65th Annual PAPA Conference 2025

Development of Field Compaction Curves for Asphalt Mixtures Based on Laboratory Workability Tests

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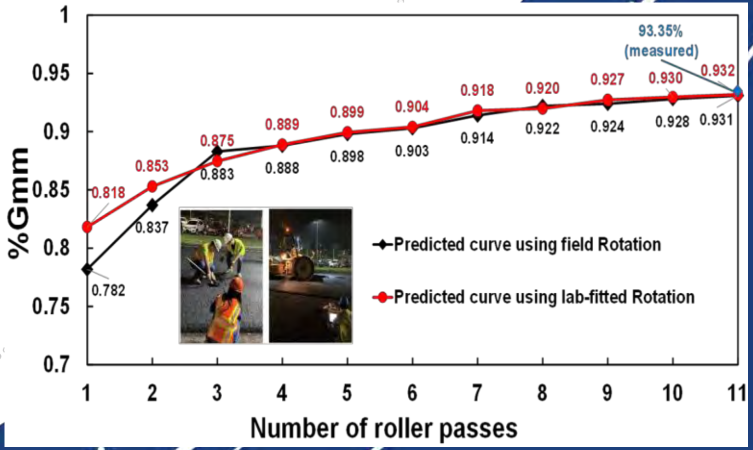
January 22th, 2025



CONTENT

■ PART I Introduction

1. Introduction

◻ Mix Workability and Compaction

- ➢ Workability: how easily the mix can be compacted.
- ➢ Good workability can help distribute particles more evenly during compaction.

Viscoelastic material

Modified asphalt mixture

Good workability is affected by material property and compaction conditions

1. Introduction

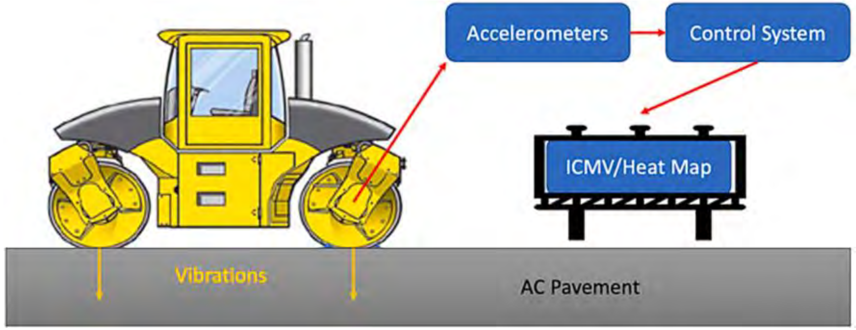
◻ Mix Workability and Compaction

✓ How to assess field compaction?

Non-destructive testing (NDT) technologies

(Al-Qadi., et al., 2021)

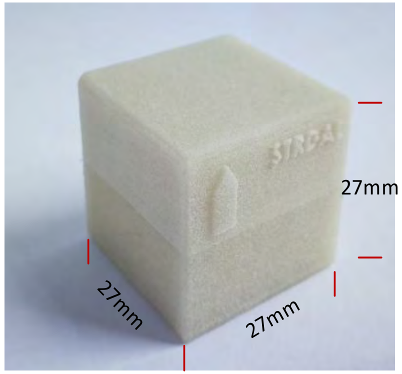
Intelligent compaction (IC) technologies

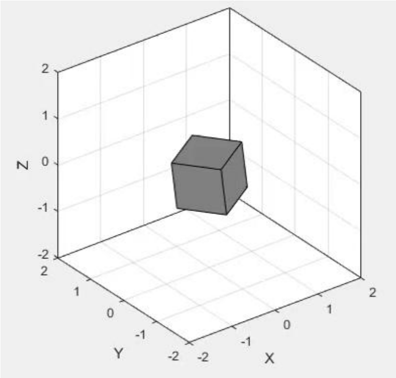


(Wang, S., et al., 2022)

1. Introduction

Our Innovation: integrating wireless sensors and ML modeling





(Wang, X., et al., 2018; Cheng, Z., et al., 2022; Shuai Y., et al., 2022; Shuai Y., et al., 2023)

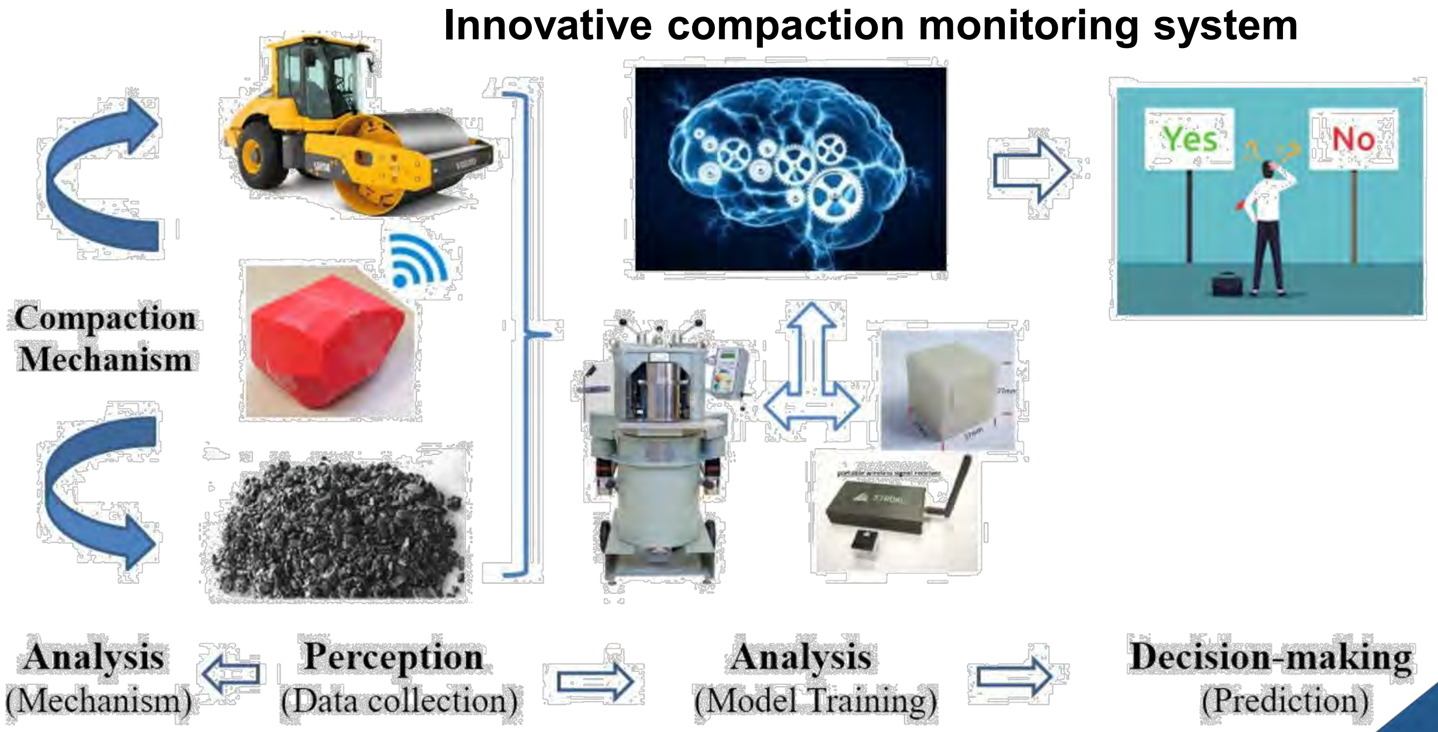
- Portable and embeddable for both lab and field testing
- Collect real-time motion data (rotation, acceleration, etc.)
- Compatible with ASTM D8541 for workability assessment
- Machine learning models for prediction

I. Introduction

Objectives

➢ An innovative monitoring system and methodology to assess the compaction behavior of asphalt mixtures by utilizing AI and sensing technologies.

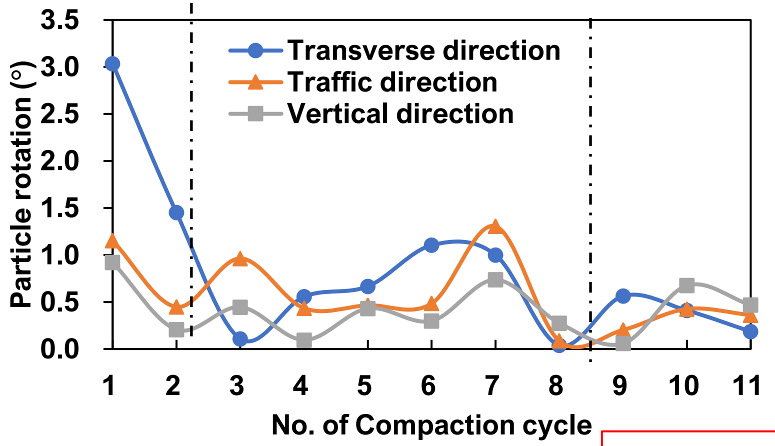
- To develop the field compaction curve
- To provide guidance for asphalt mixture design

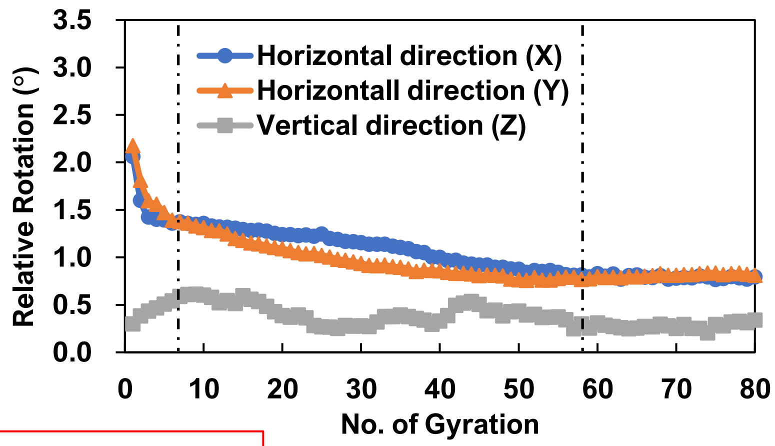


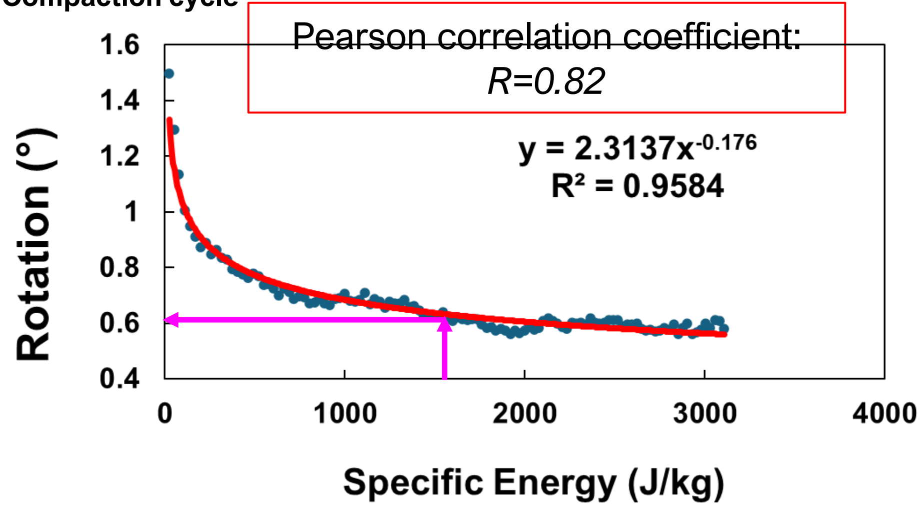
■ PART II Methodology

II. Methodology

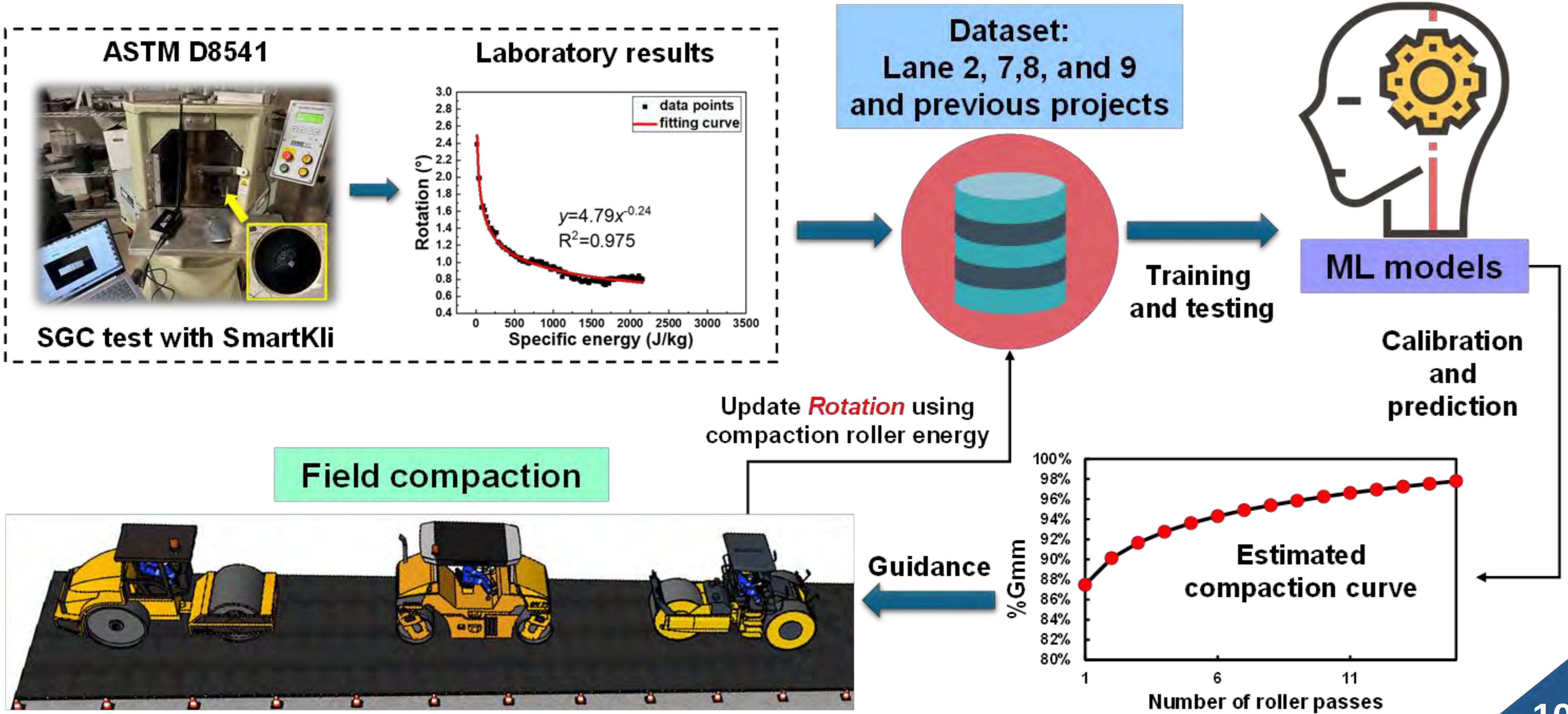
☐ Hypothesis: *Rotation for Effective Compaction*







II. Methodology



II. Methodology

☐ Pavement Structures and Materials

FHWA Pavement Testing Facility (PTF) 2023 project

Bay A			Bay B			Bay C			Bay D	
Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Lane 6	Lane 7	Lane 8	Lane 9	Lane 10	Lane 11
Mix Types Study			*(Premium) Binders Study*			*Top-down / Durability / High RAP Study*			*Inverted Pavement Study*	
SMA Study		Resiliency Study	Premium Binders Study		Resiliency Study	High RAP Study		Resiliency Study	Short-term Studies AC Thickness < 2"	
2" DGA 64H-22 20%RAP (SBS)	2" SMA 64H-22 20%RAP (SBS+Fiber)	2" Control-DGA 64S-22 20%RAP	2" DGA 64E-22 20%RAP	2" DGA 64S-22 40%RAP	2" Control-DGA 64S-22 20%RAP	2" DGA 64S-22 40%RAP Bio RA	2" DGA 64S-22 40%RAP Petroleum RA	2" Control-DGA 64S-22 20%RAP	1.5" DGA PG 64S-22 0% RAP 9.5mm mix	2" DGA PG 64S-22 0% RAP 9.5mm mix
2"DGA 64H-22 20%RAP (SBS)	2"SMA 64H-22 20%RAP (SBS+Fiber)	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP	2"Control-DGA 64S-22 20%RAP		

SMA 20% RAP

HMA 40% RAP Bio RA

HMA 40% RAP Petroleum RA

HMA 20% RAP

II. Methodology

☐ Pavement Structures and Materials

FHWA Pavement Testing Facility (PTF) 2023 project

II. Methodology

☐ Pavement Structures and Materials

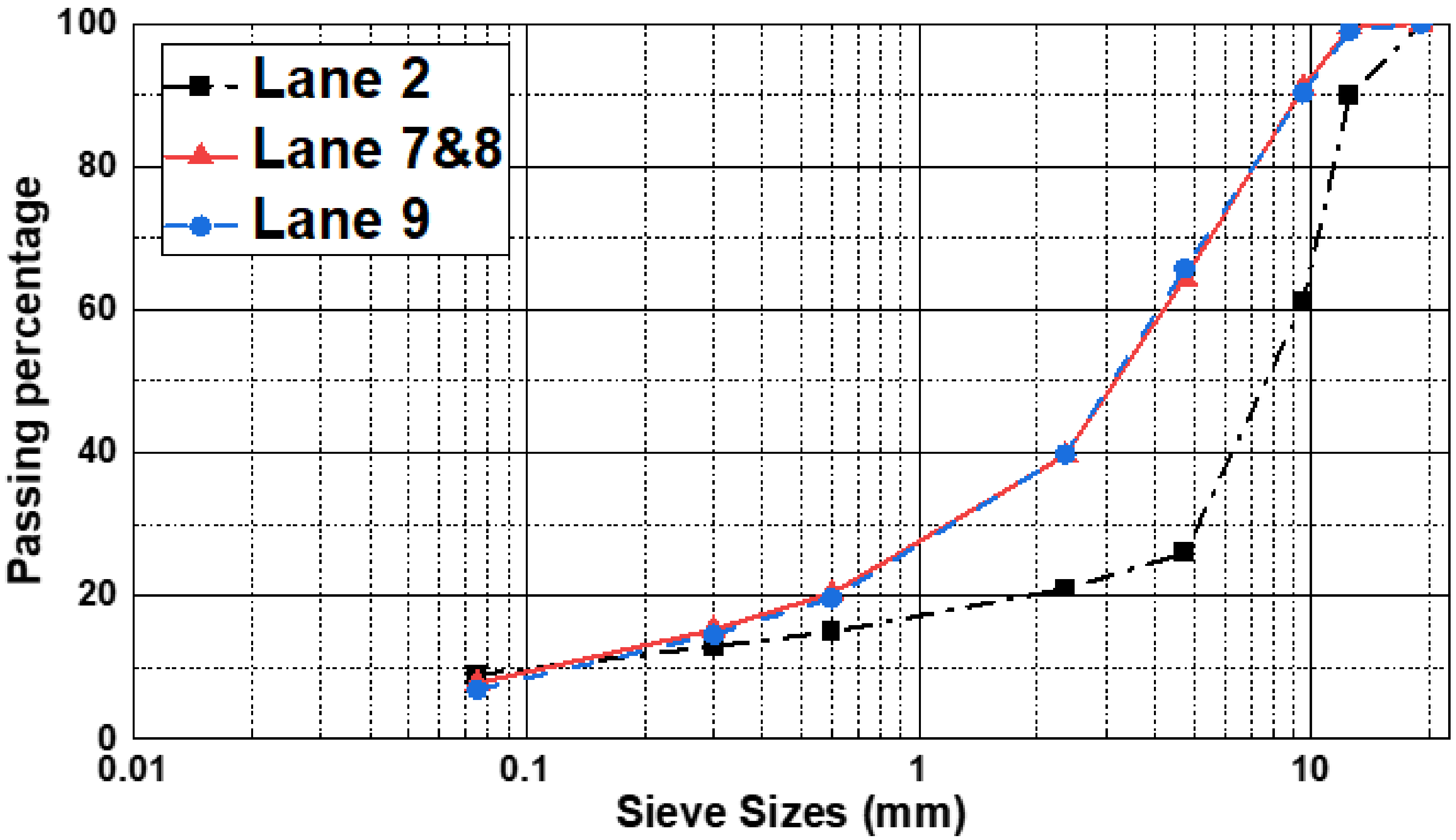
FHWA Pavement Testing Facility (PTF) 2023 project

Lane	Mix Type	NMAS (mm) [1]	G_{mb}	Design V_A (%)	RAP content (%)	P_b (%) [2]	Asphalt binder	Compaction Temperature (°C)
2	SMA	12.5	2.567	3.0%	20	6.4	64E-22	145
7	HMA	12.5	2.599	3.7%	40	5.8	64S-22	135
8	HMA	12.5	2.599	3.7%	40	5.8	64S-22	135
9	HMA	12.5	2.602	3.5%	20	5.8	64S-22	135

II. Methodology

□ Pavement Structures and Materials

FHWA Pavement Testing Facility (PTF) 2023 project



II. Methodology

Pavement Structures and Materials

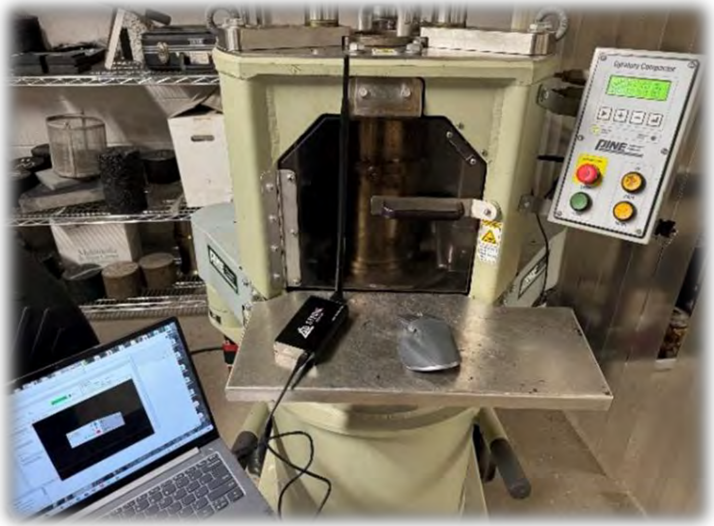
FHWA Pavement Testing Facility (PTF) 2023 project

Information on the vibratory rollers

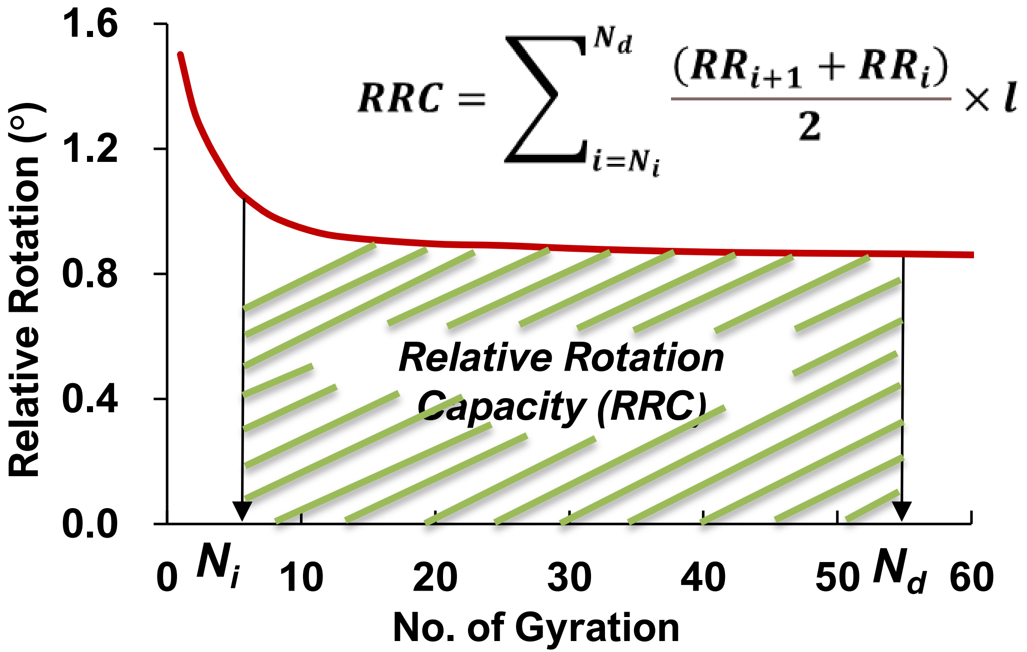
Lane	Compactor	Frequency (Hz)	Speed (m/s)	Width (m)	Amplitude (mm)	Weight (tons)	Centrifugal force (kN)	Number of roller passes	Final density (g/cm^3)
2	Sakai SW880-1	50.7	1.14	3.66	0.87	12.87	177	10.6	2.575
7		65.7	1.00	4.27	0.49	12.87	177	4.1	2.550
8		66.0	1.02	3.66	0.48	12.87	177	4.6	2.565
9		48.6	1.19	4.27	0.47	12.87	177	7.8	2.592

II. Methodology

□ Laboratory Workability Test



ASTM D8541



Relative Rotation Capacity (RRC) can be calculated from the particle rotation curves using the analysis software.

II. Methodology

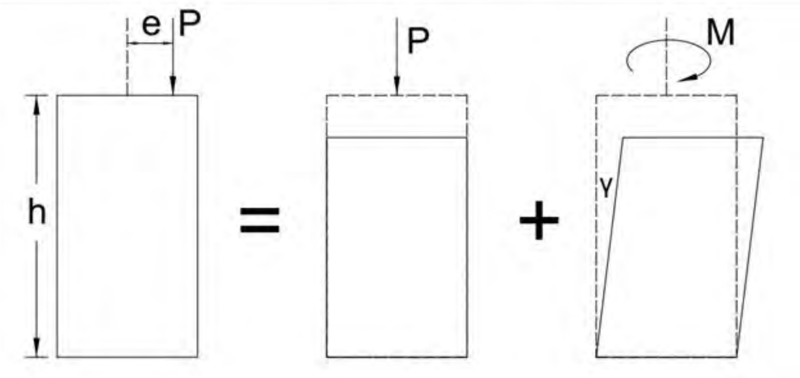
□ Compaction Energy Calculation

SGC compactor

$$E = E_1 + E_2 = \frac{P \times S \times h + 4\pi\theta \sum M_i}{m}$$

Vibratory roller compactor

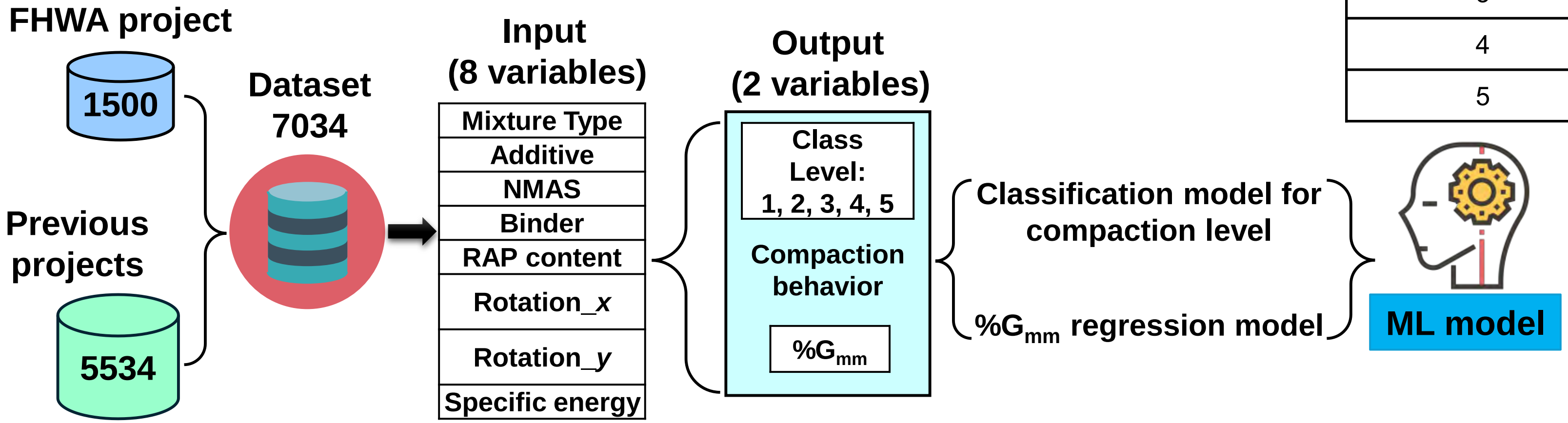
$$E_v = \frac{2Af}{v\rho hb}\left(Wg + \frac{\pi F_e}{4}\right)$$



II. Methodology

□ Dataset for Predicting Compaction Curves

Compaction level	Density (%Gmm)
1	%Gmm<88%
2	88%≤%Gmm<90%
3	90%≤%Gmm<92.5%
4	92.5%≤%Gmm<96.5%
5	96.5≤%Gmm



Criteria for classification

	Input							Output	
Type	Additive (%)	NMAS (mm)	Binder Type	RAP content (%)	Rotation_x (°)	Rotation_y (°)	Specific energy (J/kg)	Compaction Level	$\%G_{mm}$
0	0.00	9.5	64E	0	1.491	1.340	42.8	1	79.87
1	0.35	12.5	64	0	1.029	1.470	41.9	1	82.26
0	0.00	9.5	76	0	1.005	1.109	293.3	2	89.94
1	0.70	12.5	64	0	1.094	1.017	196.1	3	90.25
0	0.00	12.5	64	0	0.676	0.887	478.9	3	92.32
1	0.35	9.5	76	15	1.175	1.011	492.4	4	92.75
1	0.35	9.5	76	15	0.781	0.787	2233.1	4	96.30
2	0.00	12.5	64	20	0.693	0.546	2708.2	5	96.92

■ PART III Results and Discussion

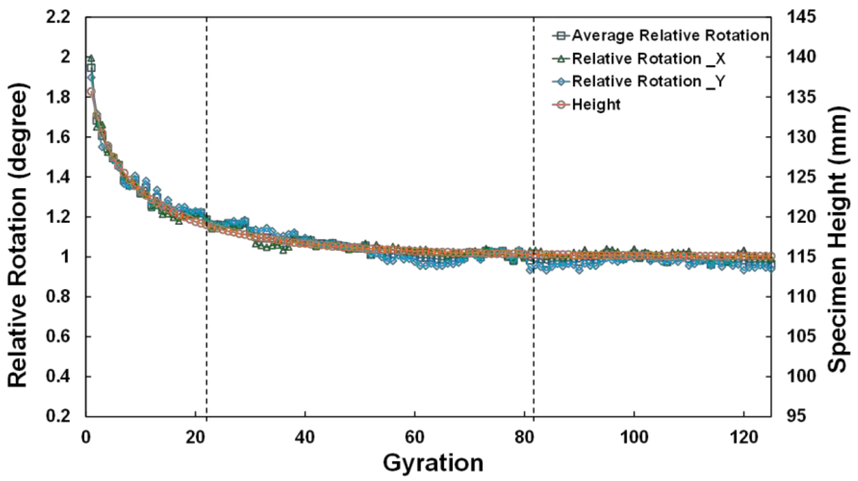
III. Results and Discussion

Laboratory Workability Test

➢ Relative Rotation Curve

Sample	Lane 2	Lane 7	Lane 8	Lane 9
	SMA, 20% RAP	HMA, 40% RAP, Bio RA	HMA, 40% RAP, Petroleum RA	HMA, 20% RAP
1#	82.62	109.8	146.39	111.60
2#	83.93	129.17	135.85	108.46
3#	82.25	122.92	135.58	101.55
Average	**82.93 ± 0.72**	**120.63 ± 8.06**	**139.28 ± 5.04**	**107.21 ± 4.20**

An extremely high correlation between rotation and height (density)



➢ HMA showed higher workability than SMA.

➢ RA effectively enhanced workability of 40% RAP mixtures.

➢ Petroleum-based RA slightly better than the specific bio-based RA.

III. Results and Discussion

□ Laboratory SGC Test Results

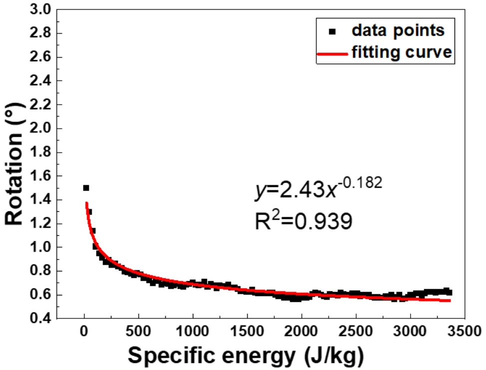
➢ Relative Rotation and Specific Energy

Particle rotation under the same compaction energy.

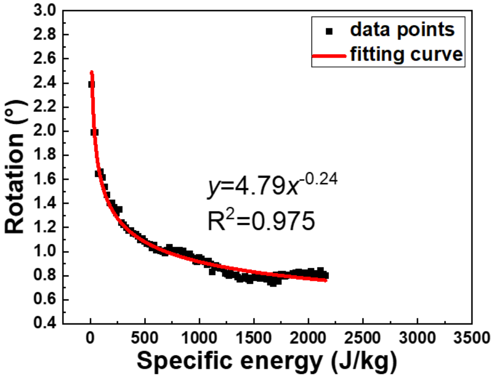
Cycle	Particle rotation under roller (°)	Density-equivalent particle rotation under SGC (°)	Energy-equivalent particle rotation under SGC (°)
1	2.094	1.779	1.705
2	0.950	1.431	1.371
3	0.536	1.396	1.267
4	0.495	1.345	1.189
5	0.566	1.297	1.140
6	0.794	1.236	1.072
7	1.153	1.197	1.024
8	0.063	1.154	0.945
9	0.383	1.134	0.875
10	0.418	1.085	0.838
11	0.273	1.045	0.816

Yu, Shuai, Shihui Shen, et al. "Data sensing and compaction condition modeling for asphalt pavements." Automation in Construction 154 (2023): 105021.

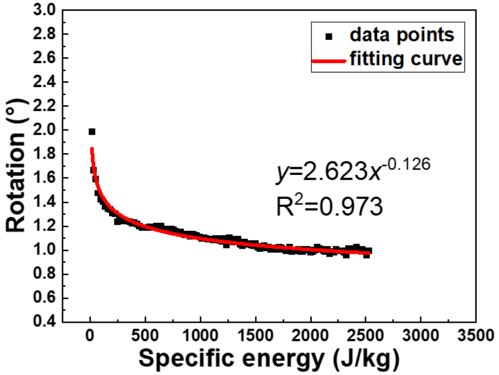
This relationship is fundamental for a specific mix.



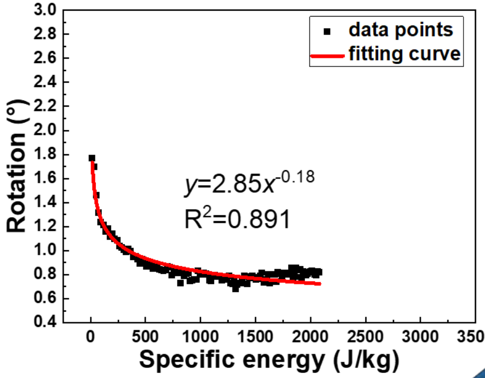
Lane 2



Lane 7



Lane 8



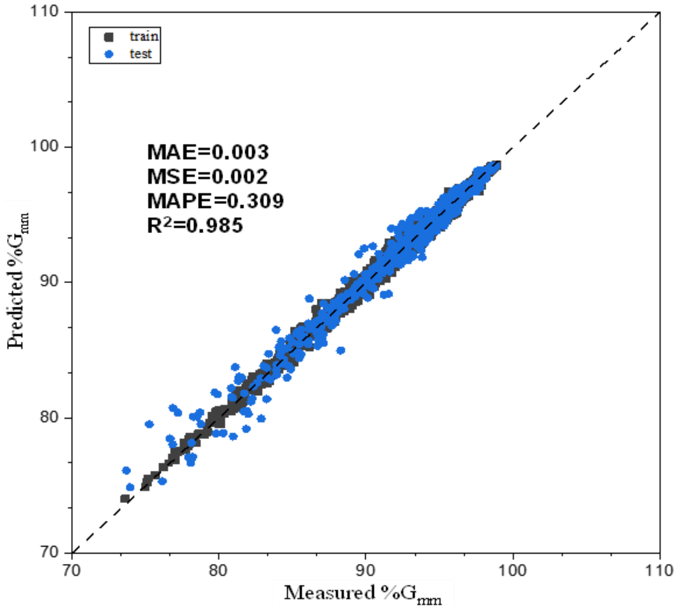
Lane 9

III. Results and Discussion

☐ Experimental Results

➢ Regression Model for Density

ML Models	R^2	RMSE	MAE
LightGBM	**0.98441**	**0.00483**	**0.00247**
XGBoost	0.97831	0.00570	0.00348
Random Forest	0.96866	0.00685	0.00434
ANN	0.93172	0.01011	0.00798



➢ Compaction energy – external control factor (most significant)
- The higher the specific energy values, the greater the predicted density (%G_{mm}).

➢ Rotation – internal response factor (significant and mix specific)
- With the rotation values decrease, the predicted density achieves the maximum (%G_{mm}).

➢ Other influencing factors: binder, NMAS, RAP content, mix type, additive

III. Results and Discussion

☐ Model Calibration based on Field Compaction Data

35 field cores were taken from each lane of the FHWA PTF sections to obtain the average density

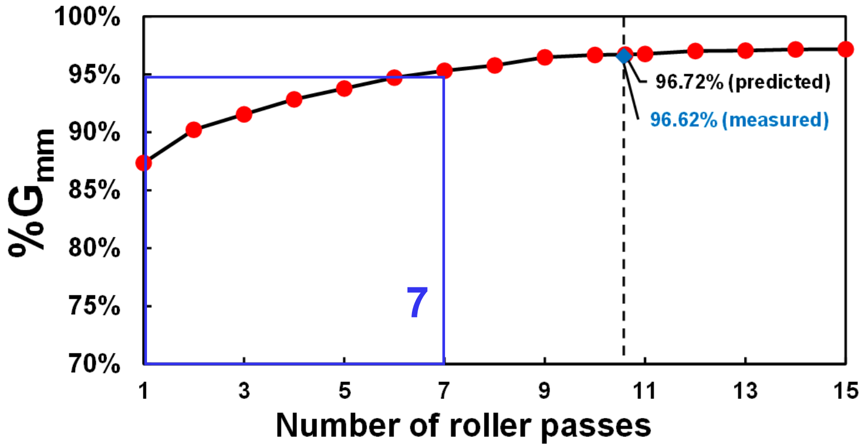
Lanes	Measured Values		Predicted values		Error
	$\%G_{mm}$	Compaction level	$\%G_{mm}$	Compaction level	
Lane 2	96.62%	5	96.72%	5	0.10%
Lane 7	95.76%	4	94.76%	4	1.04%
Lane 8	97.86%	5	97.15%	5	0.73%
Lane 9	96.61%	5	96.25%	4	0.37%

- The average error in $\%G_{mm}$ prediction for the four lanes was within 1%.
- Only one test point in lane 9 showed a slight deviation, it still demonstrates that the model achieved excellent results in calibration with field-measured data.

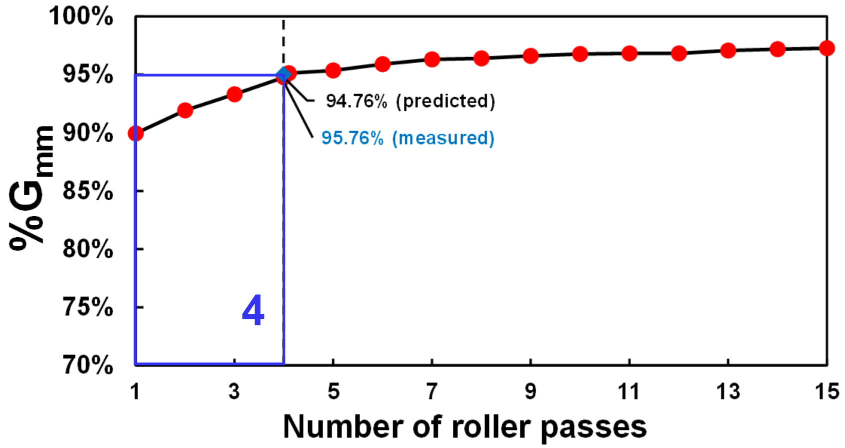
III. Results and Discussion

☐ Development of Field Compaction Curves

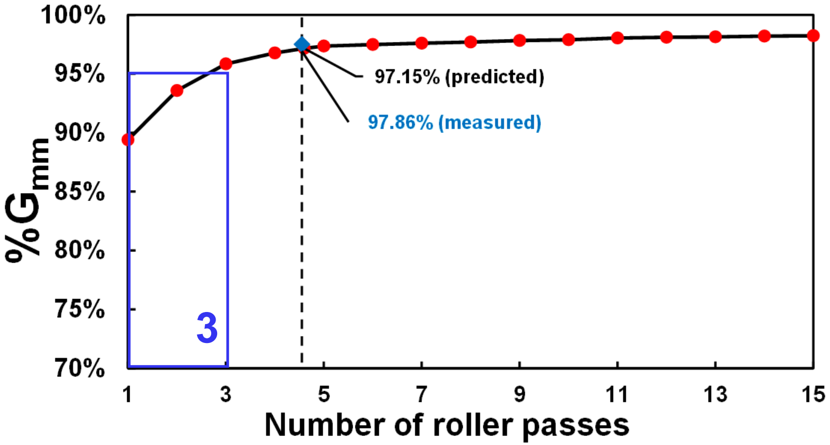
Lane 2
SMA
20% RAP



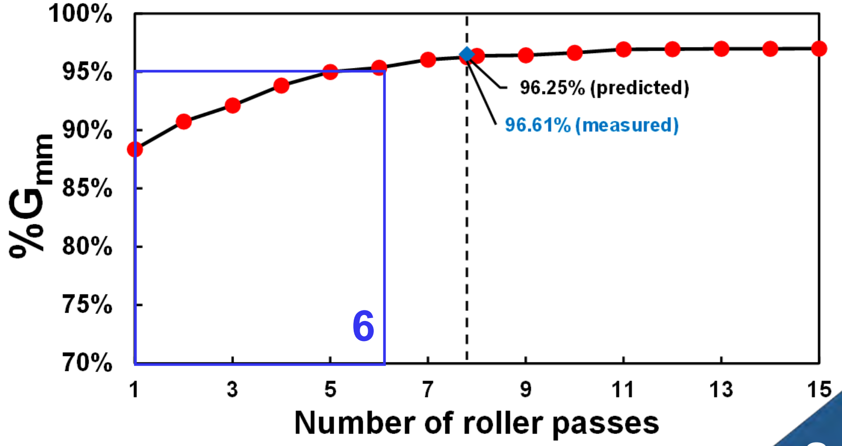
Lane 7
HMA
40% RAP
Bio RA



Lane 8
HMA
40% RAP
Petroleum
RA



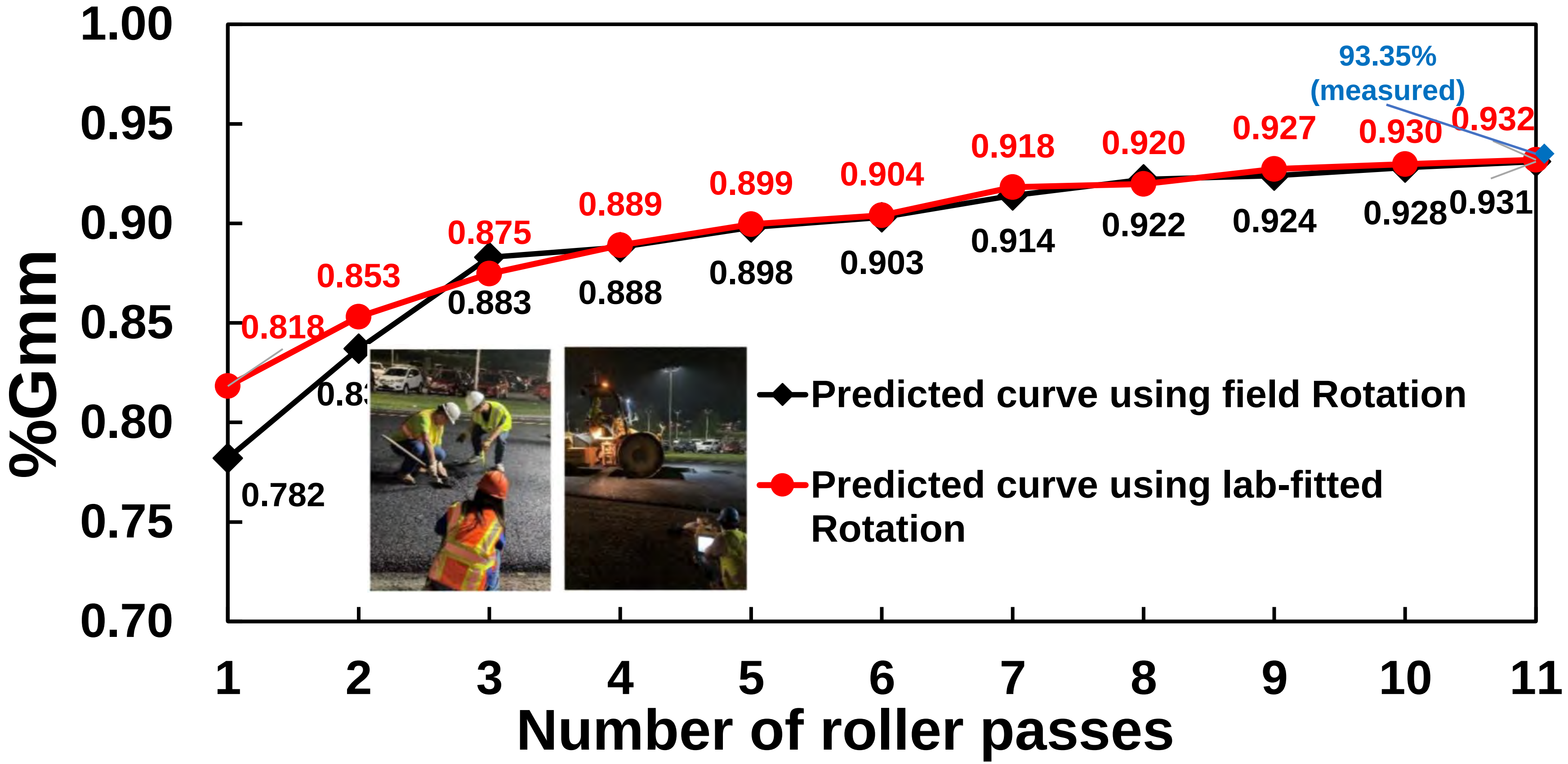
Lane 9
HMA
20% RAP



III. Results and Discussion

□ Model Validation and Hypothesis Reasonableness

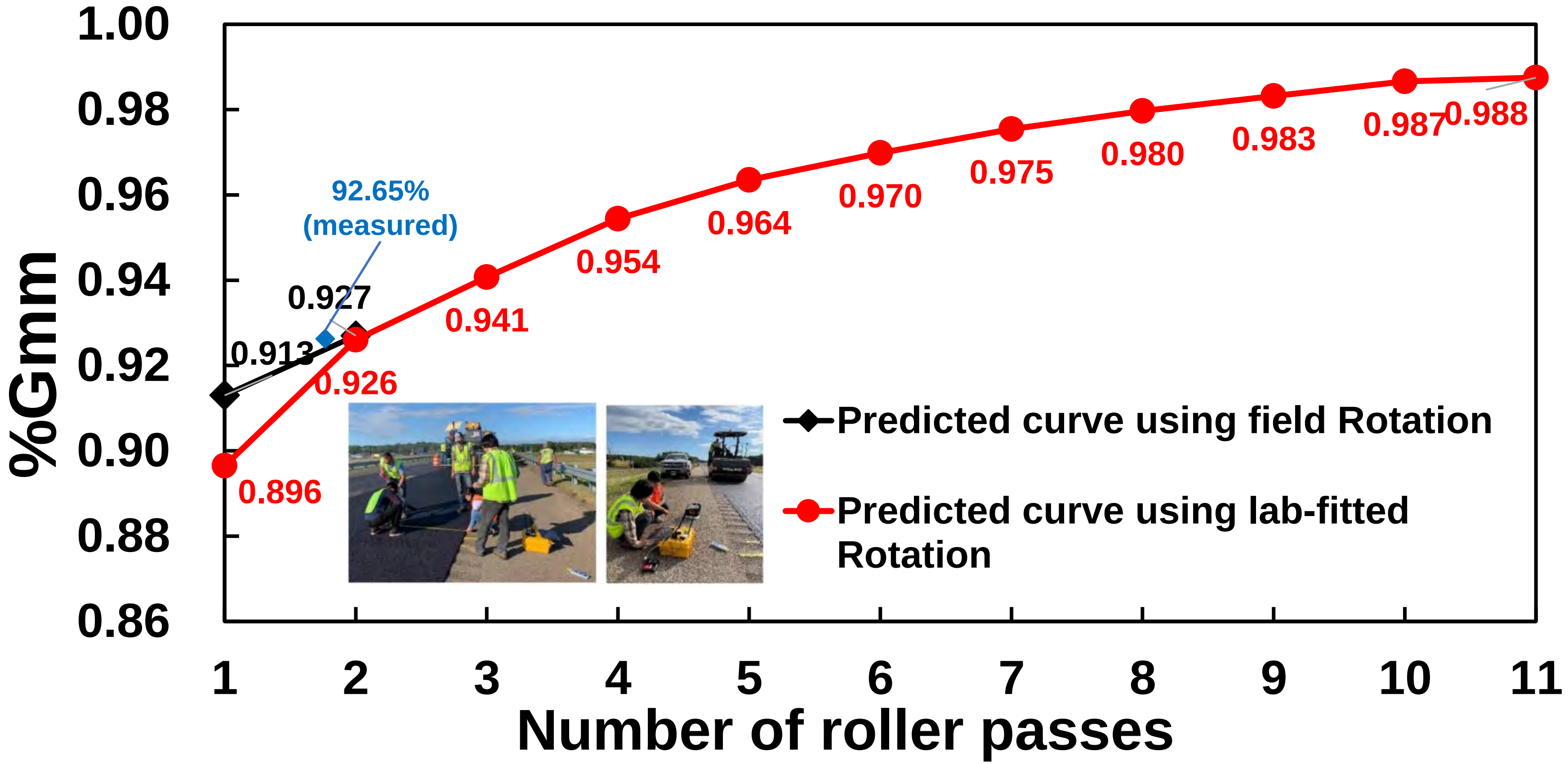
Predicted field compaction curves for Altoona, PA project (HD Static and 120i VO Tandem Rollers)



III. Results and Discussion

□ Model Validation and Hypothesis Reasonableness

Predicted field compaction curves for Angola, IN project (Dynapac CC7200 for static and vibratory rollers)

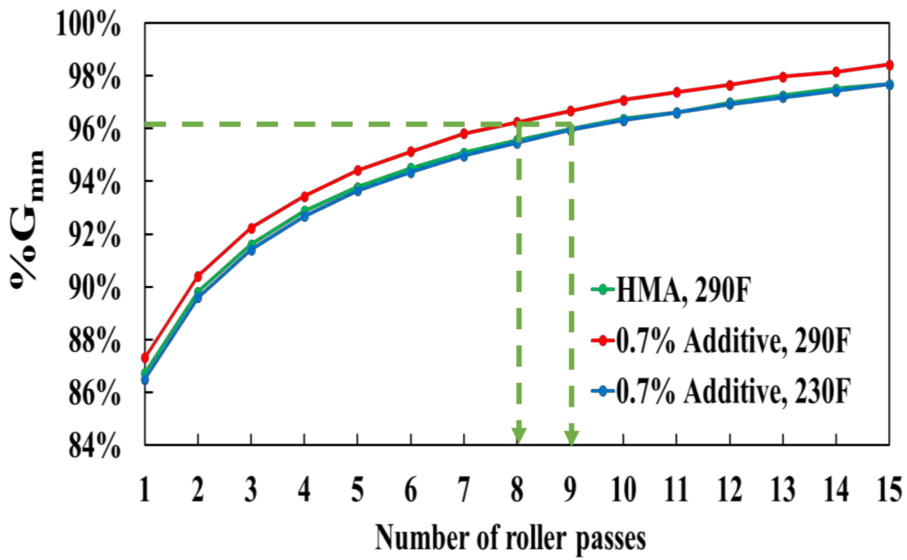


■ PART IV Conclusions

IV. Conclusions

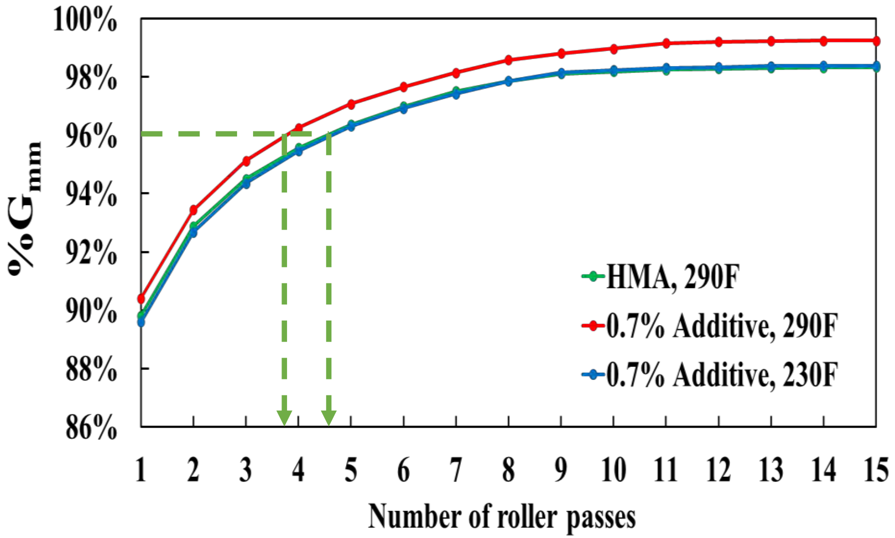
- **Compaction energy** and **particle rotation** are critical parameters.
- **Field compaction curves** were developed.
- Insights into compaction applications
  - Determine compaction temperatures
  - Guide mix design and identify potential problematic mixtures in terms of compaction behaviors.
  - Plan compaction patterns and select roller parameters
  - Compaction density QA/QC

WMA Applications: Effect of Temperature, Additive, and Roller



- Green: Mix 4 (290F, HMA)
- Blue: Mix 6 (230F, 0.7% additive)
- Red: Mix 7 (290F, 0.7% additive)

- Compactor: HD + 120i VO Tandem Roller
- Specific Energy: 107.9 J/kg



- Green: Mix 4 (290F, HMA)
- Blue: Mix 6 (230F, 0.7% additive)
- Red: Mix 7 (290F, 0.7% additive)

- Compactor: CAT CB4.4 + Sakai SW880-1 roller
- Specific Energy: 220.42 J/kg

Acknowledgments

- Funding Support: USDOT CAMTIS UTC.
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- SmartKli® (MixWorx™) sensor: Railroad Technology & Services (RTS), LLC.; InstroTek.

CAMTIS
U.S. DOT Region 3 University Transportation Center

ingevity

New Enterprise Stone & Lime Co., Inc.

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Thank you!

We are looking for field implementation projects in 2025!

Contact: Shihui Shen szs20@psu.edu