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Experimental Analysis of Aggregate Densities and Deflections for Compaction Quality Control with Light Weight Deflectometer

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Abstract

Nuclear gauge has been widely used to determine the in-place dry densities of pavement layers in compaction quality control. However, there is a trend for transportation agencies to use light weight deflectometer (LWD) to measure compaction sufficiency of pavement construction. LWD measurement can provide the in-situ modulus of geomaterials that is one of the key parameters used to characterize the properties of pavement structural layers. Since the measurements of nuclear gauge (density) and LWD (deflection) are different, it is necessary to analyze their relationships with compaction properties, such as moisture content, layer thickness, and construction condition. This study performed intensive laboratory experiments on the aggregate materials to evaluate the effects. Extensive experiments were also performed in the test pits with LWD to determine the effect of aggregate layers on pavement structure. Proctor tests were conducted on selected pavement base materials to establish the moisture-density relationships. Material deflections were also measured on the compacted materials in the Proctor molds to reveal the moisture-deflection relationships. Through the test pits experiments, the contribution of each aggregate layer to the pavement structure capacity was analyzed and quantitated. It was concluded that moisture content has a significant effect on LWD deflection or modulus. Aggregates compacted near the optimum moisture are capable of providing a stable deflection value. After compaction, LWD measured deflection decreases as the moisture content decreases.

Keywords

LWD, Compaction, Moisture Content, Dry Density, Deflection

1. Introduction

Light weight deflectometer (LWD) is designed to measure the compaction quality of a structural layer (Umashankar et al., 2016; Kavussi et al., 2019). However, the measured deflection and modulus are affected by the underlying structural materials. The measured modulus is the modulus of the entire structural system, rather than the modulus of the compacted top layer. Therefore, the effects of the materials below the compacted top layer should first be analyzed to accurately measure the modulus of the compacted material in the top layer with LWD. In this study, Proctor tests were conducted on selected pavement base materials to establish the moisture-density relationships. Material deflections were also measured on the compacted materials in the Proctor molds to reveal the moisture-deflection relationships. According to the pavement engineers of the Indiana Department of Transportation (INDOT), the No. 53 aggregate has been the major type of granular materials with specified gradations for subgrade treatment, and granular base and subbase for Portland cement concrete pavement and hot mix asphalt (HMA) pavement in Indiana. Therefore, the main effort of the laboratory experiments was focused on the properties of the No. 53 aggregates relatedto the construction quality, including gradation, optimum moisture content, maximum dry density, deflection, and modulus. In addition, some other materials recently used for road construction, such as No. 43 aggregate, steel slag, and recycled asphalt pavement (RAP), were also tested to provide first-hand data and baseline information. In additionto the indoor Proctor-LWD experiments, outdoor test pits were designed and constructed to simulate the real pavement structures. Through the test pits experiments, the contribution of each aggregate layer to the pavement structure capacity was analyzed and quantitated.

2. Laboratory Experiments of Material Modulus

2.1. Gradations of the Sample Materials

No. 53 aggregates samples, denoted as No. 53A and No. 53B, were obtained from two different suppliers for this study as shown in Figure 1. The information on the materials from the suppliers includes gradations, optimum moisture contents, and maximum dry densities. Table 1 presents the gradations provided by the suppliers of the two samples along with the INDOT gradation specifications (INDOT, 2017). The given gradations of the material samples were within the INDOT specified ranges and, therefore, satisfied the requirements of the gradation specifications. Sieve analyses were conducted with the two material samples. The results of the sieve analyses as well as the gradations given by the suppliers are also presented in Table 1. It is shown that the actual gradations were very close to those provided by the suppliers. Therefore, both No. 53A and No. 53B aggregates meet the standard specifications.


(a) No. 53A (b) No. 53B

Fig. 1. Two Samples of No. 53 Material

Table 1. Gradations and Specifications for No. 53 Aggregates

Sieve Size	% Passing Sieve Size				
	No. 53A		No. 53B		INDOT Specification
	Supplier	Test	Supplier	Test	
1½" (37.5mm)	100.0	100.0	100.0	100.0	100
1" (25 mm)	90.9	90.7	91.3	94.0	80 - 100
¾" (19 mm)	79.2	79.7	80.7	84.3	70 - 90
½" (12.5 mm)	66.0	66.0	64.0	66.5	55 - 80
3/8" (9.5 mm)	58.7	60.6		59.4	
#4 (4.75 mm)	47.1	51.6	39.6	39.4	35 - 60
#8 (2.36 mm)	33.1	35.4	29.5	29.4	25 - 50
#30 (0.6 mm)	14.5	14.0	16.0	17.7	12 - 30
#200 (0.075 mm)	8.9	8.1	10.0	10.0	5 - 10

2.2 Maximum Dry Density and Optimum Moisture Content

The optimum moisture content and the corresponding maximum dry density of a soil mixture are the most important values for achieving the desired compaction. These values provided by the suppliers of No. 53A and No. 53B are shown in Table 2. The given optimum moisture content and maximum dry density for No. 53A are 8.9% and 134.2 pcf, and those for No. 53B are 10.9% and 127.8 pcf. To analyze the relationships between the degree of compaction and LWD measurements, Proctor tests were performed to establish the moisture-density relationships for No. 53A and No. 53B materials. Notice that the AASHTO Designation T 99 Method D (AASHTO, 2017) was chosen for the

Proctor tests. This method is applicable to the materials with a maximum of 30% of the particles retained on the 19.0 mm (3/4 in.) sieve. As illustrated in Table 1, the No. 53A aggregate sample contained 20.3% of the particles greater than the sieve size of 19.0 mm (3/4 in.) according to the lab sieve analysis. The No. 53B aggregate sample had 15.7% of the particles greater than the sieve size of 19.0 mm (3/4 in.).

Table 2. Proctor Test Results for No. 53 Aggregates by Suppliers

Proctor Test Value	**Aggregate Sample**	
	No. 53A	**No. 53B**
Optimum Moisture Content	8.9%	10.9%
Maximal Dry Density	134.2 pcf	127.8 pcf

With Method D of the AASHTO Designation T 99, all aggregate particles larger than the sieve size of 19.0 mm (3/4 in.) is defined as oversized material. Therefore, a correction may be necessary if the oversize material is above a certain percentage specified by the agency. If the agency does not specify such a percentage, it is recommended that a correction be made when more than 5 percent by weight of oversize particles is present (NDDOT, 2015). Since INDOT did not have the specified the percentage of oversize material, according to the recommended 5 percent criteria, corrections were necessary for both No. 53A and No. 53B materials. The correction method for Method D of the AASHTO Designation T 99 is specified as the AASHTO Designation T 224 (AASHTO, 2010). Correction tests were conducted for the two No. 53 aggregate samples to adjust the densities to compensate for oversize coarse particles that were greater than the sieve size of 19.0 mm (3/4 in.). Presented in Figures 2 and 3 are the original and corrected Proctor curves for both the No. 53A and No. 53B aggregate samples, respectively.

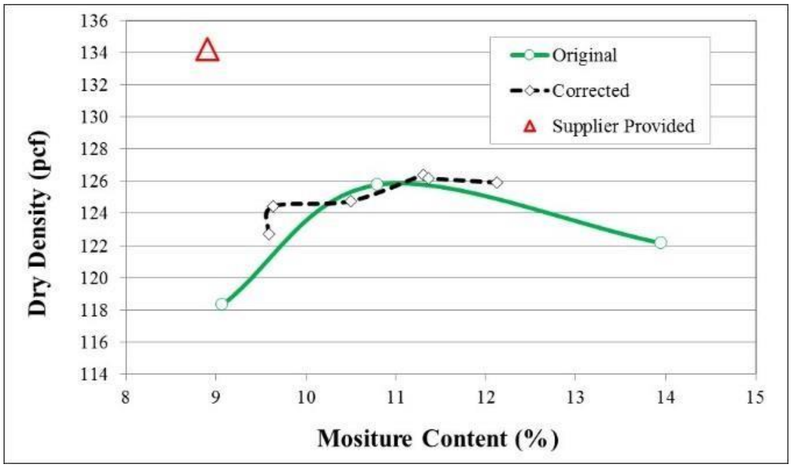


Fig. 2. Original and Corrected Moisture-Density Curves for No. 53A

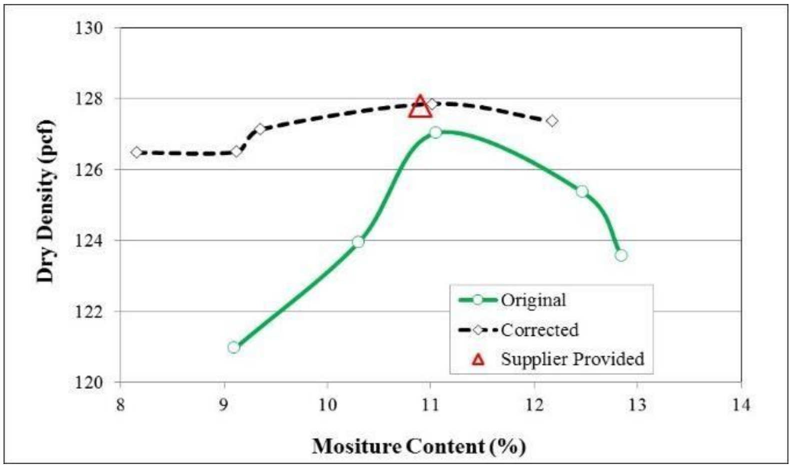


Fig. 3. Original and Corrected Moisture-Density Curves for No. 53B

It is shown that for No. 53A aggregates, the original maximum dry density and optimum moisture content were 125.8 pcf and 11.2%, while the corrected maximum dry density was 126.3 pcf and the corrected optimum moisture content was 11.4%. The corrected values were both slightly higher than their corresponding original values. For No. 53B aggregates, the original maximum dry density and optimum moisture content were 127.0 pcf and 11.1%, while the corrected maximum dry density was 127.9 pcf and the corrected optimum moisture content was 11.0%. The corrected values were very close to the original values. Therefore, the differences between the original and corrected maximum densities and between the original and corrected optimum moisture contents for both materials were not significant for practical applications. For comparison, the moisture contents and dry densities provided by the two suppliers are also presented in Figures 2 and 3. It is apparent that the laboratory results and the supplier provided values are quite different for No. 53A aggregates. For No. 53B aggregates, however, the optimum moisture content and the maximum dry density from the supplier are very close to those from the laboratory tests.

Table 3 summarizes all the moisture and density values from the suppliers and from the laboratory tests for both No. 53A and No. 53B aggregates. Comparing No. 53A and No. 53B aggregates, the laboratory tests, original or corrected, yielded very similar values of optimum moisture contents and maximum dry densities of the two material samples. Also, as presented in the sieve analysis results, the gradations of No. 53A and No. 53B aggregates were also similar. It was therefore justified to use either No. 53A or No. 53B to represent No. 53 material in the experiments and analysis. Therefore, only No. 53A was utilized to perform other experiments and analysis henceforth. The material would then be denoted as No. 53, rather than No. 53A, as presented in the remaining sections of this chapter.

Table 3. Supplier Provided and Laboratory Moisture-Density Values

Sample	**Optimum Moisture Content**			**Maximum Dry Density**		
	Supplier Provided	**Original (T 99-D)**	**Corrected (T 224)**	**Supplier Provided**	**Original (T 99-D)**	**Corrected (T 224)**
No. 53A	8.9%	11.2%	11.4%	134.2 pcf	125.8 pcf	126.3 pcf
No. 53B	10.9%	11.1%	11.0%	127.8 pcf	127.0 pcf	127.9 pcf

2.3 Laboratory Testing of Material Densities and Deflections

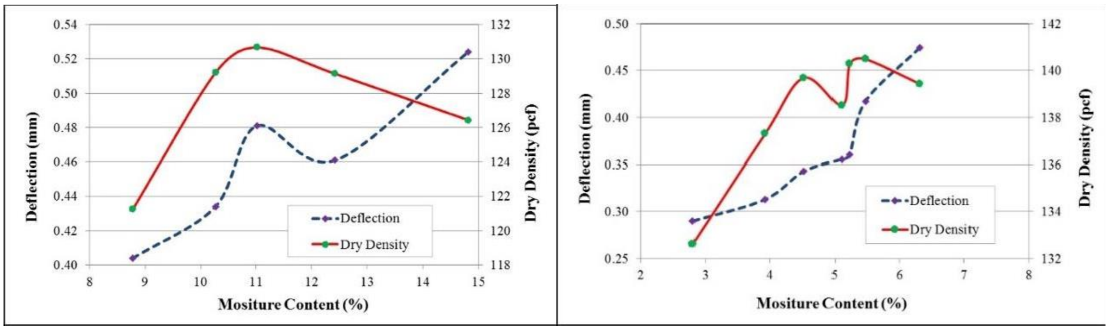
To establish the relationship between optimum moisture content and LWD measurement, a series of laboratory tests were conducted. In addition to No. 53 aggregates, some other types of materials, including No. 43 material, steel slag aggregate, and reclaimed asphalt pavement (RAP), have also been utilized in pavement bases in Indiana. The samples of these materials were obtained and used in the laboratory experiments for modulus analysis. As it is well known, for a given compaction effort, a soil's dry density will increase to a peak point as the moisture content of the soil increases and then the dry density will decrease if the moisture content further increases beyond the peak point of the dry density. A moisture-density curve of a soil from the Proctor test is typically a bell-shaped curve. The bell shape of the moisture-density curve is usually more apparent for clayey soils. Therefore, a clay sample was also included in the laboratory tests because of its typical plastic moisture-density relationship and its widespread existence in pavement subgrade in Indiana.

Like the study by Schwartz, et al. (2017), an aggregate sample was first compacted confirming to the AASHTO standard Proctor method, and then, the LWD measurements were made directly on the compacted sample in the Proctor mold. Figures 4 demonstrates the Proctor compaction and LWD measurement during the laboratory experiment. The deflections were measured six times on the material sample in the mold with the LWD. The first three deflection values were discarded and the average of the last three of the six deflection values were calculated as the measured deflection. The device was a Zorn LWD with a 5 kg drop weight and a 150 mm diameter base plate.

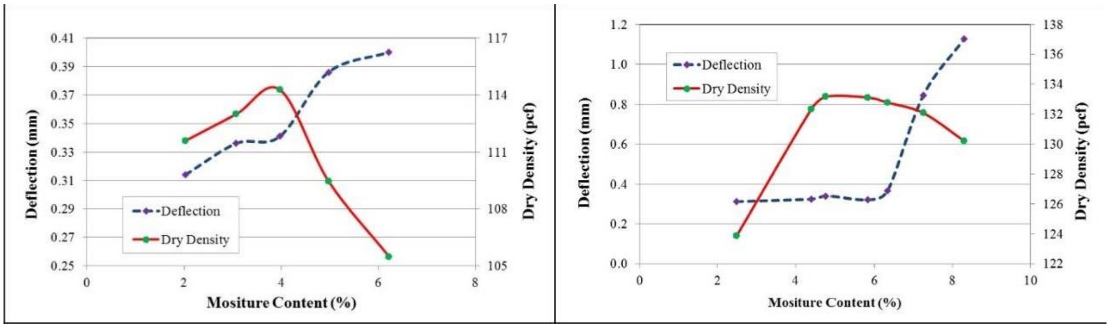
(a) Proctor Compaction (b) LWD Test in Mold

Fig. 4. Photos of laboratory LWD testing

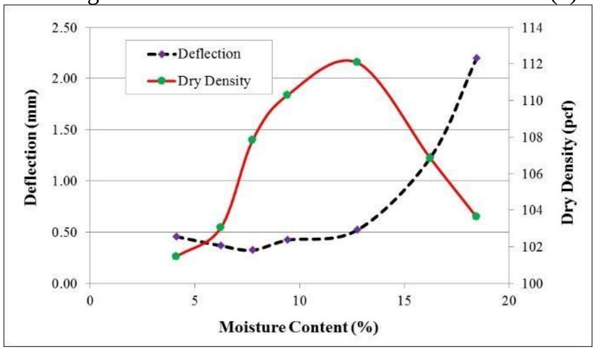
The main purpose of the LWD measurements over Proctor compacted materials was to reveal the change patterns of deflections and moisture contents in comparison with the moisture and density relationships. Plotted in Figure 5 are the moisture-density curve and the moisture-deflection curve for No. 53, No. 43, steel slag, RAP, and clay samples. It was expected that the changes of deflections and densities would have an inverse relationship so that as density increases the deflection decreases and vice versa. As shown in Figure 5, however, the materials do not demonstrate the inverse correlations between density and deflection. Only RAP and clay materials show slight deflection declines and reached a minimum deflection value as density increases within a limited range. In general, the materials exhibited a common pattern that as moisture content increases the deflection increases. It is indicated that the moisture content plays important but different roles in densities and deflections. Different from the well-known bell-shaped moisture-density relationship, the moisture-deflection relationships do not commonly show an optimum moisture content at which the deflection would be at a turning point. Therefore, the results of the laboratory experiments imply that a minimum deflection might not exist in terms of different moisture contents. This is because aggregate modulus increases as density increases, moisture content decreases, and aggregate interlocking increases. Compaction increases soil density and interlocking by reducing the voids in a soil with permanent deformation, while deflection is induced by an instant LWD impact with recoverable deformation.



(a) No. 53 aggregate (b) No. 43 aggregate



(c) Steel slag (d) RAP



(e) Clay soil

Fig. 5. Moisture, dry density, and deflection relationships for different materials

An important implication of the moisture-density and moisture-deflection relationships is that a range of moisture contents must be specified when establishing the maximum allowed LWD deflection value to effectively control compaction quality. Therefore, during construction, compaction should be performed when the moisture content is at or close to the optimum moisture content and the LWD deflections should be made as soon as the compaction is completed or before the moisture content decreases beyond the specified range. That is, it should not be allowed to measure LWD deflections on compacted layer after the moisture content has dropped below the specified range of moisture contents.

2.4 Effect of Moisture Content on Modulus

Moisture content is one of the important factors affecting the degree of compaction of geomaterials. In the traditional moisture-density controlled compaction process, a layer of pavement material is compacted at the optimum moisture content until the dry density of the material has reached the specified value. To examine the effect of moisture content on the modulus of geomaterial, laboratory tests were conducted to measure LWD deflections on the compacted materials at different moisture contents.

Two sets of the laboratory experiments were performed to reveal the change patterns of modulus at different moisture contents under compaction. The first set of the laboratory experiments was to compact the material specimen in Proctor mold at the optimum moisture content and to measure the deflection of the compacted specimen immediately after the compaction. After the first measurement with LWD, the specimen was placed in an oven at 230°F for 30 minutes and then deflection was measured, and the moisture content was determined. This process was repeated until the specimen was completely dried. The second set of the laboratory was to compact material at a moisture content in Proctor mold and to measure the deflection on the compacted specimen. This laboratory was conducted on six material specimens of different moisture contents to obtain the corresponding deflections. The measured deflections were all converted to moduli with the following equation.

$$E = \frac{Hq}{d}\left(1 - \frac{2\mu^2}{1-\mu}\right) \quad (1)$$

Where, E = material modulus; H = specimen height; q = LWD measured pressure; d = LWD measured vertical deflections; μ = Poisson's ratio.

Because a range of Poisson’s ratio μ=0.1 to 0.4 is recommended in the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2015), μ=0.3 was selected to calcuate the modului from the LWD measured deflections. Plotted in Figures 6 and 7 are the results of the laboratory experiments for No. 53 and No. 43 aggregates, respectively. The first observation from the two charts is that, for both No. 53 and No. 43 materials, after the material was compacted at the optimum moisture content the modulus increased considerably as the moisture content was reduced each time. This phenomenon may have some significant practical implications in compaction quality control with LWD devices. The practical meanings of compaction quality control with LWD would include: 1) Compaction must be performed at the optimum moisture content to achieve sufficient dry density; and 2) LWD deflection or modulus must be measured within a limited time window after compaction to obtain meaningful deflection values pertinent to the degree of compaction. The second observation from the laboratory results is that No. 53 and No. 43 reflected differently to the changes of moisture contents in terms of moduli when the materials were compacted at different moisture contents. The modulus of No. 53 remained relatively stable at different moisture contents. On the other hand, the modulus of No. 43 material increased noticeably as the moisture content decreased. The different patterns of the two materials indicate that the coarser material (No. 43) was more sensitive to the moisture content than the finer material (No. 53) with respect to LWD measured deflections or moduli.

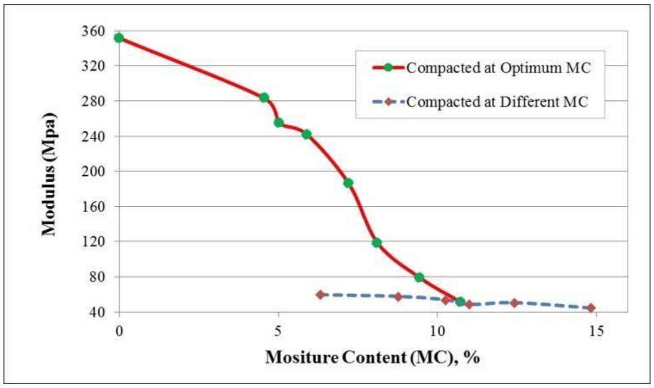


Fig. 6. Variation of Modulus with Moisture Content for No. 53 Aggregates

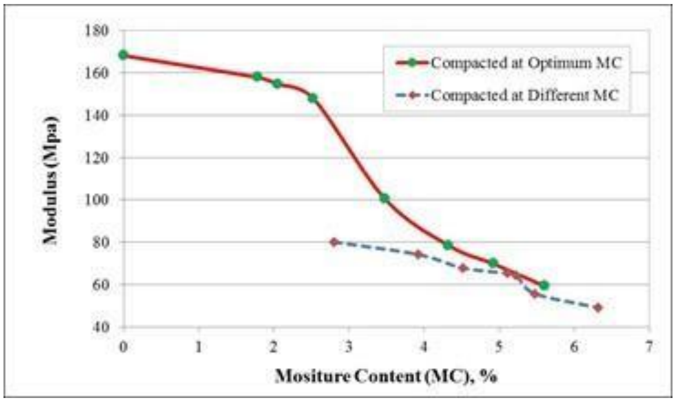


Fig. 7. Variation of Modulus with Moisture Content for No. 43 Aggregates

3. Test Pits Experiments of material deflections

Two 1m×1m×1m test pits were constructed to test the No. 53 and No. 43 aggregate materials. The soil in the bottom of the pit was first compacted before placing aggregates. The process of the experiment included the following steps (Figure 8): mixing water with the material, placing a layer of the material and compacting the layer with a jumping jack, leveling the layer, and measuring deflection at the center of the pit with LWD. To assure sufficient compaction at each layer, the moisture content of the material must be at or close to the optimum value and the material must be compacted at least two times and deflection must be measured after each compaction. If the difference between the two deflections is less than 0.01 mm, the compaction is considered satisfactory. Otherwise, additional compaction will be performed until the difference between deflections of two adjacent compactions is below 0.01 mm.

(a) Adding Water (b) Compaction

(c) Leveling (d) LWD Measurement

Fig. 8. Test Pit Experiment Process

The thickness of each layer was 6 inches for the No. 53 material and was 4 inches for the No. 43 material. The compaction and measurement process at each test pit was repeated until the test pit was full. The test results are illustrated in Figure 9. The two curves in the figure demonstrates different effects of the materials on the deflections or moduli as more materials were added to the structures. For No. 53, the deflection decreases as the structure thickness increases. It is apparent that the No. 53 material improves the overall stiffness of the structure. However, for No. 43, the deflection remains stable when as much as 8 inches of the material are added to the structure. That is, the No. 43 material would not contribute to the structural capacity during construction when the thickness of the material is less than 8 inches.

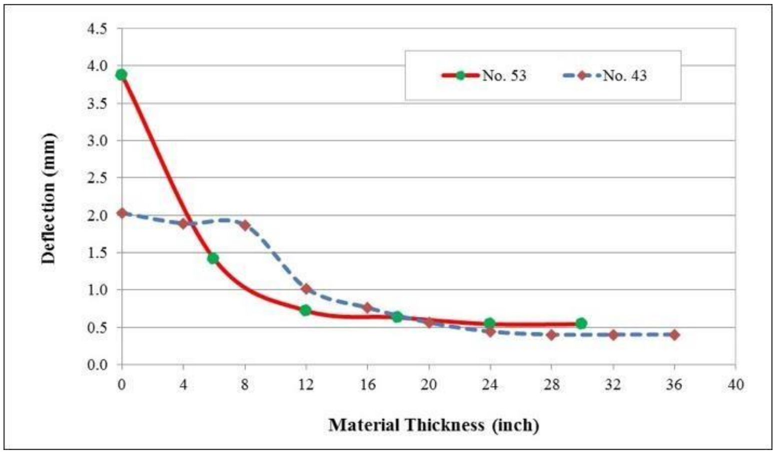


Fig. 9. Variation of Deflection with Layer Thickness in Test Pits

4. Conclusions

The Proctor test for aggregates was performed in accordance with the AASHTO Designation: T 99 by INDOT. Corrections may be necessary if the oversize material is above a certain percentage. However, the laboratory test results indicate that the differences between the original and corrected maximum densities and between the original and corrected optimum moisture contents for both materials were not significant for practical applications. Different from the well-known bell-shaped moisture-density relationship, the moisture-deflection relationships for aggregates did not show an optimum moisture content at which the deflection would be at a turning point. The results of the laboratory experiments imply that a minimum deflection may not exist in terms of different moisture contents. When compacted at the optimum moisture content, the modulus of aggregates increased considerably as the moisture content decreased. When compacted at a random moisture content, the modulus of No. 53 aggregates remained relatively unchanged, but the modulus of No. 43 aggregates increased noticeably as the moisture content decreased. Coarser aggregates are more sensitive to the moisture content than finer aggregates with respect to deflection or modulus. The results of LWD tests in the test pits indicate that No. 53 aggregates can contribute to the structural capacity, but No. 43 aggregates can only contribute to the structural capacity when its thickness is eight inches or more. The deflection decreased as the thickness of aggregate layer increased. As the layer thickness increased to a certain level, the deflection became stable.

References

AASHTO (2015). Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 2nd Edition, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AASHTO. (2010). AASHTO Designation: T 224-10. Standard Method of Test for Correction for Coarse Particles in the Soil Compaction Test. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AASHTO. (2017). AASHTO Designation: T 99-17. Standard Method of Test for Moisture-density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop. American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

INDOT. (2017). Standard Specifications. Indiana Department of Transportation (INDOT), Indianapolis, Indiana.

Kavussi, A., Qorbaninik, M., and Hassani, A. (2019). The Influence of Moisture Content and Compaction Level on LWD Modulus of Unbound Granular Base Layers. *Transportation Geotechnics*. https://doi.org/10.1016/j.trgeo.2019.100252

NDDOT. (2015). ND T 99 AND ND T 180: Moisture-density relations of soils. North Dakoda Department of Transportation (NDDOT), Bismarck, North Dakoda.

Schwartz, C., Afsharikia, Z., and Khosravifar, S. (2017). Standardizing Lightweight Deflectometer Modulus Measurements for Compaction Quality Assurance. Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland.

Timoshenko, S.P. and Gere, J.M. (1961). Theory of Elasticity, 2nd Edition. McGraw-Hill Publishing Company, New York.

Umashankar, B., Hariprasad, C., and Kumar, G.T. (2016). Compaction Quality Control of Pavement Layers Using LWD. *Journal of Materials in Civil Engineering*, ASCE. Vol. 28, Issue 2.