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The Lightweight Deflectometer (LWD) as an Acceptance Tool for Compacted, Open-graded Aggregates in Permeable Pavements

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Abstract

The most common permeable pavements used in the United States and Canada are porous asphalt, pervious concrete and permeable interlocking concrete pavement (PICP). These permeable pavements use open-graded aggregates for water storage, infiltration and structural support. Most compaction specifications indicate a specific number of passes with a roller compactor or a plate compactor exerting a specific force. The basis of acceptance is often no visible movement of the compacted aggregate. Other compaction guidelines specify attaining a minimum of 95% Proctor density. The former has no means to measure and verify the quality of the compacted aggregates. The latter is generally not measurable on an open-graded aggregate with a nuclear density gauge used in backscatter mode.

To address these limitions, a lightweight deflectometer (LWD) can be used to assess the stiffness of permeable pavement bases. Existing American Society for Testing and Materials International (ASTM) standards [1][2] and emerging American Association of State Highway and Transportation Officials (AASHTO) by Schwartz [3] provide draft standards on LWD use which enables them to be accepted by provincial and state departments of transportation. LWDs may eventually replace density measurements of compacted soils and dense-graded bases. Similarly, LWDs also offer a means to quickly measure the extent and variation in compaction of open-graded bases in permeable pavements.

This paper provides data from four construction sites where compacted ASTM No. 2 open-graded aggregate subbase and ASTM No. 57 base deflections were measured using an LWD. The data suggests ranges and acceptance criteria for bases used in permeable interlocking concrete pavements. These ranges are adopted into Interlocking Concrete Pavement Institute literature [4] and a national standard on permeable interlocking concrete pavement to be published by the American Society of Civil Engineers in 2018 [5]. LWDs can also be used to assess the compaction and stiffness of open-graded aggregate bases under porous asphalt, pervious concrete and for other permeable pavements.

Key Words: permeable pavement; lightweight deflectometer (LWD); open-graded aggregate base compaction and stiffness quality control/quality assurance

Background

With porosities typically between 20% and 40%, open-graded aggregates function as water storage reservoirs and as structural support for most permeable pavements. During construction, these aggregates must be compacted for stability and support. This is done with a roller compactor or a plate compactor. Unlike dense-graded bases, density cannot be accurately and consistently measured due to high variability of using the backscatter setting (rather than a probe) on nuclear density gauges.

Two ASTM test methods have been developed for LWDs. One has a geophone in the center of the LWD plate; the other does not. Use of a geophone depends on the material to be tested. If a monolithic, isotropic pavement

surface is being tested, the LWD with a geophone is used, often with additional geophones extending from the LWD plate to measure the deflection bowl. If a granular material such as soil or base is being tested, the LWD with a plate alone and no geophones are used. The ASTM test method for the geophone-type LWD is E2583 *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)*. The test method for the plate type LWD is E2835 *Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device*. The latter test method (and device) is preferred for testing open-graded stone because the 300 mm diameter plate (without a pin) seats on the surface of open-graded aggregate.

Figure 1 illustrates an LWD. A 10 kg weight drops down a 75 cm long shaft and hits the top of a 300 mm diameter plate. This simulates an 18 millisecond impact of a 24 kN truck tire traveling at 80 kph. An accelerometer measures the stiffness in kN/m^2 and deflection in millimeters. The 300 mm diameter plate typically covers many aggregate pieces while reading their deflection. A GPS provides location data as well.



Figure 1. LWD showing the weight, shaft, plate and data collection

ASTM D2835 requires the LWD operator to make three seating drops and then three more drops of the sliding weight on the circular plate. The average deflection of the last three drops is considered the measured deflection. A question with measuring deflection of highly elastic and stress-dependent open-graded aggregate bases is that the final three drops may or may not accurately characterize the in-service deflection, i.e. the final settled state. This question will be addressed later in this paper.

Originally developed in Germany with initial use in the 1980s, LWDs were first used to meausure the elastic modulus and deflection of open-graded ballast supporting railroad tracks and ties. German Rail has acceptance criteria found in the appendix of Zorn's LWD user manual [6]. Also included are acceptance criteria for compacted soils and base for roads. The LWD is used to check compaction and stiffness for conformance to German catalogs of road cross sections with stated minimun elastic modulii for soils and bases for various road classes.

More recently, the University of Maryland Department of Civil Engineering developed protocols for using LWDs for a group of state DOTs led by the Maryland State Highway Administration [3]. This work included writing draft AASHTO standards for correlating laboratory Proctor density of soils and bases to laboratory LWD deflections as targets to reach in field LWD measurements. Led by the Indiana, Minnesota and Nebraska State Departments of Transportation, other state DOTs are considering adoption of LWDs for quality control of soil and base compaction. Unfortunately, the AASHTO testing protocols are only for assessing the compaction and stiffness of soils and dense-graded aggregate bases. AASHTO draft standards provide no guidance on assessing the deflecton of open-graded bases common to permeable pavements.

While the initial cost of an LWD is higher (US$6,000 to $15,000) than a nuclear density gauge, no operator or device ceritifcation is needed with (non-nuclear) LWDs. In addition, many more deflection measurements can be taken over a given period of time than density measurement. It is the authors' experience that 60 LWD measurements were easily taken within two hours. These advantages result in lower costs due to no regulations and higher efficiency. LWDs require an annual verification process. If the device fails the verification test, then calibration is required per the aforementioned ASTM test methods.

LWD Field Testing of Open-Graded Aggregates

Based on preliminary testing by the Interlocking Concrete Pavement Institute, LWDs have demonstrated the ability to quickly assess stiffness of compacted, open-graded aggregate bases for permeable pavements. The authors collected deflection data following the test method in ASTM D2835 on compacted open-graded aggregate for installation of permeable interlocking concrete pavement (PICP) on sites in California, Maryland, Wisconsin and Toronto.

California - Figures 2 and 3 illustrate the test sites the University of California Pavement Research Center

(UCPRC) in Davis in 2014. The 242 m^2 area of PICP was built in 2014 to conduct full-scale load testing with mechanistic modeling that resulted in subbase thickness designs up to 1 million 80 kN standard axles. That research project was conducted by Li et alia [7]. The ASTM No. 2 aggregate sizes ranged from 63 mm to 19 mm, varied in thickness from 450 mm, 650 mm and 950 mm compacted in ~200 mm lifts. These were capped with a 100 mm thick layer of compacted ASTM No. 57 aggregate ranging in size from 25 mm to 2.4 mm. Both aggregate layers were compacted with 31 kN roller compactor and a 60 kN plate compactor. The clay soil subgrade was compacted prior to placing nonwoven geotextile and aggregates on it. Table 1 provides the results of of the deflection data.



Figure 2. LWD testing on ASTM No. 2 subbase at UCPRC



Figure 3. LWD testing on ASTM No. 57 base at UCPRC

Table 1. UCPRC LWD deflection results

University of California at Davis	ASTM No. 2 subbase	ASTM No. 57 base
Test Locations	17	17
Subbase & Base Thicknesses	450 to 950 mm	100 mm
Average Deflection	0.425 mm	0.374 mm
Deflection Standard Deviation	0.070 mm	0.038 mm
Deflection Coefficient of Variance	16.0%	9.9%

Havre d' Grace, Maryland - This site is a small (approximately 200 m^2) PICP parking lot behind a newly constructed public library in 2016. The soil subgrade was clay and there was no geotextile on the subgrade. The No. 2 subbase varied in thickness from 300 mm to 600 mm due to the slope of the subgrade. It was impossible to know the exact thickness of the subbase during deflection testing. The No. 2 subbase did not appear to be compacted. See Figure 4. An author returned a week later to measure deflections on the compacted No. 57 layer.

Table 2 presents deflection data.

Table 2. Havre d'Grace LWD results

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%



Figure 4. ASTM No. 2 subbase at Havre d'Grace. Maryland

Franksville, Wisconsin - This site is used as a training facility for installation of PICP operated by The School for Advanced Segmental Paving and Pave Tech, Inc. The training area consists of exposed No. 2 stone subbase, approximately 300 mm thick, and a larger adjacent area of 300 mm thick No. 2 stone under 100 mm of No. 57 stone base. This area is used to train installers on manual and mechancial installation of the bedding layer and concrete paving units.

Table 3. LWD data on ASTM No. 2 in Wisconsin

Franksville, Wisconsin	ASTM No. 2 subbase Previously Compacted Strip	ASTM No. 2 subbase Re-compacted Strip
Test Locations	10	10
Subbase Thickness	300 mm	300 mm
Average Deflection	1.575 mm	1.902 mm
Deflection Standard Deviation	0.472 mm	0.565 mm
Deflection Coefficient of Variance	30%	29.7%

The data in Table 3 is from the area with exposed No. 2 stone shown in Figure 5. Ten deflection meaurements were taken on a undisturbed area. An area was then recompacted with a 60 kN Weber CR7 plate compactor with a compaction indicator. Ten deflection measurements were taken again in approximately the same locations. Comparing the average deflections in Table 3, the re-compaction appears to have loosened the aggregate and/or the LWD is responding to deflections from the wet clay soil subgrade with no geotextile on it.



Figure 5. ASTM No. 2 subbase compacted strip where deflection measurements were taken.

A limition of LWD testing is the device reads deflections to a depth between one to two times the plate diameter. In the case of a 300 mm diameter plate, the LWD reads deflections of materials within 300 mm to 600 mm under it. This rule can limit the maximum lift height for compaction to the plate diameter. In this case, the subbase was less than 300 mm thick and deflections from the soil subgrade were likely being measured with the sub base. In

addition, a nearly saturated soil subgrade may have influenced higher deflections.

To confirm this notion, one end of the previously compacted strip with 300 mm thick No. 2 stone was tested 10 times. Then it was thickened to 400 mm, the area compacted again and deflections measurements taken. Table 4 shows the deflections decreased substantially. Figure 6 shows the area with the subbase thickened to about 400 mm. This appears to confirm that aggregate layers need to be thickner than 300 mm to reduce the risk of including higher deflections from a nearby subgrade.

Tests were the done on a nearby area with 100 mm thick ASTM No. 57 stone over 300 mm thick ASTM No. 2 stone. Figure 7 illustrates this area.

The soil subgrade had no geotextile on the uncompacted soil subgrade. Deflections were measured on an undisturbed area of No. 57 base. Deflections were measureed again after re-compacting with one pass of a 60 kN vibratory plate compactor. The results in Table 5 indicate that re-compaction which disturbed this layer resulted in higher average deflections.

Table 4. Deflections before and after subbase thickening

Franksville, Wisconsin	ASTM No. 2 Undisturbed Compacted End	ASTM No. 2 Re-compacted End
Test Locations	10	10
Subbase Thicknesses	300 mm	375 to 400 mm
Average Deflection	1.846 mm	1.165 mm
Deflection Standard Deviation	0.626 mm	0.214
Deflection Coefficient of Variance	33.9%	18.3%

Table 5. Deflection results in Franksville, Wisconsin

Franksville, Wisonsin	Existing No. 57 over No. 2	No. 57 over No. 2 Re-compacted
Test Locations	15	15
Base & Subbase Thicknesses	100 mm of No. 57 over 300 mm of No. 2	100 mm of No. 57 over 300 mm of No. 2
Average Deflection	0.514 mm	0.676 mm
Deflection Standard Deviation	0.067	0.072 mm
Deflection Coefficient of Variance	13.1%	10.6%



Figure 6. Testing the No. 2 subbase thickened from 300 mm to 400 mm



Figure 7. Recompacting an existing No. 57 layer over No. 2 stone

Finally, two areas on the opposite side of this area were measured for deflections. These areas had been in place for about ten years and used as training for PICP installation. Table 6 below illustrates the results. This area had no geotextile with an uncompacted soil subgrade. These results yielded deflections similar to those at UCPRC noted on Table 1.

Table 6. Deflection results from a ~10 year old base and subbase

Franksville, Wisconsin	Existing No. 57 over No. 2	Existing No. 57 over No. 2
Test Locations	18	15
Base & Subbase Thicknesses	100 mm of No. 57 over 300 mm of No. 2	100 mm of No. 57 over 300 mm of No. 2
Average Deflection	0.473 mm	0.387 mm
Deflection Standard Deviation	0.070 mm	0.074 mm
Deflection Coefficient of Variance	14.8%	19.1%

Vaughan, Ontario - The last site tested was constructed in summer 2017 at the Kortright Centre for Conservation. This test site consists of two PICP areas to evaluate cleaning equipment and another to evaluate winter deicer use by the University of Toronto. The dimensions for the former area are 3 m x 21 m and 1.8 m x 9 m for the latter. The aggregate for both areas are 150 mm thick ASTM No. 2 subbase under 100 mm thick No. 57 base. The unsaturated silty clay soil subgrade was not compacted and it was covered with Mirafi RS380i geotextile. Table 7 provides the deflection results for both areas.

Table 7. Deflection results in Vaughan, Ontario

	Vaughan, Ontario Areas G to L	Vaughan, Ontario Areas M to Q
Test Locations	**6**	**5**
Base & Subbase Thicknesses	**100 mm of No. 57 over 150 mm of No. 2**	**100 mm of No. 57 over 150 mm of No. 2**
Average Deflection	**0.806 mm**	**0.867 mm**
Deflection Standard Deviation	**0.385 mm**	**0.063 mm**
Deflection Coefficient of Variance	**47.8%**	**6.5%**



Figure 8. Areas G to L are evenly distributed within this area in Vaughan, Ontario.

The larger area was used to address the question regarding how many drops are sufficient. This area was evenly divided into 6 subsections labeled G through L. Deflections tests were repeated at least three times in each subsection at the same location per ASTM E2835. Table 8 below provides the deflection data. The deflections for the initial three seating drops were not recorded by the LWD device. The shaded cells on Table 8 indicate the deflection range among each set of three drops that determine an average value. The ranges are reduced with each subsequent set of deflection tests.

Table 8. Deflection results when repeated in the same location

Drops Count	G		H	.	I		J		K		L	
Three seating drops												
4	2.687		1.887		4.832		1.876		1.110		0.118	
5	1.031		1.239		1.072		1.086		0.666		0.868	
6	0.802	Range	1.122	Range	1.420	Range	0.931	Range	0.587	Range	0.701	Range
Average	1.507	1.885	1.416	0.765	2.441	3.760	1.298	0.945	0.788	0.523	0.785	0.750
Three seating drops												
10	0.595		1.016		1.539		0.860		0.545		0.634	
11	0.574		0.953		1.584		0.809		0.512		0.627	
12	0.578	Range	0.927	Range	1.672	Range	0.801	Range	0.528	Range	0.601	Range
Average	0.582	0.021	0.965	0.089	1.598	0.133	0.823	0.059	0.528	0.033	0.621	0.033
Three seating drops												
16	0.557		0.941		1.596		0.787		0.500			
17	0.540		0.916		1.607		0.755		0.484			No
18	0.539	Range	0.945	Range	1.670	Range	0.718	Range	0.479	Range		data
Average	0.545	0.018	0.935	0.029	1.624	0.094	0.753	0.069	0.488	0.021		

Discussion

The depth of the subbase affects deflections. Tests on the 300 mm thick ASTM No. 2 subbase indicated higher deflections than those taken with the No. 57 base over the subbase. In addition, Table 4 indicates a substantial reduction in deflections when thickening the subbase aggregate from 300 to 400 mm.

Table 8 represents an initial attempt to determine how many drops are sufficient to characterize acceptance compacted, open-graded aggregate. The additional drops over six is further compacting the aggregate under the plate. This may not represent the compaction across the wider pavement. The data on Table 8 is further complicated by the subbase being 150 mm thick and not at least 300 mm thick to help avoid reading deflections from the soil subgrade. In of spite this, more drops clearly reduce the range of deflections. Drops 4 through 6 in Table 8 had a range of 1.362 mm deflection, blows 10 through 12, 0.112 mm and blows 16 through 18, 0.051 mm. After how many drops is deflection assessed? Dr. Soheil Nazarian at the University of Texas in El Paso informally suggested 10 ±2 drops in the same location. This approach likely does not test deflection of compacted aggregate during the construction process. Instead, additional compactive force applied by the LWD and likely lower deflections measured do not represent the compacted (constructed) condition.

One can debate whether six drops represents a completely compacted state of open-graded aggregates. The difference in deflections between six and twelve drops may be analogous to differences between Proctor density and modified Proctor density in soils. The latter with higher densties is a result of continued compaction with more force. However, with open-grades aggregates, additional compactive force to achieve lower deflections resulting from 12 LWD drops may not be achievable on some project sites. Additional research is needed, but for the present, LWDs with six drops (three seating and the average of the next three measurments) can check consistent deflections. Additional research should also assess the effects of saturated soil subgrades, as well as any differences in deflections with or with the presence of geotextile on the subgrade.

Conclusions

When testing deflections on compacted subbases, they should at least 300 mm thick and the soil should not be saturated. A compacted ASTM No. 57 base over a compacted No. 2 subbase with a total thickness of at least 300 mm thickness is recommended for testing. A recommended requirement is that average deflections not exceed 0.5 mm. UCPRC (Table 1) and Wisconsin (Table 6) met this requirement with base and subbase thicknesses exceeding 300 mm. The ≤ 0.5 mm acceptance criteria is included in Interlocking Concrete Pavement Institute literature [4] and a national standard on PICP to be published by ASCE in 2018 [5].

Given the high variability in deflection data for subbases, regardless of thickness, no deflection criteria are recommended for them at this time. However, LWDs can be used to check consistency in compaction across a subbase. The No. 2 stone subbases at UC Davis rendered deflections less than 0.5 mm. All of these were 450 mm or thicker. Further research on subbase deflections may affirm 0.5 mm as a reasonable limit on deflection given minimum thickness requirements.

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