). Lamas-Lopez (2016) conducted LWD tests on ballast layer to validate modulus estimated from PANDA tests and found that the values recorded by the two devices were correlated.

Choi et al. (2018) studied field compaction of open-graded aggregate materials based on Plate loading tests. Their test matrix comprised of five different aggregate types with a 10-ton vibratory roller applying up to 12 passes. They studied the mechanical behavior of aggregates after every 2 passes. Based on their study, the strain modulus at the first loading seemed to provide more consistent results with respect to aggregate types and level of compaction compared to other stiffness measures from plate load tests. They also concluded that the minimum requirement of four (4) roller passes recommended by the Interlocking Concrete Pavement Institute (ICPI) and the American Society of Civil Engineers (ASCE) is sufficient. Large particles exhibited greater modulus at the lowest compaction level than smaller particles at the maximum compaction level in several situations. They also concluded that material selection plays a critical role in ensuring adequate performance as increased amount of compaction cannot compensate for poor material selection.

**Summary**

This chapter presented findings from an extensive review of published literature carried out focusing on modulus/ deflection-based compaction quality control methods for soil and aggregate layer. The Light Weight Deflectometer (LWD) was selected as the primary measurement device of interest during this effort. First, the basic principles of LWD operation were discussed, followed by different material or site-related factors that affect LWD measurements significantly.

The most challenging task in front of deflection-based compaction quality control specification development efforts was identified to be the establishment of a target modulus or deflection value. Establishing a target modulus or deflection value requires either extensive laboratory characterization of soils and aggregates under different moisture conditions and stress states. Implementing a modulus-based compaction protocol is particularly challenging because there is a significant difference between laboratory-measured resilient modulus values and modulus values measured in the field using LWDs.

A recently completed study at the University of Maryland attempted to determine the target modulus for LWD measurements in the field by performing LWD tests on soil and aggregate samples inside Proctor molds. Through extensive laboratory and field testing, the researchers observed that target modulus values established through LWD testing in Proctor molds can be used as reference values for compaction control in the field with reasonable success. Test sections that satisfied density-based compaction thresholds values, also satisfied the modulus-based threshold values established through LWD testing on Proctor molds. Similarly, under-compacted sections failed to meet both the density- as well as modulus-based criteria.

Finally, this literature review summarized some of the state DOT specifications currently available concerning the use of LWDs for compaction quality control of soils and aggregates. However, it should be noted that all such specifications are valid for fine-graded soils or dense-graded aggregate base/subbase courses only. No specifications are currently available governing the use of LWDs for compaction quality control of open-graded aggregate bases such as the ones used underneath permeable concrete pavements. There is a clear need for research in this area, and development of new modulus-or deflection-based compaction quality control approaches using LWDs will significantly improve the design and construction practices for these open-graded base courses.

CHAPTER III

MANUSCRIPT ONE - COMPACTION STUDIES ON OPEN-GRADED AGGREGATES USING PORTABLE IMPULSE PLATE LOAD TEST DEVICES

## Introduction

Pavement unbound layers (base/subbase) are generally constructed using locally available aggregate materials to avoid material transportation costs. The degree of compaction has a major influence on the stability of these layers. Traditionally, dense-graded aggregates are used to construct base and subbase layers, which serve as one of the major load-bearing layers in flexible pavement. Dense-graded aggregate layers tend to store moisture for a given period of time, based on the amount of fines content. The shear strength of these layers may be substantially reduced because of the stored moisture, making them prone to severe permanent deformation or even shear failure. As a result, the drainage factor assigned to each layer has a significant impact on the pavement design thickness. Recurrent freeze-thaw cycles undermine the stability of a well-compacted base/subbase layer, whereas excessive moisture in a pavement unbound layer reduces

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This chapter includes results already reported in the following publication. Contribution of the coauthors is sincerely acknowledged:
Ratul Mondal, Md. Fazle Rabbi, David Smith, Debakanta Mishra, (2022). Compaction studies on open-graded aggregates using portable impulse plate load test devices, Construction and Building Materials, Volume 327, DOI: 10.1016/j.conbuildmat.2022.126876.

its load-carrying capability. For use in unbound granular pavement layers, open-graded aggregate materials have numerous benefits over their dense-graded counterparts. The low fines content, for example, results in better drainage characteristics making the layer much less susceptible to moisture-induced and freeze-thaw-related damage. Furthermore, open graded aggregate layers often have larger top-sizes, which contributes to increased shear strength. It is typically possible to construct these layers under mild to moderate weather (rain) conditions since the layer is not susceptible to moisture-induced strength reduction.

Despite their numerous benefits, long- and short-term performance of open-graded materials as base and subbase layers has not been investigated thoroughly. Limited number of research publications have focused on the performance of open-graded aggregate materials as base/subbase layers. One of the most likely explanations involves the lack of standard compaction and construction specifications for these materials. Open-graded aggregate materials present significant challenges when it comes to density-based compaction control. Although the compaction process is the same as that for dense-graded aggregate layers (vibratory compaction), large pores in the aggregate matrix make in-situ density measurements virtually impossible; conventional density verification techniques such as the nuclear density gauge are impractical. Setting a precise target during field compaction is quite challenging in such situations. Rather than attempting to satisfy any target performance criteria, the current practice is to compact these layers using recipe-based approaches. For example, some highway agency specifications require these layers to be compacted *"to the engineer's satisfaction"*. Obviously, such compaction specifications can be quite subjective, and require to be updated to facilitate the implementation of construction practices supporting mechanistic pavement design.

The primary objective of this research effort is to develop a deflection-based compaction control specification for open-graded aggregate base courses commonly used in permeable pavements. This is accomplished by studying the packing characteristics of open-graded aggregate materials under different compaction efforts. Multiple LWD units are being tried out to ensure the developed specification is device-agnostic. This study uses an integrated approach including extensive laboratory testing, and full-scale pavement testing. Further, the laboratory testing phase also involves testing at two different scales to evaluate how the behavior of open-graded materials can be affected by testing boundary conditions. Detailed findings from the laboratory testing effort are presented in this chapter, along with inferences regarding how these findings can be extended to LWD testing of these aggregates in the field.

**Material Selection**

As this study is focused on developing deflection-based compaction criteria for open-graded aggregate materials commonly used in the base/subbase course for permeable pavements, two commonly used aggregate materials were selected for use in laboratory testing as well as field construction. The two aggregate materials selected were: ASTM# 4 (nominal size of 19 to 37.5 mm) and ASTM# 57 (nominal size of 4.75 to 25 mm).

Figure **9** shows pictures of the representative materials. Figure 10 shows the particle size distributions for the two aggregate materials along with the corresponding gradation limits specified by ASTM.


(a) (b)

**Figure 9: Particles from (a) ASTM # 4, and (b) ASTM # 57 Stockpiles**

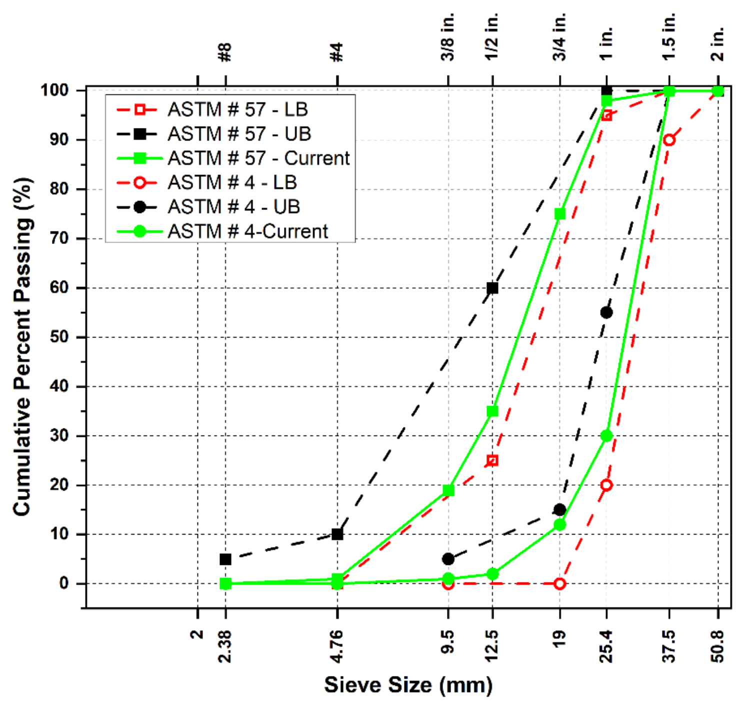



**Figure 10: Particle Size Distribution of the Two Aggregate Materials used in the Current Study along with the ASTM Specification Upper and Lower Bounds.**

## Development of Laboratory Test Matrix

### *Testing Philosophy*

Before details about the laboratory testing effort are presented, it is important to first explain the philosophy adopted during development of the laboratory test matrix. As already mentioned, the ultimate objective is to develop a deflection-based compaction criterion that can be implemented in the field for compaction control of open-graded aggregate layers. However, for this, it is important to first establish a reference value that would indicate whether a particular layer is well-compacted or not. For example, in case of conventional density-based compaction control of soils and dense-graded aggregates, the field-measured densities are measured against MDD values established in the laboratory using the standard or modified compaction effort. Similarly, for the LWD-based compaction control procedure developed by Schwartz et al. (2017), the reference value is first established by testing of the soils using LWD in conventional molds. These values are then used as the reference when checking layers compacted in the field. In the current study, if a deflection-based compaction control specification is to be developed, the first step should be to establish a reference/target value through laboratory testing.

However, the open-graded nature and the maximum size of these aggregates present certain challenges when it comes to laboratory testing. For example, conventional Proctor molds (101.6 mm or 152.4 mm in diameter) may not be adequate for testing these materials. Therefore, the modulus-based method developed by Schwartz et al. (2017) may not be directly applied in this case using conventional Proctor molds. If in some manner, the boundary effects due to the mold size can be eliminated, then it may be possible to extend this method to the open-graded aggregate materials.

The second challenge in this study involves the nature of compaction to be applied to these aggregate materials. In the field, these aggregate layers are compacted using vibratory rollers.

However, the question remains, what kind of compaction should be applied in the laboratory while establishing the reference compaction targets. For example, in conventional testing in Proctor molds, the material is compacted using the drop hammer method. Obviously, standard hammers used with Proctor molds will not be suitable for compacting open-graded aggregates. Therefore, other methods to compact the material need to be devised. The above-mentioned factors were carefully considered while developing the laboratory test matrix in this study.

***Small-Scale Lab Testing in Proctor Molds***

Considering the recent success with LWD testing in Proctor molds reported by Schwartz et al. (2017), the most logical first step was to try and replicate their approach with the material at hand. The two aggregate materials (ASTM # 4 and ASTM # 57) used in the current study have nominal sizes of 37.5 mm, and 25 mm, respectively. Standard rule of thumb in geotechnical engineering testing is that for any sample to be representative of the constituent material behavior, the sample diameter needs to be at least 5-6 times the maximum particle size. Therefore, based on this logic, any mold where these aggregates can be compacted, should be at least 225 mm in diameter for the ASTM # 4 aggregate, and 150 mm in diameter for the ASTM # 57 aggregate. Obviously, the 101.6-mm diameter Proctor mold will not be adequate for testing either of these materials. The 152.4-mm diameter Proctor mold may be adequate for testing the ASTM # 57 material, but not the ASTM # 4 material. To eliminate boundary effects, while still exploring the possibility of laboratory testing in a mold, the research team manufactured a custom-made mold with a diameter of 304.8 mm (12 in.), which was nothing but a scaled-up version of the standard 152.4-mm diameter Proctor mold. The researchers acknowledge that a mold of such dimensions may not be readily available to researchers/practitioners. However, if the concept of testing open-graded aggregate materials in the enlarged mold is found to be effective, contractors/engineers can easily procure such a mold to improve the overall state of practice in open-graded aggregate layer construction and compaction. Figure 11 shows a picture of the custom-made mold along with a conventional 152.4-mm diameter

Proctor mold for size comparison. In this manuscript, the large mold may be sometimes referred to as a Proctor mold. However, the authors are aware, Proctor's testing never involves a mold of such dimensions.

**Figure 11: Picture Showing the Custom-Made Mold along with a Conventional 152.4-mm Diameter Proctor mold.**

In total, three configurations were used for LWD testing inside Proctor molds. In the first configuration, the aggregate materials were tested inside a conventional 152.4-mm diameter Proctor mold (Mold Configuration 1 or MC-1). In the second configuration, the custom-made mold (304.8-mm diameter) was used, but the height of aggregate inside the mold was kept at the same level as that in a conventional mold (sample height = 116.5 mm). This configuration has been referred to as Mold Configuration 2 or MC-2 and was selected to simulate a case where the aggregate layer has been constructed as a very thin lift on top of a stiff base. In the third configuration, the custom-made mold was filled to its full height (292.1 mm). Figure 12 shows schematic representations of the three mold configurations used in this study for LWD testing.

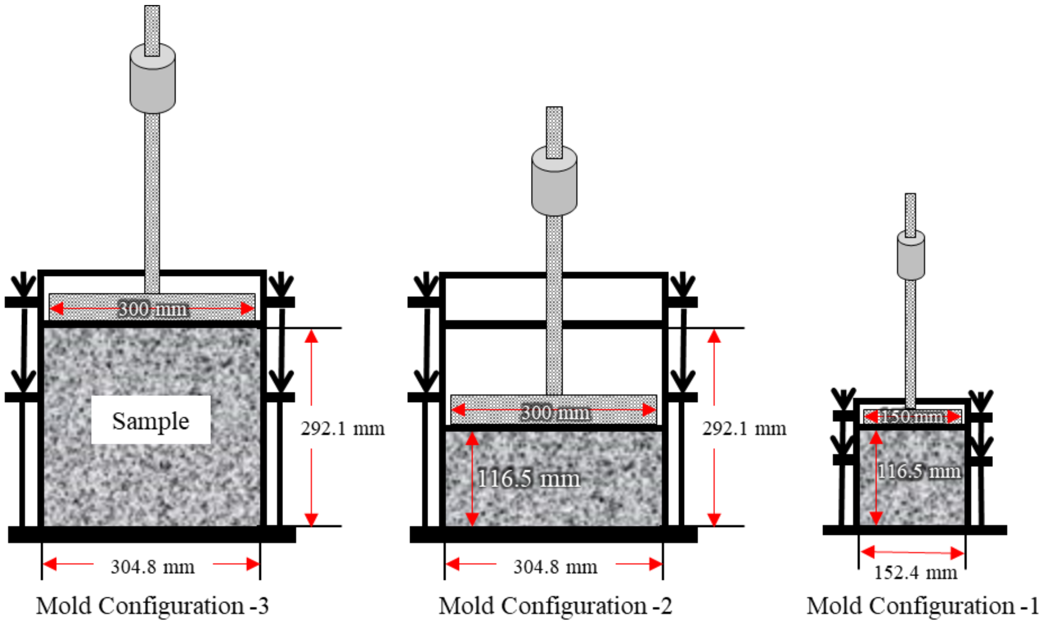
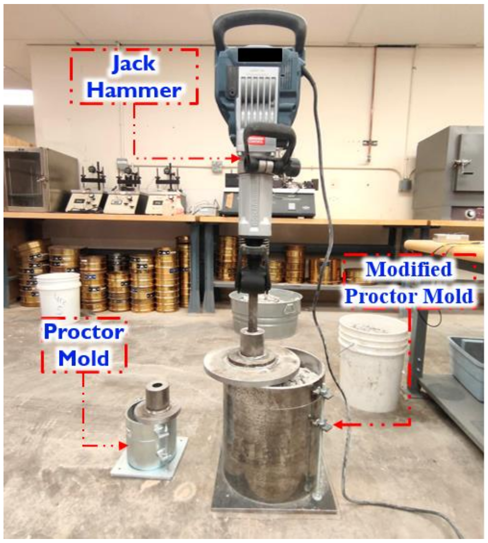



**Figure 12: Schematic Representation of Three different Mold Configurations used in the Current Study**

Variations in LWD-measured surface deflections were studied under the following three different modes of compaction: (1) drop-hammer type compaction using drops of the LWD mass, (2) vibratory and impact compaction using a jackhammer, and (3) constant vibratory compaction using a vibratory shake table. For the first method, different number of drops of the LWD weight were used to simulate different levels of compaction. This was particularly straight-forward for testing inside the mold as the LWD plate diameter is slightly less than the mold diameter and dropping the LWD weight could apply uniform compaction pressure over the entire specimen surface. The impact vibration was applied to the samples using a jackhammer on top of a custom-made top plate. Figure 13 shows a picture of the jackhammer, as well as the custom-made top plate. The third compaction mode used in this study involved the use of a vibratory shake table. Aggregates were tested in the three mold configurations using LWD after applying different compaction efforts using the three compaction approaches. The main objective was to study the "growth" in aggregate packing condition for each method, and later compare the results with intermediate-scale laboratory testing as well as field testing to evaluate which compaction and testing method combination can be used in the laboratory to establish reference compaction criteria for the open-graded aggregate materials. The specimen preparation followed recommendations provided by ASTM D75 and ASTM C702 to ensure representative sample selection, and to avoid segregation.



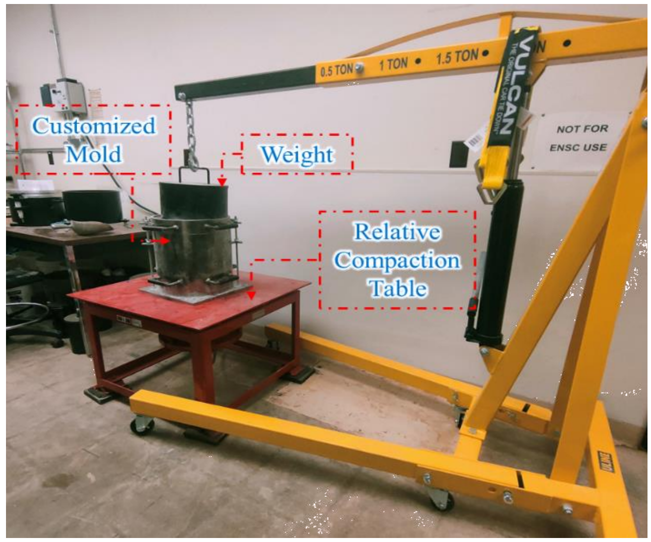
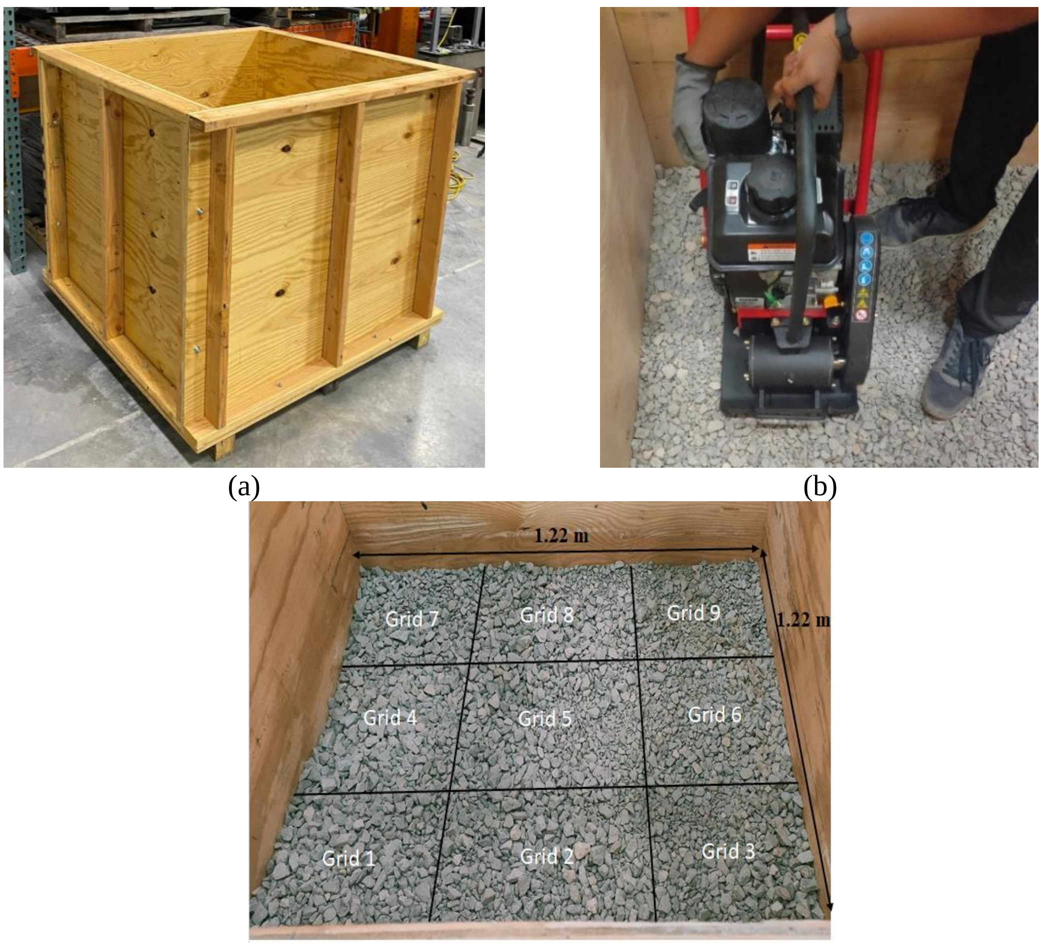




**Figure 13: Pictures Showing the Jackhammer (Left) and Vibratory Table (Right) Set Ups.**

***Intermediate-Scale Lab Testing in Wooden Box***

As already mentioned, LWD testing of open-graded aggregates in Proctor molds is not a trivial task even when a custom-made large-diameter mold is used. Due to the coarse nature of these aggregates, they are quite sensitive to boundary effects, and testing inside a confined mold could give significantly different results compared to those observed in the field, where the material is not subjected to such boundary effects. To establish some reference values to be targeted during field compaction, it is important to perform laboratory testing that is free from boundary effects. For this reason, a large wooden box of dimensions 1.22 m x 1.22 m x 1.22 m (4 ft. x 4 ft. x 4 ft.) was constructed in the laboratory for testing the aggregates under different compaction conditions. The bottom of the wooden box was continuously supported against the floor to eliminate excessive deformations during testing. In the first stage of box testing, no subgrade layer was used, and the aggregate material was directly poured into the box to construct layers of different thicknesses

(152.4-mm, 304.8-mm, and 381-mm thick layers). These layers were then tested using LWDs under different compaction efforts: uncompacted stage, as well as different passes of a commercially available portable vibratory plate compactor. Figure 14 shows pictures of the wooden box, the vibratory plate compactor, and a testing grid marked inside the box to compare the effect of testing position on LWD-measured results. In Figure 14(c), Grid 5 represents an ideal location that is free from boundary effects, and therefore, simulates a field-like condition. Results from the box testing have not been included in the current manuscript for the sake of brevity and will be included in next manuscript.




(a) (b)

(c)

**Figure 14: Pictures Showing (a) Wooden box; (b) Vibratory Plate Compactor; and (c) Grid Orientation Inside the Box to Mark the LWD Testing Spots**

## Results and Discussions

This section presents results from the small-scale laboratory tests results carried out for LWD testing of ASTM # 4 and ASTM # 57 aggregates under different compaction efforts. Two different LWD devices were used. The first one is manufactured by Olson Instruments (Olson LWD-1), whereas the second one is a Zorn ZFG-3000.

### *Results from Small-Scale Laboratory Testing in Proctor Molds*

#### *Identifying the Number of Seating Drops Required*

The first task was to determine how many "seating" drops are required to ensure adequate contact between the LWD plate and the open-graded aggregate layer surface. To study this aspect, both aggregate materials (ASTM #4 and ASTM #57) were compacted inside the standard and customized Proctor molds. The samples were tested with Olson LWD in uncompacted as well as compacted conditions. Five (5) samples were taken from the aggregate pile following standard sample collection protocols. In Figure 15, the LWD-measured surface deflection values and the surface stress levels are presented for the uncompacted ASTM #4 aggregate material inside MC-3. The surface deflection values have been plotted using solid lines, whereas dashed lines represent the surface stress levels. From this figure it is observed that, initially surface deflection value decreases rapidly with increasing number of drops. However, after 9-15 drops, the variation reduces, and approaches a "stable" state. Based on these results, the researchers selected nine (9) drops as a suitable number for seating drops during LWD testing. As the surface of the open graded aggregate layer is not smooth for uniform contact with the LWD plate, the energy from these "Seating Drops" is used to ensure adequate contact between the LWD plate and the layer surface. Once this initial "seating" is achieved, subsequent measurements of surface deflection are representative of the entire aggregate matrix, rather than reflecting rearrangement of the surface particles. Figure 15 also reveals that the surface deflection values vary from sample to sample which indicates different packing characteristics owing to the angularity and surface texture of these non-homogenous materials.

Close inspection of the surface stress levels in Figure 15 also indicates no significant "jumps" as the samples undergo particle rearrangement. The only significant change in surface stress level was observed for Drop # 15 in Sample C, which also led to a significantly lower surface deflection value. The authors are not sure what caused this significant jump for this particular point. No change in the stress level is observed with increasing number of drops. Nevertheless, the surface deflection decreases, indicating particle rearrangement into a 'denser' matrix.

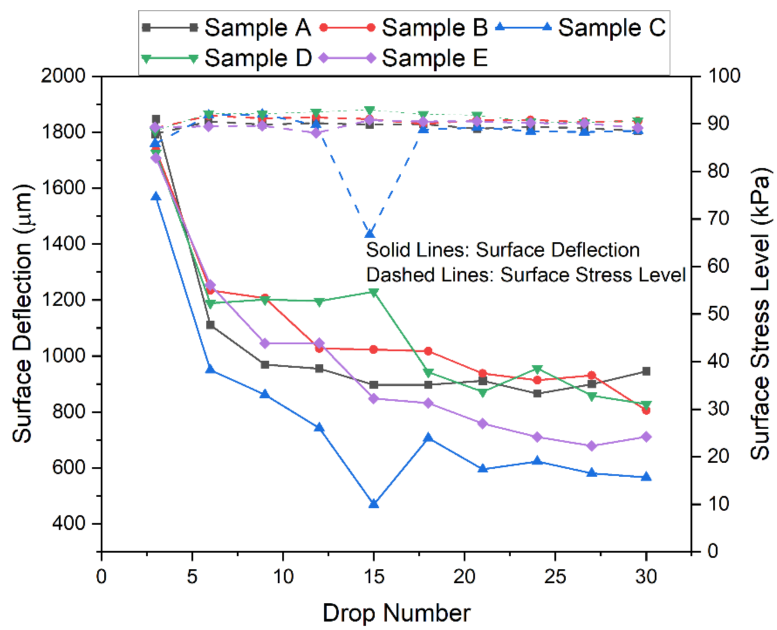



**Figure 15: LWD Test Results for ASTM#4 Aggregate in MC-3.**

*Impact Compaction (LWD drop)*

Despite its convenience and ease of operation, it is important to note that deflection or modulus measurements by LWDs can be significantly affected by slight variations in the testing procedure. For example, the results can vary noticeably if the user does not hold the device firmly against the surface of the layer being tested while dropping the weight. In the past, researchers have found that LWD devices from various manufacturers provide somewhat varied results due to design and operational differences [21-23]. In the current study, 30 drops using the Olson (standard 10 kg weight) LWD was applied on top of an uncompacted mass of ASTM #4 aggregate inside MC-3 followed by 30 standard drops of the Zorn LWD weight. This process was continued until 150 total drops were completed. The same process was repeated for the ASTM #57 aggregate. The measured surface deflection values from this test sequence are presented in Figure 16 & Figure 17. Figure 16 shows that after 30 drops the surface deflection values measured using the Olson and Zorn LWDs are quite similar for the ASTM #57 aggregate. At the same time, for ASTM #4 aggregate, the Zorn and Olson follow similar trends in calculating surface deflections up to 150 drops (Figure 17). Note that 30 LWD drops were applied to the ASTM #57 material to observe weather the measured result is device-agnostic. On the other hand, 150 LWD drops were applied to the ASTM #4 material to observe the impact of LWD drop on surface deflections, as well as to assess whether the results become device sensitive under increased number of drops. Figure 17 also includes the bulk density levels achieved by the samples during different number of LWD drops.

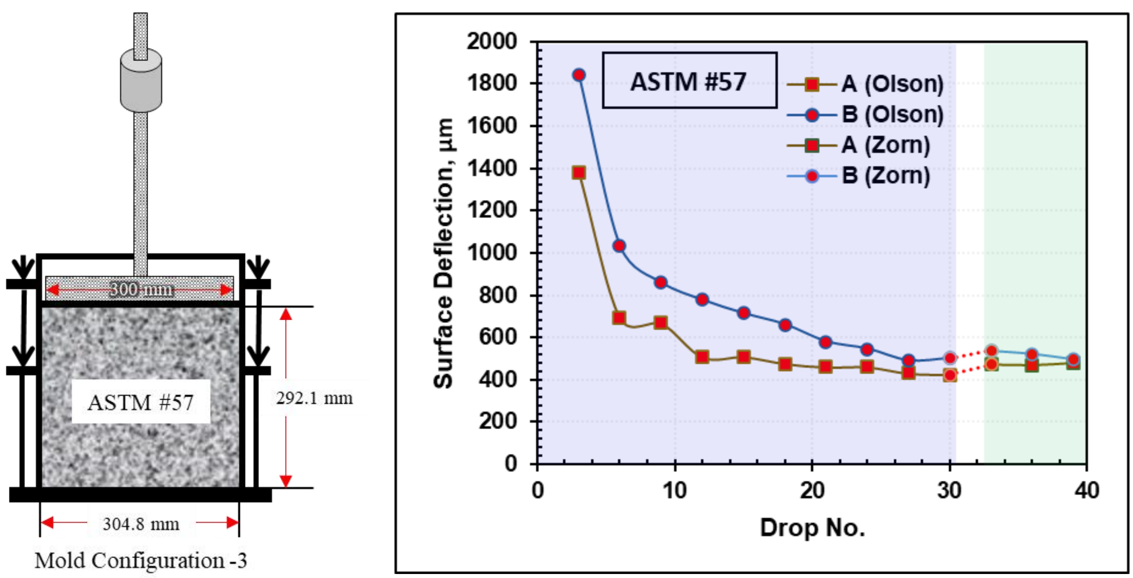



**Figure 16: Comparing the Results from Olson and Zorn LWDs for ASTM # 57 Aggregate**

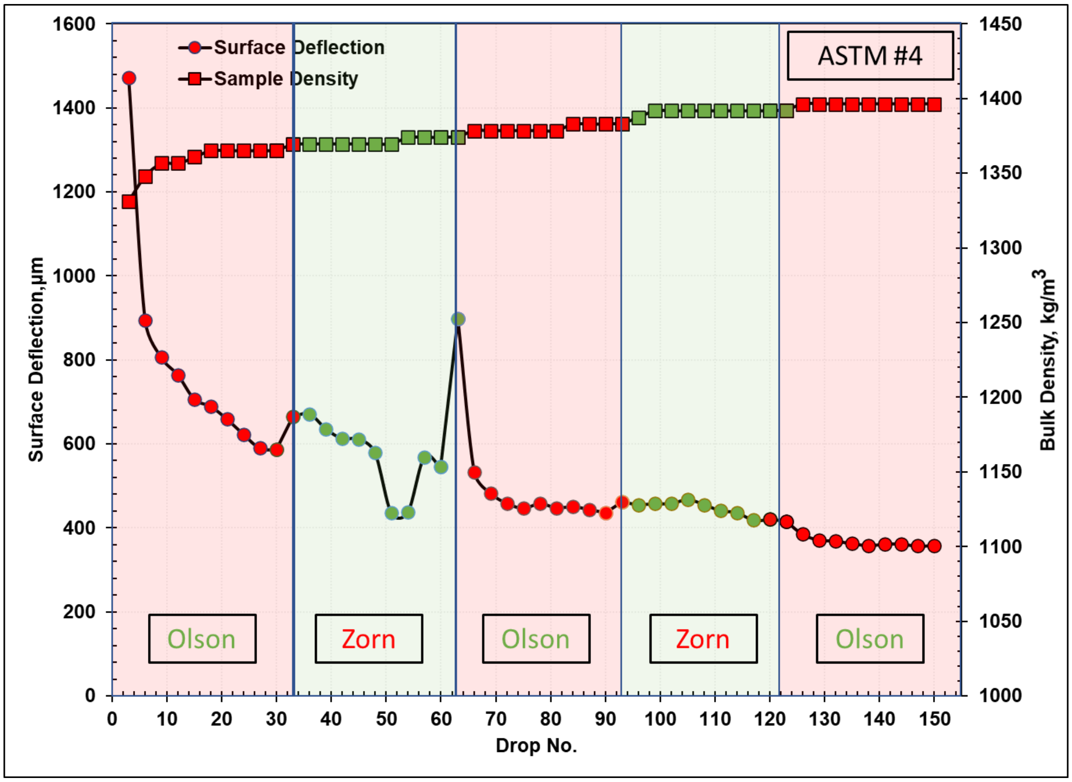



**Figure 17: Effect of Increasing Drop Numbers on the Surface Deflection and Density Values Measured for ASTM # 4 Aggregate Material using both Olson and Zorn LWDs**

Figure 17 reveals that initially the surface deflection values change rapidly with increasing number of LWD drops, but the curve gradually flattens. This is a direct indication of change in packing condition of the aggregate matrix. Starting from an uncompacted stage, the surface deflection value decreases rapidly as the aggregate packing condition improves. This conclusion can also be confirmed by the initial rapid increase in density. However, the rate of change in packing condition decreases with increasing number of drops, therefore flattening the deflection reduction and density increment curve. Except for 2-3 instances of sudden 'jumps' in the surface deflection values observed at approximately 60 drops, variations in the surface deflection values were somewhat limited for both devices. *Based on these results, it can be concluded that the use of either Zorn or Olson LWD would result in similar surface deflection values for open-graded aggregate materials when all other conditions such as level of compaction remain constant.*

*Vibratory and Impact Compaction using a Jackhammer*

The compaction response of the open-graded aggregates to the simultaneous vibratory and impact compaction (top-to-bottom compaction) has been studied in this section. This compaction effort was applied by using an electric jackhammer on top of a 300-mm diameter plate. Although the vibration frequency in a jackhammer is not constant, use of the jackhammer and a top plate simulates the compaction procedure commonly applied by researchers for preparing unbound aggregate samples for laboratory testing. Assuming the vibration amplitude and frequency are consistent with time, the specimens were compacted with the jackhammer for different durations. For example, the ASTM#4 aggregate in MC-3 was compacted by applying six (6) cycles of 5-second each, followed by two (2) cycles of 15-second each. LWD tests (9 consecutive drops) were performed after completion of each compaction cycle. The test results are presented in Figure 18. This figure also includes the density levels achieved by the sample under jackhammer vibration. Figure 18 illustrates that after completion of the first 5 seconds of compaction, the additional 55 seconds of compaction has minimal impact on surface deflection and density level achieved. It is important to note that even when significantly high 'jumps' in the surface deflection values are measured, the corresponding jump on the density value is not significantly. The sample shows a relatively rapid increase in density under the very initial stages of compaction, and the density levels remain more or less constant thereafter. This again proves that the change in surface deflection is primarily due to 'stabilization' and 'destabilization' of the aggregate matrix, and not because of sudden changes in the sample density. After 5-10 seconds of jackhammer compaction, the sample achieves a bulk density value of approximately 1450 kg/m$^3$, which is in the range of values typically expected for open-graded aggregate materials. This means five (5) seconds of jackhammer vibration is sufficient to reach maximum achievable compaction with this compaction method. Note that similar trends were observed for the LWD-measured modulus values. However, for the purpose of developing compaction control criteria using LWDs, it is recommended to use surface deflections. This is particularly important when using the Zorn LWD as it does not have the feature to directly measure the applied load levels. Therefore, modulus (or stiffness) calculations in the Zorn LWD are approximate in nature, based on prior calibration results. At this stage it is important to highlight that the Zorn LWD is commonly used by state DOTs because of its simplicity, and lower cost. Moreover, most LWD-based compaction specifications currently implemented by state DOTs rely on surface deflections, and not modulus values.

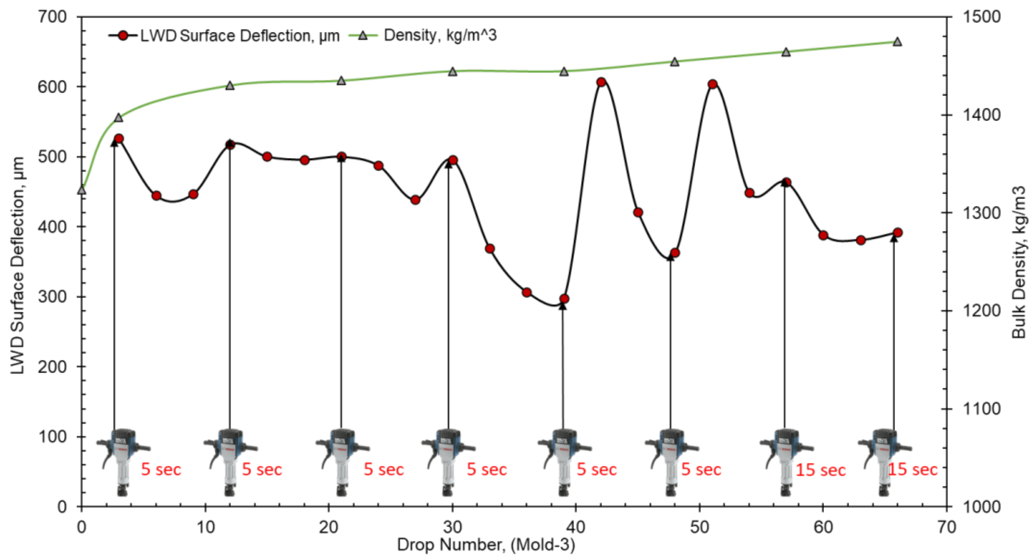



**Figure 18: Effect of Jackhammer Compaction Time on the Surface Deflection and Density Values Measured for ASTM # 4 Aggregate**

The results from extensive LWD tests after different levels (5, 10, and 15 second) of jackhammer compaction inside the three mold configurations for the two aggregate materials are presented in Figure 19 & Figure 20. Note that, the reported surface deflection and density values are the averages from 5 samples after nine (9) seating drops. From Figure 19 it is observed that the deflection values for ASTM# 4 & ASTM# 57 are similar in MC-1. Beyond 5 seconds of jackhammer compaction, there is an increase in the surface deflection values. This is counter-intuitive, as increased compaction effort should lead to improved packing of the aggregate matrix, which should in turn lead to lower surface deflections. From the achieved density levels, there is also a decrease in density after 10 seconds of vibration for the ASTM#4 material. For ASTM#57, on the other hand, no change in density was observed when the vibration time was increased from 5 seconds to 10 seconds. The primary reason for this is the size of the mold. In MC-1, the conventional 152.4-mm diameter Proctor mold is used. As this mold is too small for the aggregate materials being tested, the energy from the jackhammer compaction results in the destabilizing of the aggregate matrix, and with increased compaction effort, the LWD-measured surface deflections increase. *Therefore, the use of MC-1 was discontinued in the test matrix after this stage.*

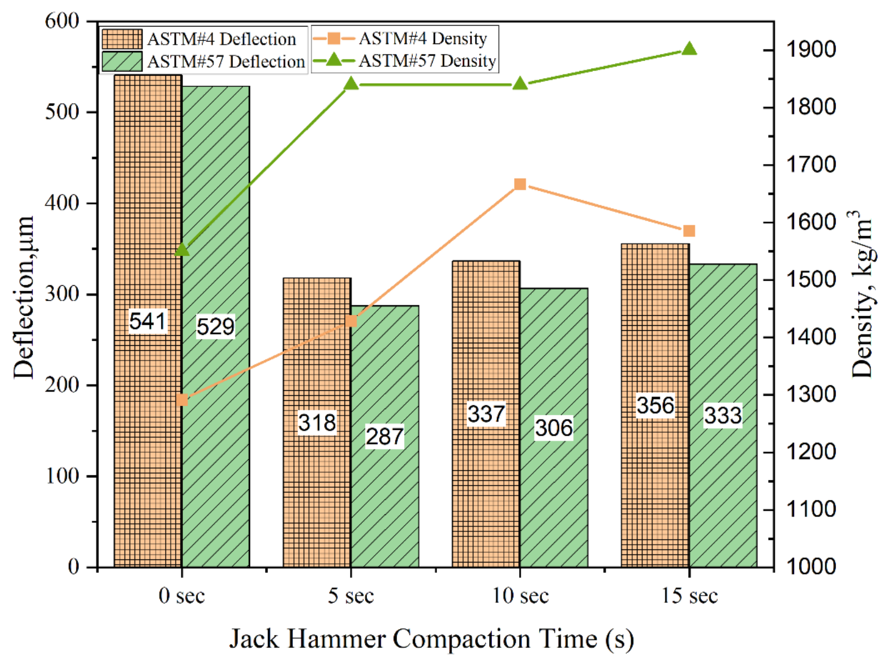
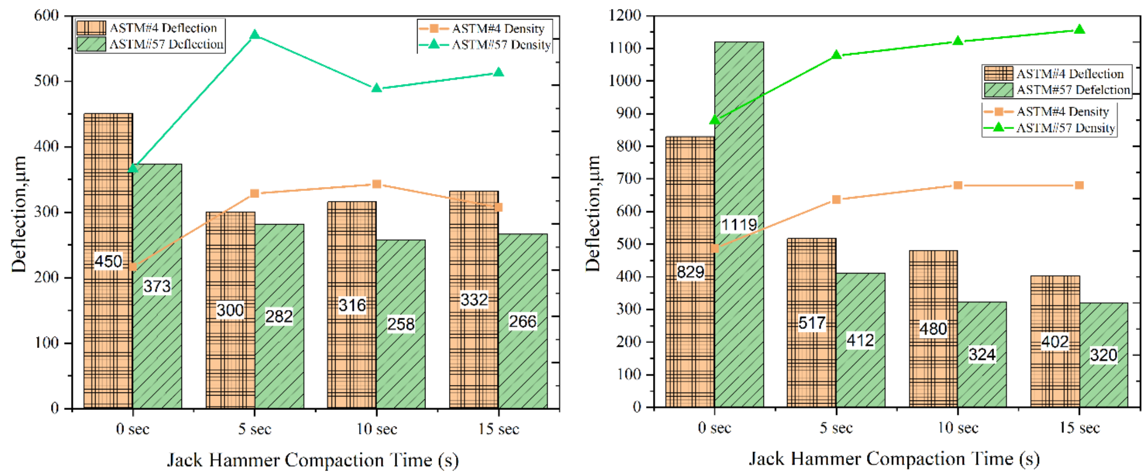



**Figure 19: LWD Test Results in MC-1 under Varying Jackhammer Compaction Times**

Figure 20 (a), presents similar results for MC-2 (mold diameter of 304.8 mm, but sample height of 116.5 mm). From the results, the surface deflections after compaction inside MC-2 for both ASTM #4 (300 to 332 µm) & ASTM #57 (258 to 282 µm) are close to the surface deflection values found inside MC-1. Also, no particular stabilization of the aggregate matrix was observed with increasing compaction time, just like in MC-1. This indicates that the 116.5 mm (4.6 in.) sample height is not sufficient for these larger particle-sized materials. When sample size is not sufficiently large compared to the particle size, larger materials can reorient under excessive compaction, destroying the packing. However, in case of MC-3 where the height of the sample is increased to 292.1 mm

(11.5 in), the recorded average surface deflections (Figure 20 (b)) are 402 to 517 μm for compacted ASTM #4 and 320 to 412 μm for the compacted ASTM #57 material. The surface deflections measured in MC-3 are noticeably greater than those in MC-1 and MC-2. It is important to note that some of the differences highlighted in Figures 12a and 12b may be difficult to appreciate (or replicate) in the field with a device that has lower precision requirements (for example, devices meeting ASTM E 2853 precision requirements, but not ASTM E 2583 precision requirements). Nevertheless, the current study used the Olson LWD for these tests, and with a precision level of ± 2 μm, these differences can be reliably detected.

From Figure 11 & 12, it can be observed that testing in MC-1 & MC-2 provides an unusual density trend with increased compaction. For ASTM#4 & ASTM#57 after 10 & 5 sec of vibration, there is a decrease in density level indicating the destruction of packing in both MC-1 & MC-2. This behavior can be attributed to the boundary effects imposed by the small mold sizes. As MC-1 & MC-2 represent significantly small boundaries for the particle sizes being used, after 5sec of jackhammer vibration the maximum packing is achieved. Additional compaction effort beyond 5 seconds does not contribute towards further densification of the matrix, rather leads to destabilization of the packing structure. This leads to a decrease in density and increase in measured surface deflections. Generally, with increasing compaction effort (often indicated by increased density), surface deflections should decrease; this trend is observed for MC-3. It should also be noted that for the ASTM # 4 material, 10 seconds of jackhammer compaction is required to stabilize the aggregate matrix, whereas the ASTM # 57 aggregate matrix stabilizes after only 5 seconds of jackhammer compaction. This indicates that the particle size has an influence on the compaction time required to stabilize the aggregate matrix when the vibration frequency is constant. The reader is cautioned not to take these compaction times as absolute values, rather as a comparison between how the two aggregate matrices behave under similar compaction efforts. In the field, the same two materials may require different compaction times under different roller vibration amplitude and frequencies. Nevertheless, the authors believe, the larger-sized ASTM # 4 material will require longer compaction time to achieve a stable matrix, compared to the smaller-sized ASTM # 57 material.




(a) (b)

**Figure 20: LWD Test Results under Varying Jackhammer Compaction Times in (a) MC-2 & (b) MC-3**

*Constant vibratory compaction (using a Relative Compaction Table)*

The third and final compaction method tried in this study was with a vibratory shake table. Testing in the vibratory shake table was carried out for MC-2 and MC-3 set-ups for both the aggregate materials. The results are presented in Figure 21. In this process, the mold with aggregate is placed on the vibratory table, and a heavy surcharge weight is placed on top of the top plate to ensure adequate compaction using a bottom-to-top mechanism. After different vibration times, the mold is removed from the table (without disturbing the aggregate), and LWD tests are conducted to measure the surface deflections. Three (3) sets of samples were collected from the two aggregate material stockpiles following standard sampling protocols. Testing was carried out using the Olson LWD only, under both uncompacted conditions as well as after the sample was subjected to vibratory compaction for different durations. As usual, nine seating drops were applied, and the surface deflections were measured by taking averages of three subsequent drops. As seen from Figure 21(a), for the compacted ASTM #4 material in MC-2, the average recorded surface deflection ranged between 589 µm to 631 µm, whereas the same value for ASTM #57 was between 571 µm to 581 µm. A gradual decrease in the surface deflections was observed for the ASTM # 4 material as the Vibration Time (VT) was increased from 0 to 10 seconds to 25 seconds. However, for the ASTM # 57 material, no significant decrease in the surface deflections was observed when the VT was increased from 10 seconds to 25 seconds.

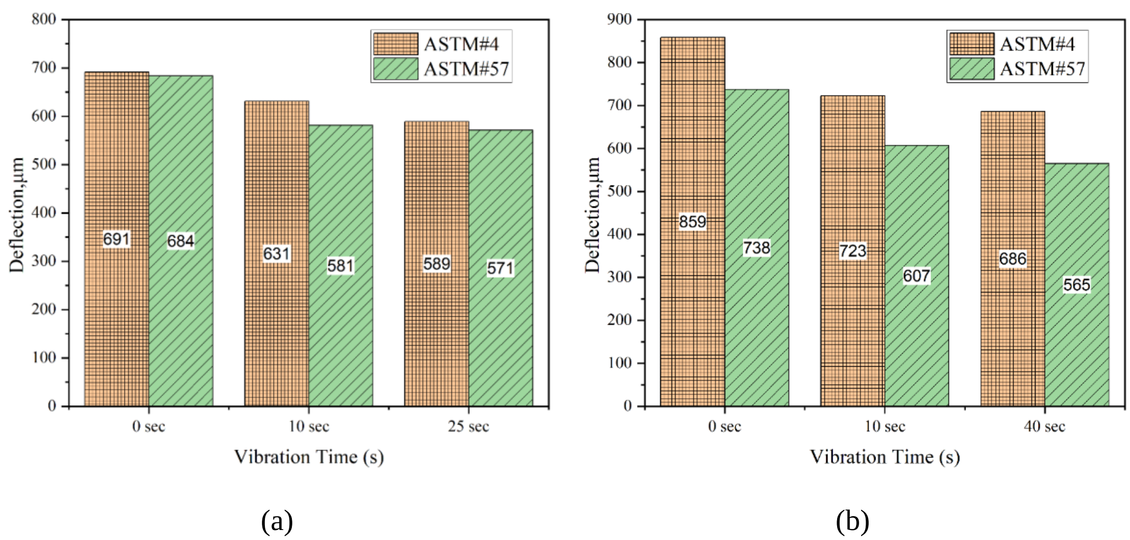



**Figure 21: LWD Test Results under Varying Vibration Times with the Shake Table in (a) MC-2 & (b) in MC-3**

In case of constant bottom-top vibration in MC-3 the average surface deflection was between 686 µm to 723 µm for compacted ASTM # 4 and 565 µm to 607 µm for compacted ASTM #57 (Figure 21(b)) for different durations of vibratory compaction. For both the ASTM # 4 and ASTM # 57 materials, the surface deflection decreased significantly with increasing time of vibratory compaction.

***Intermediate Scale Lab Testing in Wooden Box***

Results from LWD testing in the wooden box are presented in Figure 22. As shown in Figure 14 (c), the box filled with aggregate (ASTM#57) was divided into 9 grids for the purpose of LWD testing. From this figure, Grid-5 is near the middle of the box, and is away from the box boundaries; accordingly, LWD testing at Grid-5 should not be affected by presence of the box boundaries and should resemble testing on full-scale pavement section. With this hypothesis, LWD tests were performed in the wooden box on the ASTM#57 aggregate material with three different layer thicknesses (152.4 mm, 304.8 mm, and 381 mm). In each case, the aggregate layers were compacted by applying different compaction efforts using a vibratory plate compactor. First, a 152.4-mm thick aggregate layer was constructed, and LWD tests were conducted at three different stages of compaction: (1) No compaction; (2) One pass of the vibratory plate compactor, and (3) two passes of the vibratory plate compactor. Once LWD testing for each compaction effort on the 152.4-mm thick layer was compacted, another layer of aggregate was placed to get the total thickness up to 304.8 mm. In other words, the bottom 152.4-mm thick layer was compacted before additional aggregates were placed. Once a total thickness of 304.8 mm was achieved, LWD tests were again conducted corresponding to 0, 1, 2, and 3 passes of the vibratory plate compactor on the top 152.4-mm thick layer. Finally, a third layer of aggregates was placed, and LWD tests were conducted corresponding to 0, 1, 2, and 3 passes of the vibratory plate compactor on the top 76.2-mm thick aggregate layer. For each compaction effort, five (5) LWD tests were performed. The surface deflections presented in Figure 22 are the average values from three consecutive drops after six (6) seating drops were applied.

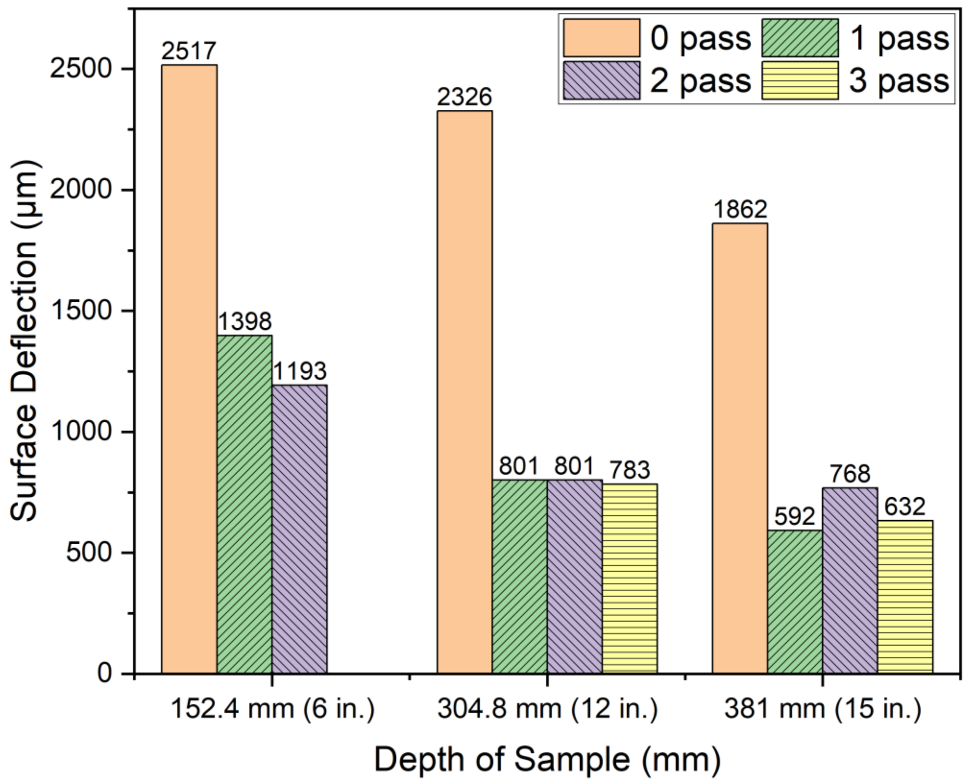



**Figure 22: LWD Test Results in Wooden Box for ASTM #57 Aggregate Material (Vibratory Plate Compaction)**

From Figure 22, it is observed that surface deflection values decrease significantly after one (1) pass of the vibratory plate compactor. When the number of passes increases from 1 to 2, the surface deflection values decrease for the 152.4-mm thick layer. However, no noticeably reduction in surface deflection is observed between 1 to 2 passes for the 304.8-mm thick layer. In fact, for the 381-mm thick layer, the surface deflection increased moving from one to two passes of the vibratory plate compactor. In this case, a 'destabilization' of the compacted matrix was observed when more than one pass was applied. The surface deflection after three (3) passes was still higher than that after one (1) pass. Based on the results presented in Figure 14, it is evident that the LWD-measured surface deflection values are significantly affected by the level of compaction of the underlying layers. Once the bottom 152.4-mm thick layer is compacted, the second 152.4-mm thick layer achieves optimum compaction even after a single pass of the vibratory plate compactor. When an additional 76.2 mm of aggregate is placed, that layer achieves optimum compaction after just one pass of the compactor. When additional compaction effort is applied, the aggregate matrix gets 'destabilized'.

***Comparison between Small- and Intermediate-Scale Lab Test Results***

This section compares the results obtained from the small- and intermediate-scale laboratory tests, in an effort to make inferences that can be subsequently verified during full-scale testing. As already discussed in the manuscript, LWD testing in molds was conducted on both aggregate materials (ASTM # 4 and ASTM # 57). However, till date, the box test has only been conducted on the ASTM # 57 material. Figure 23 shows the reduction in surface deflection compared to an uncompacted stage, under different compaction and testing conditions.

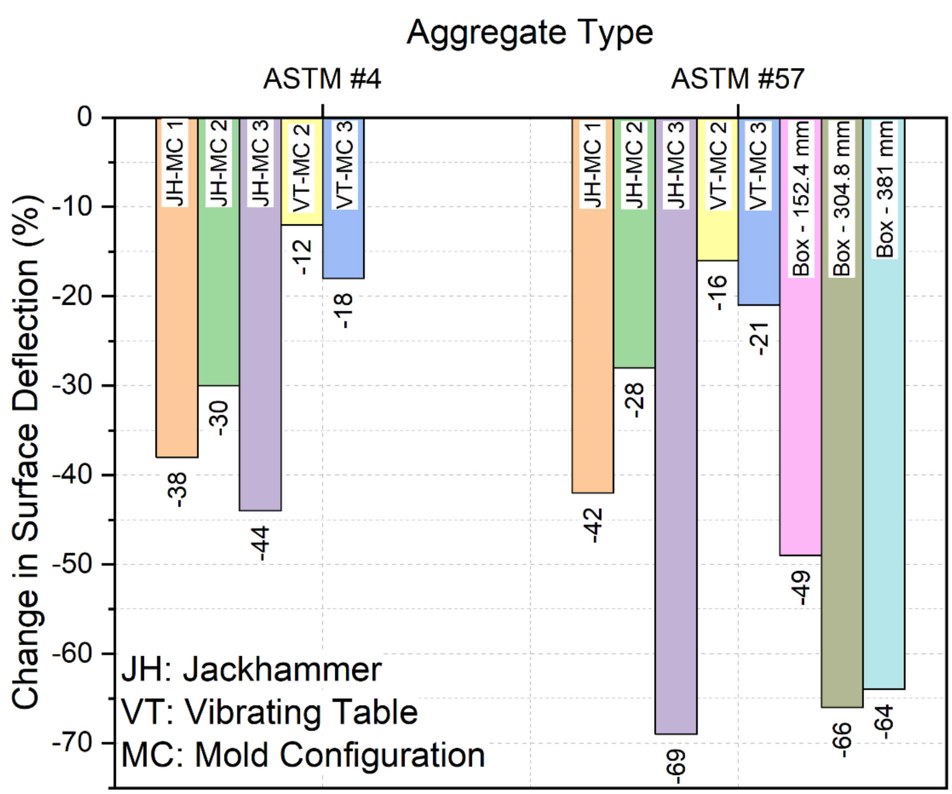



**Figure 23: Comparison between Mold and Box Test Results: Change in Percent Surface Deflection Compared to an Uncompacted State**

From Figure 23, for compaction efforts, the reduction in surface deflection compared to an uncompacted state was greater for ASTM # 57 compared to ASTM # 4. In other words, the relatively smaller ASTM # 57 achieved better packing under compaction compared to the coarser ASTM # 4. This justifies why ASTM # 57 is often used as a capping layer above ASTM # 4 in permeable pavement applications. For both aggregate materials, the reduction in surface deflection was lowest under vibrating table (VT) compaction. Jackhammer (JH) compaction in Mold Configuration 3 (MC-3) resulted in the best packing configuration for both aggregate materials. Comparing the box and mold test results for ASTM # 57 leads to another interesting observation. For JH compaction in MC-3, the reduction in surface deflection compared to an uncompacted state was 69%, which is very close to the value obtained during the box test (66%). This indicates that JH compaction in MC-3 and vibratory plate compaction in the box can lead to similar packing of the aggregate matrix. This also indicates that LWD testing in the scaled Proctor mold (305.4 mm diameter) for ASTM # 57 is capable of producing results that are similar to larger scale tests. This observation is yet to be verified for the ASTM # 4 material. Finally, no significant difference in the surface deflection was observed between 305.4-mm and 381-mm thick aggregate layers in the wooden box.

**Summary & Conclusions**

This manuscript presented findings focusing on the development of a deflection-based compaction control specification for open-graded aggregate base/subbase courses. The Light Weight Deflectometer (LWD) was used as the device of choice for this purpose. Due to the non-homogeneous nature of these aggregates, getting consistent results from LWD testing can be challenging. Currently, there is no established protocol for LWD testing on these materials. For example, the number of drops to ensure adequate “seating” of the LWD plate on the aggregate surface is still unknown. The current study adopted an integrated approach involving laboratory testing and field testing to develop the compaction control protocol. Two different aggregate materials were used in this study. LWD testing was conducted using two different devices, manufactured by Olson and Zorn, respectively. The compaction control specification being developed should be device-agnostic.

The first part of the laboratory test matrix, reported in this manuscript, included LWD testing of the two aggregates materials in cylindrical molds. Three different mold combinations were used for the testing, including a custom-designed mold of 304.8 mm diameter and 292.1 mm height. Three different compaction methods were used, and LWD tests were conducted in each case under different compaction efforts. Major findings from the first part of the laboratory testing effort are as follows:

1. There was no significant difference between the results produced by the Olson vs. Zorn LWDs under the same compaction and testing conditions

2. The 152.4-mm diameter mold was found to be inadequate for testing of open-graded aggregate materials

3. Even for the large (304.8-mm diameter) mold, when the specimen height was limited to 116.5 mm to simulate a thin layer, stabilization of the aggregate matrix could not be achieved through impact or vibratory compaction.

4. For the open-graded aggregate materials, nine (9) drops of the LWD weight were found to be adequate to ensure “seating” of the plate on the aggregate surface. Subsequent tests in this study have utilized nine (9) drops to provide seating before surface deflection data is collected.

5. When the sample is compacted using a jackhammer, five (5) seconds of compaction worked well for both aggregate materials.

6. As compaction effort was increased, the relatively smaller ASTM # 57 aggregate achieved better packing compared to the coarser ASTM # 4 aggregate.

7. Excessive compaction did not improve the packing condition in either aggregate material. In fact, the aggregate matrix for the coarser ASTM # 4 was ‘destabilized’ under excessive compaction.

8. Customized 304.8 mm diameter mold (full depth) with jackhammer compaction represents best compaction scenario with LWD testing in box.

# CHAPTER IV

# MANUSCRIPT TWO - USE OF PORTABLE IMPULSE PLATE LOAD TESTING DEVICES IN THE COMPACTION STUDY OF OPEN GRADED AGGREGATE THROUGH LABORATORY AND FIELD EVALUATION

## Introduction

Pavement unbound layers offer foundation support during the development of the upper layers of the pavement and give the pavement structure strength and stability under vehicular loads. Open graded aggregate materials are usually being used for unbound aggregate layer. These types of materials are popular for the applicability in moderate weather specially in rain. Water can easily drain out from the layer due to the presence of large void. The load bearing capacity can be significantly affected by the presence of moisture due to the reduction of shear strength.

In one hand, presence of large void is providing benefit to the open graded aggregate materials in terms of moisture susceptibility. On the other hand, absence of fine particle and coarse nature of this aggregate makes the compaction of these materials extremely challenging. The compaction

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This chapter includes results already reported in the following publication. Contribution of the coauthors is sincerely acknowledged:
Ratul Mondal, Md. Fazle Rabbi, David Smith, Debakanta Mishra, (Under Submission). Use of Portable Impulse Plate Load Testing Devices in the Compaction Study of Open Graded Aggregate through Laboratory and Field Evaluation, Transportation Geotechnics Journal.

procedure in the field for these materials is quite similar to the dense graded aggregate. Usually, vibratory roller compaction is done to compact the open graded aggregate material. But when it comes with the question of quality control of the compaction, there is no specific guideline or specification for these materials. Density based approach like nuclear density is not practical again to the presence of large void. Currently, the practice is to compact based on recipe-based approach. For example, some agencies might consider the compaction level should meet the engineer's judgement.

However, the primary objective of this study was to establish a surface deflection-based compaction quality control criteria for open graded aggregate material. The objective was accomplished by studying the packing behavior of the open graded aggregate under different compaction effort. This study utilized a comprehensive approach that includes extensive small-scale laboratory testing, intermediate-scale laboratory testing, and full-scale pavement testing. The findings from the small-scale laboratory testing are presented by Mondal et al. (2022) [see CHPTER III]. The detailed test results from the intermediate-scale laboratory testing and full-scale field testing are presented in this manuscript.

**Material Selection**

As already mentioned in Manuscript-1, most utilized two open graded aggregate materials were chosen for laboratory testing and field construction. ASTM# 4 (nominal size 19 to 37.5 mm) and ASTM# 57 (nominal size of 4.75 to 25 mm) were the two aggregate materials used. **Table 3** shows the particle size distributions for the two aggregate materials along with the corresponding gradation limits specified by ASTM.

.

**Table 3: Gradation of the Material used with ASTM Specification.**

| Sieve Size | | ASTM Specification (% Passing) | | Selected Gradation (% Passing) | |
|---|---|---|---|---|---|
| mm | US (in.) | ASTM # 4 | ASTM # 57 | ASTM # 4 | ASTM # 57 |
| 63 | 2.5” | 100 | | | |
| 50 | 2” | 90-100 | | 100 | |
| 37.5 | 1.5” | 35-70 | 100 | 100 | 100 |
| 25 | 1” | 0-15 | 95-100 | 30 | 98 |
| 19 | 0.75” | | | 12 | 75 |
| 12.5 | 0.5” | 0-5 | 25-60 | 3 | 35 |
| 10 | 0.39” | | | | 19 |
| 4.75 | # 4 | | 0-10 | | 1 |
| 2.36 | # 8 | | 0-5 | | 0 |

## Development of Test Matrix

### *Testing Hypothesis*

Before going to full scale testing, setting up a reference target point is very important through laboratory testing. With a view to establish a deflection-based quality control criteria for the compaction of open graded aggregate materials, a wide laboratory testing protocol was undertaken inside standard and customized proctor mold at beginning of the study. The test results are reported in the first publication done by Mondal et. al (2022). In that study necessity of seating drops, reference values of surface deflection under different compaction type were reported.

Though LWD tests were performed in a scaled up customized mold (D = 304.8 mm, H = 304.8 mm) the authors assumed that the test might be still affected by the boundary of the mold. So, with a view to eliminating the boundary effect and simulating the field like condition in laboratory, LWD test were caried out inside a wooden box and the compaction was done using vibratory plate compactor. The authors believe that this will eliminate the boundary effect and replicate the filed like scenario. The intermediate scale laboratory test will help to understand the compaction behavior of the open graded aggregate material before going into full scale field test.

***Intermediate-Scale Lab Testing in Wooden Box***

Intending to understand the behavior of the open-graded aggregate as base/subbase material, box testing involves testing with different configurations inside a wooden box. Several factors that could potentially affect the LWD evaluation was studied in this phase. That includes: (1) Effect open-graded base layer thickness, (2) Influence LWD types and applied load. To establish some reference values to be targeted during field compaction, it is important to perform laboratory testing that is free from boundary effects. For this reason, a large wooden box of dimensions 1.22 m x 1.22 m x 1.22 m (4 ft. x 4 ft. x 4 ft.) was constructed in the laboratory of OSU for testing the aggregates under different compaction conditions. The bottom of the wooden box was continuously supported against the floor to eliminate excessive deformations during testing.

Box testing was done primarily without any subgrade layer, the aggregate was directly poured into the box to make different layer thickness (three layer- 152.4 mm, 304.8 mm & 381 mm) and each layer was compacted with different passes of vibratory compactor (up to 3 passes). LWD tests were performed after every pass of compaction effort. Figure 24 (a) presents the grid distribution for LWD testing. Grid-5 is the target grid for LWD testing which represents the ideal condition, free from the boundary effect.

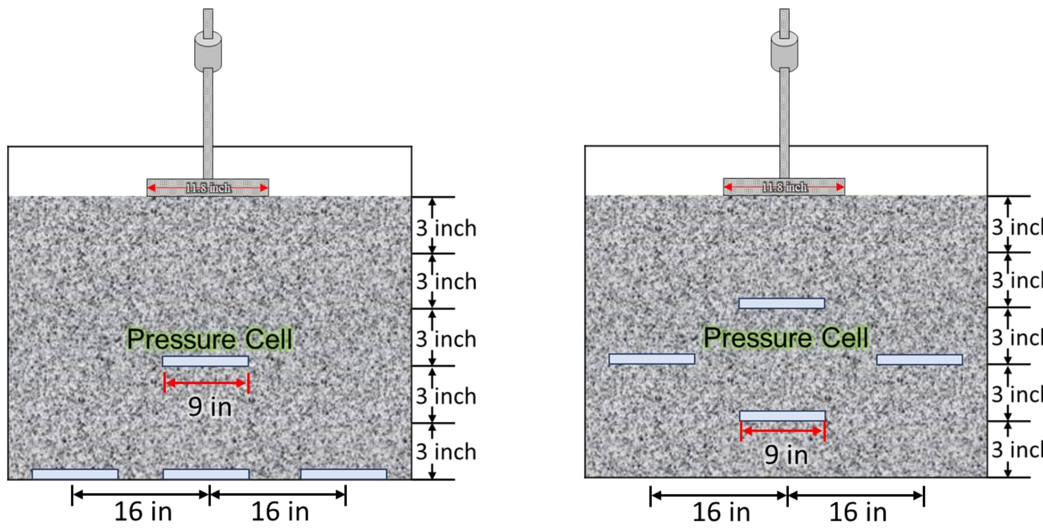
In this study, earth pressure cells were installed to measure the stress or pressure level and the stress patterns at different elevations. Due to limited resources, four (4) pressure cells were placed using two different configurations for unreinforced aggregate and one configuration for the geocell reinforced set. Figure 24 (b) &(c) shows a pressure cell and their placement.


(a)

(b) (c)

**Figure 24: Design of the Test Setup: (a) Grid Orientation in Box and Photo(a) and Placement(b) of the Earth Pressure cell.**

The pressure cells were placed at 75, 150 and 225 mm (3, 6, and 9 in.) from the bottom of the box. Figure 25 shows the orientation of the pressure cells. The figure shows the cross section through Grids 2-8 so that the pressure cells seen in the figure are Grids 2, 5 and 8. Two pressure cells were placed in Grid 2 and 8 to observe the stress pattern while LWD drops were applied on top surface of the Grid 5.




Pressure Configuration- 1 Pressure Configuration- 2

**Figure 25: Pressure cell placement configuration without any geogrid reinforcement.**

***Full-Scale Field Testing***

*Test Section Location and Design*

The test section for the field implementation is located on the North side of the CEAT Construction Engineering Technology Laboratory at Oklahoma State University (OSU). This section of land was not exposed to significant vehicular movement. The research team worked with the OSU Facilities and Management Department to designate this location for use during the field construction effort of this study.

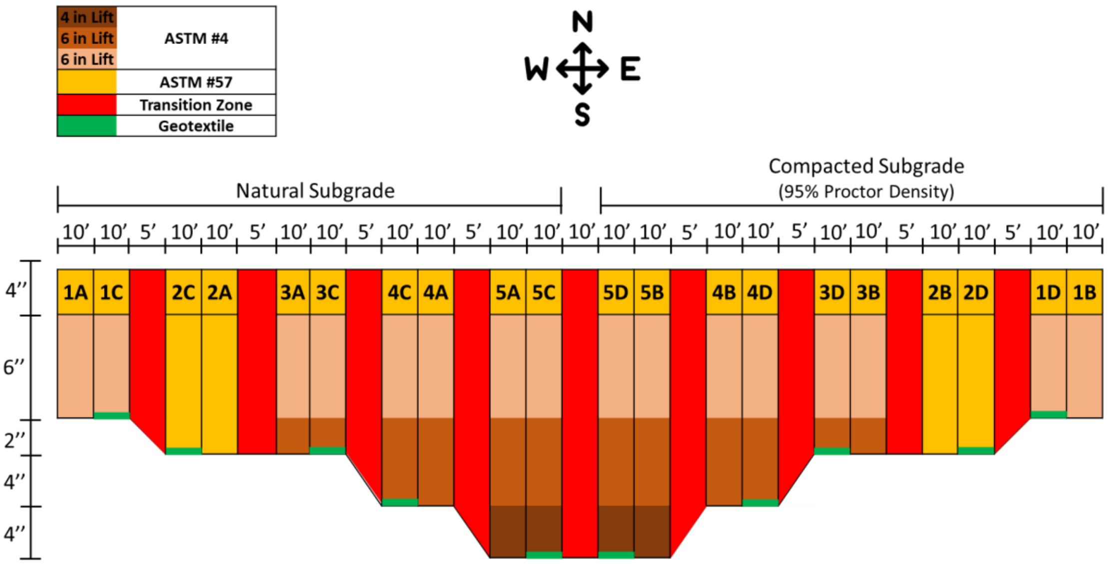



**Figure 26: Schematic Design of the Test Section in Field.**

The test section was designed with variation in subgrade condition (Compaction), direct lift thickness, total thickness, and geotextile use in mind. The overall objective was to study the surface deflections of open-graded aggregate base/subbase layers constructed over different subgrade conditions, following different layer configurations, under different levels of compaction. Figure 26 shows a longitudinal schematic of the test section layout followed in the current study. ASTM #57 was used in the base layer, whereas the ASTM #4 material was used in the subbase layer. Materials were placed over both natural and compacted soil with varied thicknesses. Different test sections have been designated with names ranging from 1A, 1B, 1C, 1D, through 5A, 5B, 5C, and 5D. It is important to note that construction of the different sections in the lab and in the field were planned so as to facilitate comparison of the different approaches. For example, similar lift thicknesses were used in the field as well as during box testing in the lab to investigate whether the laboratory results can be extended to the field.

*Test Section Construction*

The test section was constructed from September 14, 2021 to September 17, 2021. The location identified for construction of the test section comprised a surface layer of approximately 6-in. thick crushed aggregates. This layer was removed to start preparing the ground for test section. Most of the excavation was carried out using a backhoe. Boundaries between different sections, and the target excavation depths were measured using a rotating laser and marked with a string. Figure 27 shows photographs of the excavation and ground site preparation process. The excavated soil was collected for laboratory testing such as Atterberg limits, moisture-density characterization, and shear strength testing. After excavation, the subgrade soil was smoothened with a blade attached to the backhoe. The subgrade for the test cells on the East end (Cells 1B, 1D, 2D, 2B, 3B, 3D, 4D, 4B, 5B, 5D) were compacted using two passes of the vibratory, smooth-drum roller. Dynamic Cone Penetrometer (DCP) and Nuclear Density Gauge (NDG) tests were carried out to measure the as-constructed California Bearing Ratio (CBR) values (from the DCP results), as well as the dry and wet density values (using NDG). The DCP testing focused on the top 152.4 mm (6 in.) of the prepared subgrade layer to obtain a picture of the subgrade strength, and to evaluate the uniformity of prepared subgrade strength over the top 152.4 mm.

As already mentioned, shown in Figure 26 , one of the objectives of the current research effort was to study if the compaction behavior of these open-graded aggregate layers changed depending on whether a geotextile was placed at the subgrade-subbase interface. Therefore, some of the test cells were constructed by placing a layer of non-woven geotextile at the subgrade-subbase interface. The primary objective was to simulate a condition where pumping of the subgrade into the subbase layer can be prevented. However, the current field-testing effort did not include significant rainfall events to realize the benefits of such geotextile placement. In cases where the constructed layer is subjected to significant precipitation, pumping of the fines into the subbase is likely to significantly change the aggregate layers behavior. Figure 27 (d) shows a photograph of geotextile placement at the subgrade-subbase interface for selected tests cells in the current study.

(a) (b)

(c) (d)

(e) (f)

**Figure 27: Photographs Showing Different Stages of the Site Preparation Process: (a) Subgrade Excavation (b) Grading of the Subgrade Surface; (c) Compaction using the Vibratory Smooth Drum Roller; (d) Geotextile Placement at the Subgrade-Subbase Interface; (e) Elevation Checking; and (f) Compaction**

After subgrade preparation, aggregates were placed into the test cells in 4 (four) stages. Aggregate placement was planned to optimize the layer compaction process. Accordingly, test cells where the finished subgrade was at the greatest depth, were filled with aggregate first. Following this protocol, a 101.6 mm (4-in.) thick layer of ASTM #4 aggregate was first was placed in Cells 5A, 5B, 5C and 5D and compacted using two passes of a single-drum smooth vibratory roller. LWD tests were then carried out on this 101.6 mm thick aggregate layer.

Once testing on the first lift was complete, the second lift was prepared by placing ASTM # 4 in Cells 3, 4, and 5, and ASTM # 57 in Cell 2. The objective of this stage of aggregate placement was to achieve the same final elevation with all the compacted aggregate layers. Therefore, aggregate placement during this stage involved the following: (i) 152.4 mm (6-in.) thick layer of ASTM # 4 in Cells 4A, 4B, 4C, 4D, 5A, 5B, 5C, 5D; (ii) 50.8 mm (2-in.) thick layer of ASTM # 4 in Cells 3A, 3B, 3C, and 3D; (iii) 50.8 mm (2-in.) thick layer of ASTM # 57 in Cells 2A, 2B, 2C, and 2D. Only Sections 4 and 5 were compacted at this stage with two passes of the vibratory roller. LWD tests were conducted on Sections 4 and 5 at this stage.

After LWD testing on the second stage, the third stage involved placement of a 152.4 mm (6-in.) thick lift of ASTM # 4 for Sections 1, 3, 4, and 5. A 6-in. thick lift of ASTM # 57 was placed in Section 2. All the test sections were again compacted using two passes of the vibratory roller. LWD testing after this stage facilitated surface deflection measurements corresponding to the following scenarios: (i) 203.2 mm (8-in.) thick constructed lift of ASTM # 4 (Section 3); (ii) 203.2 mm (8-in.) thick constructed lift of ASTM # 57 (Section 2); (iii) 152.4 mm (6-in.) thick constructed lift of ASTM # 4 placed directly on the subgrade (Section 1); (iv) 152.4 mm (6-in.) thick constructed lift of ASTM # 4 placed on previously compacted layers of ASTM # 4 (Sections 4 and 5). Finally, a 4-in. thick layer of ASTM # 57 was placed as the capping layer on all Sections. This layer was also compacted with two passes of the vibratory roller, and LWD tests were conducted for all Sections.

Throughout the aggregate placement process, thicknesses of the placed layers were constantly checked using the rotating laser. Cross-contamination of the aggregate materials between different sections was prevented by placing transition zones in between adjacent cells where the material type or layer configuration changed. During construction, half of the transition zone was constructed using materials from the test cell to the east, whereas the other half was constructed using material from the test cell to the west. Figure 27 (e-f) shows photographs of the material placement, leveling, elevation checking, and compaction for the aggregate layers.

*Testing Protocol and Equipment Used*

Instruments

Two (2) LWD devices, one manufactured by an Olson LWD-1, and a Zorn ZFG-3000, were used throughout this field-testing effort. As previously mentioned, the ZFG-3000 does not measure the applied force directly (ASTM E2835), whereas a loadcell in the Olson LWD-1 provides a direct measure of the applied load (ASTM E2583). Accordingly, the Olson has a precision buffer of ± 2μm where the Zorn has a precision buffer of ± 40 μm. A Dynamic Cone Penetrometer (DCP) was used for assessing the uniformity of the prepared subgrade layer. A pre-established correlation was used to estimate the in-situ California Bearing Ratio (CBR) values for the top six inches of the subgrade layer. A Nuclear Density Gauge (NDG) was used to check the compaction levels in the subgrade layer. The NDG testing also provided the in-situ moisture contents in the subgrade layer. The NDG testing followed ASTM D 6938 protocols.

Testing Protocol for Subgrade

The testing protocol for the subgrade layer involved tests to confirm layer uniformity, compaction levels, and the in-situ stiffness (measured indirectly using surface deflection values). The compacted density and moisture contents for each cell were measured using an NDG. Once the subgrade surface was prepared to meet the required profile, DCP tests were conducted to assess the uniformity of compaction over the top 101.6 mm (6 in.). Surface deflection values for the subgrade were measured using the two LWD devices. One set of LWD tests was conducted for every two consecutive test cells with identical configurations. Close inspection of Figure 26 would clearly indicate consecutive test cells in each section are identical in configuration, with the only difference being the placement of the non-woven geotextile at the subgrade-subbase interface. Therefore, it is logical to conduct only one test per consecutive test cells. In most cases, testing at a given location was carried using both LWD devices to ensure the results were independent of the device type used. Each LWD test comprised data collection under twelve (12) drops. No seating drops were applied before recording of the data. This approach was taken intentionally to study the significance of seating drops while testing on fine-grained subgrade layers. These results would then be compared against those for the two aggregate materials (ASTM # 4 and ASTM # 57), for which, seating drop played a significant role. Figure 28 (c) shows the photographs of the LWD testing on the prepared subgrade layer using the Zorn.

(a)

(b)

(c)

(d)

**Figure 28: Photographs Showing Different Tests Carried Out on the Prepared Subgrade/Aggregate Layer: (a) DCP Testing; (b) NDG Testing; (c) Zorn LWD Testing; and (d) Olson LWD Testing**

Testing Protocol for Aggregate Layers

The test sections in Sections 1 through 5 were tested for surface deflection using LWDs at four (4) different stages during the aggregate placement and compaction. First, LWD testing was performed after placement of the first 101.6 mm (4-in.) thick aggregate layer Section 5 (Cells 5A, 5B, 5C, and 5D). LWD testing was conducted to measure the surface deflection under an uncompacted stage as well as 1, and 2 passes of the vibratory roller. Close inspection of Figure 26 indicates that LWD testing on these 101.6 mm thick layers of ASTM # 4 material in Cells 5A, 5B, 5C, and 5D would facilitate the following comparisons: (1) Effect of Geotextile placement on surface deflections (by comparing Cells 5A vs. 5C or 5B vs. 5D); (2) Effect of Subgrade Compaction on surface deflections (by comparing Cells 5A vs. 5B or 5C vs. 5D; (3) Effect of Subgrade Compaction and Geotextile Placement vs. a scenario where neither is implemented (by comparing Cells 5D vs. 5A). The second set of LWD tests were carried out in Sections 4 (4A, 4B, 4C, 4D) and 5 (5A, 5B, 5C, and 5D) after the second phase of aggregate placement. This resulted in total aggregate thickness of 254 inches in Section 5, and 6 inches in Section 4. Once again, LWD tests were conducted on the uncompacted layer, as well as after one and two passes of the vibratory roller. LWD testing at this stage would give the following information: (i) Surface deflections for a 152.4 mm (6-in.) lift thickness of ASTM # 4 (Section 4); (ii) Surface deflections for a 203.2 mm (10-in.) thick layer of ASTM # 4 constructed by first placing and compacting a 4-in. lift followed by a 152.4 mm lift (Section 5). A similar approach was followed for LWD testing in all test cells after different phases of aggregate placement. During LWD testing, surface deflection (as well as modulus) data was recorded under twelve (12) drops. During the field-testing effort, data was collected under all drops to facilitate the investigation of optimum drop number during LWD testing.

Aggregate placement in the test sections following the above-mentioned sequence facilitated surface deflection measurement using LWDs for different lift thicknesses (101.6 mm, 152.5 mm, and 203.2 mm) under different compaction efforts (0, 1, and 2 passes of the vibratory roller). The subbase layers were primarily constructed using ASTM # 4 aggregate, except for Section 2, which was constructed with ASTM # 57 material only. Construction of Sections 2 and 3 also facilitated LWD testing on 203.2 mm thick single lifts of ASTM # 57, and ASTM # 4, respectively. Figure 28 (d) shows photographs of LWD testing on the aggregate layers.

**Results and Discussions**

This section includes the large-scale laboratory testing and full-scale field-testing results caried out with ASTM#4 & ASTM#57 aggregate under different compaction efforts.

***Results from Intermediate-Scale Laboratory Testing***

The box filled with ASTM#57 & ASTM#4 was divided into 9 (nine) approximately equal grids as shown in Figure 26(a). As Grid-5 is the middle grid, which is away from the box walls, the author's assumption is that testing on Grid-5 would not encounter with the boundary effect and tests results would simulate the field conditions. With this hypothesis, the box was filled with three different thicknesses using both ASTM #4 & ASTM #57 and compacted at different compaction efforts. LWD testing was caried out after each compaction level. In this study, fifteen (15) LWD drops were applied to measure the surface deflection after every compaction effort.

*Number of Seating Drops Required*

Figure 29 presents the LWD test results at Grid-5 with ASTM# 57 under different compaction effort. From the figure it is observed that the surface deflection values get stabilized with the drop number increase after 6 drops. Even the Grid-5 is away from the boundary effect, still the open graded aggregate materials need seating drops to achieve stable contact between LWD plate and aggregate surface. The LWD results from box testing presented in this manuscript, is the average surface deflection values of 9 drops after six (6) seating drops. Close observation from the figure reveals that the surface deflection is going down with the increment of the layer thickness.

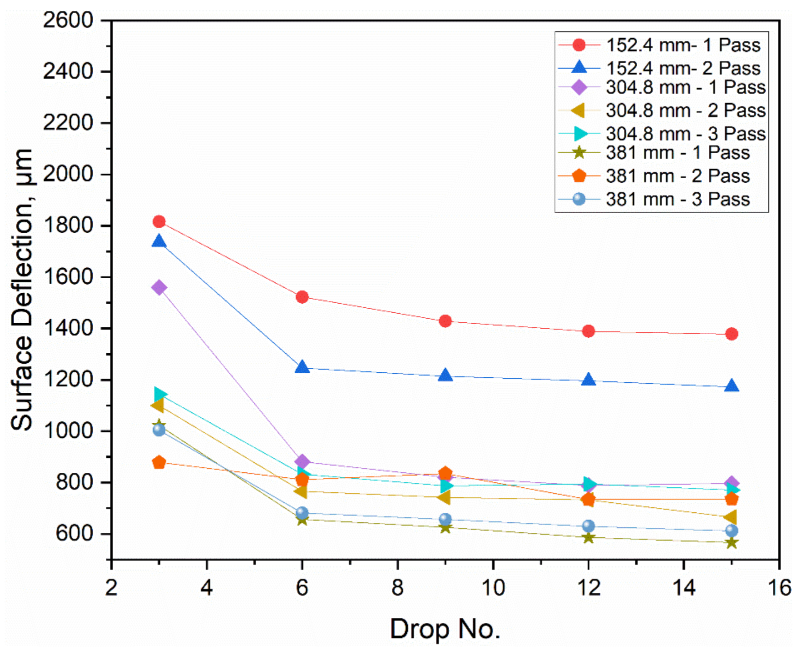
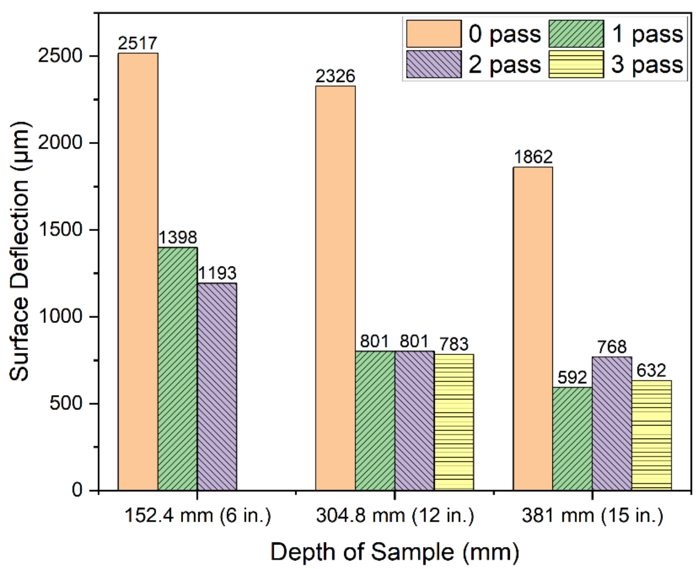



**Figure 29: LWD Test Results at Grid-5 with ASTM# 57 Aggregate after Different Compaction Effort.**

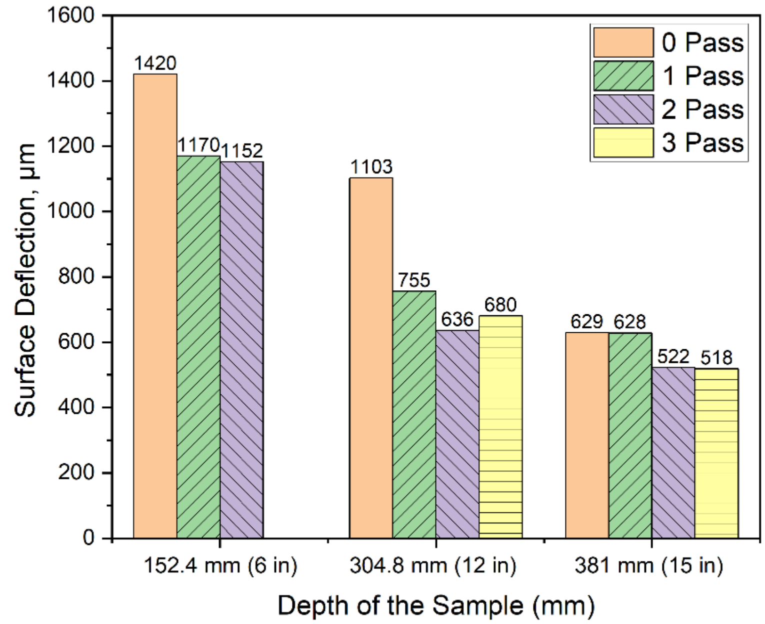
*Compaction Using Vibratory Plate Compactor*

Figure 30 (a &b) presents the LWD test results obtained from the wooden box test at Grid-5. Each vertical column in the figures represents the average value of the surface deflection after six (6) seating drops.

From Figure 30(a), it is noticed that after one (1) pass of vibratory plate compactor the surface deflection values decrease significantly for ASTM #57. The decrease continues from 1 pass to 2 pass in case of 152.4 mm layer. However, no significant reduction in surface deflection is noted from 1 to 2 passes for the 304.8-mm thick layer. Moreover, the surface deflection increases from 1 pass to 2 pass for the 381-mm thick layer indicating ‘destabilization’ of the compacted matrix. The surface deflection after three (3) passes was still higher than that after one (1) pass. Based on these results, it can be concluded that the surface deflection values are significantly affected by the underlaying layer stiffness. As the bottom 304.8 mm layer is well compacted, the aggregate matrix of the top 76.2 mm layer get easily destabilized by the additional 1 pass of the vibratory plate compactor beyond 1 pass.




(a)




(b)

**Figure 30: LWD Test Results in Wooden Box for (a) ASTM #57 (Mondal et al. 2022) & (b) ASTM #4 Aggregate Material (Vibratory Plate Compaction)**

Similar results for the ASTM # 4 materials are presented in Figure 30 (b). The first thing to note from Figure 30 (b) is that the overall surface deflection values for the ASTM # 4 in an uncompacted stage were less than those for the ASTM # 57 material. However, this difference decreased significantly with the application of compaction energy. Just like the ASTM # 57 material, the ASTM # 4 material also showed a sudden decrease in surface deflections while moving from an uncompacted stage to the application of one compactor pass. However, this reduction is significant only for the 152.4 mm and 304.8 mm. thick layers. The reduction is not significant for the 381 mm. thick layer, where the top-most layer was only 76.2 mm. thick. Therefore, the application of compaction energy did not lead to significant benefits as there was no space within the 76.2mm. thick surface layer for the aggregate materials to achieve a better packing. This clearly indicates that for the benefits of compaction to be realized, the aggregate particles need enough space within the layer to rearrange and achieve a better packed stage. Interestingly, upon the application of the second and the third compaction passes on the 381 mm. thick layer, the LWD-measured surface deflections decreased further. This was not the case with the 304.8 mm. thick layer. Interestingly, the ultimate surface deflection value after 3 compactor passes on the 304.8 mm. thick layer was 680 µm, and for the 381 mm. thick layer, was 518 µm. Even for the ASTM # 57 material (see Figure 30(a)), the lowest average surface deflection value recorded was 592 µm. This indicates that for these open-graded materials, in a compacted state the LWD-measured surface deflection should be approximately 500 µm or 0.5 mm. However, whether each layer can consistently achieve compacted state that would lead to surface deflection values less than 500 µm, remains to be seen. This will be further investigated using the field-test results.

*Pressure Distribution through OGA*

As already mentioned, one of the auxiliary tasks carried out in the current study involved measurement of pressure levels at different depths within the aggregate layer during LWD testing. The objective was to study how the pressure levels recorded by the earth pressure cells change with increasing compaction efforts applied to the aggregate layers. The level of pressure at different elevations was measured during the LWD testing. The results are presented in Figure 31 (ASTM #57) and Figure 32 (ASTM #4). Pressure was recorded using 4 earth pressure cells using two configurations.

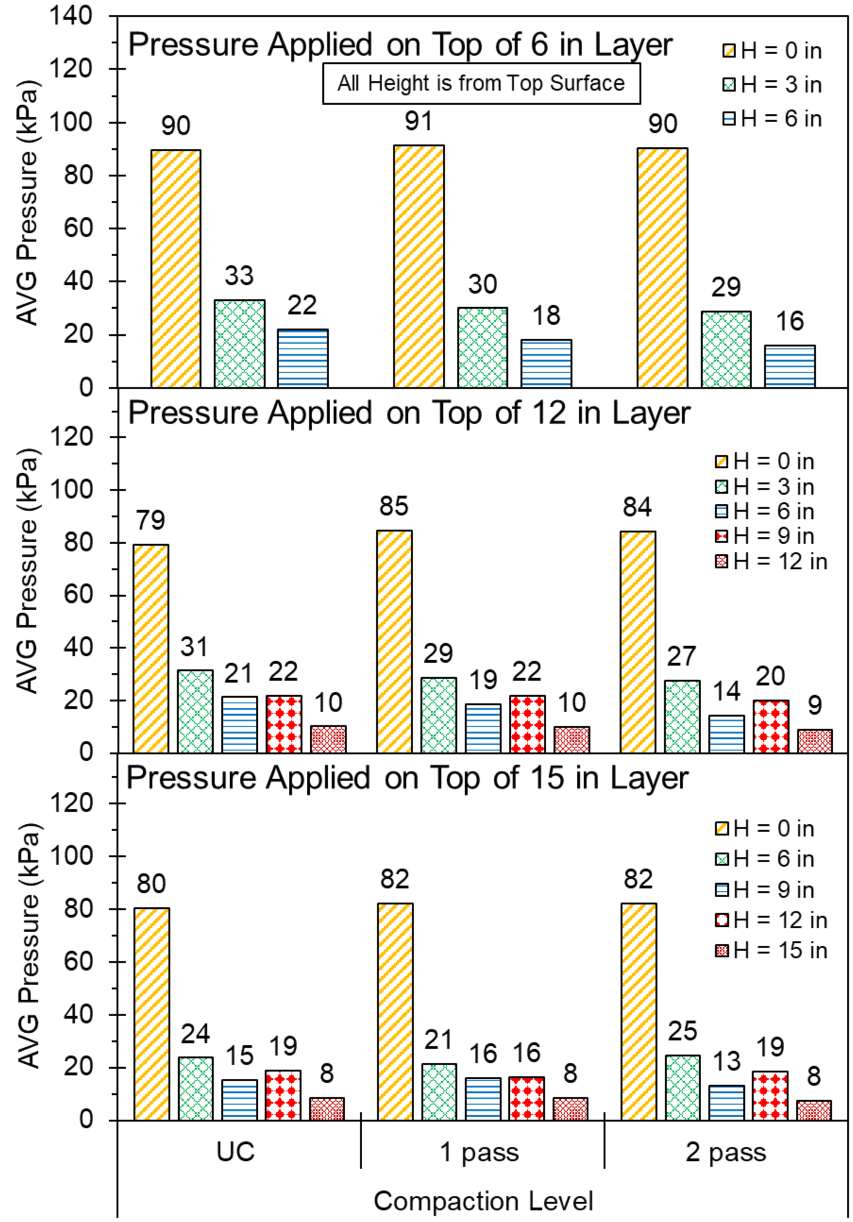



**Figure 31: Pressure level at different elevation under LWD drops at different compaction level (ASTM #57).**

From Figure 31 and Figure 32 following observations are as follows:

- Most of the pressure appears to be dissipated within the top 76 mm or 3 in. layer irrespective of the type of the aggregate used. As seen for ASTM #57 after applying 79-91 kPa (11.4-13.2 psi) pressure on the top surface the pressure level becomes almost one-third at a 76 mm or 3 in. depth. Past 76 mm, the reduction of pressure level as great. Similar behavior is also seen for ASTM #4 material. As most of the stress is reduced in the top layer, the required base/subbase thickness using these materials should decrease.

- For ASTM #57, when the LWD drops are applied on top of 381 mm (15 in.) and 304 mm (12 in.) layer, stress level at the bottom kept are constant with increasing compaction levels. For ASTM #4 the bottom stress level is seen to be very close at different compaction levels. From this observation it can be concluded that for both for ASTM #4 and ASTM #57, pressure level at different elevations due to the LWD drops is not affected by the additional compaction level.
- The pressure distribution for the open-graded aggregate material is not same as the dense-graded material. Instead of distributing the pressure to a larger area with the depth increment, these materials absorb the pressure without spreading to a larger area. This behavior defines the stress pattern as a “cylinder” shape under the applied load and not the classic “cone” shape. This statement is evidenced by the negligible pressure recorded at Grid 2 and Grid 5 when LWD drops are applied at Grid 5. This phenomenon underscores the use of this material a “stress relieving” base/subbase layer.

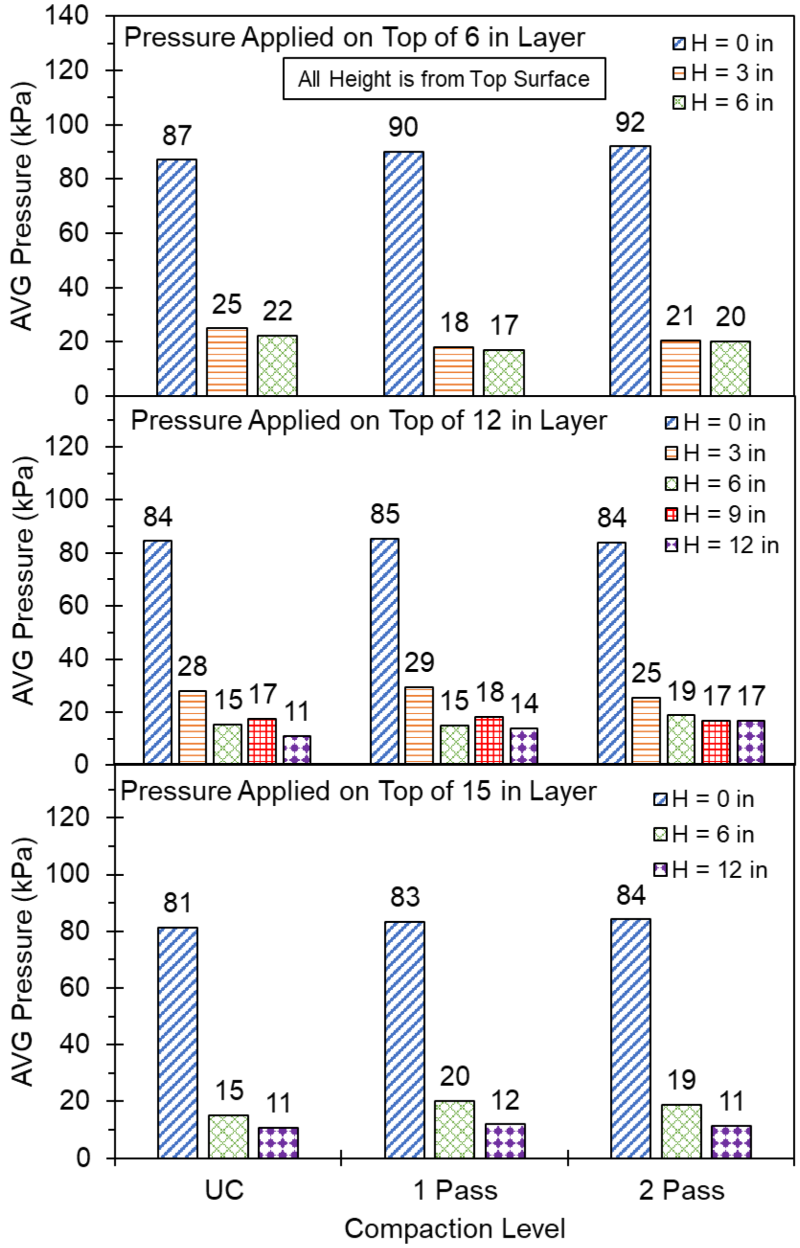



**Figure 32: Pressure level at different elevation under LWD drops at different compaction level (ASTM #4)**

### ***Results from Full-Scale Field Testing***

*Subgrade Properties*

Soil samples collected from the test strip subgrade were tested in the laboratory to for basic characterization. Visual classification of soil samples collected from different test cells did no show significant variation. Therefore, all samples collected from different locations of the test strip were merged, and just one set of tests were conducted to represent the subgrade for the entire section. Atterberg's Limit tests were carried out following ASTM D 4318 specifications. The LL value for the soil was 43, whereas the PL value was 28 (PI = 15). Based on the Atterberg limit values, and the overall particle size distribution, the USCS classification for the soil was CL (low-plasticity clay), whereas the AASHTO classification was A-7-6.

As already mentioned, one of the objectives during this field construction effort was to build half of the test sections without any subgrade compaction control, whereas the remainder of the sections were to be compacted to 95% of standard compaction dry density. From the laboratory test, *the maximum dry density (MDD) was determined to be 111 pcf*. Table 4 shows results from the moisture-density checks in the field using a Nuclear Density Gauge. Cells B and D in Sections 1 through 5 were supposed to be compacted to 95% of maximum dry density established using the standard compaction effort. The rows corresponding to these cells have been highlighted in gray in Table 4.  As seen from the table, several of the test cells did not achieve the target density even after roller compaction. The research team decided to stop compaction at that stage and continue with the testing no growth in the compaction percentage was observed even after additional roller passes. This slight lower density compared to the target value of 95% is not likely to affect the study results as the test sections are not subjected to vehicular loading, and the LWD-imposed surface deflections are not likely to be affected by such small differences in the achieved layer density. Besides checking the moisture-density values, Dynamic Cone Penetrometer (DCP) tests were also conducted on the subgrade layer to check the uniformity of compaction. The DCP test focused primarily on the top 101.6 mm (6 in.) of the prepared subgrade layer for the same reasons stated above (no vehicular loading applied to the test sections). The DCP penetration rates were used to calculate the in-situ CBR values for the compacted subgrade layer. The following equation, developed by Kleyne et al. (1982) was used to calculate the in-situ CBR values from DCP penetration rates.

**Log (CBR) = 0.84-1.26 x Log (PR)----------------------------------------------------------------------(5)**

Where, CBR = California Bearing Ratio, PR = penetration rate (in./blow) of DCP.

**Table 4** also lists the moisture contents, LWD-measured surface deflections, LWD-measured surface modulus values, CBR values calculated from the first DCP drop, as well as the average CBR values calculated over the top 101.6 mm of the subgrade layer for each test cell. As seen from the table, the moisture content varied form 10.6% to 24.9 %, whereas the surface deflection varied from 0.45 mm to 1.78 mm.

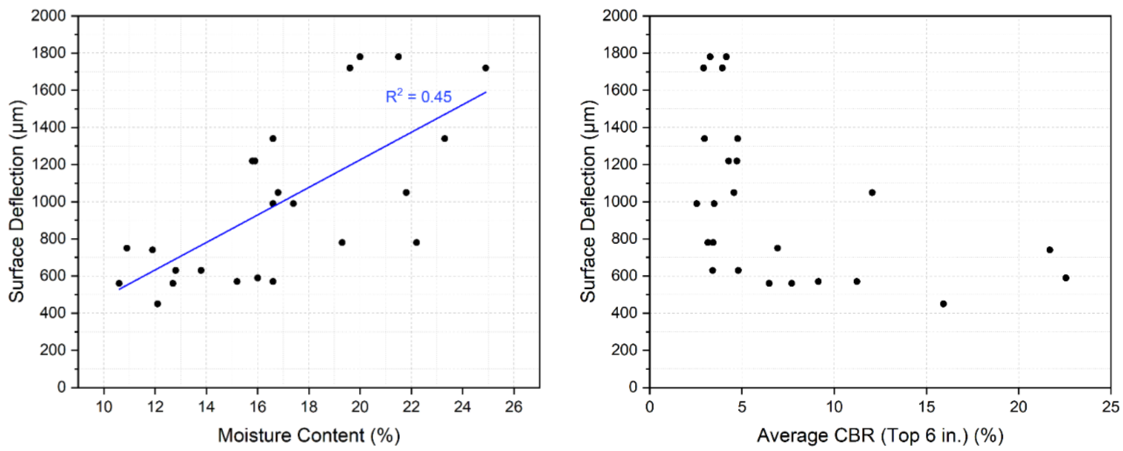
**Table 4: Results from Moisture-Density Checks on the Compacted Subgrade**

| Test Cell | Moisture Content (%) | Dry Density (pcf) | Percent Compaction (%) | Surface Deflection (mm) | LWD Modulus (MPa) | 1st drop CBR | Avg. CBR Value (Top 101.6 mm) |
|---|---|---|---|---|---|---|---|
| **1A** | 16.6 | 94.5 | 91.8 | 0.57 | 35.20 | 5.22 | 11.23 |
| **1B** | 16.8 | 94.6 | 91.9 | 1.05 | 12.92 | 5.61 | 4.57 |
| **1C** | 15.2 | 85.2 | 82.8 | 0.57 | 35.20 | 3.94 | 9.14 |
| **1D** | 21.8 | 93.2 | 90.6 | 1.05 | 12.92 | 9.35 | 12.06 |
| **2A** | 12.7 | 80.8 | 78.5 | 0.56 | 21.38 | 6.12 | 7.70 |
| **2B** | 19.6 | 94.6 | 91.8 | 1.72 | 22.08 | 4.03 | 3.94 |
| **2C** | 10.6 | 85.4 | 83 | 0.56 | 21.38 | 3.90 | 6.48 |
| **2D** | 24.9 | 94.1 | 91.4 | 1.72 | 22.08 | 2.74 | 2.93 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **3A** | 13.8 | 74.4 | 69.3 | 0.63 | 36.41 | 5.17 | 4.80 |
| **3B** | 16.6 | 94.6 | 91.8 | 1.34 | 27.86 | 5.38 | 4.77 |
| **3C** | 12.8 | 86.6 | 84 | 0.63 | 36.41 | 3.27 | 3.42 |
| **3D** | 23.3 | 92.3 | 89.6 | 1.34 | 27.86 | 4.79 | 2.97 |
| **4A** | 15.9 | 85.6 | 83.1 | 1.22 | 14.47 | 4.98 | 4.28 |
| **4B** | 19.3 | 98.3 | 95.4 | 0.78 | 19.00 | 2.61 | 3.44 |
| **4C** | 15.8 | 89.7 | 87.1 | 1.22 | 14.47 | 3.67 | 4.72 |
| **4D** | 22.2 | 98 | 95.2 | 0.78 | 19.00 | 3.67 | 3.15 |
| **5A** | 17.4 | 99 | 96.2 | 0.99 | 33.83 | 4.31 | 3.49 |
| **5B** | 20 | 100.3 | 97.4 | 1.78 | 16.74 | 3.79 | 3.28 |
| **5C** | 16.6 | 97.9 | 95.1 | 0.99 | 33.83 | 2.81 | 2.55 |
| **5D** | 21.5 | 102.6 | 99.6 | 1.78 | 16.74 | 6.41 | 4.15 |

Looking at the 1$^{st}$ drop CBR values listed in **Table 4**, the variation was between 2.61 to 9.35. On the other hand, when the CBR values were averaged for the top 101.6 mm of the subgrade layer, the variation was from 2.97 to 22.57. Most of the data points correspond to CBR < 10.

The Figure 33 (a) presents a scatter plot showing the variation of LWD-measured surface deflections on the subgrade surface with soil moisture contents. From the figure, as the subgrade moisture content increases there is a general increasing trend in the LWD-measured surface deflections. This is expected as increasing moisture content can reduce the soil shear strength, thereby increasing both the elastic as well as plastic deformations. Figure 33 (b) shows a scatter plot of LWD-measured surface deflection with average CBR for the top 101.6 (6 in.). For average CBR values less than 5, a large scatter in the LWD-measured surface deflection values is observed. However, as the subgrade CBR increases above 5, a rapid decrease in the LWD-measured surface deflection is observed. Except for a few outliers, the surface deflection values remain constant around 0.5 mm as the CBR value increases.




(a) (b)

**Figure 33: Scatter Plot Showing Variation in LWD-Measured Surface Deflection with (a) Subgrade Moisture Content & (b) Average CBR Value. (1 in. = 25.4 mm)**

*Device Agnostic*

LWD testing on the compacted subgrade layer was conducted using both LWD devices used in this research effort. Figure 34 compares the surface deflections measured on each subgrade test cell using the two devices. From the figure it is apparent that for some test cells (2B/2D, 4B/4D) the Zorn LWD resulted in higher surface deflection values compared to the Olson device. For the remainder of the test cells, both devices resulted in similar surface deflections. Here it should be re-emphasized that the Zorn device, confirming to ASTM 2853 specifications has a precision tolerance of ± 40 µm, whereas the Olson device, confirming to ASTM 2583 specifications has a precision tolerance of ±2 µm. This difference in the tolerance values kept in mind when comparing results from the two devices. Nevertheless, results from the subgrade tests clearly indicates that either device can be reliably used during field compaction control activities.

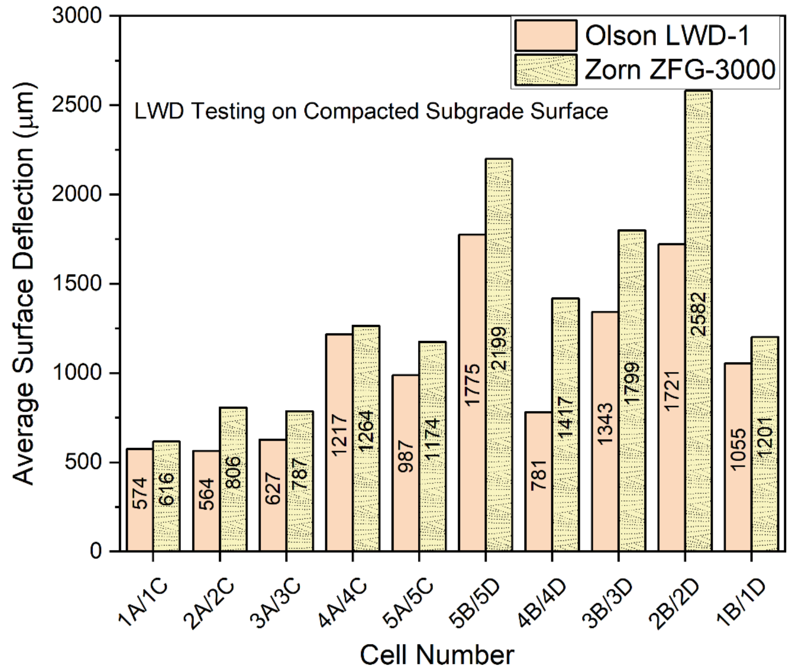
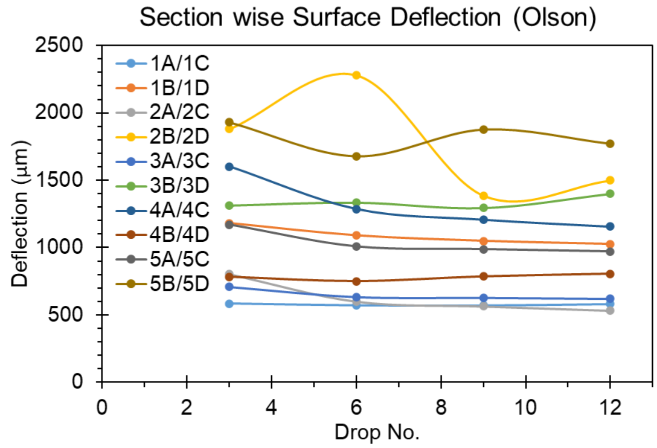


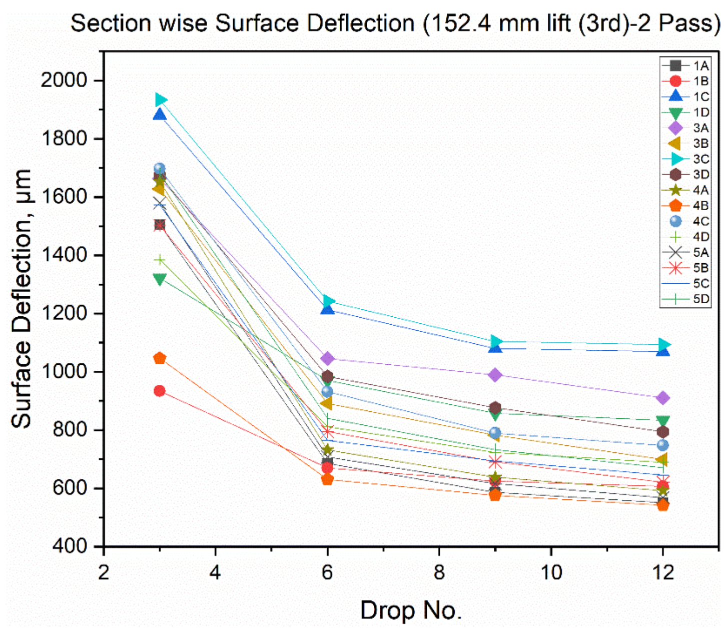

**Figure 34: Comparison of Surface Deflection Measured by Two Devices (Zorn and Olson).**

*Necessity of Seating Drop*

Figure 35 shows the variation in LWD-measured surface deflection with increasing number of drops during testing on top of the finished subgrade layer. As seen from the figure, there was not that variation in the surface deflection with increasing drop numbers except for Cells 2B/2D, and 5B/5D. No justification for this strange variation could be found. The negligible change in surface deflections with increasing drop number is expected when testing on a well-compacted subgrade layer. The layer has likely achieved a dense packing state under the rollers; accordingly, no significant change in the packing occurs with increasing number of drops during LWD testing. This also indicates that no seating drops are needed during LWD testing when testing on top of a compacted fine-grained subgrade layer.




(a)




(b)

**Figure 35: Surface Deflection with LWD Drop Increment for (a) Subgrade & (b) Aggregate.**

Surface deflection values were recorded after every drop of the LWD mass. Results from the 3rd stage of aggregate placement (6-in. thick aggregate layer) is presented in Figure 35 (b). From the figure, it can be observed that beyond the application of 6 drops, no significant reduction in the measured surface deflections is observed. This indicates that while testing on this ASTM # 4 material, at least six drops are necessary as 'seating' drops to ensure adequate/uniform contact between the aggregate surface and the LWD plate. It should be noted that the data in Figure 35 (b) corresponds to the case where two vibratory passes of the smooth-drum roller were already applied to the aggregate layer. Due to the coarse nature of this layer, even two passes of the vibratory roller do not completely smoothen the aggregate layer surface.

From these results, it can be concluded that though necessity of seating drops is not significant for dense graded aggregate, but it is very essential for recording surface deflection of open graded aggregate materials. Both in the box and field it is found that at least six (6) seating drops are necessary before recording the surface deflection value for open graded aggregate. *Here it needs to be noted that the measured surface deflection on top of the aggregates and analyzing the results (presented in the following sections) did not isolate the effects of the subgrade.*

*Effect of Aggregate Type.*

The type of aggregate material, in terms of gradation, used for construction might be an important factor governing the surface deflection measurement (an indicator of degree of compaction). To investigate this effect Figure 36 compares the LWD-measured surface deflection values for the two aggregate materials (ASTM # 4 and ASTM # 57) at different layer thicknesses. The columns with green horizontal stripes represent the measured surface deflection values after 1pass of the vibratory roller, whereas the columns with the red inclined stripes represents the deflection values after 2 passes. Overall, as the cumulative layer thickness increases from 203.2 mm, 254 mm & 304.8 mm, there is a decreasing trend in the measured surface deflection values. From the figure, when the total layer thickness equals 304.8 mm, there is no significant difference in the surface deflection values irrespective of whether the layer is constructed using ASTM # 4, ASTM # 57, or by placing a layer of ASTM # 57 over a layer of ASTM # 4. On the other hand, for the ASTM # 4 material, when the total layer thickness was increased from 203.2 mm to 254 mm, the average surface deflection value decreased from 951 μm to 781 μm after 2 passes of the vibratory roller. A similar reduction in surface deflection was also observed for the ASTM #57 material: from 823 μm to 689 μm (after two roller passes) when the layer height was increased from 203.2 mm to 304.8 mm.

From these results it can be concluded that the compaction level achieved within a particular layer does not vary significantly between ASTM # 4 and ASTM # 57 materials. On the other hand, the degree of compaction after a certain number of roller passes is directly governed by the cumulative layer thickness, and degree of compaction of the layer(s) underneath the surface layer being compacted. The compaction behavior of these open-graded aggregates is largely governed by particle shape and angularity, and not as much by the overall grain size distribution. However, it is important to note that the compaction behavior will most likely be significantly different from what would be observed for dense-graded aggregate layers.

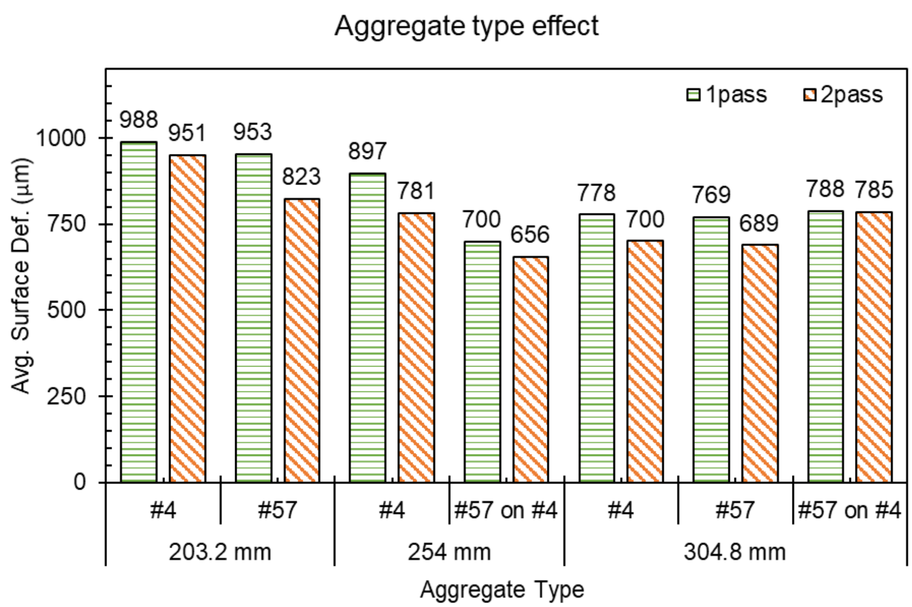



**Figure 36: Comparing the LWD-Measured Surface Deflection Values for Different Material-Layer Thickness Combinations**

Finally, the results presented in Figure 36 indicate that for none of the material-thickness combinations, the surface deflection values were less than 0.5 mm (500 µm). At this stage, it appears like a threshold value of 0.5 mm (500 µm) may be too stringent as far as compaction requirements are concerned.

*Effect of Direct and Staged Lift Construction*

LWD-measured surface deflections from different test cells at different stages of aggregate placement are sorted and compared in **Figure 37**& Figure 38. These figures show results from LWD testing on both Direct Lift (DL) as well as Staged Lift (SL) constructions. A SL construction corresponds to the case where multiple layers are compacted on top of each other to achieve a cumulative layer thickness. The figure also includes data for section with and without placement of the non-woven geotextile at the subgrade-subbase interface. The following subsections are the primary observations that can be made from close inspection of **Figure 37** & Figure 38.

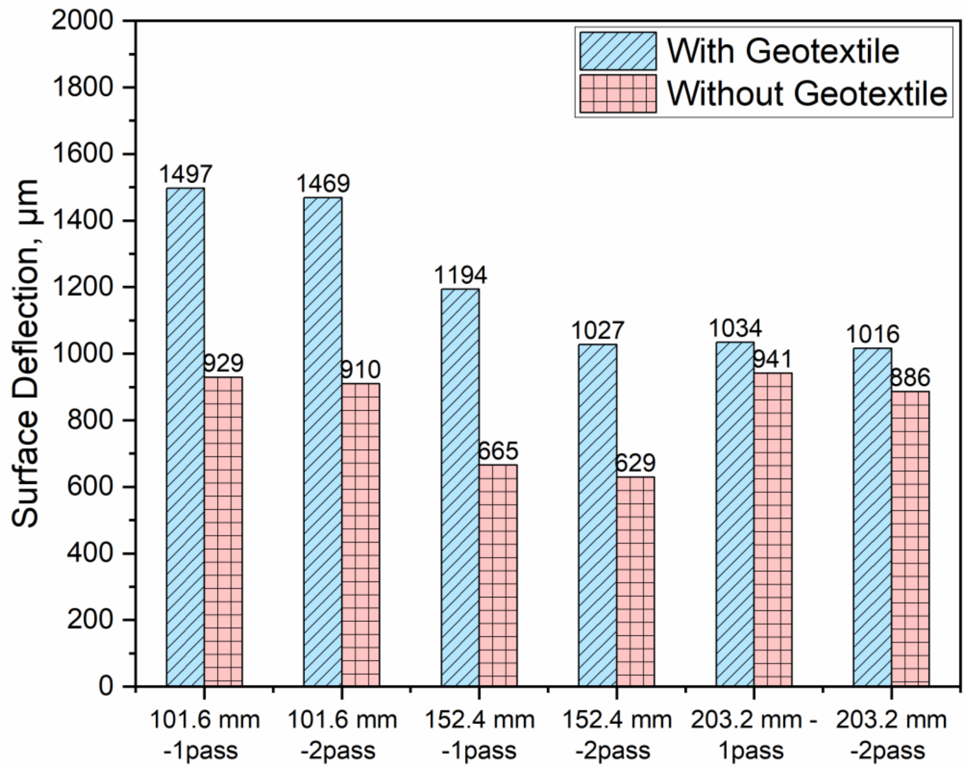



**Figure 37: Direct Lift (DL) Construction Results with ASTM# 4.**

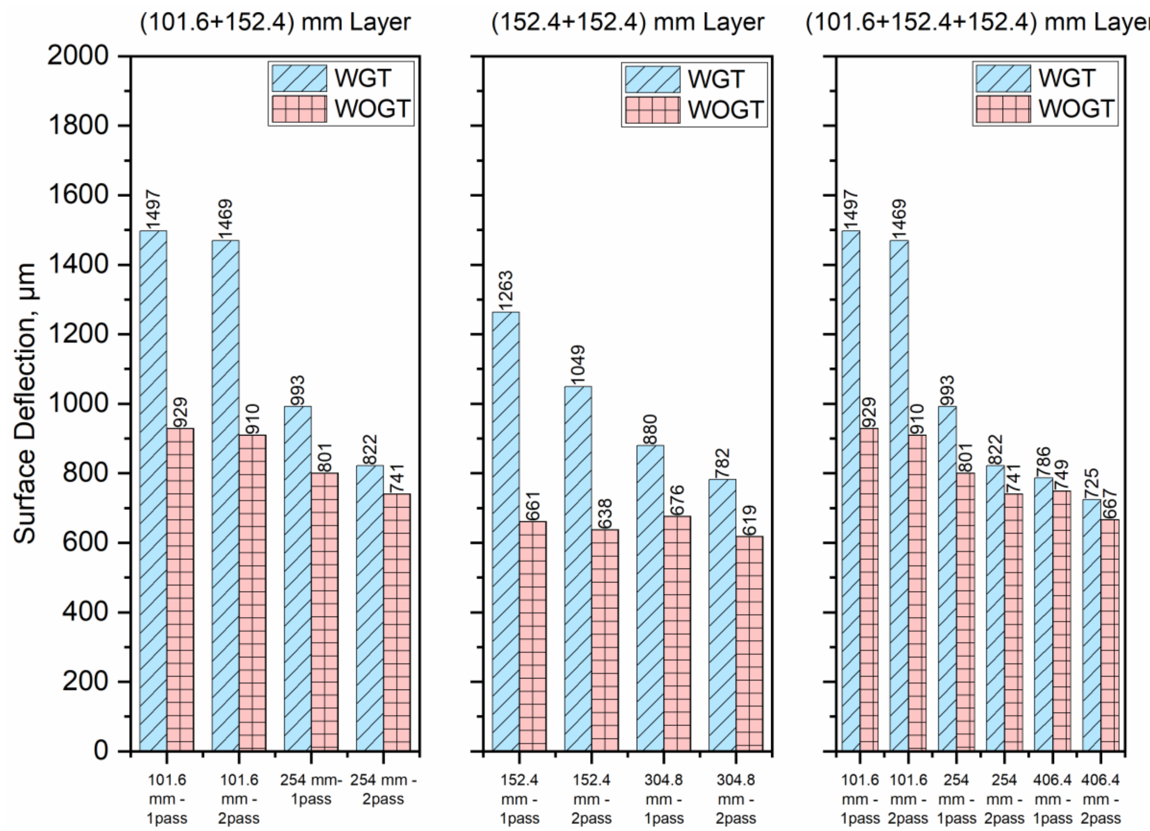



**Figure 38: Staged Lift (SL) Construction Results with ASTM# 4.**

*Effect of Geotextile Use*

Overall, comparing the surface deflection values for the sections with and without geotextile at the subgrade-subbase interface, it is seen that the cells with geotextile results in higher surface deflection values compared to those without. This difference is greater for the thinner aggregate layers, and gradually diminishes as the cumulative layer thickness increases. This interesting observation can be attributed to the fact that placement of the geotextile at the subgrade-subbase interface creates an artificial plane of slippage (or failure plane). This prevents penetration of the aggregates into the subgrade surface for better packing. For thinner layers, when the geotextile is within the depth of influence of the LWD stress pulse, detrimental effect of this artificial plane of slippage is reflected through higher recorded surface deflections. However, as the layer thickness increases, the geotextile gets farther and farther away from the LWD, and its detrimental effects is not as clearly noticeable. At this point it is important to discuss the role that a geotextile is intended to play in actual pavement sections. When the pavement section is subjected to water intrusion, and subgrade pumping and migration of fines into the subbase/base layer is likely to be an issue, the geotextile plays an important role as a 'separator'. Presence of the geotextile greatly benefits the pavement section in the long term, and integrity of the layers is preserved. In the current study, the subgrade was dry, and migration of fines into the subbase layer was not an issue. Moreover, the constructed test sections were not subjected to any vehicular traffic that would present a possibility of fines migration or pumping. Therefore, the geotextile did not serve any beneficial purpose, rather presented a 'weak' plane for aggregate slippage, thus leading to greater surface deflection. <u>*This trend should not be construed as an indicator of geotextiles being detrimental to pavement performance.*</u>

*Effect of DL vs SL*

The surface deflection values reduce with increasing of direct lift thickness. Also, there is a reduction in surface deflection with the application of additional vibratory passes except for the 4-in. direct lift case. This indicates that the energy coming from a single pass of the vibratory compactor is sufficient to induce maximum interlocking between the aggregate particles. Additional compaction does lead to improved packing (densification), rather can lead to 'destabilization' of the aggregate matrix. Therefore, in the field, the number of compactor passes should be changed depending on thickness of the layer being compacted. Excessive compaction of thin aggregate layers is likely to 'destabilize' the packing structure.

*Effect of Cumulative Layer Thickness*

As the cumulative layer thickness increases, compaction of the underlying (intermediate) layers leads to lower surface deflection measurements in the surface layer. This is the reason, the surface deflections for staged lift construction were lower than those for thick single lift constructed layers.

**Comparison Among Small-Intermediate-Full-Scale Test Results**

As mentioned earlier, this study is an integrated approach of small-scale, intermediate-scale laboratory testing & field testing with a view to establish a target surface deflection value for the field compaction control. Observations from each phase of this research project are crucial for the development of logical, evidence-based construction and compaction control guidelines. Therefore, as the final task in this study, the results from different phases were compared to identify similarities and differences. The ultimate objective was to assess whether any of the laboratory testing approaches can be used to realistically simulate the compaction behavior of OGA materials in the field. Once such a method has been identified, it would be possible to establish compaction targets for implementation in the field. These targets can be based on LWD-measured surface deflections. The comparison among the test scenario is presented in Figure 39 for the aggregate used in this study. The bars represent the average surface deflection of 12-in. (304.8-mm) thick ASTM #4 and ASTM #57 aggregate layers while the error bar lines represent the standard deviation. This layer is constructed with single lift inside mold with two compaction method (Vibratory & Jackhammer Compaction) and two equal lifts inside box & field.

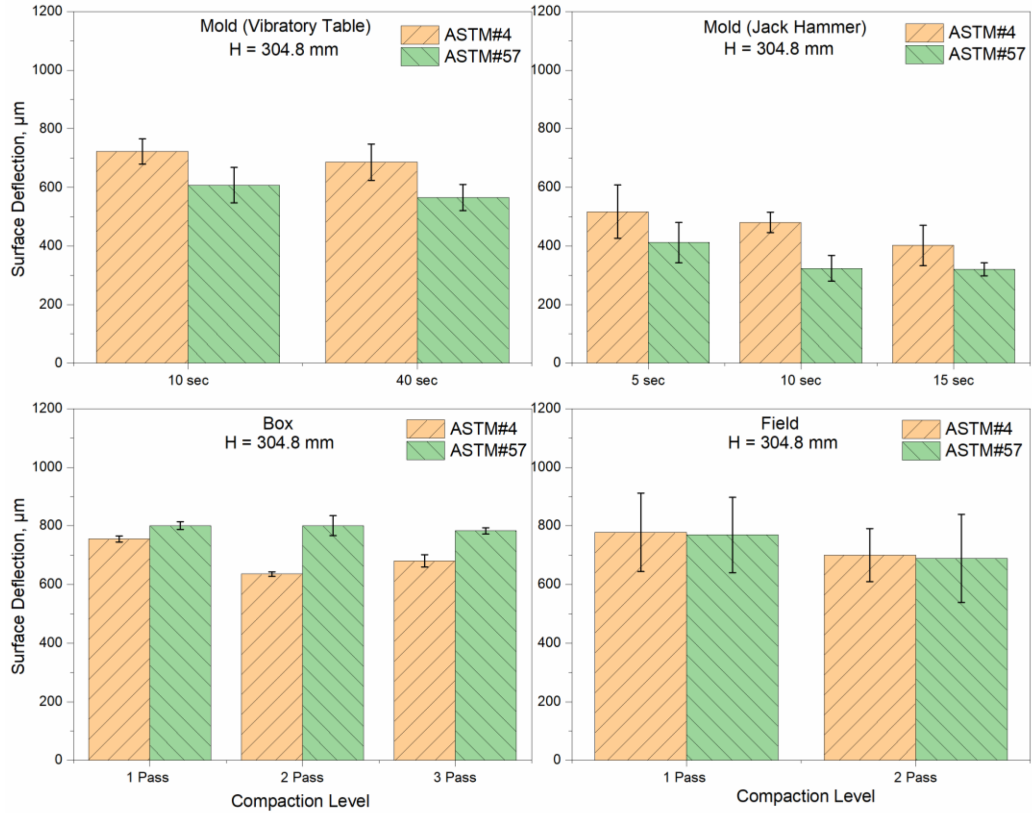



**Figure 39: Comparison among the Test Method in terms of Surface Deflection.**

Figure 39 shows that the LWD-measured surface deflection values on top of an aggregate specimen in the custom-made Proctor mold, compacted using the vibratory shake table, closely matched the surface deflections measured on the same aggregate material in the wooden box as well as the field. As seen from the figure, the surface deflections for a sample compacted in the lab for 10 seconds (on the vibratory shake table) closely matched the results for samples subjected to one pass of the vibratory plate compactor in the wooden box as well as one pass of the vibratory smooth-drum roller in the field. Similarly, 40 seconds of vibratory compaction using the vibratory shake table corresponded to two (2) passes of the vibratory plate compactor (in the wooden box) or two (2) passes of the vibratory smooth-drum roller (in the field).

From the field data, the surface deflections after 1-pass of the vibratory roller is 778 μm for the ASTM #4 material, and 769 μm for the ASTM # 57 material. Similarly, after 2-passes of the vibratory roller, the corresponding surface deflections are 700 μm (ASTM #4) and 689 μm (ASTM #57). The corresponding surface deflection values in the mold were 686 μm for ASTM #4 (40 sec) with 2% error, 565 μm for ASTM #57 (40 sec) with 18% error. Similarly, the corresponding surface deflection in the box were - 636 μm for ASTM #4 (2 pass) with 9% error, 801 μm for ASTM #57 (2 pass) with 16% error. On the other hand, samples compacted using the jackhammer resulted in significantly lower surface deflection values compared to those in the wooden box or the field. This indicates that the jackhammer compaction is not representative of field compaction condition. Even 5 seconds of jackhammer compaction resulted in significantly lower surface deflections compared to those in the wooden box or the field.

Figure 40 shows the Coefficients of Variation (CoVs) of the measured surface deflection values among different aggregate samples for 304.8 mm (12 in.) thick layer of ASTM#4 & ASTM#57. From this figure, the variability is less than 10% for compaction using the vibratory shake table. On the other hand, the variability in surface deflection for samples compacted using a jackhammer was greater than 10%. This indicates that the jackhammer compaction not only imparts significantly higher compaction levels to the sample, it also leads to inconsistent surface deflection measurements. Therefore, the jackhammer compaction approach should not be considered as a suitable replication of field compaction efforts. The variabilities in the field-measured surface deflections were found to be between 12% to 21%, which is greater than the variation observed in the lab using the vibratory shake table. This is expected as response of the OGA layer in the field is affected by several other factors such as subgrade properties, relative position of the compactor with respect to the testing position, etc. Therefore, CoV values less than 20% are considered to be acceptable.

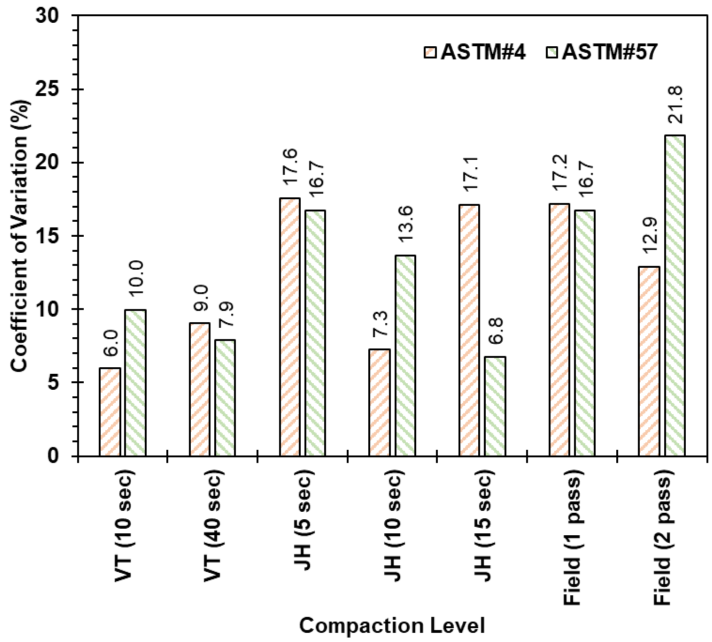



**Figure 40: Coefficient of Variation Among Surface Deflection Measurements from Different Phases of the Research Study**

**Summary & Conclusions**

This manuscript presented findings from intermediate-scale laboratory and full-scale field test results of the research study focusing on the development of a deflection-based compaction control specification for open-graded aggregate materials. Portable Impulse Load Plate Testing Devices such as Light Weight Deflectometer (Zorn and Olson) are used for measuring the surface deflection for this study. Due to the coarse nature and presence of large void in this material, testing with LWD becomes intriguing. To establish a compaction quality control protocol for these materials an integrated approach of laboratory and field testing is undertaken in this study. The most used ASTM#4 &ASTM#57 aggregate are selected for the study of the compaction behavior of this material. Different layer configurations in box with both the aggregate were tested under different compaction effort. Finally, a full-scale 76.2 m (250 ft) test section was constructed in the facility of Oklahoma State University to investigate the findings from the laboratory tests. Layer thickness is varied as well as the compaction effort. LWD tests was performed after each lift and compaction effort (Vibratory Drum Roller Compaction). Major findings from the laboratory and filed testing effort are as follows:

1. The Olson and Zorn LWD measured surface deflection values are reasonably similar.

2. The surface deflection value significantly decreases after 1 pass of the vibratory compaction, but the decrease is not significantly additional 1 pass of vibratory compaction effort is applied. The value slightly increases with the 3rd pass indicating the destabilization of the test matrix due to excessive compaction.

3. For open graded aggregate, six (6) seating drops are found to be adequate to achieve maximum contact between the plate and the aggregate surface.

4. Underlying layer stiffness plays a vital role to the achieved compaction level of any layer if the compaction energy is kept constant However, increased layer thickness results in decreased surface deflection after same amount of compaction effort.

5. For soil subgrade, there is a linear increasing trend of surface deflection with the increase of moisture content. But, the surface deflection and Avg. CBR value has a slightly inverse relation. LWD measured surface deflection might be an indicator of the subgrade moisture, strength. However, no necessity of seating drop is found is case of LWD testing on soil subgrade.

6. For the use of open graded aggregate materials as base/subbase layer, surface deflection of a layer is not significantly affected by the type of aggregate mix rather affected by the height of the layer. The compaction level achieved by a layer depends on the shape, angle, the orientation of the particle size when the compaction energy is kept constant.

7. With geotextile use, there is a reduction pattern of surface deflection with the increase of layer thickness. However, in case of absence of geo-textile, exception of this trend is found due to aggregate penetration into the subgrade during compaction.

8. Vibratory shake table compaction in customized mold is replicating the compaction scenario of the box and field in terms of surface deflection.

# CHAPTER V

## SUMMARY, CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

### Summary

This report summarized findings from a recently completed research study at the Oklahoma State University focusing on the development of a deflection-based compaction control specification for OGA base/subbase courses commonly used in permeable pavements. For this purpose, Portable Impulse Plate Load Testing Devices, also known as Light Weight deflectometers (LWDs) were used to measure the surface deflections on the aggregate layers under different compaction levels. Although the LWD device has several advantages (Portable, Nondestructive, Easy to use, Quick assessment, and Commercial availability), due to the non-homogeneous nature of OGA types, getting consistent results from the LWD test was challenging. Apart from that, currently, there is no established protocol for LWD testing on these materials (e.g., the required number of “seating” and “measurement” drops). Therefore, the study adopted an integrated approach involving laboratory testing, numerical modeling, and field testing to develop a compaction control protocol for the OGA materials.

This study comprised laboratory and field testing on two types of OGA materials, following gradation specifications for ASTM #4 and ASTM #57, respectively. Two commercially available LWD devices, manufactured by Olson and Zorn respectively, were used in this research to study the influence of LWD types on the measured surface deflection. The first part of the laboratory test matrix includes extensive LWD tests conducted on top of the selected aggregate materials inside a custom-made large cylindrical mold, and wooden box, respectively. As mentioned earlier, the ASTM standard vibratory shake table and a typical jackhammer were used to impart vibratory compaction energy to the samples inside the mold, whereas the aggregate sample placed inside the box were compacted using a commercially available vibratory plate compactor. Both the mold and box configurations were used to test aggregate OGA samples corresponding to various thickness and compaction efforts. Finally, a full-scale test section was constructed in the field to correlate the box and mold test samples with the field test section results. Layer thickness is varied as well as the compaction effort. LWD tests was performed after each lift and compaction effort (Vibratory Drum Roller Compaction).

**Conclusions**

Major findings from the laboratory and field-testing efforts are as follows:

1. There was no significant difference between the results produced by the Olson and Zorn LWDs under the same compaction and testing conditions. Even considering the measurement precision difference between the LWD types, Olson & Zorn provided similar deflection both in laboratory and field.

2. Several external factors influenced the LWD measurement inside the custom/modified Proctor mold (e.g., mold support condition and contact between mold and the floor surface). Moreover, the LWD operator's testing style can also influence the test results. Accordingly, good contact between the LWD loading plate and aggregate samples is crucial for accurate measurement of LWD surface deflection.

3. For the OGA materials inside the customized mold, nine (9) “seating” drops were found to be adequate to ensure good contact between the LWD loading plate and aggregate surface. However, while testing in the wooden box or in the field, six (6) “seating” drops were

sufficient to establish adequate contact between the loading plate and the aggregate layer surface.

4. As compaction effort was increased, the relatively smaller ASTM #57 aggregate achieved better packing compared to the coarser ASTM #4 aggregate. This is expected as the ASTM #4 matrix has a significantly low number of smaller particles that can provide a “stabilizing” effect to the aggregate matrix. Unless very high confining pressures are applied, coarse-grained particles rarely achieve “tight” packing. This clearly explains the variability in the LWD test results.

5. Excessive compaction did not improve the packing conditions in either aggregate material. In fact, the aggregate matrix for the coarser ASTM #4 was ‘destabilized’ under excessive compaction. In fact, there are some compactors used in construction practice that have indicator lights to avoid over-compaction in the field. From the box, the surface deflection value significantly decreased after one pass of the vibratory compactor; however, the reduction was not significant when additional vibratory compaction effort was applied. The value slightly increased with the third pass, indicating the aggregate matrix's destabilization due to excessive compaction.

6. For the ASTM #57 and ASTM #4 aggregate materials, 5 seconds of jackhammer pre-compaction inside Proctor molds (both conventional as well as customized) was sufficient to achieve maximum packing. Based on results on the custom-made larger mold, it was observed that compaction in layers (application of vibratory compaction on 100 mm or 4-in. compaction lifts) resulted in more consistent deflection trends compared to the case where the mold was completely filled before the vibratory compaction was applied. This may have some implications on the maximum lift thickness in the field before compaction can be applied.

Similarly, in the field, it was observed that staged construction reduced the surface deflection significantly.

7. Underlying layer stiffness plays a vital role to the achieved compaction level of any layer if the compaction energy is kept constant.

8. From the pressure cell data in the box, the pressure level at a particular elevation did not change significantly after different number of passes of the vibratory plate compactor. A major portion of the stress levels applied to the top of the aggregate layer (through the LWD drop) was dissipated within the top 3 to 6 in. of the layer. The reduction of pressure level with the depth was not significant beyond this. The pressure dissipation within the OGA layer formed a "cylindrical" pattern unlike the "conical" pressure dissipation pattern observed in dense-graded aggregate layers. Even when the aggregate layer was reinforced using geocells, the pressure dissipation pattern did not change significantly.

9. For the subgrade layer in the field, seating drops were not needed before LWD testing. Adequate contact between the loading plate and the subgrade layer could be established from the beginning, ensuring consistent measurements with each drop.

10. For unreinforced base/subbase layers constructed with OGA materials, the LWD-measured surface deflections were not significantly affected by the type of aggregate material; rather, the surface deflections were significantly affected by layer thickness.

11. When geotextiles were used at the subgrade-subbase interface, the LWD-measured surface deflections reduced with increasing layer thickness. When no geotextiles were used at the subgrade-subbase interface, an exception to this trend observed due to penetration of aggregate particles into the subgrade layer. The difference between the measured surface deflection with or without geotextile reduced significantly with increasing layer thickness,

especially when the layer thickness was increased beyond 10 in. (254 mm), and construction was carried out in lifts.

**Recommendations for Implementation**

This section provides overall recommendations concerning the implementation of research findings from the current study. These recommendations can guide subsequent development of a deflection-based compaction control protocol for OGA base/subbase layers, particularly, the ones used underneath permeable block pavements.

1. *Device Agnostic:* As the surface deflection measurements from the two LWD types used in the current study were consistently close to each other, it is safe to assume that LWD-based surface deflection measurements on OGA layers is device-agnostic. Therefore, any deflection-based compaction control protocol to be developed for such layers can allow the use of any commercially available LWD device. However, it is important to note that due to irregularities in the OGA layer surface, it is important for the LWD to measure the deflection of the plate as a whole. The deflection measurement should not be point-based (for example, using a sensor protruding through the center of the loading plate). OGA layer surfaces are non-uniform, and point-based measurements can lead to significant errors due to movement/reorientation of individual particles.

2. *Laboratory Testing Mold Size:* From the laboratory testing in Proctor molds, it was concluded that the conventional Proctor mold (6-in. diameter) is not adequate for testing of such coarse-grained materials. The custom-made Proctor mold (D = 12in. & H = 11.5 in.) yielded results similar to the field, especially when a vibratory shake table was used to compact the samples. Agencies can use such a set-up in the laboratory to get a close picture of the overall compaction behavior of different OGA materials. However, the authors acknowledge that the

availability of a custom-made mold or a vibratory shake table may not be a trivial matter for all agencies.

3. *Application of "Seating" Drop:* Due to the uneven nature of OGA layer surface, seating drops become extremely critical before consistent surface deflection measurements can be accomplished using LWDs. While testing in the custom-made mold at least nine (9) seating drops were required. This was because of the confined nature of the mold, and 'reflection' of the stress pulses from the mold boundaries. However, in the in the field, it was observed that six (6) seating drops were sufficient to ensure adequate contact between the LWD loading plate and the OGA layer surface. It is recommended that after the six (6) seating drops, six (6) measurement drops should be used, and the average surface deflection values from the six measurement drops should be reported. It is also important to track the CoV for the six measurement drops. For a well-compacted layer, the CoV should be less than 20%.

4. *Compaction Method and Time (in Laboratory):* If an agency is to use a custom-made mold to perform preliminary testing to establish target deflection values, it is recommended that a vibratory shake table be used. As reported earlier, 10 seconds vibratory shake table compaction (at 80 Hz) replicated one pass of a vibratory smooth-drum roller, whereas 40 seconds of compaction replicated two passes of the roller. The authors acknowledge that these values are not universal and can change significantly on the type or roller being used in the field as well as the layer depths. Nevertheless, some idea could be obtained about the expected LWD-measured surface deflection values for well-compacted OGA layers.

5. *Geotextile Effect:* For OGA layers less than 10-in. in thickness, placement of a geotextile at the subgrade-subbase interface resulted in higher surface deflections during LWD testing. Therefore, unless the site conditions absolutely require, the use of geotextile is discouraged

for OGA layers less than 10-in. in thickness. For layers thicker than 10 in. (254 mm), no significant difference was observed for layers with or without the geotextile separation layer.

6. *Staged vs Direct Lift Construction:* Staged construction provided better compaction to the OGA layers compared to direct-lift construction, as observed from the lower surface deflection measurements. Therefore, it is recommended that OGA layers thicker than 8 in. (203 mm) should be constructed using a staged approach, rather than using a direct lift.

7. *Recommended Deflection-Based Compaction Control Protocol*

   For the ASTM #4 aggregate material, for a 12-in. thick aggregate layer, the minimum surface deflection achieved after 2 passes of vibratory roller compaction was 0.689 mm. It is possible that the surface deflection will further reduce upon application of a third roller pass. However, based on results from the current study, it is not likely that the surface deflection will reduce below 0.50 mm or 500 μm, which is the current standard used by the Interlocking Concrete Pavement Institute (ICPI). For the ASTM#57 material, for a 12-in. thick layer, the minimum surface deflection achieved after 2 passes of vibratory roller compaction, is 0.735 mm. Once again, this value may be further reduced upon a third pass of the vibratory roller.

   Nevertheless, based on results from the current study, it is recommended that the target surface deflection should be changed to less than or equal to 0.6 mm (600 μm). From extensive laboratory and field testing, the research team strongly believes that an OGA layer with LWD-measured surface deflections less than or equal to 0.6 mm (600 μm) represents an adequate packing condition.

**Limitations & Recommendation for Future Research**

1. The research study is limited to the use of only Two types of aggregate gradation. Compaction behavior for other gradations need to be investigated for the compaction & testing method recommended in this study.
2. This study was limited to standard LWD drop weight, but there are options for drop weight increment to some LWD devices like Olson. If higher drop weight is used, the influence zone by the drops will be larger. Although the intermediate scale lab testing is done inside of a wooden box, it is recommended to use a non-deformable box bottom for future research to confirm a stiff boundary. However, this study did not measure any possible lateral expansion of the wooden box during placement and compaction of the aggregate layers. Measurement of the lateral movement of the side boundary can be incorporated in the future research.
3. Coming up with a standard compaction protocol requires a lot of field testing with the variation in testing location, aggregate type, and operator of the LWD. A discrete element based numerical study can make this task easier. So, simulation of the mold and aggregate in the modeling can be beneficial to explore the compaction behavior under LWD loading for a huge number of varied conditions.
4. In the field, it is hard to control the amount of fine particles. They can come into the base/subbase layer from the different sources. Once the amount of fine particle increases, there will be effect of moisture to the compaction level. So, the effect of fine particles on the compaction behavior in terms of LWD measured surface deflection needs to be investigated in the laboratory.
5. This study was limited to use two types of compaction method in the lab. An extensive study needs to be caried out to establish a relation between the compaction method in terms of time or so. A statistical model can be developed to find this correlation.

## REFERENCES


AASHTO T 191, (2014). Standard Method of Test for Density of Soil In-Place by the Sand-Cone Method. Standard Specifications for Transportation Materials and Methods of Sampling and Testing, And AASHTO Provisional Standards, 2014 edition, Washington, D.C.

AASHTO T 310-19, (2019). Standard Specification for In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth). Standard Specifications for Transportation Materials and Methods of Sampling and Testing, And AASHTO Provisional Standards, 2019 edition, Washington, D.C.

Afsharikia, Z. (2019). MODULUS BASED COMPACTION QUALITY ASSURANCE FOR UNBOUND MATERIALS USING LIGHTWEIGHT DEFLECTOMETER. 229.

ASTM D1556-15, (2015). Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method. Annual Book of ASTM Standards, Vol. 04.03, ASTM International, West Conshohocken, PA

ASTM D6938-17a, (2017). Standard Test Methods for In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth). Annual Book of ASTM Standards, Vol. 04.03, ASTM International, West Conshohocken, PA

ASTM E2583-7, (2007). Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD). Annual Book of ASTM Standards, Vol. 04.03, ASTM International, West Conshohocken, PA

ASTM E2835-11, (2011). Standard Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device. Annual Book of ASTM Standards, Vol. 04.03, ASTM International, West Conshohocken, PA

Benz, M.,2009. Mesures Dynamiques Lors du Battage du Pénétromètre Panda 2 (Doctor of Philosophy Dissertation). University Blaise, France.

BS 1924-2, (2018). Hydraulically bound and stabilized materials for civil engineering purposes: Sample preparation and testing of materials during and after treatment. BSI Standards Publication.

Cho, Y., Kim, Y., Kabassi, K., Zhuang, Z., Im, H., Wang, C., & Bode, T. (2011). Non-nuclear method for density measurements (No. SPR1 (10) P335). Lincoln, NE: Nebraska Department of Roads, Report SPR1 (10).

Choi, Y.-J., Ahn, D., Nguyen, T., & Ahn, J. (2018). Assessment of Field Compaction of Aggregate Base Materials for Permeable Pavements Based on Plate Load Tests. Sustainability, 10(10), 3817.

D.J. White, P.K.R. Vennapusa, and M.J. Thompson. (2007). Field Validation of Intelligent Compaction Monitoring Technology for Unbound Materials. Technical report, Center for Transportation Research and Education, Iowa State University.

Embacher, R. (2008). “LWD Fundamentals”. 12th Annual Minnesota Paving Conference, St. Paul, Minnesota, February 2008.

Frost, M. W., Fleming, P. R., Gordon, M., and Edwards, J. P. (2010, August). Pavement foundation stiffness testing–a new regime. In Proceedings of the Institution of Civil Engineers-Transport (Vol. 163, No. 3, pp. 119-125). Thomas Telford Ltd.

Jibon, M., & Mishra, D. (2021). Light Weight Deflectometer Testing in Proctor Molds to Establish Resilient Modulus Properties of Fine-Grained Soils. Journal of Materials in Civil Engineering, 33(2), 06020025.

Kleyn, E. G; Savage P. F. The Application of the Pavement DCP to determine the Bearing Properties and Performance of Road Pavements. The International Symposium on Bearing Capacity of Roads and Airfields, Trondheim, Norway, June 1982.

KP George, Mississippi. Dept. of Transportation. Research Division, University of Mississippi. Dept. of Civil Engineering, and Portland Cement Association. Portable FWD (Prima 100) for In-situ Subgrade Evaluation. University of Mississippi, 2006.

Lamas-Lopez, F., Cui, Y. J., and Calon, N. (2016). Geotechnical auscultation of a French conventional railway track-bed for maintenance purposes. Soils and Foundations, 56(2), 240-250.

Li, H., Jones, D. Wu, R., and Harvey J, (2014), Development and HVS Validation of Design Tables for Permeable Interlocking Concrete Pavement: Final Report, University of California Pavement Research Center, UCPRC-PP-2011-01

M.A. Mooney and P.K. Miller. (2009) Analysis of Lightweight Deflectometer Test Based on In Situ Stress and Strain Response. Journal of Geotechnical and Geoenvironmental Engineering, 135:199

Nazarian, S., Mazari, M., Abdallah, I. N., Puppala, A. J., Mohammad, L. N., & Abu-Farsakh, M. Y. (2015). Modulus-based construction specification for compaction of earthwork and unbound aggregate. Washington, DC: Transportation Research Board.

Nazarian, S., Mazari, M., Abdallah, I., Puppala, A. J., Mohammad, L. N., and Abu-Farsakh, M. Y. (2014). Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate. NCHRP Project 10-84.

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

Ratul Mondal, Md. Fazle Rabbi, David Smith, Debakanta Mishra, (2022). Compaction studies on open-graded aggregates using portable impulse plate load test devices, Construction and Building Materials, Volume 327,2022,126876, ISSN 0950-0618

Rowshanzamir, M. A. (1995). "Resilient Cross Anisotropic Behavior of Granular Base Materials Under Repetitive Loading". Ph.D. Dissertation. University of New South Wales, Australia.

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

Schuettpelz, C. C., Fratta, D., Edil, T. B., (2010), "Mechanistic Corrections for Determining the Resilient Modulus of Base Course Materials Based on Elastic Wave Measurements," Journal of Geotechnical and Geo-environmental Engineering, Vol. 136, No. 8

Schwartz, C. W., Z. Afsharikia, and S. Khosravifar (2017). "Standardizing Lightweight Deflectometer Modulus Measurements for Compaction Quality Assurance". Report No. MD-17-SHA/UM/3-20, Maryland Department of Transportation State Highway Administration.

Shafiee, M., Nassiri, S., Khan, R.H., Bayat, A., (2011). Evaluation of New Technologies for Quality Control/Quality Assurance of Subgrade and Unbound Pavement Layer Moduli.

Smith, D. R., R. Bowers, and G. Aicken (2018). “The Lightweight Deflectometer (LWD) as an Acceptance Tool for Compacted Open-Graded Aggregates in Permeable Pavements”. Proceedings of the 12th International Conference on Concrete Block Pavement; Oct. 16 19, 2018, Seoul, Korea.

Smith, D.R. (2017). Permeable Interlocking Concrete Pavements, 5e. Interlocking Concrete Pavement Institute (ICPI).

Staatsministerium, Bayerischen, (2012). Dynamic Plate-Load Testing with the Aid of the Light Drop-Weight Tester. TP BF-StB Part B 8.3.

Tamrakar, P., and Nazarian, S., (2019). Permanent Deformation and Stiffness of Fouled Ballast Based on Static and Impact Load Tests. GAP 2019 Proceedings, Colorado Springs, CO.

Terzaghi, K., Peck, R. B., and Mesri, G. (1996). Soil mechanics in engineering practice. John Wiley and Sons.

Titi, H. H. (2012). Base Compaction Specification Feasibility Analysis. Wisconsin Highway Research Program

Tompai, Z.,(2008). Conversion between static and dynamic load bearing capacity moduli and introduction of dynamic target values. Period. Polytech. – Civil Eng.52,97–102.

Tutumluer, E., and U. Seyhan, U. (1998). “Neural Network Modeling of Anisotropic Aggregate Behavior from Repeated Load Triaxial Tests”. In Transportation Research Record: Journal of the Transportation Research Board, No. 1615, Transportation Research Board of the National Academies, Washington, D.C., pp. 86-93.

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

Woodward, P.K., Kennedy, J., Laghrouche, O., Connolly, D.P., Medero, G., (2014). Study of railway track stiffness modification by polyurethane reinforcement of the ballast. Transp. Geotech. 1,214–224 Elsevier Ltd.

Zhao, G., Yao, Y., Li, S., & Jiang, Y. (2018). Maximum Allowable Deflection by Light Weight Deflectometer and Its Calibration and Verification.

# APPENDICES

## PHOTOGRAPHIC RECORD OF THE CONSTRUCTION

Unprepared Subgrade

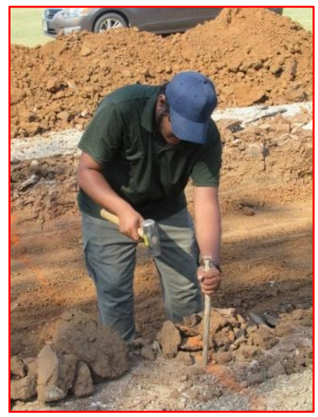
Soil Sample Collection for Laboratory Testing

Removal of Grass, Weeds

Soil Excavation

Leveling of Soil by Backhoe Loader

Leaser Level Instrument



Base-Line Marking

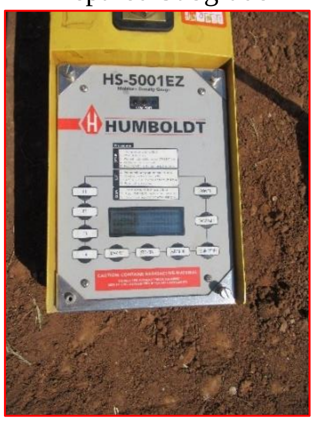
Indication Test cells and Transition zone by Metal Rod

Depth Checking from Baseline

Compacting Subgrade

Prepared Subgrade

DCP Testing




Nuclear Density Gauge

Nuclear Density testing

Geotextile Placement

Zorn LWD Testing on Subgrade

Zorn lab LWD Testing on Subgrade

Aggregate Placement and Depth Check

Compaction of $1^{st}$ 4in Lift

LWD Testing on $1^{st}$ Lift after Compaction

Preparing Other Test cells for Aggregate Placement


Aggregate Placement

Compaction After 2nd 6in Lift

LWD Testing after 2nd Lift (Olson)

LWD Testing after 3nd Lift (Zorn)

Zorn testing Plate

Olson Testing Plate

LWD Testing after 3nd Lift (Olson)

Placement of 4th Lift (4in ASTM#4)

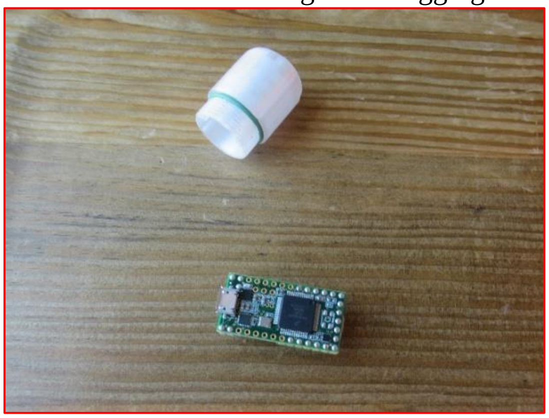
LWD Testing after 4th Lift and Compacting it


Test Cell Marking

Transportation of the Excavated Soil

Used Single Steel Drum Vibratory Compactor

Breaking of the Aggregate Particle due to Over Compaction



Smart-Rock

Smart-Rock Instrumentation

Finished Subbase and Base

# VITA

Ratul Mondal

Candidate for the Degree of

Master of Science

Thesis: COMPACTION STUDIES ON OPEN-GRADED AGGREGATE MATERIALS: MOVING TOWARDS DEFLECTION-BASED COMPACTION CONTROL

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Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December 2022.

Completed the requirements for the Bachelor of Science in Civil Engineering at Bangladesh University of Engineering & Technology, Dhaka, Bangladesh in 2018.

Experience:

- 1.5+ years’ experience in Geotechnical Engineering and Project Management
- Experienced in testing Aggregate and Soil in laboratory
- Experienced in Asphalt Testing and Mix Design
- Shop and safety skills honed from lab as a research assistant
- Strong organizational and team collaboration skills. Collaborated with graduate students and undergraduate assistants to achieve project goals