An Approach to Assess As-built Moduli of Compacted Foundation Layers Using Intelligent Compaction

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Abstract. The satisfactory performance of well-designed pavement sections hinges on the appropriate compaction of layers in the field, especially compacted geomaterials forming the foundation layers. In-situ spot density tests are standard practice for assessing the compaction effort, even though the mechanistic-empirical design procedures are based on layer moduli. The state of the practice in in-situ density measurements, and more recently modulus measurements, relies on limited in-situ spot testing meant to represent a large area of compacted geomaterial. Intelligent compaction (IC) can be utilized to access the as-built moduli by vibratory rollers across the entire compacted geomaterial area to overcome the limitation of spot density tests.

This paper presents an approach to assess the layer-by-layer variation in the as-built moduli. The real-time IC mapping process has proved to be practical, efficient, and robust. The assessment results can be obtained by combining the IC measurement values (ICMV) with limited lightweight deflectometer (LWD) measurements for local calibration and laboratory-based resilient modulus non-linear parameters. The method's veracity and applicability are demonstrated through comprehensive data from two cells collected during the Minnesota Road Research Facility (MnROAD) reconstruction. The assessment results showed that the local in situ calibration of the ICMVs with the limited LWD modulus is necessary to obtain accurate layer-specific as-built moduli.

Keywords: intelligent compaction, pavement foundation, modulus, lightweight deflectometer

1 Introduction

The quintessential idea in pavement construction is to reach optimal density and uniformity across various pavement layers, traditionally based on a few in-situ density tests. Intelligent Compaction (IC) is a tool that allows for the assessment of the compaction process through the use of vibratory rollers equipped with a GPS, accelerometers, and an onboard data collection screen for on-the-go monitoring. IC is specifically designed to quantify the compaction effort exerted by vibratory rollers across large regions of the earthwork and provide a record of the passes/location, thus providing a more detailed and continuous understanding of the compaction practice.

Since the 1970s, researchers and manufacturers alike have proposed various methodologies to gauge the dynamic response of compacted geomaterials using vibratory rollers [1-7]. These methodologies provide generically Intelligent Compaction Meter Values (ICMV). As a surrogate for stiffness, ICMV is not directly correlated to either dynamic modulus-based or density-based field measurements. This lack of direct correlation is attributed to the variabilities of the in-situ moisture content, density, segregation of granular material, and influence of deeper layers [9-11].

With the introduction and adoption of the Mechanistic-Empirical Pavement Design Guide, there is a need to verify the layer moduli along with density, using a robust and holistic approach to quality acceptance standards [12-13]. To address this difference in construction quality acceptance (i.e., as-built) and pavement design, several studies [14-16] have explored the use of modulus-based deflection measurement devices, such as the Lightweight Deflectometer (LWD). In this paper, a process to assess the layer-by-layer variability in compaction and as-built modulus is presented. The process is illustrated by data collected from two flexible reconstructed pavement sections.

2 Field Measurement and Analysis

Testing was conducted at the MnROAD test track in Otsego, Minnesota, in June 2022. Two test cells, referenced as 2228 and 2229, consisting of a natural clay subgrade, sandy subbase, and gravely unbound base, were tested. The cells measured 25 ft (7.6 m) wide by 225 ft (69 m) in length. Table 1 summarizes the geomaterial properties of both pavement sections. The subbase and base layers contained recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP) that conformed to Minnesota Department of Transportation (MnDOT) standards. The base had a thickness of 9.5 in. (240 mm) and was placed on top of a 12 in. (300 mm) subbase. A moisture-wicking geotextile was placed between the subgrade and subbase of Cell 2229.

The Caterpillar smooth drum vibratory roller, shown in Figure 1a, was retrofitted with accelerometers (Figure 1b) and connected to a data acquisition system. A GPS was mounted to the top of the roller cabin (Figure 1c) to geo-reference the collected data. IC data were acquired after compaction and acceptance using the nuclear density gauge (NDG). Commonly referred to as the final pass or proof mapping, the roller was set to vibrate at 23 Hz and low amplitude for collecting data for quality management. Four forward vibratory line passes were conducted to map each test section. The section was subdivided into smaller georeferenced 25 ft (7.6 m) by 6 ft (1.8 m) sublots, as shown in Figure 2, corresponding to one-tenth of the total length of the lot and the roller width. These sublots allowed for a more objective interpretation of the uniformity of the layer based on the roller data and by taking spot tests at the center of each sublot. Within each sublot, the IC system recorded about 44 CMV measurements at a rate of about one CMV every 0.7 ft (0.2 m).

Table 1. Summary of Geomaterial Properties.

Classification		Dry Constituents, %				Compaction Parameters	
USCS[1]	MnDOT	Gravel	Coarse Sand	Fine Sand	Pan	OMC[3], %	MDD[4], pcf (kg/m^3)
CL	Clay subgrade	8	66	18	7	14.4	118.4 (1897)
SW	CL3 subbase	43	44	13	0	10.7	124.5 (1994)
GW	Class 5Q	82	14	4	0	9.6	124.5 (1994)

[1]Unified Soil Classification System, [2]Optimum Moisture Content, [3]Maximum Dry Density.

Fig. 1. (a) Caterpillar Vibratory Roller Fitted with (b) Accelerometers and (c) GPS

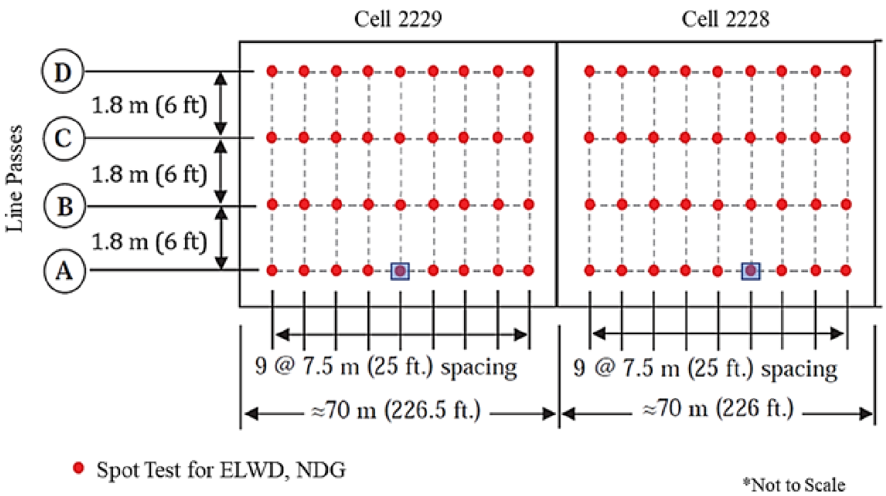

Fig. 2. Spot Test Schematic for IC Roller Line Passes

After the proof mapping stage was completed, the data was processed to map the roller pass (Figure 3a), compaction meter value (CMV, Figure 3e), and the coefficient of variation (COV) of CMV within the sublots (Figure 3d). The drum force was also estimated using the georeferenced acceleration measurements and the drum mass as an additional measurement value (Figure 3f). The different ICMV color keys are explained within the figures; each color coding is adapted to the specific range of measurements. Using green, yellow, and red colors to exhibit the COV of CMVs within each sublot of the two different cells is a practical way of assessing the variability of compaction [17].

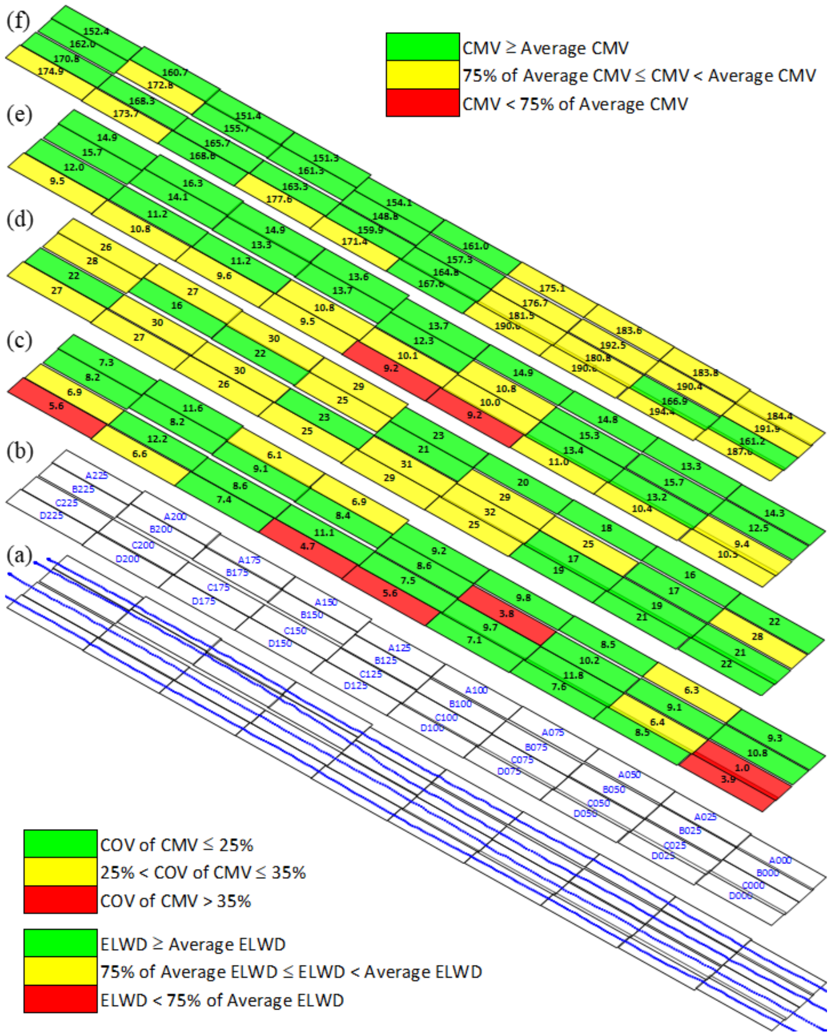

Fig. 3. Mapping of ICMVs of MnROAD Cell 2228. (a) Roller Pass, (b) Sublot ID, (c) ELWD, (d) COV of CMV, (e) CMV, (f) Drum Force

Additional point measurements were conducted at the center of the sublots immediately after IC mapping to get the in situ response before any change in the moisture condition using NDG and LWD per AASHTO T310 and ASTM E2835. The NDG tests were carried out at every other sublot. LWD tests were carried out in triplicates to estimate their corresponding moduli, E_{LWD}, from:

$$E_{LWD} = \frac{(1 - \nu^2)\sigma_0 f}{\pi r d_z} \tag{1}$$

where ν = Poisson's ratio, σ_0 = stress applied by LWD, f = LWD shape factor (π/2), r = plate radius (4-in, 10.2 cm), and d_z = recorded LWD deflection. LWD moduli were also mapped using the georeferenced spot test locations, as shown in Figure 3(c).

3 Process of Layer Condition Assessment

Layer-specific moduli were backcalculated for the compacted layers as per the procedure recommended by NCHRP Project 24-45 [17] using the georeferenced drum force, LWD modulus, and other IC measurements. The average CMV, the coefficient of variation of CMV, the average drum force, and the average LWD modulus for each sublot for the subgrade of Cell 2228 are shown in Table 2 as an example. Color coding is superimposed on top of the tabulated values as per the criteria used for each mapped variable shown in Figure 3. Five sublots that satisfied the following criteria were selected for the local calibration of the modulus-IC relationship:

1. Green: Two sublots with CMV ≥ 90% of the average layer CMV
2. Yellow: Two sublots with CMV between 75% and 90% of the average layer CMV
3. Red: One sublot with CMV of ≤ 75% of the average layer CMV

Table 2. Cell 2229 Subgrade Data

Sublot	CMV	COV	E_{LWD} (ksi)	F_d (kip)	Sublot	CMV	COV	E_{LWD} (ksi)	F_d (kip)
A000	14.3	31.1	6.3	154.1	C000	14.1	36.9	5.4	160.2
A025	12	24.9	4.6	151.4	C025	8.3	28.7	2.9	138.9
A050	12.9	25	6.7	160.0	C050	7.8	25.2	3.5	141.3
A075	12.2	24	7.5	156.6	C075	9.6	28.9	8.2	159.3
A100	13.5	27.4	7.9	166.5	C100	10.2	25.6	8.1	167.5
A125	15.4	22	6.5	172.2	C125	10.7	20.9	10.3	175.1
A150	15.7	25.4	5.6	168.0	C150	8.6	25.9	10.3	166.1
A175	14.7	25.6	9.1	173.7	C175	8.6	25.4	8.9	168.2
A200	16.4	19.2	7.8	177.5	C200	7.4	23.3	6.9	169.7
A225	15.6	21.7	8.5	179.6	C225	7.5	30.7	5.9	167.4
A250	14.8	33.3	8.6	180.9	C250	7.5	20.3	6.7	166.5
B000	15	31.2	3.8	168.4	D000	9.3	54.9	4	151.1
B025	9.2	22.2	6.4	157.9	D025	6	26.6	1.8	148.7
B050	9.5	29	6.2	155.7	D050	5.3	32.8	5.4	150.5
B075	10.3	29.4	8.3	161.1	D075	6.6	25.9	6.8	160.7
B100	12.1	21.5	10.6	179.6	D100	7.7	20.9	6.6	167.4
B125	13.3	18.6	9.8	182.5	D125	7.1	22.3	7.2	160.3
B150	12.5	21.1	9.9	183.3	D150	6.4	27.6	4.8	154.5
B175	13.7	22.8	6.9	188.8	D175	6.3	25.7	7	161.7
B200	14.6	18.2	6.6	189.5	D200	6.7	28.3	6.3	162.9
B225	11.8	23	7.5	184.4	D225	5.6	29.1	3.5	161.1
B250	12.3	25.7	8.1	179.9	D250	6.6	23.5	6.1	162.4

Five Selected Sublots				
Sublot	CMV	COV	E_{LWD} (ksi)	F_d (kip)
A025	12	24.9	4.6	151.4
C125	10.7	20.9	10.3	175.1
B025	9.2	22.2	6.4	157.9
D100	7.7	20.9	6.6	167.4
D125	7.1	22.3	7.2	160.3

The variability of CMVs due to the inherent variability of the compacted geomaterials and compaction effort was considered part of the selection of sublots. Sublots with COV of CMV of less than 25% ensure a higher certainty in the estimated moduli [17].

To develop the locally-calibrated relationship, the drum force and LWD modulus of the selected sublots (e.g., cells A125, C225, C150, D075, and D000, in the case shown in Table 2) are plotted against each other, as shown in Figure 4(a). The slope of the best-fit line to calculate modulus from IC measurements.

A one-to-one comparison of the extracted moduli with the corresponding LWD moduli from all sublots is shown in Figure 4(b). A strong trend (as judged with an R^2 of 0.95) with some dispersion is observed. The scatter of the results around the best-fit line can be attributed to the less uniform sublots as judged by their COVs of CMV. Figure 4(c) shows the same information when measurements are averaged across the four lines per station (i.e., chainage). Error bars indicate the standard deviation across the chainage. Most averaged measurements fell within a 25% error bound. The average extracted modulus is compared with the average LWD modulus for each chainage in Figure 4(d). The extracted moduli follow the LWD moduli along the compacted lot well.

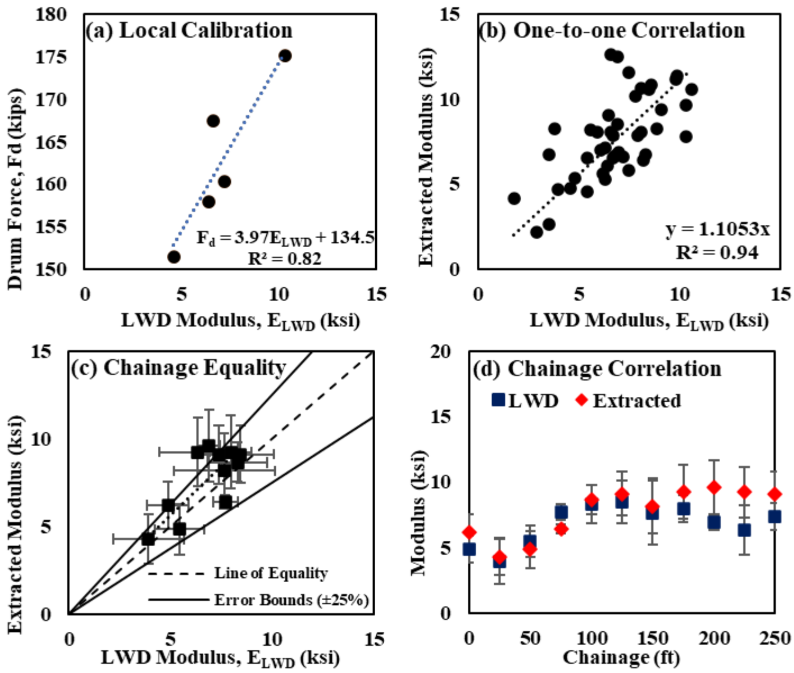

Fig. 4. Process of Extracting Modulus of Cell 2229 Subgrade

The procedure detailed was applied across all layers of Cells 2228 and 2229. As depicted in Figure 5, the average extracted moduli in most cases compared well with the corresponding LWD moduli. The deviations observed serve as a need to refine the method further rather than detract from its overall validity.

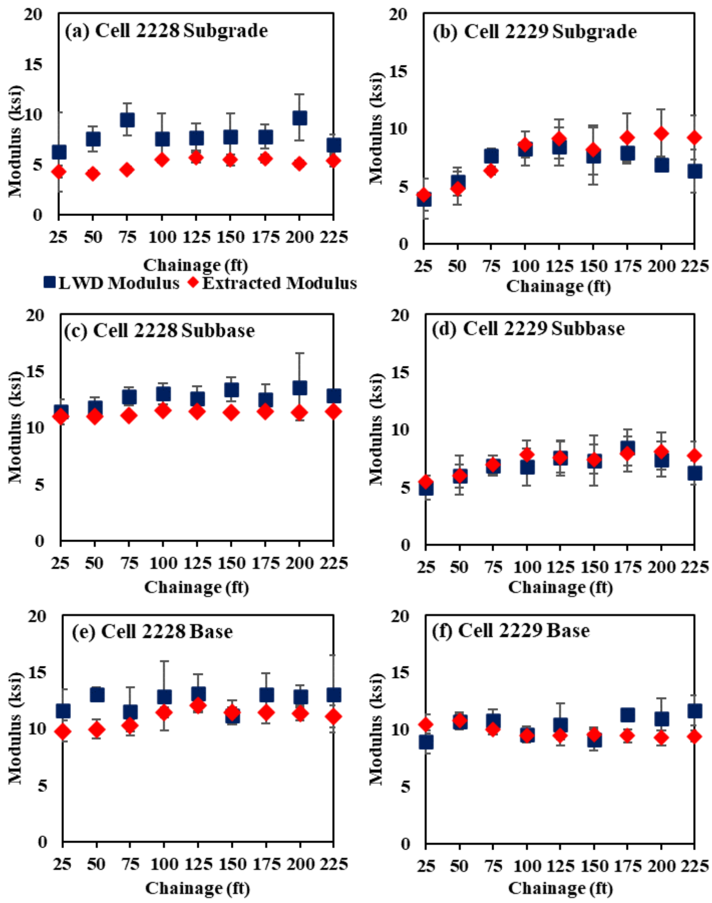

Fig. 5. Average Extracted and LWD Modulus per Cells 2228 and 2229

4 Conclusion

The presented analysis outlines a systematic approach for assessing the layer-by-layer variation of compaction efforts and the resulting as-built modulus of pavements. This study utilizes a combination of IC data and LWD measurements to provide a methodology for extracting layer-specific moduli. The backcalculation of modulus, as demonstrated by the data from MnROAD Cells 2228 and 2229, effectively captures the variations across the compacted layers. The correlation between drum force and LWD modulus offers a relationship between the mechanical behavior of geomaterials and the use of IC to enhance traditional quality assessment practices. The described process ensures that as-built pavement layers meet the design modulus to achieve the designed pavement life.

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