ST-008 Appendix IX. PROJECT TEST RESULTS

Introduction

Ingios COMP-Score RT provides real-time monitoring of compaction measurements to aid in earthwork and pavement foundation compaction process and quality assessment. Compaction equipment is outfitted on any vibratory smooth drum roller (in less than 1 day) with state-of-the-art hardware for measuring, recording, and visually monitoring the results of the compaction process. Once outfitted, a field calibration process involving the Automated Plate Load Testing (APLT) system is implemented.

COMP-Score RT uses advanced data analytics and requires site specific calibration of the roller sensor measurements using in situ plate load test measurements (i.e., modulus of subgrade reaction, in situ elastic modulus, or in situ resilient modulus), and uses the full spectrum of the drum acceleration signature. This allows the monitoring equipment to deliver a high degree of reliability in the predicted measurements. Recent field calibrations on subgrade and base materials using this approach showed coefficient of determination (R^2) > 0.9 are achievable using this technique (compared to R^2 of 0.6 using compaction meter value (CMV) for the same data (White et al. 2014)). Another recent example was on a recent construction site on an Illinois Tollway construction project west of O'Hare airport (White et al. 2018, Tutumluer et al. 2018), which showed a R^2 of 0.27 for predicting $M_{r\text{-}Comp}$ using CMV versus R^2 = 0.93 using the COMP-Score RT approach. Similarly, calibration using CMV for predicting static plate load test modulus of subgrade reaction (*k*) value produced R^2 of 0.74 versus R^2 = 0.96 using the COMP-Score RT approach. White and Vennapusa (2017) recently documented calibration results with stress-dependent M_r values with R^2 values ~ 0.9 or greater, from testing on MnROAD field test sections in Albertville, MN with foundation layers consisting of granular and non-granular materials with varying stiffness and layered conditions.

The advantage with the COMP-Score RT approach is that the site calibration process significantly reduces the measurement error associated with the correlation, and the calibration relationships can be reliably used to develop the desired mechanical property maps.

During contractor production operations, the RT technology also uses advanced algorithms to provide real-time feedback of the compaction operations. COMP-Score RT also independently verifies to the project engineering team that the contractor's work: (1) achieves the minimum critical engineering parameter values (e.g., in-situ k-value) over a defined percentage (e.g., 80 to 90%) of the area monitored; (2) limits the variability of critical engineering parameter values of the area monitored; and (3) restricts the size of localized contiguous areas of non-compliance (i.e., "soft spot").

For this project, a CS56 smooth drum vibratory roller weighing approximately 27,450 lbs outfitted with Ingios RT retrofit system was used (Figure 1). Calibration was developed from APLT results to output stress-dependent k and M_r values (Figure 2).

Figure 1 .Caterpillar CS56 vibratory smooth drum roller outfitted with Ingios COMP-Score RT system and GPS.

Figure 2. Automated Plate Load Testing trailer.

Definitions

COMP-Score® RT Technology

Ingios COMP-Score® RT involves installing a computer/sensor(s) on a soil compaction machine and displaying sensor data to the operator whereby the operator then makes decisions on how best to use the compaction machine to meet compaction target values for the project. The data is presented real-time as color-coded geospatial maps. The compactor is outfitted with GPS equipment to measure drum location which is coordinated with data to create color-coded compaction maps.

Applications

Contractors (local and remotely), Engineers (remotely), and Owners (remotely). Contractors use the real-time data at the operator and project superintendent levels. Engineers use the data to assess quality control and assurance requirements (with results generated within minutes). Owners use the data to validate and document construction, and longer-term, link mapping results to life-cycle cost analysis. The value of the RT data is time-dependent and different for different users. Users access the COMP-Score CONNECT web portal via desktop/laptop computer or mobile device.

Key Features and Scenarios

The compaction machine on the project is setup with the Ingios COMP-Score RT system to collect and present data to the operator. The operator views geospatial and color-coded map results overlain on georeferenced aerial photo and then makes improved decisions about compaction process (e.g., number of roller passes require and other process control decisions such as moisture control). Non-operator users will access the real-time results via a remote desktop application and then receive e-Compaction reports via email/text. Ingios technology is state of-the-art both in terms of the hardware/quality of data and with customized analytics for the project.

Compliance

Ingios data is calibrated with independent testing and validated whereby the data is compared to calibration limits that are preset in the machine. The data output is strictly controlled by Ingios and not the contractor (machine operated per Ingios requirements). Data results are reported as invalid if the compaction machine is not operated per the calibration requirements for compaction amplitude and vibration frequency.

Software Architecture

The computer on the compaction machine runs Windows 7/10 and is connected to the internet via LTE mobile gateway. Data on the compaction machine is collected using Ingios proprietary software and security applications. The raw data exported from the machine is collected, sent to a server (Microsoft Azure), filtered, analyzed, backed-up, and is then available for report generation.

Remote Real-Time Monitoring Services

Users who want to view the data in real-time (via laptop and mobile devices), can view the data through COMP-Score CONNECT dashboard.

e-Compaction Report

Once the operator is done “mapping” an area with the compaction machine, the operator pushes a button that triggers the raw data file to be submitted automatically into a folder on Ingios server. Ingios software tools read the data and automatically generate the e-Compaction report. The compaction report includes various data analytics/statistical summaries and various plots of color-coded information (see Appendix VIII). A “clean” data file including all data analytics and positional coordinates on a 1 ft x 1 ft grid using state plane coordinates is made available to the user.

Email/Text Alert

When a e-Compaction report is initiated, completed, downloaded, and report generated, email alerts are automatically sent to users associated to the project.

Control Charts

Using results from the individual e-Compaction reports, COMP-Score CONNECT dashboard provides a summary of values on a timeline plot to display selected statistical parameter values over time. The generated e-Compaction report is available for quick reference by clicking on any of the data points presented on the control charts.

Quality Indices

Percent Passing Target Values: % passing the target values is based on the number of geospatial grid points from the output that meet or exceed the minimum target engineering parameter value (e.g., k-value) for the selected material.

Compaction Quality Index (CQI): Compaction quality index (CQI) is a relative compaction index based on the percentage of the geospatial area that meets the minimum target values for the set engineering parameter value that accounts for the uniformity of compaction using a weighting factor. The default minimum target CQI is 95% using a uniformity weight factor of 50%.

$$CQI = 100 - (Min.TV\ \%\ Passing - Measured\ \%\ Passing) \\ - [(Measured\ COV - Max.TV\ \%\ COV) * Uniformity\ Weighting\ Factor]$$

Calibration Quality Check: Ingios calculates statistical parameters that can be used to assess the "spread" of the compaction data relative to the allowable spread of the data based on the lower and upper limits of a calibration data set. These indices are traditionally applied for assessing data within control limits in production work. Ingios uses calibration index value to assess variation and centralization between the upper and lower limits determined from in situ calibration testing. The calibration index (CI) parameter provides a measure of whether the calibrated measurements (i.e., predicted k-value) are within or out of calibration. CI parameter value is determined for each production map, using the calibration test results as follows:

$$CI = min\left(\frac{UL - \mu}{3\sigma}, \frac{\mu - LL}{3\sigma}\right)$$

where, UL = upper limit of the calibration; *LL* = lower limit of the calibration; μ = calculated average of the predicted value, and σ = calculated standard deviation of the predicted values.

- If *CI* < 0 = reported values are outside calibration limits.
- If *CI* < 0.5 = Some reported values are outside calibration limits.
- If 0.5 > *CI* < 1.0 = Most of the reported values are within calibration limits.
- IF *CI* > 1.0 = All reported values are within calibration limits.

Statistical Sampling for Calibration

A valid field calibration effort should require statistical determination of the minimum number of test measurements needed to achieve a desired level of reliability and confidence level in future predictions. The minimum sample size needed for this calibration effort was determined using a procedure recommended by Dupont and Plummer (1998). The inputs needed to determine the minimum sample size include the mean and coefficient of variation (COV) of the measured and the predicted values, standard error of the regression fit, the expected slope of the regression fit between the measured and the predicted values, and desired confidence level in the future estimates. These inputs are first estimated based on prior testing/experience and are later clarified based on the in situ calibration test results.

Field Projects

To conduct field demonstrations in the State of Iowa, the project team worked with the Iowa DOT and the Contractor personnel on eleven DOT and two County projects during the 2019 and 2020 construction season. Figure 3 shows the project locations, where the technologies have been deployed, and Table 1 summarizes additional information regarding each of the projects.

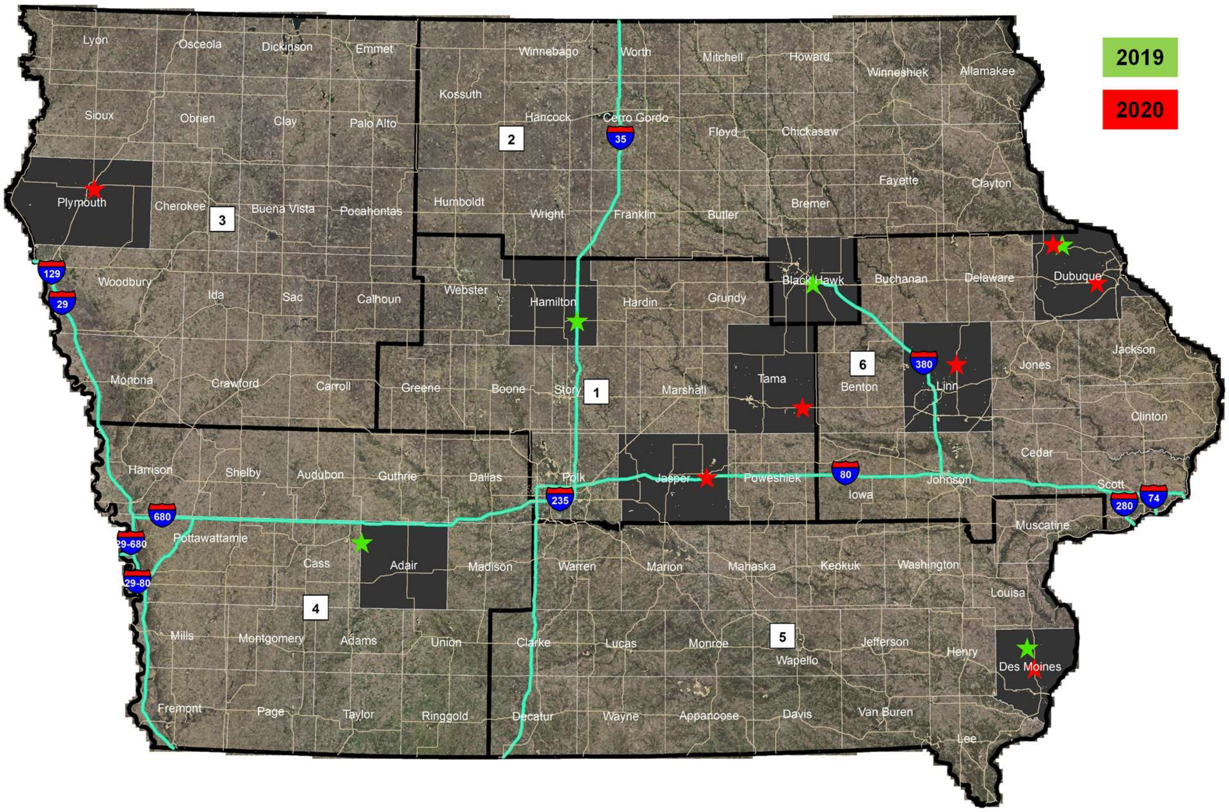


Figure 3. Project demonstration locations in 2019 and 2020.

Table 1. 2019 and 2020 Project Summary

County	Project Number	Contractor	Type of Project
2019 Demonstration Projects			
Blackhawk	NHSX-020-6(71)--3H-07	Cedar Valley	PCC Pavement
Hamilton	IM-035-5(111)133--13-40	CJ Moyna	PCC Pavement
Dubuque	HSIPX-052-2(120)--3L-31	CJ Moyna	PCC Pavement
Adair	LFM-LGG27--7X-01	County	Grading
Des Moines	L-P103GRADE--73-29	County	Grading
Des Moines	NHSX-061-2(62)--3H-29	Ames Construction	Grading
2020 Demonstration Projects			
Des Moines	NHSX-061-2(68)--3H-29	Streb Construction	PCC Pavement-New
Dubuque	NHSX-052-2(121)--3H-31	CJ Moyna & Sons	PCC Grade and Replace
Dubuque	NHSX-020-9(183)--3H-31	CJ Moyna & Sons	PCC Pavement-Grade and New
Jasper	IM-NHS-080-5(303)174--03-50	Peterson Contractors	PCC Pavement-Grade and New
Linn	NHSX-013-1(53)--3H-57	CJ Moyna & Sons	PCC Grade and Replace
Plymouth	NHSX-075-2(96)--3H-75	Peterson Contractors	PCC Grade and Replace
Tama	NHSX-030-6(191)--3H-86	Manatts	PCC Pavement-New

Laboratory Characterization of Project Materials

A summary of laboratory index property test results for the materials tested as part of this project is provided in Table 2.

Additional lab testing results by the Michigan State University research group including laboratory permeability and resilient modulus testing (per AASHTO T307 loading sequence on prismatic samples) results at different compaction efforts are included in Appendix A. In the appendix, the results of sieve analyses and specific gravity, Atterberg limits, standard Proctor compaction, permeability, and laboratory resilient modulus (MR) tests are presented for the materials collected from 5 project sites [Dubuque County (US-52), Plymouth County (US-75), Linn County (US-13), Tama County (US-30), and Des Moines County (US-61)]. These materials were a mixture of reclaimed asphalt pavement (RAP) and reclaimed Portland cement concrete (RPCC) materials (modified subbase from US-52), a RAP material (special backfill from US-75), an RPCC material (granular subbase from US-13), crushed limestone aggregates (referred to as Crushed Limestones – granular subbases from US-30 and US-61), and subgrade (SG) materials (from US-30 and US-61).

Dry & wet sieve analyses and specific gravity and Atterberg limits tests were performed to classify these materials based on their index properties. Then, standard Proctor compaction tests were conducted to determine the optimum moisture content (OMC) and maximum dry unit weight (MDU) values of these materials. Based on standard Proctor compaction test results, a series of permeability and MR tests were performed.

Hydraulic conductivity tests were conducted on all materials at 95, 90, and 85% compaction levels to see the effect compaction on permeability (K). Test results showed that a decrease in the compaction level caused an increase in the K values. However, this reduction in drainage characteristics was not as significant and impactful compared to the reduction in stiffness values of the materials at lower compaction levels. Open graded materials (US-30 (CL) and US-61 (CL)) had the highest K values at each compaction level.

MR tests were performed on US-52 (RAP & RPCC), US-75 (RAP), US-13 (RPCC), US-30 (SG), and US-61 (SG) at 95, 90, and 85% compaction levels to see the effect of compaction on MR. Results are summarized in Table 3. Overall, test results showed that a decrease in the compaction level caused a decrease in the MR values (at the 6^{th} loading sequence) and increase in plastic strain at the end of the test. While the MR values of US-52 (RAP & RPCC), US-75 (RAP), and US-13 (RPCC) increased with increasing bulk stress due to the stress-hardening behavior of coarse-grained materials, the MR values of US-30 (SG) and US-61 (SG) decreased with increasing bulk stress due to the stress-softening behavior of fine-grained materials. Among US-52 (RAP & RPCC), US-75 (RAP), and US-13 (RPCC), US-75 (RAP) provided the highest MR values, while US-13 (RPCC) showed the lowest SMR values. In addition, US-30 (SG) yielded higher MR values (at the 6^{th} loading sequence) than US-61 (SG).

Table 2. Summary of lab index properties of the different materials.

Project	Layer	Material Description	Classification		Gravel (%)	Sand (%)	Fines (%)
			AASHTO	USCS			
Adair 160th Street LFM-LGG27--7X-01	Modified Subbase	Crushed Limestone	A-1-a	GP-GM	50.7	37.2	12.0
Blackhawk US20 NHSX-020-6(71)--3H-07	Granular Subbase	Recycled PCC	A-1-a	GP	74.1	24.3	1.6
	Subgrade treatment (special backfill)	Recycled PCC	A-1-a	GP-GM	58.8	34.4	6.9
	Class 10 Subgrade	Glacial Till subgrade	A-6	CL	4.4	53.1	42.4
Des Moines US61 NHSX-061-2(62)--3H-29	Select Subgrade	Glacial till subgrade	A-6	CL	0.5	44.2	55.3
Des Moines Iowa City Rd L-P103GRADE--73-29	Choke stone Base	Crushed Limestone	A-1-b	GP	48.3	29.7	22.0
	Class 10 Subgrade	Native glacial till with organics	A-6	CL	11.8	21.5	66.6
Hamilton IA 175 IM-035-5(111)133--13-40	Select Subgrade	Glacial till subgrade	A-6	CL	6.2	45.8	48.0
	Modified Subbase	Recycled PCC	A-1-a	GW	65.8	32.0	2.2
Dubuque US52 HSIPX-052-2(120)--3L-31	Modified Subbase	Mixture of recycled PCC and asphalt pavement material	A-1-a	GW	60.3	38.1	1.6
Dubuque US52 NHSX-052-2(121)--3H-31	Modified Subbase	Mixture of recycled PCC and asphalt pavement material	A-1-a	GW	50.5	44.6	4.9
Plymouth US75 NHSX-075-2(96)--3H-75	Subgrade treatment (special backfill)	Recycled asphalt pavement material	A-1-a	GW	52.8	45.4	1.8
Linn US13 NHSX-013-1(53)--3H-57	Granular Subbase	Recycled PCC material	A-1-a	GP-GM	68.7	24.8	6.5
Tama US30 NHSX-030-6(191)--3H-86	Granular Subbase	Virgin crushed limestone	A-1-a	GP	90.3	5.1	4.6
Des Moines US61 NHSX-061-2(68)--3H-29	Granular Subbase	Virgin crushed limestone	A-1-a	GP-GM	71.8	20	8.2
Tama US30 NHSX-030-6(191)--3H-86	Select Subgrade	Glacial till subgrade	A-6	CL	3.8	41.3	54.9

Table 3. Summary of MR test results.

Material	Compaction level (%)	Model parameters			Mr (ksi) at the 6th loading sequence	Plastic strain at end of test, ε_p (%)
		k_1	k_2	k_3		
US-52 (RAP & RPCC)	95	1,774	0.60	-0.64	26	0.55
	90	1,479	0.71	-0.78	22	0.80
	85	1,565	0.62	-0.72	22	0.89
US-75 (RAP)	95	1,912	0.54	-0.70	28	0.61
	90	1,932	0.49	-0.81	26	0.91
	85	1926	0.53	-1.08	25	1.12
US-13 (RPCC)	95	1,022	0.55	-0.27	18	0.10
	90	980	0.63	-0.45	17	0.21
	85	739	0.57	-0.12	13	0.87
US-30 (SG)	95	2,215	0.26	-5.34	12	0.12
	90	1,594	0.37	-3.63	11	0.16
	85	1,215	0.19	-3.69	9	0.49
US-61 (SG)	95	2,213	0.29	-7.71	9	0.16
	90	1,114	0.15	-4.9	7	0.17
	85	1,139	0.14	-4.77	8	0.76

In Situ Point Testing for Calibration

An experimental plan was developed in collaboration with the Iowa DOT pavement design and construction engineering team to perform field testing to determine mechanistic properties on pavement foundation layers in situ at selected project sites across the State of Iowa. The goal at each site was to perform cyclic APLTs to determine composite resilient modulus ($M_{r\text{-}comp}$) properties using a 12 in. diameter loading plate (Figure 4) and perform static APLTs to determine k values with 30 in. diameter loading plate Figure 5). A dynamic cone penetrometer (DCP) test was conducted at each test location to determine penetration resistance profile and assess layer thicknesses.

The APLT testing plan summarizing the loading sequences for cyclic and static testing provided in Table 4. Cyclic APLTs involved performing a total of 1,500 loading cycles, which involved a 500 cycle conditioning sequence at 15 psi maximum stress followed by 100 to 250 cycles at 5 to 40 psi maximum stresses. Plate deformations and deflection basin measurements at 2x, 3x, and 4x, the plate radius were obtained for back-calculation of the two-layered M_r properties for each stress sequence. The average of the last 5 cycles was used for representation of Mr for each loading sequence. A 0.2 sec load time and a 0.8 sec dwell time was used. Static APLTs were performed following AASHTO T222 (2012), using two loading cycles.

A summary of project locations and testing performed, along with RT mapping is provided in Table 5.

Table 4. Cyclic and static plate load testing configuration.

Test Designation	Step	Number of cycles, N	Cyclic Stress, σ_{cyclic} [psi]	Minimum stress, σ_{min} [psi]	Maximum Stress, σ_{max}	Plate Configuration/Notes
A [1,100 cycle APLT]	Cond.	500	13	2	15.0	12 in. diameter flat plate with deflection readings at r, 2r, 3r, and 4r from plate center [r = plate radius]. 0.2 second load time and 0.8 second dwell time
	1	100	4	2	6.0	
	2	100	8	2	10.0	
	3	100	13	2	15.0	
	4	150	18	2	20.0	
	5	200	28	2	30.0	
	6	250	38	2	40.0	
C [Static APLT]	1	2	NA	NA	15.0	30 in. diameter stacked plate, load applied in 2.5 psi increments

Figure 4. 12 in. diameter loading plate setup for cyclic APLT [picture taken on 08/28/2019 on Blackhawk US20 NHSX-020-6(71)--3H-07 project site over compacted special backfill material]

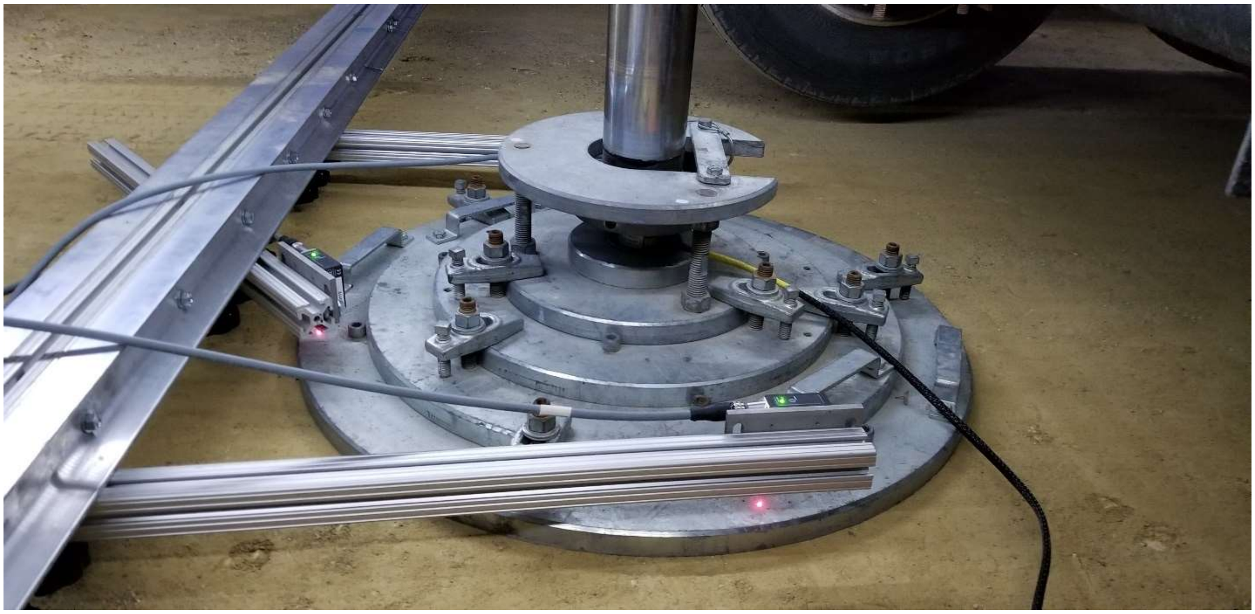


Figure 5. 30 in. diameter loading plate setup for static APLT [picture taken on 10/23/2019 on Des Moines US61 NHSX-061-2(62)--3H-29 project over compacted select subgrade]

Table 5. Summary of project sites, materials, and tests performed.

Project	Layer	Material Description	RT Mapping	APLT Test A	APLT Test B	Vu Meter Tests
Adair 160th Street LFM-LGG27--7X-01	Modified Subbase	Crushed Limestone	5	8 [9/13/2019]	—	—
Blackhawk US20 NHSX-020-6(71)--3H-07	Granular Subbase	Recycled PCC	3	—	8 [8/27/2019 & 9/5/2019]	—
	Subgrade treatment (special backfill)	Recycled PCC	1	10 [8/28/2019]	4 [8/27/2019]	
	Class 10 Subgrade	Glacial Till subgrade	—	—	—	—
Des Moines US61 NHSX-061-2(62)--3H-29	Select Subgrade	Glacial till subgrade	12	—	9 [10/23/2019]	—
	Modified subbase (haul road)	Crushed Limestone	Included within above maps	—	2 [10/23/2019]	—
Des Moines Iowa City Rd L-P103GRADE--73-29	Choke stone Base	Crushed Limestone	5	—	—	—
	Class 10 Subgrade	Native glacial till with organics	1	—	—	—
Hamilton IA 175	Select Subgrade	Glacial till subgrade	1	—	—	—

IM-035-5(111)133--13-40	Modified Subbase	Recycled PCC	1	10 [9/3/2019]	—	—
Dubuque US52 HSIPX-052-2(120)--3L-31	Modified Subbase	Mixture of recycled PCC and asphalt pavement material	6	10 [9/4/2019]	3 [8/13/2020]	—
Dubuque US20 NHSX-020-9(183)--3H-31	Modified Subbase	Virgin Crushed Limestone	12	—	3 [9/30/2020]	3 [9/30/2020]
	Macadam Base	Virgin Crushed Limestone	4	—	4 [9/25/2020]	—
Dubuque US52 NHSX-052-2(121)--3H-31	Modified Subbase	Mixture of recycled PCC and asphalt pavement material	31	—	—	2 [8/13/2020]
Dubuque US52 NHSX-052-2(121)--3H-31	Subgrade Treatment (Cement treated subgrade)	Cement treated glacial till	3	—	6 [8/12/2020]	—
Plymouth US75 NHSX-075-2(96)--3H-75	Subgrade treatment (special backfill)	Recycled asphalt pavement material	2	—	4 [7/29/2020]	—
	Class 10 Embankment Subgrade	Native Subgrade	1	—	5 [7/28/2020]	—
Linn US13 NHSX-013-1(53)--3H-57	Granular Subbase	Recycled PCC material	12	—	5 [8/20/2020]	3 [8/20/2020]
	Select Subgrade	Glacial Till	—	—	4 [8/21/2020]	—
Tama US30 NHSX-030-6(191)--3H-86	Granular Subbase	Virgin crushed limestone	2	—	11 [7/7/2020 & 7/8/2020]	3 [7/9/2020]
	Select Subgrade	Glacial Till	7	—	6 [6/25/2020 & 6/30/2020]	—
Des Moines US61	Granular Subbase	Virgin crushed limestone	2	—	2 [6/16/2020]	4 [6/16/2020]

NHSX-061-2(68)--3H-29						
Jasper I-80 IM-NHS-080-5(303)174--03-50	Select Subgrade	Glacial till subgrade	2	—	2 [6/18/2020]	—
	Select Treatment (Modified Subbase)	Crushed Limestone	2	—	5 [6/18/2020]	—

Summary of APLT Results

Example records of APLT results from Test A and Test B are provided in Figure 6 and Figure 7, respectively. All individual test reports are included in Appendix B. No moisture adjustments were made in this study for future changes in saturation levels and those corrections can be applied (AASHTO T222, NCHRP 2000).

The cyclic APLTs were performed to determine stress-dependent $M_{r\text{-}comp}$. The M_r constitutive model parameters (k_1, k_2, and k_3, per AASSHTO 2015) were then determined are presented herein as k*1, k*2, k*3, where "*" is used to differentiate with regression coefficients traditionally developed for laboratory M_r test measurements. A summary of $M_{r\text{-}comp}$ for the last loading sequence at all test locations along with the test point ID and materials is provided in Table 6.

The static APLTs were used to determine the modulus of subgrade reaction k-value. The k-value is presented herein as ku which represents the k value after plate bending correction and with no moisture correction applied, per AASHTO T222 (2012). Two loading/unloading cycles were performed in this study and the results are therefore presented as $k_{u(1)}$, and ku(2) representing values for each loading cycle. If the measurement was performed on top of the granular subbase layer, the ku values are presented as $k_{u(Comp)}$. The results are presented for a given target stress level of 10 psi, per AASHTO T222. A summary of $k_{u(1)}$, $k_{u(2)}$, ratio of $k_{u(1)}/k_{u(2)}$ and permanent deformation (dp) at the end of the test at all test locations along with the test point ID and materials is provided in Table 7. The k-value measurements are grouped into 4 categories in Table 7, based on calibration analysis and is explained in the following section.

Summary statistics of k-values and Mr-values are provided in Table 8 and Table 9, respectively.

Permanent or plastic deformation occurring from repeated traffic loading is a recognized cause of pavement distresses. For rigid pavements, increases in total permanent deformation in the unbound layers contribute to increased faulting, roughness, and transverse cracking and reduced load-transfer efficient (LTE). In a study conducted by Birkhoff and McCullough (1979), a void gap of about 0.05 in. can load to loss of support (LOS), thereby increasing the bending stresses in the pavement leading to fatigue failure. For flexible pavements, as total permanent deformation within unbound and subgrade layers increases, surface rutting, roughness, and cracking increase. It is therefore essential that permanent deformation be measured, and mechanistic-empirical models be developed to predict permanent deformation performance.

Permanent deformations (δ_p) were monitored during cyclic and static APLTs conducted for this project. A summary of δ_p values from static PLTs is provided in Table 8. Figure 8 provides a graph of $k_{u(1)}$ versus δ_p from static APLT results at all project sites, which shows a strong power relationship between the two parameters. Based on this relationship, to limit δ_p to a critical 0.05 in., a minimum $k_{u(1)}$ = 200 pci must be achieved. Further, the results indicated that 63 out of the 100 measurements obtained from this project showed k-values less than the assumed value of 150 pci.

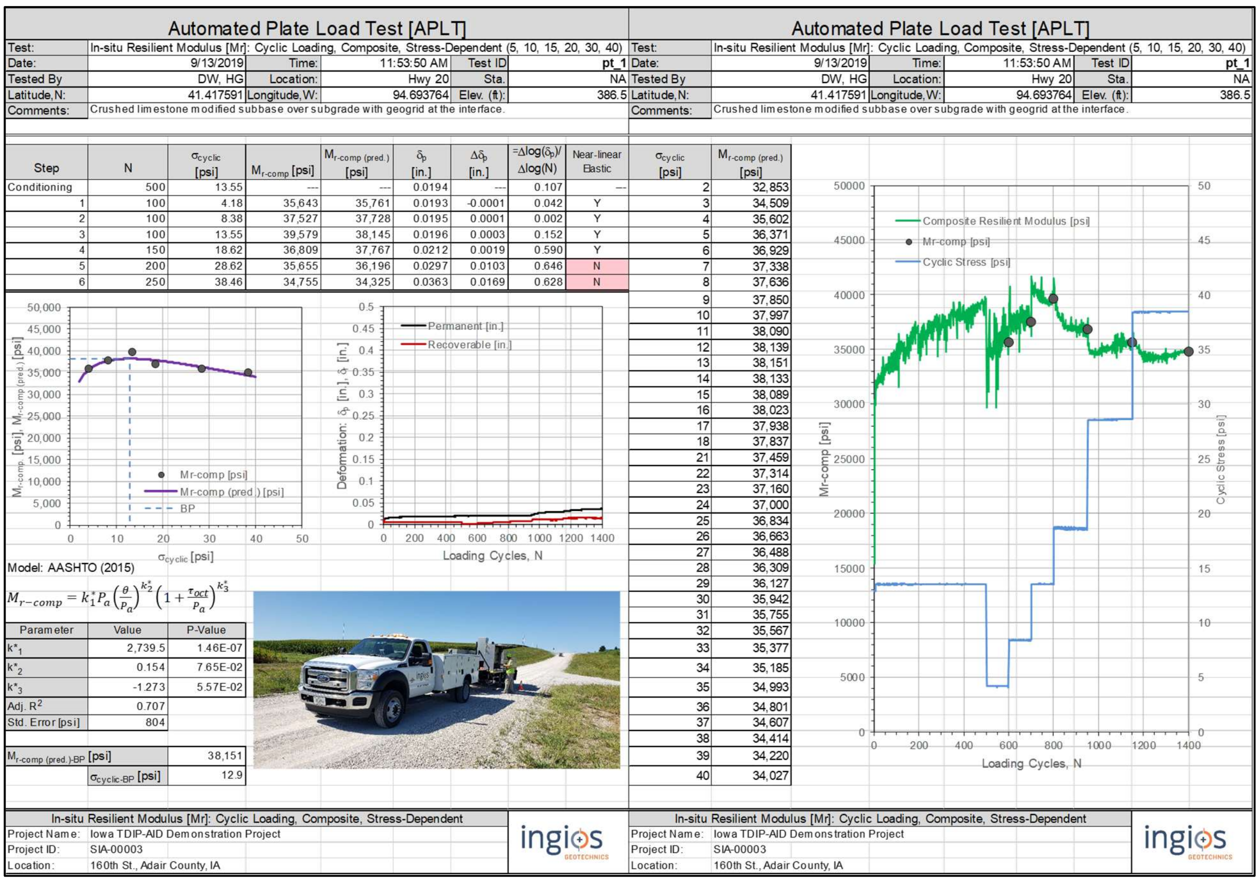
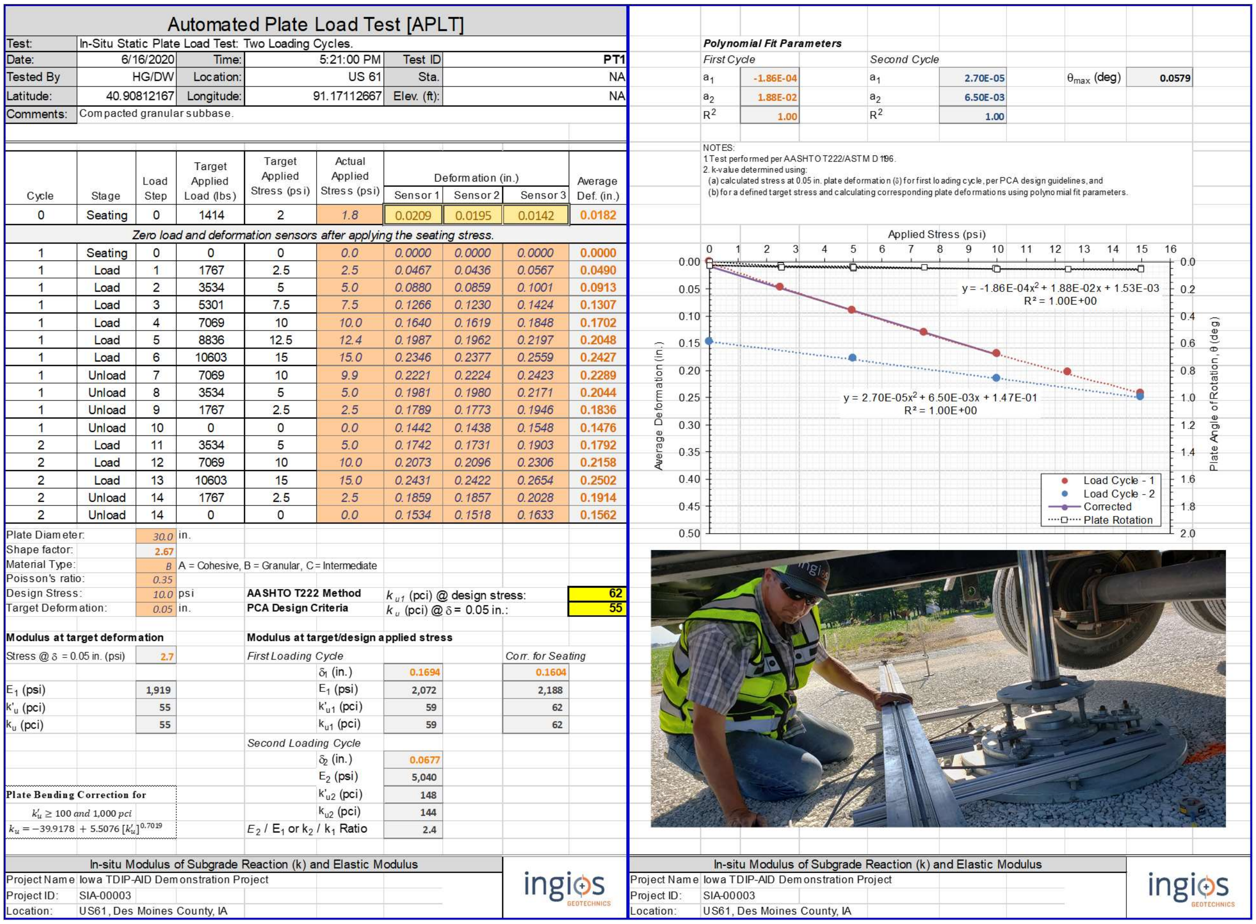


Figure 6. Example APLT data record showing 12 in. static plate load test results (Test A)



Automated Plate Load Test [APLT]

Test:	In-Situ Static Plate Load Test: Two Loading Cycles.						
Date:	6/16/2020	Time:	5:21:00 PM	Test ID	PT1		
Tested By	HG/DW	Location:	US 61	Sta.	NA		
Latitude:	40.90812167	Longitude:	91.17112667	Elev. (ft):	NA		
Comments:	Compacted granular subbase.						

Cycle	Stage	Load Step	Target Applied Load (lbs)	Target Applied Stress (psi)	Actual Applied Stress (psi)	Deformation (in.) Sensor 1	Sensor 2	Sensor 3	Average Def. (in.)
0	Seating	0	1414	2	1.8	0.0209	0.0195	0.0142	0.0182
Zero load and deformation sensors after applying the seating stress.									
1	Seating	0	0	0	0.0	0.0000	0.0000	0.0000	0.0000
1	Load	1	1767	2.5	2.5	0.0467	0.0436	0.0567	0.0490
1	Load	2	3534	5	5.0	0.0880	0.0859	0.1001	0.0913
1	Load	3	5301	7.5	7.5	0.1266	0.1230	0.1424	0.1307
1	Load	4	7069	10	10.0	0.1640	0.1619	0.1848	0.1702
1	Load	5	8836	12.5	12.4	0.1987	0.1962	0.2197	0.2048
1	Load	6	10603	15	15.0	0.2346	0.2377	0.2559	0.2427
1	Unload	7	7069	10	9.9	0.2221	0.2224	0.2423	0.2289
1	Unload	8	3534	5	5.0	0.1981	0.1980	0.2171	0.2044
1	Unload	9	1767	2.5	2.5	0.1789	0.1773	0.1946	0.1836
1	Unload	10	0	0	0.0	0.1442	0.1438	0.1548	0.1476
2	Load	11	3534	5	5.0	0.1742	0.1731	0.1903	0.1792
2	Load	12	7069	10	10.0	0.2073	0.2096	0.2306	0.2158
2	Load	13	10603	15	15.0	0.2431	0.2422	0.2654	0.2502
2	Unload	14	1767	2.5	2.5	0.1859	0.1857	0.2028	0.1914
2	Unload	14	0	0	0.0	0.1534	0.1518	0.1633	0.1562

Plate Diameter: 30.0 in.
Shape factor: 2.67
Material Type: B A = Cohesive, B = Granular, C = Intermediate
Poisson's ratio: 0.35
Design Stress: 10.0 psi — AASHTO T222 Method — k_{u1} (pci) @ design stress: 62
Target Deformation: 0.05 in. — PCA Design Criteria — k_u (pci) @ δ = 0.05 in.: 55

Modulus at target deformation

Stress @ δ = 0.05 in. (psi)	2.7
E_1 (psi)	1,919
k'_u (pci)	55
k_u (pci)	55

Plate Bending Correction for

$k'_u \geq 100$ and 1,000 pci

$k_u = -39.9178 + 5.5076\,[k'_u]^{0.7019}$

Modulus at target/design applied stress

	First Loading Cycle	Corr. for Seating
δ_1 (in.)	0.1694	0.1604
E_1 (psi)	2,072	2,188
k'_{u1} (pci)	59	62
k_{u1} (pci)	59	62

Second Loading Cycle	
δ_2 (in.)	0.0677
E_2 (psi)	5,040
k'_{u2} (pci)	148
k_{u2} (pci)	144
E_2 / E_1 or k_2 / k_1 Ratio	2.4

Polynomial Fit Parameters

First Cycle		Second Cycle			
a_1	-1.86E-04	a_1	2.70E-05	θ_{max} (deg)	0.0579
a_2	1.88E-02	a_2	6.50E-03		
R^2	1.00	R^2	1.00		

NOTES:
1.Test performed per AASHTO T222/ASTM D 1196.
2. k-value determined using:
(a) calculated stress at 0.05 in. plate deformation (δ) for first loading cycle, per PCA design guidelines, and
(b) for a defined target stress and calculating corresponding plate deformations using polynomial fit parameters.

In-situ Modulus of Subgrade Reaction (k) and Elastic Modulus
Project Name Iowa TDIP-AID Demonstration Project
Project ID: SIA-00003
Location: US61, Des Moines County, IA
ingios GEOTECHNICS

In-situ Modulus of Subgrade Reaction (k) and Elastic Modulus
Project Name Iowa TDIP-AID Demonstration Project
Project ID: SIA-00003
Location: US61, Des Moines County, IA
ingios GEOTECHNICS

Figure 7. Example APLT data record showing 30 in. static plate load test results (Test A)

Table 6. Summary of APLT results (Test A)

Date	Point	Material	$M_{r\text{-}comp}$ (psi)
8/28/2019	Hwy20_pt_11	RPCC special backfill layer over subgrade.	14,593
8/28/2019	Hwy20_pt_12	RPCC special backfill layer over subgrade.	17,997
8/28/2019	Hwy20_pt_13	RPCC special backfill layer over subgrade.	20,389
8/28/2019	Hwy20_pt_14	RPCC special backfill layer over subgrade.	21,427
8/28/2019	Hwy20_pt_15	RPCC special backfill layer over subgrade.	24,342
8/28/2019	Hwy20_pt_16	RPCC special backfill layer over subgrade.	15,871
8/28/2019	Hwy20_pt_17	RPCC special backfill layer over subgrade.	16,101
8/28/2019	Hwy20_pt_18	RPCC special backfill layer over subgrade.	18,282
8/28/2019	Hwy20_pt_19	RPCC special backfill layer over subgrade.	15,082
8/28/2019	Hwy20_pt_20	RPCC special backfill layer over subgrade.	23,770
9/4/2019	Hwy52_pt_1	Crushed limestone modified subbase over subgrade.	25,464
9/4/2019	Hwy52_pt_2	Crushed limestone modified subbase over subgrade.	37,271
9/4/2019	Hwy52_pt_3	Crushed limestone modified subbase over subgrade.	55,945
9/4/2019	Hwy52_pt_4	Crushed limestone modified subbase over subgrade.	52,216
9/4/2019	Hwy52_pt_5	Crushed limestone modified subbase over subgrade.	9,217
9/4/2019	Hwy52_pt_6	Crushed limestone modified subbase over subgrade.	5,609
9/4/2019	Hwy52_pt_7	Crushed limestone modified subbase over subgrade.	24,784
9/4/2019	Hwy52_pt_8	Crushed limestone modified subbase over subgrade.	31,756

9/4/2019	Hwy52_pt_9	Crushed limestone modified subbase over subgrade.	26,848
9/4/2019	Hwy52_pt_10	Crushed limestone modified subbase over subgrade.	31,374
9/3/2019	Hwy175_pt_1	Recycled Aggregate modified subbase over subgrade.	29,440
9/3/2019	Hwy175_pt_2	Recycled Aggregate modified subbase over subgrade.	12,567
9/3/2019	Hwy175_pt_3	Recycled Aggregate modified subbase over subgrade.	13,250
9/3/2019	Hwy175_pt_4	Recycled Aggregate modified subbase over subgrade.	15,953
9/3/2019	Hwy175_pt_5	Recycled Aggregate modified subbase over subgrade.	29,984
9/3/2019	Hwy175_pt_6	Recycled Aggregate modified subbase over subgrade.	26,062
9/3/2019	Hwy175_pt_7	Recycled Aggregate modified subbase over subgrade.	25,111
9/3/2019	Hwy175_pt_8	Recycled Aggregate modified subbase over subgrade.	17,782
9/3/2019	Hwy175_pt_9	Recycled Aggregate modified subbase over subgrade.	20,322
9/3/2019	Hwy175_pt_10	Recycled Aggregate modified subbase over subgrade.	17,858
9/13/2019	160th St_pt_1	Crushed limestone modified subbase over subgrade with geogrid at the interface.	34,325
9/13/2019	160th St_pt_2	Crushed limestone modified subbase over subgrade with geogrid at the interface.	32,436
9/13/2019	160th St_pt_3	Crushed limestone modified subbase over subgrade with geogrid at the interface.	32,564
9/13/2019	160th St_pt_4	Crushed limestone modified subbase over subgrade with geogrid at the interface.	28,320
9/13/2019	160th St_pt_5	Crushed limestone modified subbase over subgrade with geogrid at the interface.	26,762
9/13/2019	160th St_pt_6	Crushed limestone modified subbase over subgrade with geogrid at the interface.	22,532
9/13/2019	160th St_pt_7	Crushed limestone modified subbase over subgrade with geogrid at the interface.	28,894
9/13/2019	160th St_pt_8	Crushed limestone modified subbase over subgrade with geogrid at the interface.	5,880

Table 7. Summary of APLT results (Test B)

Date	Test Point	Material ID	k_{u1} (pci)	k_{u2} (pci)	Ratio	δ_p at end of test (in.)
9/30/2020	Hwy20_pt1	Modified Subbase - Crushed limestone.	129.6	388.7	3.0	0.088
9/30/2020	Hwy20_pt3	Modified Subbase - Crushed limestone.	153.6	341.5	2.2	0.075
9/30/2020	Hwy20_pt5	Modified Subbase - Crushed limestone.	176.9	361.9	2.0	0.066
8/13/2020	US52_pt1	Modifed Subbase material consisting of a mixture of Recycled PCC & RAP	69.4	168.9	2.4	0.162
8/13/2020	US52_pt2	Modifed Subbase material consisting of a mixture of Recycled PCC & RAP	135.5	626.0	4.6	0.118
8/13/2020	US52, pt4	Modifed Subbase material consisting of a mixture of Recycled PCC & RAP	92.9	249.1	2.7	0.126
7/29/2020	Hwy75_pt1	Compacted special backfill.	60.6	158.8	2.6	0.183
7/29/2020	Hwy75_pt3	Compacted special backfill.	20.4	69.0	3.4	0.571
7/29/2020	Hwy75_pt4	Compacted special backfill.	44.3	110.3	2.5	0.257
7/29/2020	Hwy75_pt5	Compacted special backfill.	111.9	369.0	3.3	0.104

8/27/2019	Hwy20_pt7	Recycled PCC special backfill over subgrade.	67.7	219.8	3.2	0.179
8/27/2019	Hwy20_pt8	Recycled PCC special backfill over subgrade.	152.6	318.2	2.1	0.066
8/27/2019	Hwy20_pt9	Recycled PCC special backfill over subgrade.	118.1	268.0	2.3	0.086
8/27/2019	Hwy20_pt10	Recycled PCC special backfill over subgrade.	128.9	267.5	2.1	0.077
10/23/2019	US61, pt9	Aggregate subbase over compacted subgrade.	188.5	451.0	2.4	0.063
10/23/2019	US61, pt10	Aggregate Base (access road) over compacted subgrade (Select)	138.0	372.0	2.7	0.089
8/12/2020	US52_pt1	Cement Stabilized subgrade	173.9	248.9	1.4	0.037
8/12/2020	US52_pt2	Cement Stabilized Subgrade	190.9	286.3	1.5	0.034
8/12/2020	US52_pt3	Cement Stabilized Subgrade	237.3	403.6	1.7	0.028
8/12/2020	US52_pt4	Compacted select subgrade.	112.2	276.8	2.5	0.094
8/12/2020	US52_pt5	Compacted select subgrade.	127.9	301.6	2.4	0.084
8/12/2020	US52_pt6	Cement Stabilized Subgrade, over culvert	371.4	884.9	2.4	0.025
6/18/2020	I80_pt1	Compacted subgrade - Area compacted on 06/10, per contractor. Material wet and visible rutting.	48.8	120.2	2.5	0.203
6/18/2020	I80_pt2	Compacted subgrade - Area compacted with a sheepsfoot roller, dry crust near the stuface, and experienced	36.2	101.0	2.8	0.299
8/21/2020	US13, pt1	Subgrade-Select	259.0	413.1	1.6	0.035
8/21/2020	US13, pt2	Subgrade-Select	335.1	581.6	1.7	0.029
8/21/2020	US13, pt3	Subgrade-Select	231.7	729.1	3.1	0.043
8/21/2020	US13, pt4	Subgrade-Select	125.3	303.7	2.4	0.084
7/28/2020	Hwy75_pt1	Compacted Select Subgrade.	209.3	350.1	1.7	0.036
7/28/2020	Hwy75_pt2	Compacted Select Subgrade.	183.1	294.7	1.6	0.044
7/28/2020	Hwy75_pt3	Compacted Select Subgrade.	208.9	342.3	1.6	0.035
7/28/2020	Hwy75_pt4	Compacted Select Subgrade.	219.9	336.0	1.5	0.027
7/28/2020	Hwy75_pt5	Compacted Select Subgrade.	142.5	244.1	1.7	0.061
6/25/2020	US30A_pt3	Compacted Subgrade.	145.1	296.3	2.0	0.076
6/30/2020	US30B_pt1	Compacted subgrade.	72.5	165.9	2.3	0.146
6/30/2020	US30B_pt2	Compacted subgrade.	220.2	392.3	1.8	0.038
6/30/2020	US30B_pt3	Compacted subgrade.	175.0	411.7	2.4	0.057
6/30/2020	US30B_pt4	Compacted subgrade.	104.4	252.9	2.4	0.103
6/30/2020	US30B_pt5	Compacted subgrade.	110.4	227.1	2.1	0.098
10/23/2019	US61_pt1	Compacted Subgrade (Select)	155.8	336.3	2.2	0.067
10/23/2019	US61_pt2	Compacted Subgrade (Select)	209.7	472.6	2.3	0.038
10/23/2019	US61_pt3	Compacted Subgrade (Select)	232.7	524.4	2.3	0.035
10/23/2019	US61_pt4	Compacted Subgrade (Select)	226.2	474.7	2.1	0.041
10/23/2019	US61_pt5	Compacted Subgrade (Select)	239.5	527.0	2.2	0.037

10/23/2019	US61_pt6	Compacted Subgrade (Select)	123.6	306.5	2.5	0.091
10/23/2019	US61_pt7	Compacted Subgrade (Select)	161.2	352.5	2.2	0.051
10/23/2019	US61_pt8	Compacted Subgrade (Select)	214.4	427.1	2.0	0.036
10/24/2019	US61_pt11	Compacted Subgrade (Select)	82.5	220.9	2.7	0.114
6/16/2020	US61_pt1	Compacted granular subbase.	62.3	143.6	2.3	0.156
6/16/2020	US61_pt3	Compacted granular subbase.	129.0	265.9	2.1	0.087
9/25/2020	US20_pt1	Macadam Stone Base	72.5	357.0	4.9	0.210
9/25/2020	US20_pt2	Macadam Stone Base	98.2	339.9	3.5	0.132
9/25/2020	US20_pt3	Macadam Stone Base	69.6	210.6	3.0	0.180
9/25/2020	US20_pt4	Macadam Stone Base	106.9	362.6	3.4	0.141
7/7/2020	US30_pt1	Compacted Granular Subbase - One vibratory roller mapping pass.	119.5	336.5	2.8	0.108
7/7/2020	US30_pt2	Compacted Granular Subbase - One vibratory roller mapping pass.	90.8	230.1	2.5	0.124
7/7/2020	US30_pt3	Compacted Granular Subbase - One vibratory roller mapping pass.	115.1	359.3	3.1	0.111
7/7/2020	US30_pt4	Compacted Granular Subbase - One vibratory roller mapping pass.	123.4	347.9	2.8	0.104
7/7/2020	US30_pt5	Compacted Granular Subbase - One vibratory roller mapping pass.	156.9	372.8	2.4	0.077
7/8/2020	US30_pt8	Compacted Granular Subbase - Test performed after eight vibratory roller passes.	136.7	310.3	2.3	0.084
7/8/2020	US30_pt9	Compacted Granular Subbase - Test performed after eight vibratory roller passes.	154.3	362.3	2.3	0.076
7/8/2020	US30_pt10	Compacted Granular Subbase - Test performed after sixteen vibratory roller passes.	153.1	349.3	2.3	0.088
7/8/2020	US30_pt11	Compacted Granular Subbase - Test performed after sixteen vibratory roller passes.	144.7	361.9	2.5	0.078
7/8/2020	US30_pt12	Compacted Granular Subbase - Test performed after sixteen vibratory roller passes.	141.2	358.2	2.5	0.082
7/8/2020	US30_pt13	Compacted Granular Subbase - Test performed after eight vibratory roller passes.	104.5	252.6	2.4	0.114
8/27/2019	US20_pt1_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	92.2	292.4	3.2	0.135
8/27/2019	US20_pt2_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	81.9	280.5	3.4	0.158
8/27/2019	US20_pt3_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	87.6	289.6	3.3	0.148
9/5/2019	US20_pt21_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	111.5	380.0	3.4	0.115
9/5/2019	US20_pt22_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	122.2	458.2	3.7	0.114
9/5/2019	US20_pt23_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	154.6	454.6	2.9	0.077
9/5/2019	US20_pt24_ 2019	Recycled PCC granular subbase over special backfill and subgrade.	140.5	449.6	3.2	0.087

9/5/2019	US20_pt25_2019	Recycled PCC granular subbase over special backfill and subgrade.	91.3	334.0	3.7	0.141
6/18/2020	I80_PT3	Reworked subgrade with nominal 24 inches thick granular treatment over clay subgrade, with biaxial geogrid	166.3	312.0	1.9	0.074
6/18/2020	I80_PT4	Reworked subgrade with nominal 24 inches thick granular treatment over clay subgrade, with biaxial geogrid	153.7	302.9	2.0	0.078
6/18/2020	I80_PT5	Reworked subgrade with nominal 24 inches thick granular treatment over clay subgrade, with biaxial geogrid	202.2	393.1	1.9	0.057
6/18/2020	I80_PT6	Reworked subgrade with nominal 24 inches thick granular treatment over clay subgrade, with biaxial geogrid	171.9	422.8	2.5	0.085
6/18/2020	I80_PT7	Reworked subgrade with granular treatment over clay subgrade, with biaxial geogrid at the interface.	93.2	186.2	2.0	0.094
8/20/2020	US13_PT1	Granular Subbase - Recycled PCC	175.1	551.4	3.1	0.097
8/20/2020	US13_PT2	Granular Subbase - Recycled PCC	59.8	206.0	3.4	0.199
8/20/2020	US13_PT3	Granular Subbase - Recycled PCC	55.7	175.0	3.1	0.205
8/20/2020	US13_PT4	Granular Subbase - Recycled PCC	99.6	327.9	3.3	0.132
8/20/2020	US13_PT5	Granular Subbase - Recycled PCC	119.6	438.7	3.7	0.118

Material Group ID: k-St-So
Material Group ID: k-SG
Material Group ID: k-So-So
Material Group ID: k-St-St

Table 8. Summary of k-value test results.

Material Group ID	No. of Tests	Minimum (pci)	Maximum (pci)	Average (pci)	Std. Deviation (pci)	COV (%)
k-St-So	16	20.4	188.5	111.8	123.5	48.4
k-SG	32	36.2	371.4	177.7	179.1	75.1
k-So-So	25	62.3	156.9	114.4	115.1	28.8
k-St-St	10	55.7	202.2	129.7	136.7	51.3

Table 9. Summary of $M_{r\text{-}comp}$ (at 40 psi maximum stress) value test results.

No. of Tests	Minimum (pci)	Maximum (pci)	Average (pci)	Std. Deviation (pci)	COV (%)
38	5,609	55,945	23,905	24,056	10,608

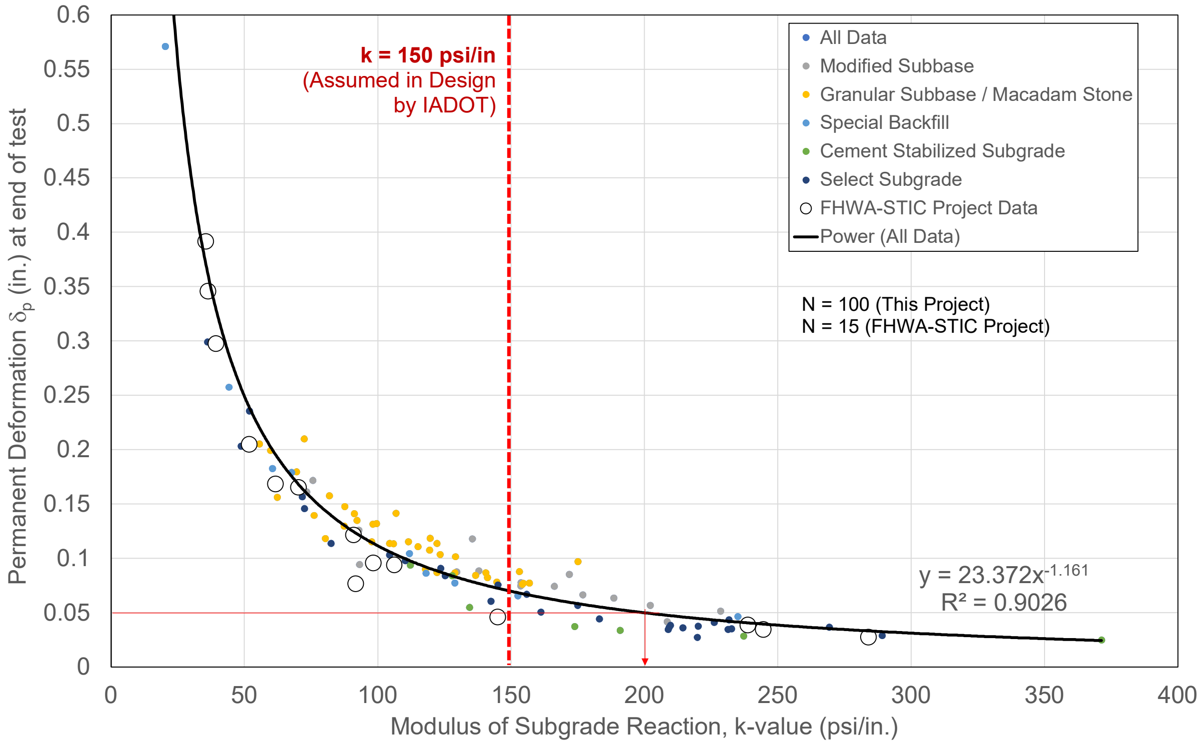


Figure 8. k-value versus permanent deformation (δ_p) at the end of test from field test measurements at all project sites

Calibration Analysis Results

COMP-Score RT calibration records showing the measured versus predicted $M_{r\text{-comp}}$ and k-values are provided in Figure 9 to Figure 13. $M_{r\text{-comp}}$ value calibration analysis was performed on measurements obtained from a few sites on granular materials. k-value calibration analysis was performed on materials with varying profiles and stiffnesses across the state, which provided four unique trends. These trends are related to the following material groups and are identified with a unique calibration model ID as follows:

1. IA-AID_k-SG – cohesive subgrade materials (cement treated/untreated)
2. IA-AID_k-So-So – granular subbase materials over untreated cohesive subgrade
3. IA-AID_k-St-So – modified subbase or special backfill materials over subgrade.
4. IA-AID_k-St-St – relatively stiff layer of modified subbase or granular subbase with CBR > 10 over relatively stiff underlying subgrade layer.

A summary of the regression statistics and the measurement validity range for each measurement value for each model is included in Figure 9 to Figure 13, and the regression statistics for all the models are summarized in Table 10. Regression relationships yielded R^2 values ranging between 0.92 and 0.94 representing strong correlations and high confidence in the predicted values.

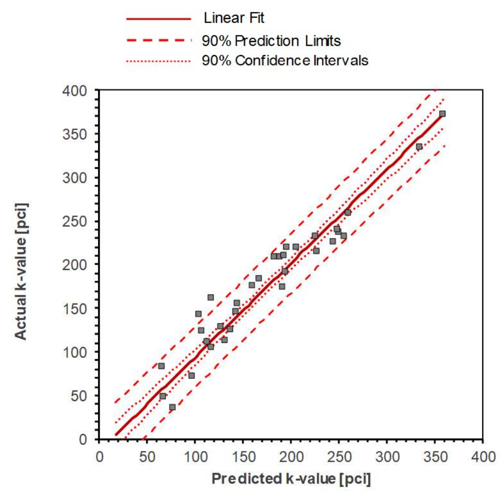
COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	10/23/2019 to 09/20/2020 — Tested By: HG, CV, DW, PV — CAL ID: IA-AID_2020_k-SG
Notes/ Comments:	Modulus of subgrade reaction value (k-value) for the first loading cycle at 10 psi applied stress with plate bending correction and correction for seating, per AASHTO T222. Field testing conducted at 32 test locations on compacted select subgrade (cohesive) and compacted cement stabilized subgrade. Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration setting, and full speed. Note: Multiply k x 19.79 to calculate Elastic Modulus (E) [Poisson's ratio of 0.4 and shape factor of $\pi/2$ for rigid plate over cohesive material]

		Selected Stress, σ = 10 psi		
Test Point ID	Profile	Actual k-value [pci]	Pred. k-value [pci]	RT Reported k-value [pci]
US52_pt1	CSS	173.9	192.7	164.9
US52_pt2	CSS	190.9	196.1	167.9
US52_pt3	CSS	237.3	251.4	217.0
US52_pt4	CSS	112.2	133.4	112.3
US52_pt5	CSS	127.9	128.9	108.3
US52_pt6	CSS	371.4	359.5	312.8
I80_pt1	SG	48.8	69.1	55.3
I80_pt2	SG	36.2	78.7	63.8
US13, pt1	SG	259.0	261.6	226.0
US13, pt2	SG	335.1	336.1	292.1
US13, pt3	SG	231.7	227.4	195.7
US13, pt4	SG	125.3	138.8	117.1
Hwy75_pt1	SG	209.3	190.6	163.0
Hwy75_pt2	SG	183.1	168.5	143.5
Hwy75_pt3	SG	208.9	184.1	157.3
Hwy75_pt4	SG	219.9	198.0	169.6
Hwy75_pt5	SG	142.5	106.0	88.0
US30A_pt3	SG	145.1	144.8	122.5
US30B_pt1	SG	72.5	99.4	82.2
US30B_pt2	SG	220.2	207.6	178.1
US30B_pt3	SG	175.0	161.7	137.4
US30B_pt4	SG	104.4	118.8	99.4
US30B_pt5	SG	110.4	114.5	95.6
US61_pt1	SG	155.8	146.5	124.0
US61_pt2	SG	209.7	194.6	166.6
US61_pt3	SG	232.7	257.6	222.5
US61_pt4	SG	226.2	245.6	211.8
US61_pt5	SG	239.5	250.5	216.1
US61_pt6	SG	123.6	108.4	90.2
US61_pt7	SG	161.2	119.4	99.9
US61_pt8	SG	214.4	228.4	196.5
US61_pt9	SG	82.5	67.7	54.0

SG - Select cohesive subgrade; CSS - Cement stabilized cohesive subgrade.

Reported k-value = (1-%SE) * Predicted k-value - Δk-value



Regression Statistics

N	32	
R^2	0.933	
R^2(adj.)	0.928	
RMSE	20.1	psi/in.
%SE*	11.3%	
F-value	202.12	
p-value	<0.0001	

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual k-value = 1.000 x RT Pred. k-value + 0

Δk-value: 6 psi/in.

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	36.2	67.7	54.0	psi/in.
Maximum:	371.4	359.5	312.8	psi/in.
Mean:	177.7	177.7	151.6	psi/in.
Median:	179.1	176.3	150.4	psi/in.
Standard Deviation:	75.1	72.5	64.3	psi/in.
Coefficient of Variation:	42%	41%	42%	

Signature: *Pavana Vennapusa*

Typed Name: Pavana Vennapusa, Ph.D., P.E.

Date: 4/22/2021 License # P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT – Calibration Record

Project Name:	Iowa TDIP-AID Demonstration Project
Project ID:	SIA-00003
Location:	Multiple Project Sites, Iowa

ingios GEOTECHNICS

Figure 9. Calibration record for treated/untreated subgrade materials (Model ID: IA-AID_2020_k-SG)

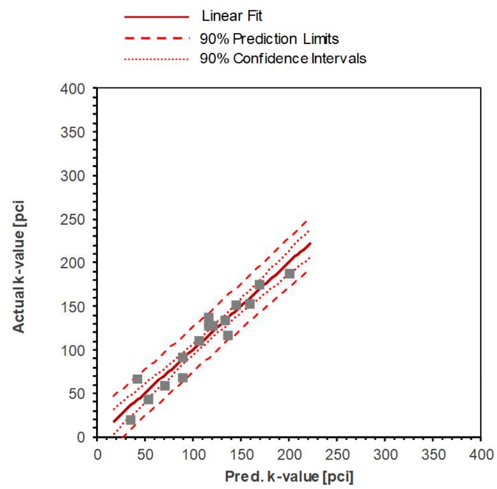
COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	10/23/2019 to 09/30/2020 — Tested By: HG, CV, DW, PV — CAL ID: IA-AID_2020_k-St-So
Notes/ Comments:	Modulus of subgrade reaction value (k-value) for the first loading cycle at 10 psi applied stress with plate bending correction and correction for seating, per AASHTO T222. Field testing conducted at 16 test locations on compacted special backfill mateiral or modified subbase mateiral. Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration setting, and full speed. Note: Multiply k x 19.79 to calculate Elastic Modulus (E) [Poisson's ratio of 0.4 and shape factor of 8/3 for rigid plate over granular material]

Test Point ID	Profile	Selected Stress, σ = 10 psi: Actual k-value [pci]	Pred. k-value [pci]	RT Reported k-value [pci]
Hwy20_pt1	MSB/SG	129.6	121.3	102.0
Hwy20_pt3	MSB/SG	153.6	159.0	134.3
Hwy20_pt5	MSB/SG	176.9	169.0	142.9
US52_pt1	MSB/SG	69.4	89.8	75.0
US52_pt2	MSB/SG	135.5	133.5	112.5
US52, pt4	MSB/SG	92.9	89.8	75.0
Hwy75_pt1	SpB/SG	60.6	70.5	58.5
Hwy75_pt3	SpB/SG	20.4	35.9	28.8
Hwy75_pt4	SpB/SG	44.3	54.2	44.5
Hwy75_pt5	SpB/SG	111.9	106.7	89.5
Hwy20_pt7	SpB/SG	67.7	43.1	35.0
Hwy20_pt8	SpB/SG	152.6	145.4	122.7
Hwy20_pt9	SpB/SG	118.1	136.2	114.7
Hwy20_pt10	SpB/SG	128.9	117.2	98.5
US61, pt9	MSB/SG	188.5	201.0	170.3
US61, pt10	MSB/SG	138.0	116.3	97.7

MSB - Modified Subbase with virgin material; SpB - Special Backfill; SG - Subgrade; SG - Select cohesive subgrade.

CRT reported k-value = (1-%SE) * RT Pred. k-value - Δk-value



Regression Statistics

N	16
R^2	**0.920**
R^2(adj.)	0.891
RMSE	**15.9** psi/in.
%SE*	14.3%
F-value	31.74
p-value	<0.0001

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual k-value = 1.000 x RT Pred. k-value + 0

Δk-value 2 psi/in.

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	20.4	35.9	28.8	psi/in.
Maximum:	188.5	201.0	170.3	psi/in.
Mean:	111.8	111.8	93.9	psi/in.
Median:	123.5	116.8	98.1	psi/in.
Standard Deviation:	48.4	46.4	39.8	psi/in.
Coefficient of Variation:	43%	41%	42%	

Signature: *Pavana Vennapusa*
Typed Name: Pavana Vennapusa, Ph.D., P.E.
Date: 4/22/2021 License # P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT – Calibration Record

Project Name:	Iowa TDIP-AID Demonstration Project
Project ID:	SIA-00003
Location:	Multiple Project Sites, Iowa

ingios GEOTECHNICS

Figure 10. Calibration record for modified subbase or special backfill top layer underlain by subgrade layers (Model ID: IA-AID_2020_k-St-So)

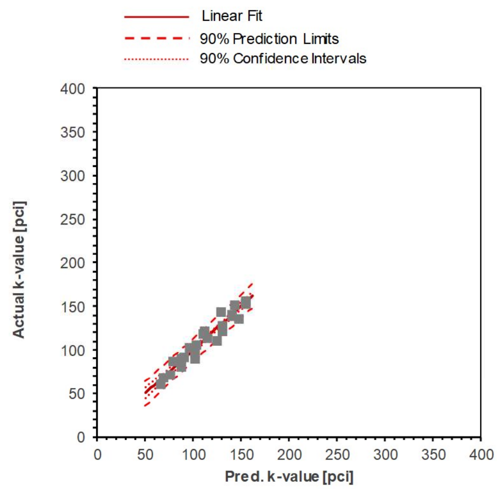
COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	08/27/2019 to 9/25/2020 · Tested By: HG, CV, DW · CAL ID: IA-AID_2020_k-So-So
Notes/ Comments:	Modulus of subgrade reaction value (k-value) for the first loading cycle at 10 psi applied stress with plate bending correction and correction for seating, per AASHTO T222. Field testing conducted at 25 test locations on compacted macadam stone base or granular subbase. Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration setting, and full speed. Note: Multiply k x 19.79 to calculate Elastic Modulus (E) [Poisson's ratio of 0.4 and shape factor of 8/3 for rigid plate over granular material]

		Selected Stress, σ = 10 psi		
Test Point ID	Profile	Actual k-value [pci]	Pred. k-value [pci]	RT Reported k-value [pci]
US61_pt1	GSB	62.3	67.4	62.6
US61_pt3	GSB	129.0	130.8	121.4
US20_pt1	MaSB	72.5	76.9	71.4
US20_pt2	MaSB	98.2	102.1	94.8
US20_pt3	MaSB	69.6	69.5	64.5
US20_pt4	MaSB	106.9	103.6	96.2
US30_pt1	GSB	119.5	111.4	103.4
US30_pt2	GSB	90.8	103.0	95.6
US30_pt3	GSB	115.1	115.7	107.4
US30_pt4	GSB	123.4	131.3	121.9
US30_pt5	GSB	156.9	154.9	143.8
US30_pt8	GSB	136.7	147.6	137.0
US30_pt9	GSB	154.3	155.1	143.9
US30_pt10	GSB	153.1	143.4	133.1
US30_pt11	GSB	144.7	129.0	119.7
US30_pt12	GSB	141.2	141.4	131.3
US30_pt13	GSB	104.5	96.7	89.7
US20_pt1_2019	GSB	92.2	90.9	84.4
US20_pt2_2019	GSB	81.9	87.9	81.6
US20_pt3_2019	GSB	87.6	79.7	73.9
US20_pt21_2019	GSB	111.5	125.3	116.3
US20_pt22_2019	GSB	122.2	112.1	104.0
US20_pt23_2019	GSB	154.6	154.9	143.8
US20_pt24_2019	GSB	140.5	141.2	131.1
US20_pt25_2019	GSB	91.3	88.6	82.3

MSB - Modified Subbase with virgin materia; SpB - Special Backfill; SG - Subgrade; SG - Select cohesive subgrade.

CRT reported k-value = (1-%SE) * RT Pred. k-value - Δk-value



Regression Statistics

N	25
R^2	0.936
R^2(adj.)	0.919
RMSE	8.2 psi/in.
%SE*	7.2%
F-value	55.44
p-value	<0.0001

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual k-value = 1.000 x RT Pred. k-value + 0

Δk-value 0 psi/in.

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	62.3	67.4	62.6	psi/in.
Maximum:	156.9	155.1	143.9	psi/in.
Mean:	114.4	114.4	106.2	psi/in.
Median:	115.1	112.1	104.0	psi/in.
Standard Deviation:	28.8	27.9	25.9	psi/in.
Coefficient of Variation:	25%	24%	24%	

Signature	*Pavana Vennapusa*		
Typed Name:	Pavana Vennapusa, Ph.D., P.E.		
Date:	4/22/2021	License #	P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT – Calibration Record

Project Name:	Iowa TDIP-AID Demonstration Project
Project ID:	SIA-00003
Location:	Multiple Project Sites, Iowa

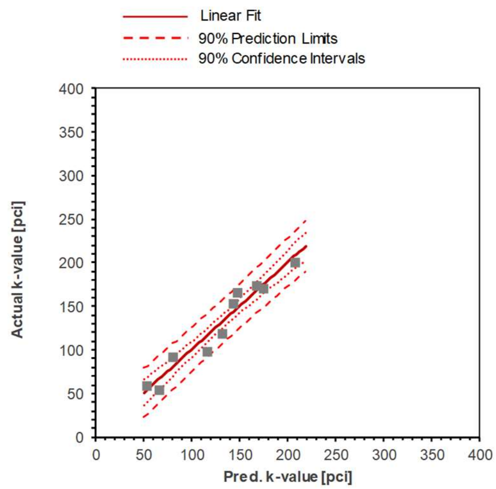
ingios GEOTECHNICS

Figure 11. Calibration record for granular subbase over soft underlying subgrade layers (Model ID: IA-AID_2020_k-So-So)

COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	08/27/2019 to 9/25/2020 — Tested By: HG, CV, DW — CAL ID: IA-AID_2020_k-St-St
Notes/ Comments:	Modulus of subgrade reaction value (k-value) for the first loading cycle at 10 psi applied stress with plate bending correction and correction for seating, per AASHTO T222. Field testing conducted at 10 test locations on compacted very stiff and thick (> 2 ft) modified subbase layer and very stiff granular subbase layer over very stiff subgrade (CBR > 30). Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration setting, and full speed. Note: Multiply k x 19.79 to calculate Elastic Modulus (E) [Poisson's ratio of 0.4 and shape factor of 8/3 for rigid plate over granular material]

Test Point ID	Profile	Selected Stress, σ = 10 psi Actual k-value [pci]	Pred. k-value [pci]	RT Reported k-value [pci]
I80_PT3	MSB/MSB	166.3	148.0	**128.3**
I80_PT4	MSB/MSB	153.7	144.1	**124.8**
I80_PT5	MSB/MSB	202.2	208.3	**182.6**
I80_PT6	MSB/MSB	171.9	175.8	**153.4**
I80_PT7	MSB/MSB	93.2	81.7	**68.5**
US13_PT1	GSB/SG	175.1	167.6	**146.0**
US13_PT2	GSB/SG	59.8	53.9	**43.6**
US13_PT3	GSB/SG	55.7	67.4	**55.7**
US13_PT4	GSB/SG	99.6	117.0	**100.4**
US13_PT5	GSB/SG	119.6	133.1	**114.9**



Regression Statistics

N	10
R^2	**0.944**
R^2(adj.)	0.937
RMSE	**12.9** psi/in.
%SE*	9.9%
F-value	135.04
p-value	<0.0001

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual k-value = 1.000 x RT Pred. k-value + 0

Δk-value 5 psi/in.

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	55.7	53.9	43.6	psi/in.
Maximum:	202.2	208.3	182.6	psi/in.
Mean:	129.7	129.7	111.8	psi/in.
Median:	136.7	138.6	119.9	psi/in.
Standard Deviation:	51.3	49.9	44.9	psi/in.
Coefficient of Variation:	40%	38%	40%	

MSB - Modified Subbase with virgin materia; SpB - Special Backfill; SG - Subgrade; SG - Select cohesive subgrade.

CRT reported k-value = (1-%SE) * RT Pred. k-value - Δk-value

Signature: *Pavana Vennapusa*

Typed Name: Pavana Vennapusa, Ph.D., P.E.

Date: 4/22/2021 License # P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT – Calibration Record

Project Name:	Iowa TDIP-AID Demonstration Project
Project ID:	SIA-00003
Location:	Multiple Project Sites, Iowa

ingios GEOTECHNICS

Figure 12. Calibration record for stiff granular top layer (modified subbase or granular subbase) and underlying stiff subgrade layers (Model ID: IA-AID_2020_k-St-St)

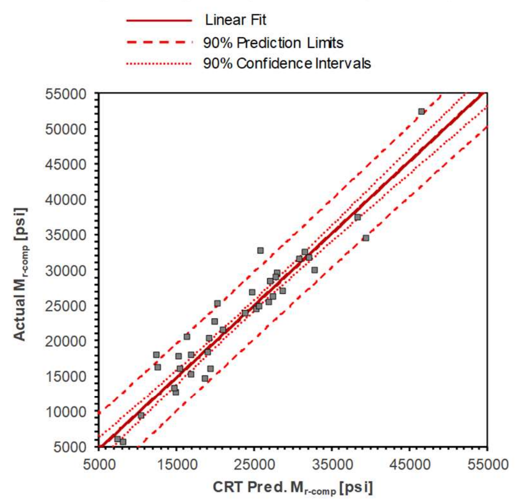
COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	08/28/2019 to 9/13/2019 — Tested By: DW, HG — CAL ID: IA-AID_2020_Mr40
Notes/ Comments:	Stress-dependent in situ composite resilient modulus (Mr-comp) data obtained from multi-stress sequence cyclic automated plate load testing (APLT). Field testing conducted at 38 test locations (28 modified subbase over subgrade and 10 special backfill over subgrade). The last cyclic stress sequence (cyclic stress of 39 psi) used for CRT calibration analysis, to match stress conditions anticipated during compaction process. Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration, and full speed.

Test Point ID	Profile	Selected Cyclic Stress, σ_{cyclic} = 39 psi: Actual $M_{r\text{-}comp}$ [psi]	RT Pred. $M_{r\text{-}comp}$ [psi]	RT Reported M_r [psi]
Hwy20_pt_11	SpB/SG	14,593	18,891	15,714
Hwy20_pt_12	SpB/SG	17,997	12,799	10,373
Hwy20_pt_13	SpB/SG	20,389	16,670	13,767
Hwy20_pt_14	SpB/SG	21,427	21,197	17,737
Hwy20_pt_15	SpB/SG	24,342	25,483	21,495
Hwy20_pt_16	SpB/SG	15,871	15,672	12,892
Hwy20_pt_17	SpB/SG	16,101	12,956	10,510
Hwy20_pt_18	SpB/SG	18,282	19,406	16,166
Hwy20_pt_19	SpB/SG	15,082	17,211	14,241
Hwy20_pt_20	SpB/SG	23,770	24,067	20,253
Hwy52_pt_1	MSB/SG	25,464	27,117	22,928
Hwy52_pt_2	MSB/SG	37,271	38,593	32,990
Hwy52_pt_3	MSB/SG	55,945	56,424	48,625
Hwy52_pt_4	MSB/SG	52,216	46,717	40,114
Hwy52_pt_5	MSB/SG	9,217	10,846	8,660
Hwy52_pt_6	MSB/SG	5,609	8,472	6,579
Hwy52_pt_7	MSB/SG	24,784	25,873	21,837
Hwy52_pt_8	MSB/SG	31,756	32,287	27,461
Hwy52_pt_9	MSB/SG	26,848	28,903	24,493
Hwy52_pt_10	MSB/SG	31,374	31,139	26,454
Hwy175_pt_1	MSB/SG	29,440	28,229	23,903
Hwy175_pt_2	MSB/SG	12,567	15,305	12,570
Hwy175_pt_3	MSB/SG	13,250	15,080	12,373
Hwy175_pt_4	MSB/SG	15,953	19,687	16,412
Hwy175_pt_5	MSB/SG	29,984	33,011	28,096
Hwy175_pt_6	MSB/SG	26,062	27,645	23,391
Hwy175_pt_7	MSB/SG	25,111	20,527	17,149
Hwy175_pt_8	MSB/SG	17,782	15,633	12,858
Hwy175_pt_9	MSB/SG	20,322	19,425	16,183
Hwy175_pt_10	MSB/SG	17,858	17,150	14,188
160th St_pt_1	MSB/SG*	34,325	39,707	33,967
160th St_pt_2	MSB/SG*	32,436	31,903	27,125
160th St_pt_3	MSB/SG*	32,564	26,099	22,035
160th St_pt_4	MSB/SG*	28,320	27,352	23,134
160th St_pt_5	MSB/SG*	26,762	25,043	21,109
160th St_pt_6	MSB/SG*	22,532	20,141	16,811
160th St_pt_7	MSB/SG*	28,894	28,080	23,772
160th St_pt_8	MSB/SG*	5,880	7,642	5,851

MSB - Modified Subbase with virgin materia; SpB - Special Backfill; SG - Subgrade; SG* - Subgrade with geogrid placed above subgrade.

CRT reported M_r value = (1-%SE) * RT Pred. $M_{r\text{-}comp}$ - $\Delta M_{r\text{-}comp}$



Regression Statistics

N	38
R^2	0.933
R^2(adj.)	0.923
RMSE	2,944 psi
%SE*	12.3%
F-value	89.68
p-value	<0.0001

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual $M_{r\text{-}comp}$ = 1.000 x RT Pred. $M_{r\text{-}comp}$ + 0

$\Delta M_{r\text{-}comp}$ 850 psi

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	5,609	7,642	5,851	psi
Maximum:	55,945	56,424	48,625	psi
Mean:	23,905	23,905	20,111	psi
Median:	24,056	22,632	18,995	psi
Standard Deviation:	10,608	10,248	8,986	psi
Coefficient of Variation:	44%	43%	45%	

Signature	*Pavana Vennapusa*
Typed Name:	Pavana Vennapusa, Ph.D., P.E.
Date:	4/22/2021 — License # P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT — Calibration Record

Project Name:	Iowa TDIP-AID Demonstration Project
Project ID:	SIA-00003
Location:	Multiple Project Sites, Iowa

ingios GEOTECHNICS

Figure 13. Calibration record for granular materials (Model ID: IA-AID_2020_Mr40)

Table 10. Summary of calibration model regression statistics.

Parameter	Model ID				
	IA-AID_2020_Mr40	IA-AID_2020_k-St-So	IA-AID_2020_k-SG	IA-AID_2020_k-So-So	IA-AID_2020_k-St-St
N	38	16	32	25	10
R^2	0.933	0.920	0.933	0.936	0.944
R^2(adj.)	0.923	0.891	0.928	0.919	0.937
RMSE	2,944	15.9	20.1	8.2	12.9
%SE*	12.3%	14.3%	11.3%	7.2%	9.9%
F-value	89.68	31.74	202.12	55.44	135.04
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Mapping Results and e-Compaction Reports

A total of 115 COMP-Score RT maps were obtained from all the project sites. The number of maps for each material type from each project site is summarized in Table 7. All e-Compaction reports generated for this project are included in Appendix C. A few highlights are presented below with a k-value map from the US20 project for granular subbase and special backfill material in Figure 14 and Mr-comp map on modified subbase and subgrade material in Figure 15.

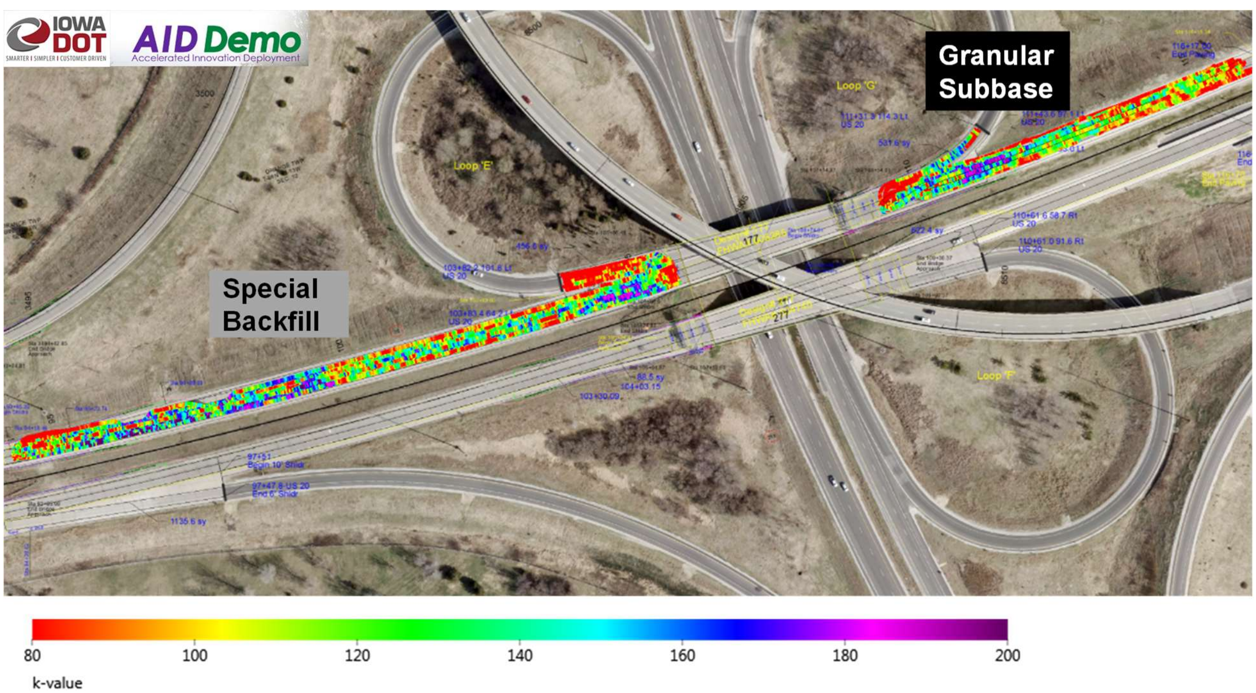


Figure 14. k-value map on granular subbase and special backfill subgrade treatment layers on Blackhawk County US20 project (08/27/2019)

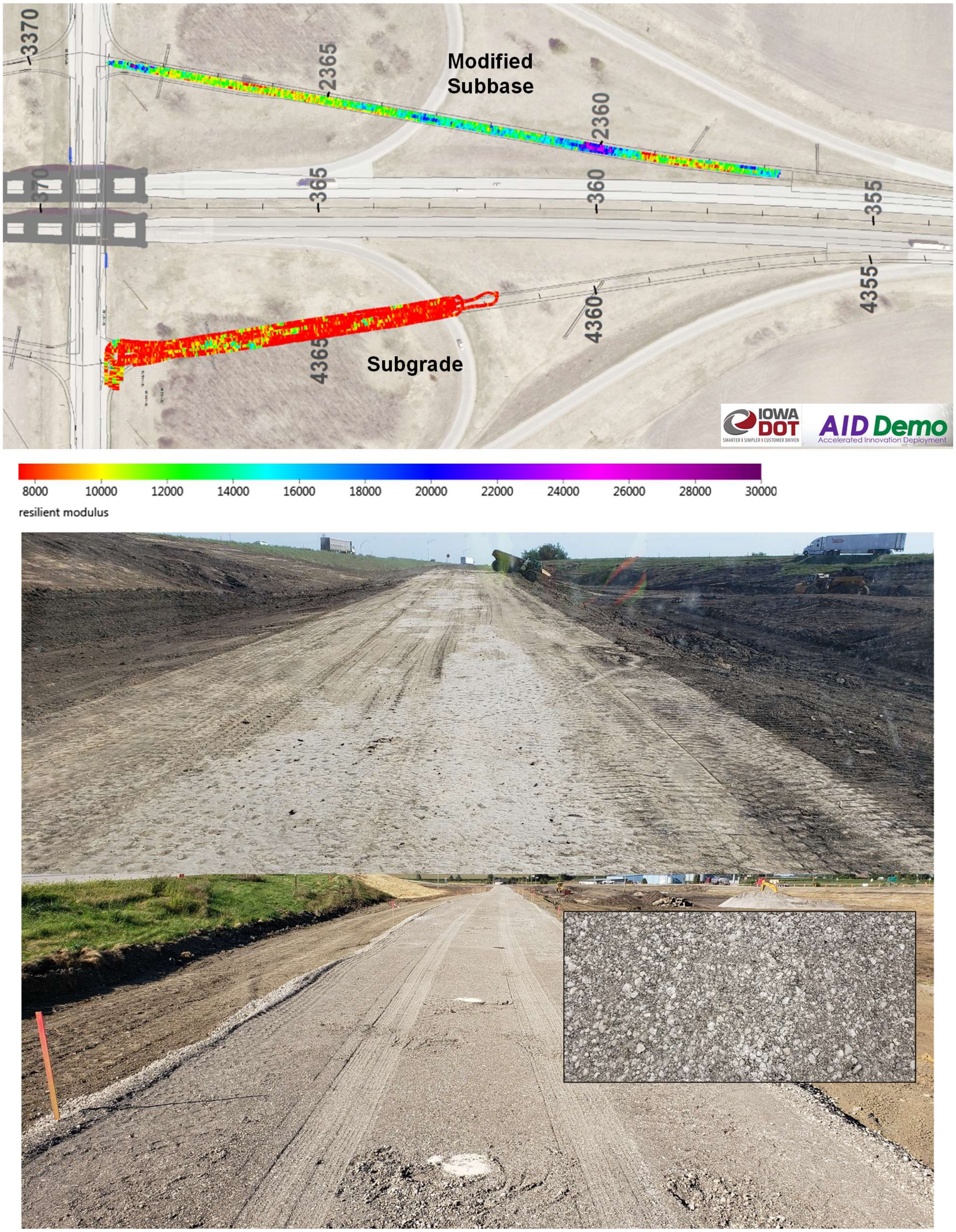


Figure 15. $M_{r\text{-}comp}$ map on modified subbase and embankment subgrade Class 10 material on Hamilton County I-35/Hwy 175 project.

Vu Meter Drainage Test Results

Iowa DOT specifications for granular subbase construction require compaction using static roller passes and no vibration is allowed due to particle breakage and the resulting effect on drainage. Field testing was conducted using the Vu meter provided by the Iowa DOT to assess relative drainage times on subbase layers after different compaction passes. This testing was performed in selected sections at a few project sites with 1 to 24 vibratory roller passes. Testing was performed on both granular subbase and modified subbase materials.

Pictures from testing are included in Figure 16 to Figure 18. Results from the testing are summarized in Table 11 and Figure 19.

Per John Hart, PCC Field Engineer, Iowa DOT, if the time taken to fully drain the way in the Vu meter is between 30 and 120 sections, the section is considered to provide "good" drainage. Results indicated that all granular subbase test sections showed ≤ 12 seconds to fully drain the water, after 1 to 24 vibratory roller compaction passes.

The drainage time in the modified subbase layer test sections ranged between 86 and 261 seconds.

Figure 16. Vu meter testing on crushed limestone granular subbase on Des Moines County US61 project (06/16/2020).

Figure 17. Vu meter testing on crushed limestone granular subbase on Tama County US30 (07/09/2020).

Figure 18. Vu meter testing on crushed limestone modified subbase on Dubuque County US20 project (09/30/2020).

Table 11. Summary of Vu meter test results from multiple project sites.

Date	Location	Material	No. of Vibratory Roller Passes	No. of Tests	Vu Drainage Meter – Time for Drainage (sec)		
					Minimum	Maximum	Average
6/16/2020	US61, Des Moines County, IA	Granular Subbase (4121) Crushed Limestone	3	1	12		12
			5	3	9	10	9
			8	1	12		12
			12	2	9	11	10
7/9/2020	US30, Tama County, IA	Granular Subbase (4121) Crushed Limestone	1	7	9	14	11
			8	3	8	9	8
			24	3	9	12	10
8/20/2020	US13, Linn County, IA	Granular Subbase (4121) Recycled Concrete	1	2	9	10	9
			8	1	11		11
			24	2	9	11	10
8/13/2020	US52, Dubuque County, IA	Modified Subbase (4123) Mixture of Recycled PCC and RAP	1	3	108	220	148
			16	2	101	261	181
9/30/2020	US20, Dubuque County, IA	Modified Subbase (4123) Crushed Limestone	1	2	149	153	151
			8	1	86		86
			24	2	95	111	103

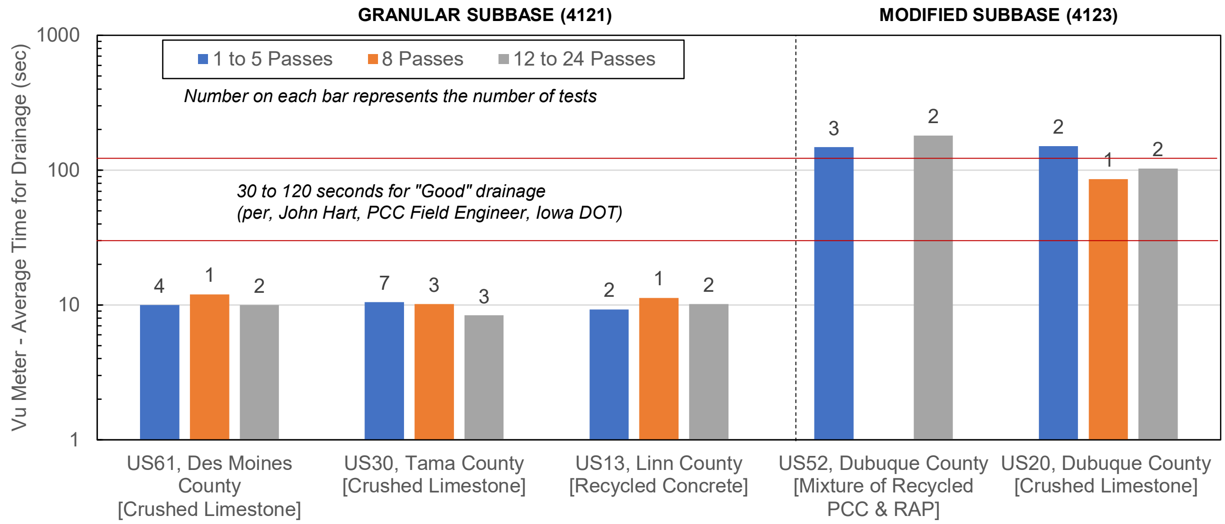


Figure 19. Bar chart of Vu meter test results form multiple project sites.

Design Life Prediction Analysis

The RT mapping results showing geospatial record of k-values allows for design life prediction analysis. To illustrate this possibility, k-value mapping results form the Blackhawk County US20 project are shown in Figure 20 and the predicted design life values are shown in Figure 21. Both these maps are shown as delta maps with a reference target value as noted in the figures.

The design life was calculated using the AASHTO (1993) rigid pavement design model using the design loading conditions (ESALs) assumed for the project by the Iowa DOT and other input parameters are noted in Figure 21, and applying a reduction in the k-value for a LOS condition. An LOS = 2 was assumed (per AASHTO 1993), because of the potential void gap at locations with > 0.05 inch permanent deformation. This was determined using the empirical relationship between k-value and δ_p from static APLTs (Figure 8), and all grid point locations on the map with k-value < 200 pci was corrected for the LOS condition.

Results indicated a 20% to 25% decrease in assumed pavement design life as an impact of the foundation support conditions. This has significant cost implications in terms of potential maintenance work and safety impacts to public and construction works due to road closures.

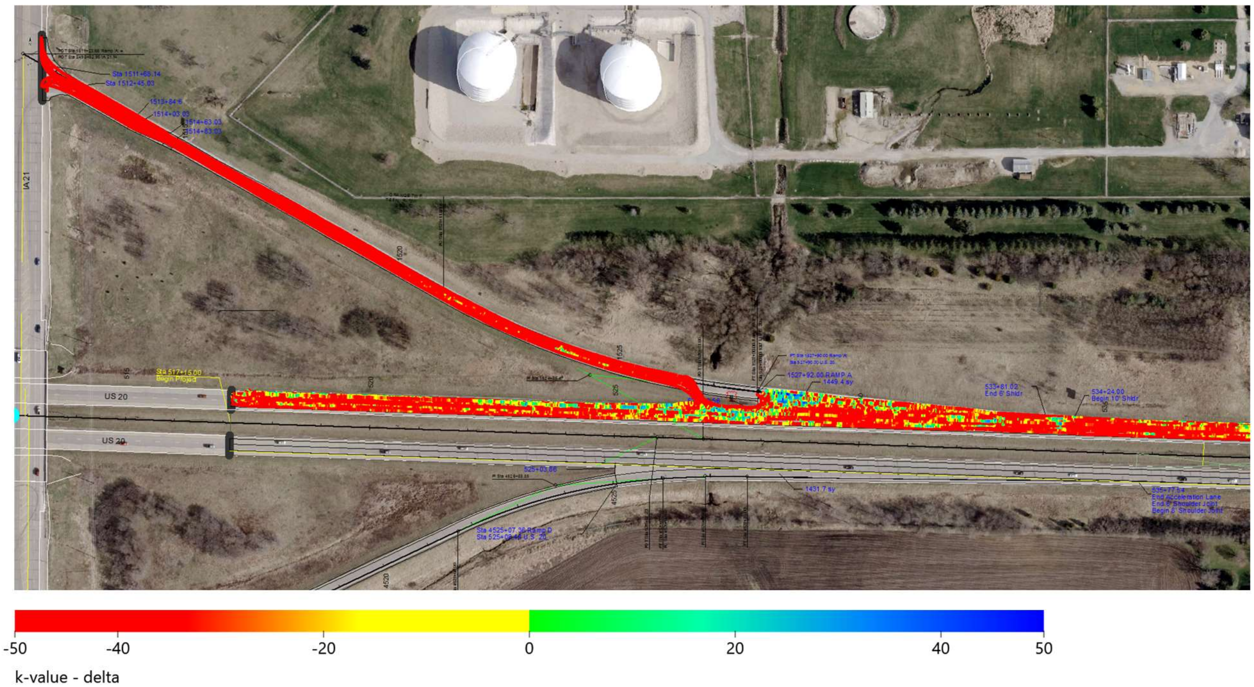


Figure 20. Delta k-value map (assuming a target k-value of 150 pci) of granular subbase layer on Blackhawk US20 project (08/27/2020).

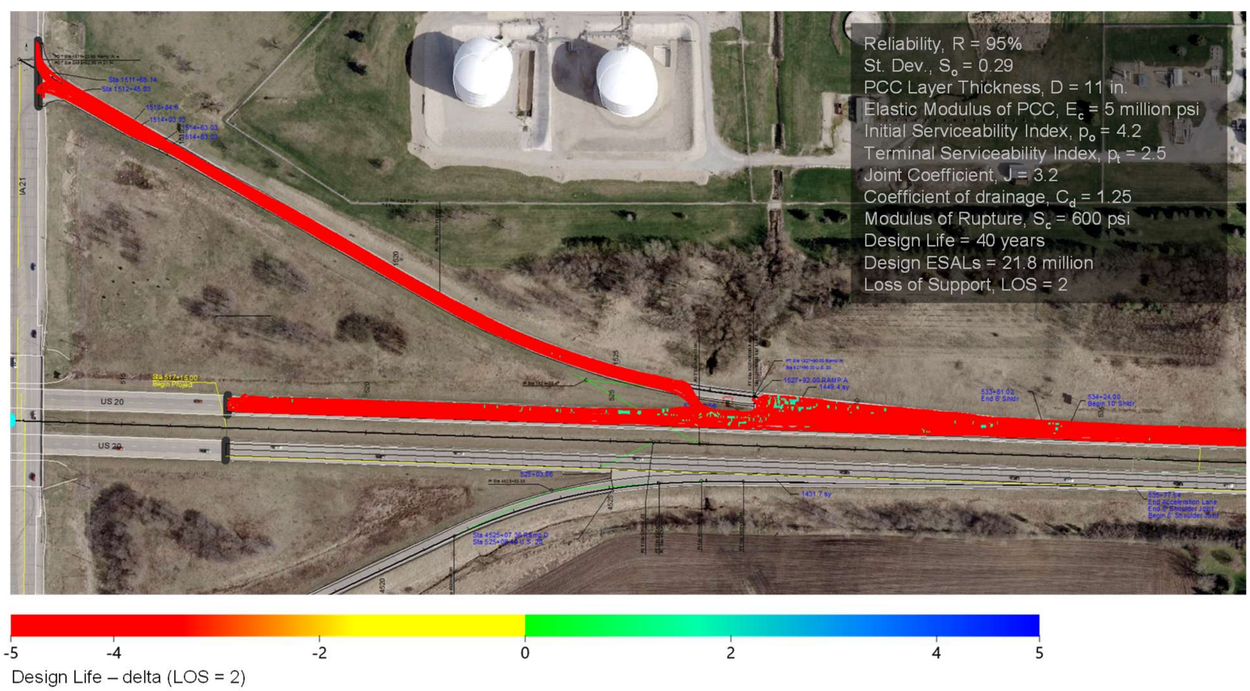


Figure 21. Predicted delta design life map (assumed target design life = 40 years) per AASHTO (1993) pavement design assuming LOS = 2.

References

Dupont, W.D., Plummer, W.D. (1998). “Power and sample size calculations for studies involving linear regression,” *Controlled Clinical Trails,* Vol. 19, 589-601.

Tutumluer, E., Moaveni, M., White, D.J., and Vennapusa, P. (2018). “Validation of intelligent compaction to characterize pavement foundation mechanical properties,” Research Report No: UILU-ENG-2018, Sponsored by the Illinois State Toll Highway Authority, Submitted by University of Illinois at Urbana-Champaign, Champaign, IL.

White, D.J., Vennapusa, P., Cackler, T. (2014). “ICM Report – Ohio River Bridges East End Crossing I-265, Section 6, Sta. 350+00 to 400+00”, Report submitted for Walsh Vinci Construction, Inc., by Ingios Geotechnics, Inc. (unpublished report).

White, D.J., Vennapusa, P., Tutumluer, E., Vavrik, W., Moaveni, M., Gillen, S. (2018). “Spatial verification of modulus for pavement foundation system.” *Transportation Research Record*, Journal of the Transportation Research Board (in print). https://doi.org/10.1177/0361198118782266

White, D. J., and Vennapusa, P. (2017). “2017 MnROAD Unbound Layer Evaluation Using Intelligent Compaction: Ingios Validated Intelligent Compaction (VIC) Results.” Final Report No. 2017-043, Ingios Geotechnics. http://www.dot.state.mn.us/mnroad/nrra/structureandteams/geotechnical/documents/FINAL_Ingios%20VIC%20Compaction%20Report_MnROAD_v7.pdf