Stiffness-Based QC/QA Testing

RESEARCH TEAM
David J. White, PhD, PE
Director, Center for Earthworks
  Engineering Research
Associate Professor
515-294-1463, djwhite@iastate.edu

Pavana K. R. Vennapusa, PhD, PE
Assistant Director, Center for Earthworks
  Engineering Research
Research Assistant Professor
515-294-2395, pavanv@iastate.edu

Peter Becker
Research Assistant

Christianna White, PhD
Technical Editor

IOWA DOT CONTACT
Mark Dunn, PE
Operations Research Engineer
Office of Research & Analytics
Iowa Department of Transportation
515-239-1447, mark.dunn@dot.iowa.gov

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Institute for Transportation

The Iowa Department of Transportation (DOT) worked with its research partners to design comparative pavement foundation test sections at the Central Iowa Expo Site in Boone, Iowa. The project was constructed from May through July 2012. Sixteen 700 ft long test sections were constructed on 4.8 miles of roadway with the following goals:

- Construct a test area that will allow long-term performance monitoring

- Develop local experience with new stiffness measurement technologies to assist with near-term implementation

- Increase the range of stabilization technologies to be considered for future pavement foundation design to optimize the pavement system

This tech brief provides an overview of the stiffness-based quality control (QC) and quality assurance (QA) testing methods used on the project to evaluate the foundation layers and comparisons between the different test measurements, and their advantages over traditional nuclear gauge density QC/QA testing.

Site Conditions

The project site consists of thirteen roads oriented in the North-South direction (denoted as 1st St. to 13th St.) and three roads oriented in the East-West direction (denoted as South Ave., Central Ave., and North Ave.). Re-construction occurred on all roads except 13th St., which was paved with hot-mix asphalt (HMA) earlier in 2012.

Construction of test sections required removal of the existing chip seal surface and subbase and 6 to 12 in. of subgrade. The subgrade consisted primarily of wet soils classified as CL or A-6(5). Pore water pressure measurements from cone penetration tests (CPT) indicated ground water elevations generally at depths of about 3 to 6 ft below the original grade across the site and at depths of about

12 ft or greater in areas close to drainage features.

Sixteen test sections were constructed on the North-South roads, which involved using: woven and non-woven (NW) geotextiles at subgrade/subbase interface; triaxial and biaxial geogrids at subgrade/subbase interface; 4 in. and 6 in. geocells in the subbase layer with non-woven geosynthetics at subgrade/subbase interface; portland cement (PC) and fly ash (FA) stabilization of subgrade; PC stabilization of recycled subbase; PC + fiber stabilization of recycled subbase with black polypropylene (PP) fibers and white monofilament-polypropylene (MF-PP) fibers; mechanical stabilization (mixing subgrade with existing subbase); and high-energy impact compaction. Triaxial and biaxial geogrids were used at the subgrade/subbase interface at select locations on the East-West roads. More detailed information about the different technologies are provided in individual tech briefs.

All test sections were topped with a nominal 6 in. of modified subbase material (MSB) classified as GP-GM or A-1-a (7% fines content). One exception was the 6 in. geocell section that required 7 in. of subbase. Crushed limestone was used in the modified subbase (MSB) layer on all North-South roads, and a mixture of recycled concrete and recycled asphalt was used in the MSB layer on all East-West roads. A few select test sections (6th St., 7th St., and 9th St.) consisted of 6 in. of recycled subbase material classified as SM or A-1-a (14% fines content) between the subbase and subgrade layers.

Stiffness-Based Testing

Light Weight Deflectometer

Light weight deflectometer (LWD) tests were conducted using a Zorn LWD setup with an 11.81 in. diameter plate and a 27.9 in. drop height (Figure 1). The tests were

conducted by performing three seating drops and three loading drops, per ASTM E2835-11.

Elastic modulus values (ESB-LWD) were determined using equation. 1:

$$E = \frac{(1-\eta^2)\sigma_0 r}{D_0} \times F \quad (1)$$

where:

E = elastic modulus (psi), D_0 = measured deflection under the plate (in.), η = Poisson's ratio (assumed as 0.4), σ_0 = applied stress (psi), r = radius of the plate (in.), and F = shape factor depending on stress distribution (assumed as 8/3).

Falling Weight Deflectometer

Falling weight deflectometer (FWD) tests were conducted using a Kuab FWD setup with an 11.81 in. diameter loading plate by applying one seating drop and four loading drops (Figure 2). The applied loads varied from about 5,000 to 15,000 lbs in the four loading drops. The actual applied forces were recorded using a load cell, and deflections were recorded using seismometers mounted on the device, per ASTM D4694-09.

Elastic modulus values from the FWD tests (E_{SB-FWD}) were determined using equation. 1. The loading plate used in the test is a segmented (four-part) plate. According to the manufacturer, the segmented plate results in a uniform stress distribution. Therefore, F = 2 was used in determination of E_{SB-FWD}.

To compare E_{SB-FWD} from different test locations at the same applied contact stress, the deflection values at each test location were normalized to a 14,000 lb load.

Figure 1. Zorn light weight deflectometer (LWD)

Figure 2. Kuab falling weight deflectometer (FWD)

Dynamic Cone Penetrometer

Dynamic cone penetrometer (DCP) tests were conducted in accordance with ASTM D6951 (Figure 3). The tests involve dropping a 17.6 lb hammer from a height of 22.6 in. and measuring the resulting penetration depth. California bearing ratio (CBR) values were determined using either equation 2 or 3, as appropriate, where the penetration index (PI) is in units of mm/blow.

$$CBR = \frac{292}{PI^{1.12}} \quad \text{for all soils with CBR > 10} \quad (2)$$

$$CBR = 1/(0.017019 \; DPI)^2 \quad \text{when CBR < 10 on CL soils} \quad (3)$$

Figure 4 shows a sample DCP-CBR profile and cumulative blows with a depth profile that illustrates the procedure used to determine layer depths and calculate the CBR of subbase layers.

Roller-Integrated Compaction Monitoring (RICM) System

Four rollers equipped with different RICM systems were used on this project:

- Caterpillar CS683 (Figure 5) vibratory smooth drum roller equipped with compaction meter value (CMV) and machine drive power (MDP) measurement technologies.

Figure 3. Dynamic cone penetrometer

PI of Subbase = Subbase layer depth/Cumulative blows at bottom of subbase
=> 6 in./108.8 blows = 0.055 in./blow = 1.4 mm/blow
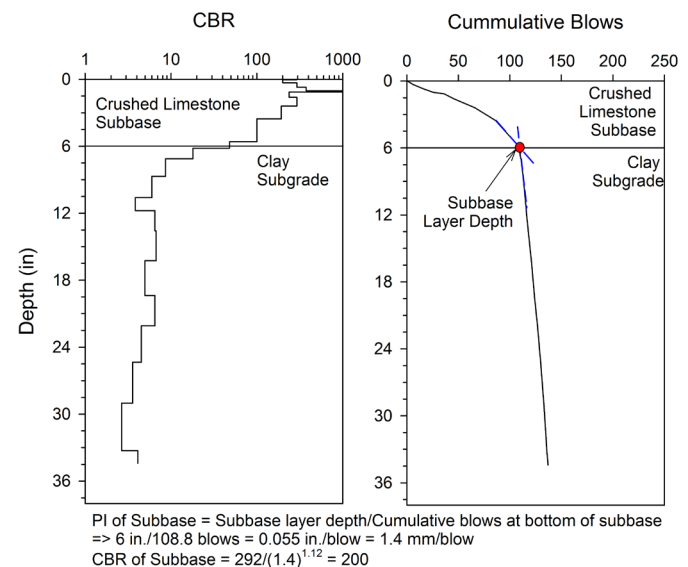CBR of Subbase = $292/(1.4)^{1.12}$ = 200

Figure 4. Example of DCP-CBR and cumulative blows with depth profiles

- Caterpillar CS74 vibratory smooth drum roller equipped with CMV and MDP measurement technologies.
- Sakai SV610D vibratory smooth drum roller equipped with compaction control value (CCV) measurement technology.
- Hamm HD120VV vibratory double smooth drum roller equipped with CMV measurement technology.

Details about these technologies are provided in the Phase I final report and RICM tech brief. In brief, each machine's RICM system consisted of recording and displaying compaction measurement values (i.e., CMV, MDP, CCV), machine operating conditions (i.e., roller speed, vibration amplitude, and vibration frequency) integrated with real-time kinematic (RTK) global positioning system (GPS) measurements (i.e., northing, easting, and elevation) in real time.

Measurement Influence Depth for Stiffness Measurements

To implement soil stiffness measurements, an assessment of measurement influence depth (MID) is needed so that the measurement value is assigned to a volume of soil beneath the test device. An influence zone can be defined as analogous to a strip footing where the depth of influence is proportional to the footing width and length.

Establishing MID values is important as part of understanding analyses of correlations between test devices and in determining remedial actions for areas of non-compliance (e.g., is it a shallow problem or an unstable deeper layer?). Complicating factors for determining influence depth include layered soft to stiff materials and setting a value for stress increase. Dynamic earth pressure cells were installed to assess MID (Figure 6).

Figure 5. CS683 vibratory smooth drum roller with RICM system and on-board RICM system display (inset)

Figure 6. Piezo-electric earth pressure cell installed in subgrade layer

The researchers assigned a +10 psi total vertical stress increase as the defining value for MID. This simple approach eliminates more-complicated analyses that require assumptions for unknown parameters. The MID values for the LWD, FWD, and RICM roller operated in static, low amplitude, and high amplitude modes are shown in Figure 7. The results show that the MIDs for the LWD and static rolling are similar, while the MIDs for FWD and vibratory rolling are two to three times greater.

Comparison of Soil Stiffness Measurements

Figure 8 shows the correlations between FWD and LWD results. Results of the FWD and LWD measurements for each test section indicated the sections with fly ash and cement-stabilized subgrade produced the highest stiffness values (see White et al. 2013).
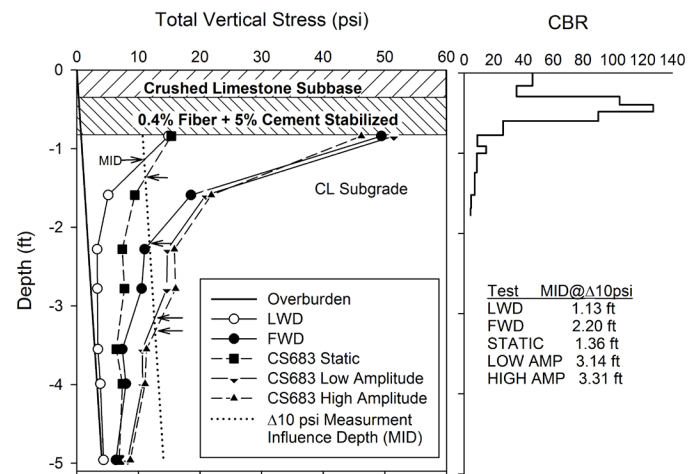

Figure 7. Measurement influence depth (MID) for LWD, FWD, and smooth drum roller using +10 psi criteria from earth pressure cells

$$E_{SB\text{-}LWD} = 6,680 \ln (E_{SB\text{-}FWD}) - 48,429$$
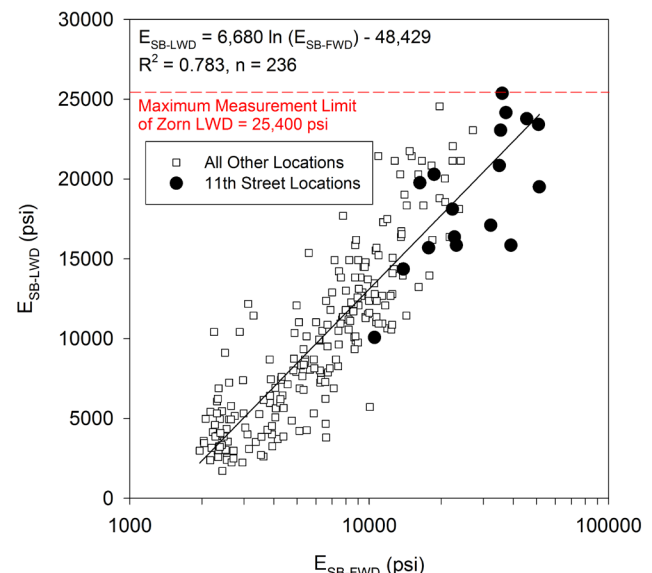$$R^2 = 0.783, n = 236$$

Figure 8. Correlations between subbase elastic modulus measurements from LWD and FWD tests (note log scale for FWD) that compare 11th St. (with 10% cement and 20% fly ash stabilized subgrade) with all other locations

Note that the FWD and LWD results from 11th St. show increased differences in moduli due to differences in the MID. The 11th St. North section subgrade layer was stabilized with 10% PC and the 11th St. South subgrade layer was stabilized with 20% FA , both about 6 in. below the surface.

Results of the CBR measurements of each layer for each test section indicate that the CBR values are generally consistent with the LWD and FWD results. The exceptions, however, are the polymer biaxial and triaxial grid test sections, which produced CBR values higher than most of the other test sections (see the geosynthetics tech brief). The sections underlain by stabilized subgrade (e.g., PC and FA stabilized subgrade) produced the highest CBR values within the crushed limestone subbase layer.

RICM measurement correlation analyses with FWD and LWD are presented in Figure 9. Results show the CMV measurements are better correlated to FWD than LWD for the range of materials and conditions tested at this site. The FWD produced vertical stress conditions more similar to the roller compared to the LWD vertical stress profile (see Figure 7).

RICM mapping, FWD, LWD, and DCP measurements are planned after the 2013 spring thaw to give a measure of the durability of the treated sections. Note that the test sections were designed as the platform for paving during Phase II of the project later in the spring.

Shortcomings of Nuclear Density Gauge QC/QA Testing

Traditional nuclear gauge moisture-density testing has played an important role in earthwork quality assessment specifications in the US for decades. This form of QC/QA can be effective but has shortcomings due to regulations, test reproducibility, limited test frequency, and serving only as a surrogate to strength and stiffness design requirements.

Figure 10 shows the QC agent and QA agent test results for this project. Results show that the QC agent results all meet the minimum 95% criteria and ±2% moisture control criteria. In contrast, the QA agent results are much more variable on both accounts.

At this point, the researchers can only speculate about these differences. It is clear, though, that the nuclear density testing does not indicate the wide stiffness variations resulting from treatments and materials (see RICM tech brief).

The distinct advantage of FWD and LWD soil stiffness measurements on this project is the identification of variations in support values between different stabilization sections that will provide inputs to the pavement thickness design phase of the project (to be completed in 2013).

The advantages of RICM measurements are that they are reported electronically on a near-continuous basis and are available to the contractor in real time, so the construction process can be controlled around identifying "soft spots" that need remediation and achieving design target values. The primary weakness with soil stiffness assessment is that moisture control remains the critical factor in the construction process.

References

White, D. J., P. Becker, P. Vennapusa, M. Dunn, and C. I. White. 2013. "Soil stiffness assessment of stabilized pavement foundations." *Transportation Research Record: Journal of the Transportation Research Board.* Washington, DC. (in press).
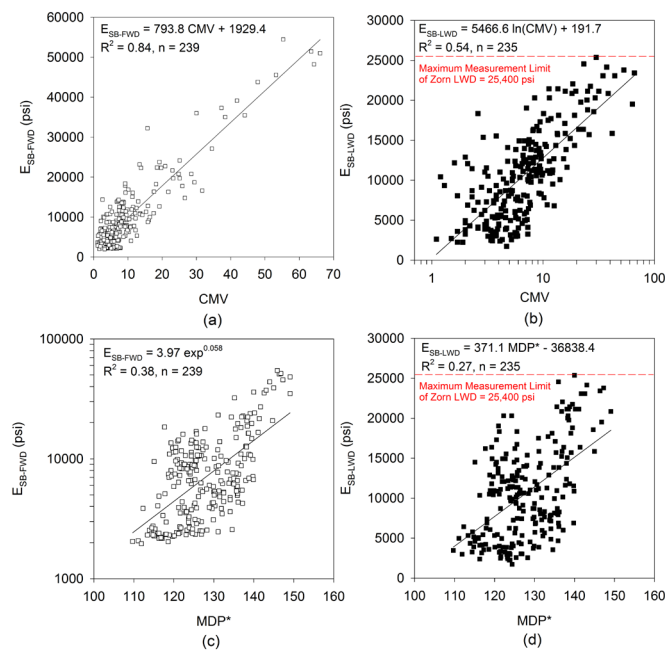

Figure 9. Correlations between (a) CMV and E_{SB-FWD} (b) CMV and E_{SB-LWD} (c) MDP* and E_{SB-FWD} and (d) MDP* and E_{SB-LWD}
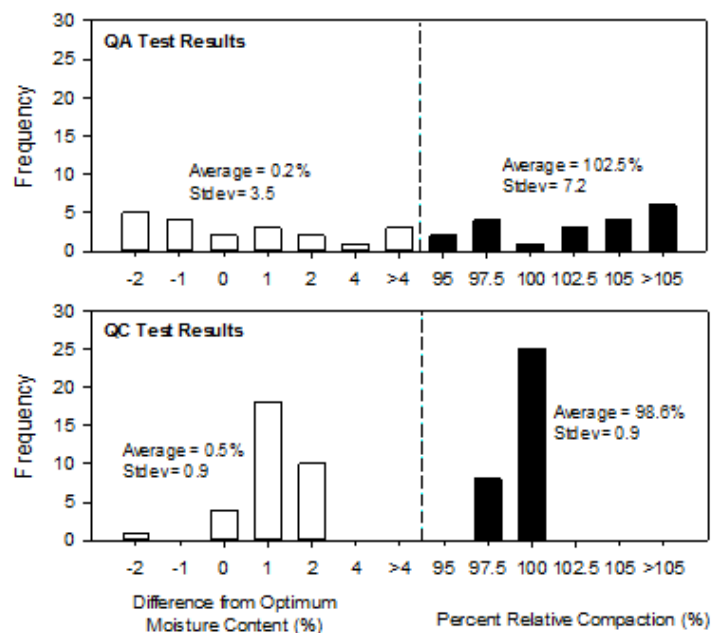

Figure 10. Comparison of nuclear density/moisture measurements for the QC and QA agents