

FWD Data Analysis without Layer Thickness Information

M. Makbul Hossain

New York State Department of Transportation
Albany, New York

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OUTLINE

- Introduction to DELMAT Method
- Basic Equations
- Data Analysis Procedure
- Validation
- Conclusions and Recommendations



Forward & Backcalculation Techniques

$$f \{ E(n), H(n), \mu(n) \}$$

↓ ↑ $d(r) + H(n)$
d(r) at known load & plate size



A Direct or Forward Calculation Method

- Perform Pavement structural evaluation from FWD load and deflection data only
 - Number of layers
 - Layer moduli and thicknesses
 - Stiff layer location and its modulus
 - Presence of more than one bound layer, e.g. HMA/PCC or HMA/Asphalt Treated Permeable Base.
- Such a direct or forward calculation method has been developed at the NYSDOT.



A NEW METHOD - DELMAT

- A pavement system has $2L-1$ unknowns, where L = number of layers. The unknowns in a layer are:
 - Modulus
 - Thickness
- FWD testing provides n known surface moduli, $E_s(r)$ and $n-1$ intra-sensor surface moduli, $E_{s_i}(r, r+1)$ where n = number of sensors.
- Layer thickness, $H(n)$ and modulus, $E(n)$ are also related through $R(n) = H(n) * \{E(n-1)/E(n)\}^{0.26}$. Thus, it is possible that both the layer modulus and thickness can be determined from these information.
- Based on these facts, a new method called DELMAT has been developed using the equations presented in the next slides.



BOUSSINESQ EQUATIONS

- Boussinesq equation for a flexible plate on the surface of the a half-space gives the equation for the modulus

$$E_s(0) = 2 (1-\mu^2) a q(0) / d(0) \quad (1)$$

Since modulus is constant at any distance r from the load center

$$E_s(r) = 2 (1-\mu^2) a q(r) / d(r) \quad (2)$$

- From (1) & (2), $q(0)/q(r) = d(0)/d(r) = f(r)$ (3)

- $E_s(0) = 2 (1-\mu^2) a q(r) / \{ f(r) * d(r) \}$ (4)

Where, $f(r)$ is the Pressure-decreasing factor.



MODIFIED EQUATIONS FOR DELMAT

- $E_s(r) = 2 (1-\mu^2) a q (0) / \{f(r)* d(r)\}$ (4)

- $E_{si} (r, r+1) = 2 (1-\mu^2) a \Delta q / \Delta d$

- $= 2 (1-\mu^2) a q (0) \{1/f(r) - 1/f(r+1)\} / \{d(r) - d(r+1)\}$ (5)

Where: $E_s(r)$ = Surface modulus at the sensor location r ,
 $E_{si} (r, r+1)$ = Intra-sensor surface modulus between sensors
 r & $r+1$



Table 1 Deflection and Pressure-decreasing Factors, $f(r)$ for a Subgrade

Distance, r	Deflection	$f\{r\} = d(0)/d(r)$
in.	mils	
0	81.42	1
4	71.11	1.145
6	49.98	1.629
8	32.70	2.49
12	20.72	3.93
18	13.37	6.09
24	10.02	8.12
36	6.68	12.18
48	5.01	16.24
60	4.01	20.30
72	3.34	24.37



Table 2 Selection Criteria for Simulated Pavements

Pavement Type	Layer Type	Layer Modulus (ksi)	Layer Numbers	Layer Thickness (inches)
Composite	HMA Overlay	200-500	4-6	4-6
	Surface	5000 (PCC) 200 -2000 (HMA)		4 - 12
PCC	Treated Permeable Base	200 -1000	2-5	4-8
HMA	Subbase	20 -50	2-5	12 -24
	Subgrade	5-50		12 -∞
	Stiff Layer	40-500		12 -∞



Table 2 Two-layer Case: Subbae/Subgrade

r	d(r)	$E_s(r)$	$E_{si}(r,r+1)$	$E_{si}(0,r)$	$E_{si}(0,r)/C3$	C1	C3
inch	mils	ksi	ksi	ksi	ksi		
0.00	52.50	15.51					
8.0	26.7	12.3	18.9	18.9	16.87	1.12	1.12
12	19.4	10.7	16.5	18.4	15.9	1.12	1.15
18	13.8	9.7	13.0	17.6	15.1	1.08	1.17
24.00	10.50	9.55	10.13	17.00	14.63	1.02	1.16
36.00	6.88	9.71	9.23	16.38	14.30	0.99	1.15
48.00	5.10	9.83	9.39	16.12	14.17	0.99	1.14
60.00	4.03	9.95	9.37	15.97	14.12	0.98	1.13
72.00	3.33	10.03	9.55	15.88	14.09	0.99	1.13



Table 3 Deflections and DELMAT parameters for three-layer PCC Pavement

r	d(r)		$E_{si}(r,r+1)$	$\Delta E_{si}(r,r+1)$	$E_{si}(0,r)/C3$	$E_{si}'(r,r+1)$	$\Delta E_{si}'(r,r+1)$
	mils	ksi	ksi	ksi	ksi	ksi	ksi
0	8.22	107.35					
8	7.90	41.5	1746.6	1121.8	634.8	2461.3	2211.4
12	7.65	27.0	533.8	340.6	438.5	249.9	112.4
18	7.24	18.5	193.3	116.7	288.5	137.5	103.0
24	6.81	14.7	76.5	38.6	214.2	34.5	-3.2
36	5.93	11.3	38.0	17.6	144.4	37.7	27.1
48	5.11	9.8	20.3	6.5	112.8	10.6	2.6
60	3.8	8.9	10.8	3.1	95.8	8.0	0.7
72	3.8	8.9	10.8		85.6	7.2	



Table 4 Layer Moduli and Thicknesses for 3-layer Case

Layer Type	DELMAT Parameters				
	$E_{si}(0, H(1))$ ksi	R (i), inches	Thickness I) inches	Modulus (i), ksi	C1 (i)
Subgrade		51.5		9.8	
Subbase		33.8	14.6	20.3	1.2*
PCC	1746	22.5	8.46	4650	2.64

Note: * - The C1 value of 1.2 was not used to calculate the subbase modulus.



Table 6 Four-layer PCC Pavement with HMA Overlay

r	d (r)	$E_s(r)$	$E_{si}(r,r+1i)$	$E_b(r,r+1)$	$\Delta d(r)$	$E_{si}(0,r)/C3$	$\Delta da'(r)$	C1(r)
0	6.3	140.0						
8	5.3	61.8	527.3	505.9	1.00	302.0	-0.40	1.75
12	5.1	40.3	814.2	1718.2	0.16	285.1	-0.02	2.18
18	5.0	26.7	568.8	1257.3	0.14	256.3	0.23	2.21
24	4.8	20.7	208.8	775.7	0.16	228.0	0.24	1.82
36	4.5	14.9	92.8	241.3	0.36	184.0	0.39	1.61
48	4.1	12.2	45.2	167.7	0.37	154.8	0.33	1.41
60	3.8	10.7	27.8	134.1	0.36	134.9	0.31	1.28
72	3.4	9.8	19.1	112.8	0.35	120.8		



Table 8 Layer Moduli and Thicknesses for 4-layer with Overlay

Layer Type	DELMAT Parameters				
	$E_{si}(0, H(i))$ ksi	R (i), inches	Thickness (i) inches	Modulus (i), ksi	C1 (i)
Subgrade		72*		9.8	
Subbase		56.8**	12.7	19.1	1.19
PCC	1718#	30	11.56	3797	1.7
HMA Overlay	500	10.35	5.9	500	1.75

Notes: -* The intersection between $E_s(r)$ and $\{E_{si}(r, r+1) - E_s(r)\}$ is used in this case.

-** Intersection of $\Delta E_{si}((r, r+1))$ and $E_s(r)$ gives 56.8 inches.

-# In this case the value of $E_{sb}(8, 12 \text{ in})$ is used



Stiff Layer Location and its Modulus

- This layer is located where $\Delta E_{sj}(r, r+1) = 0$. If this zero does not occur within the measured deflections, the stiff layer is outside the outer most sensor.
- In that case a plot of $\Delta E_{sj}(r, r+1)$ versus r will give the stiff layer location. This is the distance where $\Delta E_{sj}(r, r+1)$ intersects the x-axis. The modulus associated with that deflection is the stiff layer modulus.



FOUR FIELD TEST SITES

- This method is validated using four field cases from NYS pavements (C-1 through C-4)
- Deflections in the Field cases were collected using Dynatest FWD. Layer thicknesses were obtained through field coring and drilling.
- MODCOMP5 Program was used to backcalculate pavement layer moduli.



TABLE 9 LAYER INFORMATION OF THE FILED SITES

ID	Route Number	Region	County/Town	Description of Layer Materials	Layer Thicknesses (mm)
C1	Route 9N	1	Saratoga/ Greenfield	HMA	11.5
				Silty Sand Subbase	15
				Silty Gravel Subgrade	36
C2	Route 75	5	Erie/ Hamburg	HMA	10.5
				Asphalt Treated Base	4
				Gravelly Sand Subbase	17.5
				Gravelly Sand Subgrade	
C3	Route 222	3	Cortland/ Cortlandville	HMA	7
				Silty Sand Subbase	18
				Silty Gravel Subgrade	
C4	Route 17	6	Steuben/Corning	PCC	11
				Cement Treated Base	4
				Gravel and Sand Subbase	21
				Silty Gravel Subgrade	

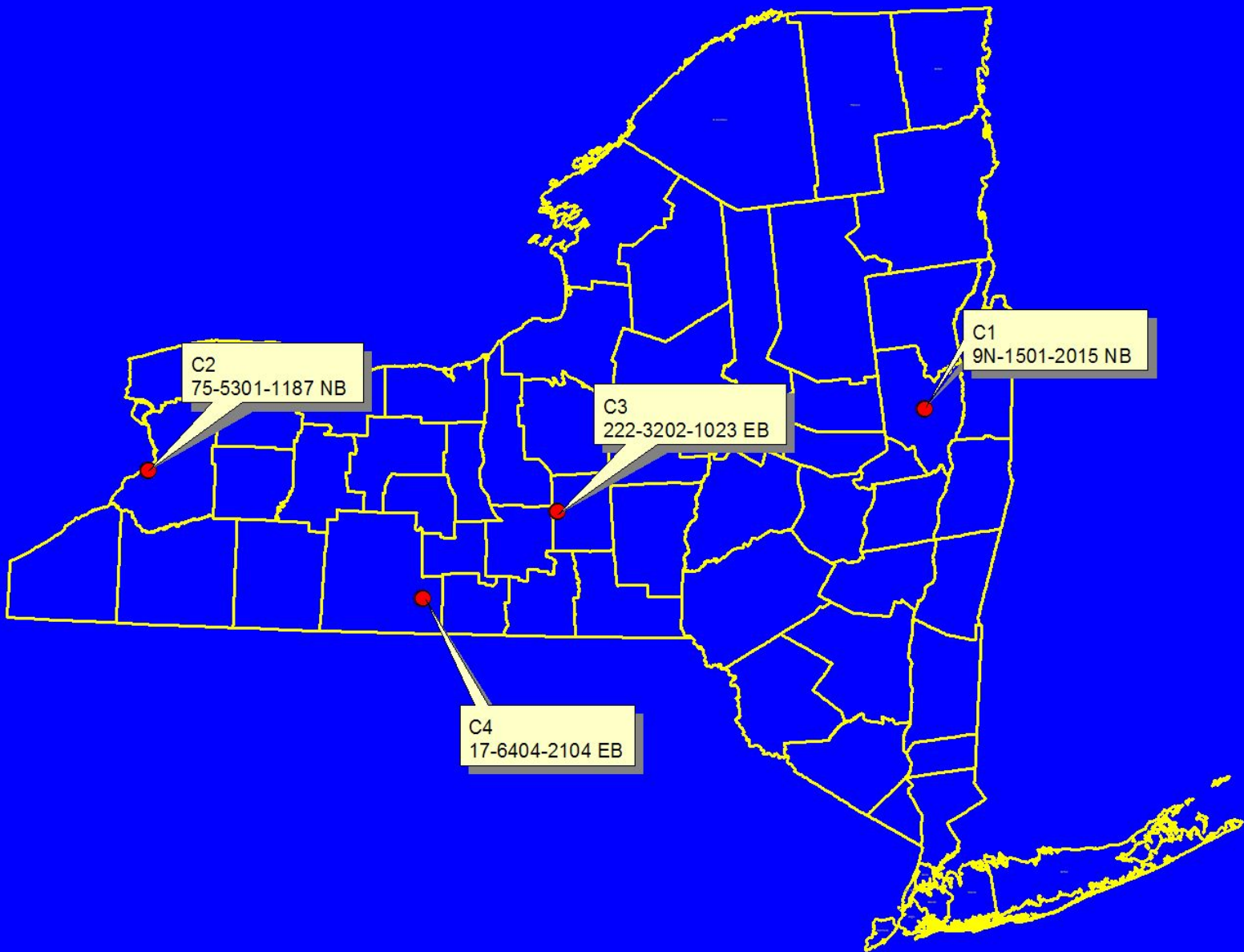


Figure 1 Measured Deflections for the Four Field Sites

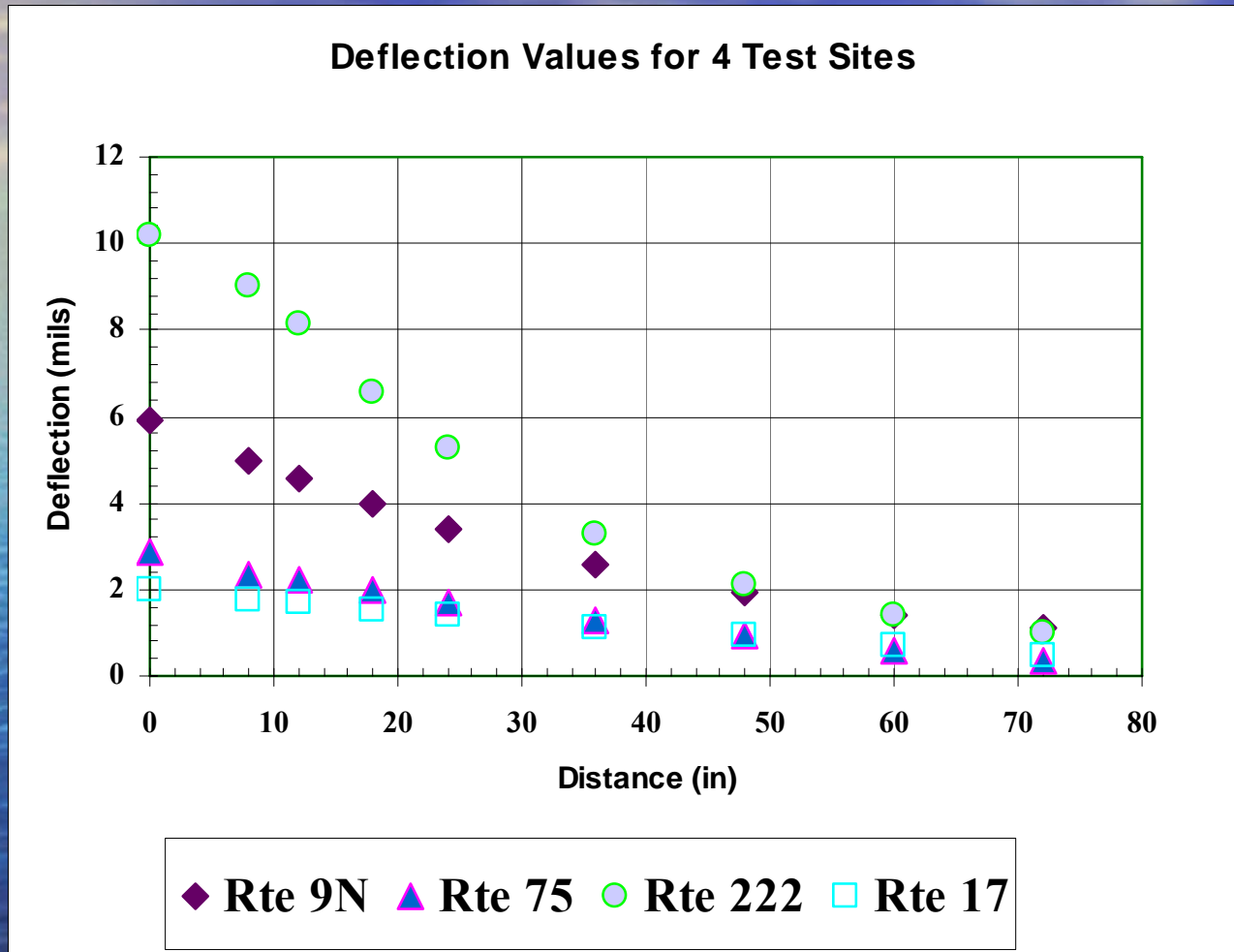


Figure 2 Surface Moduli, E_s (r) for the Four Field Sites

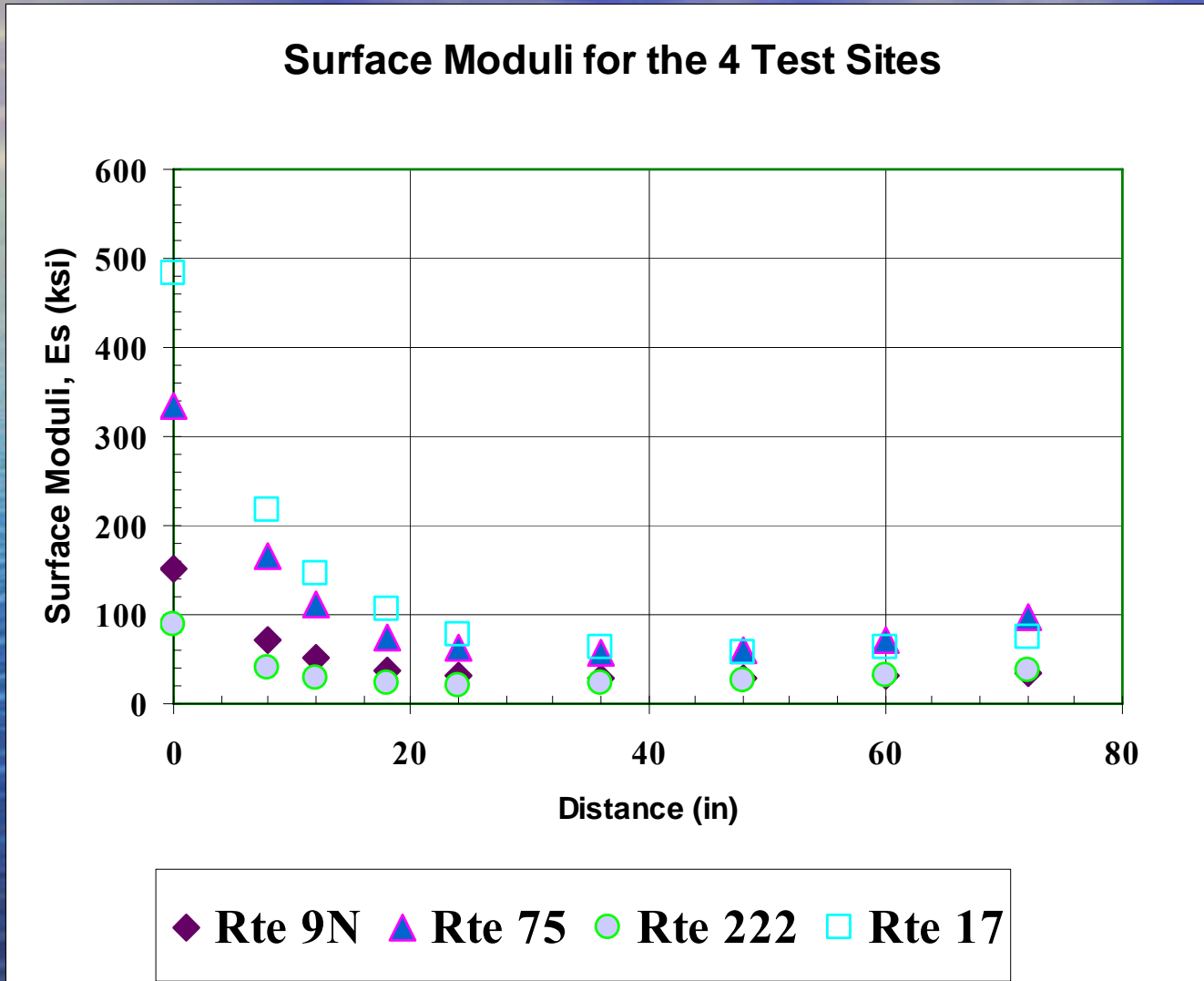


Table 10 Procedure to Correct Deflection Data for Route 9N

r (in)	0	8	12	18	24	36	48	60	72
f (r)	1	2.49	3.93	6.09	8.12	12.18	16.24	20.30	24.37
d (r), mils	5.92	4.97	4.54	3.97	3.42	2.59	1.91	1.42	1.09
d_{isc} (r)		0.91	0.91	1.26	1.89	1.99	2.33	2.18	1.80
∑ d_{isc} (r)		0.91	1.82	3.08	4.96	6.96	9.29	11.47	13.27
d'(r)	12	11.05	10.62	10.05	9.50	8.67	7.99	7.50	7.17
d_{isc}'(r)		0.91	0.91	1.60	2.46	2.73	3.38	3.36	2.94
∑ d_{isc}'(r)		0.91	1.82	3.42	5.88	8.61	11.99	15.35	18.29
Corr. d(r)	11.5	10.55	10.12	9.39	8.68	7.54	6.55	5.80	5.26



Figure 3 Corrected Deflections for the Four Field Sites

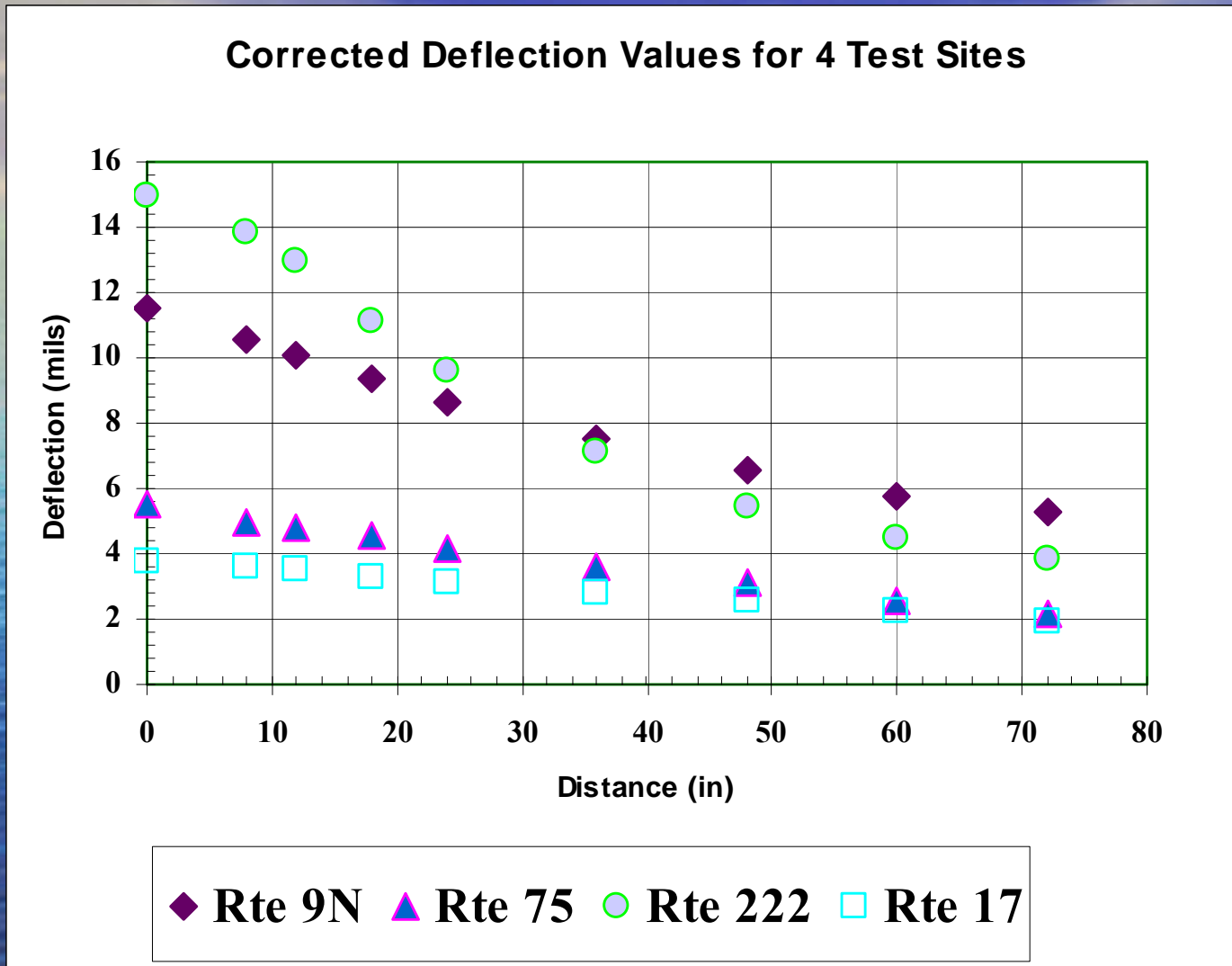
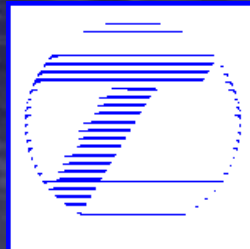


TABLE 11 RESULTS OF FIELD DEFLECTION DATA

ID		MODCOMP5 Moduli					DELMAT Moduli and Thicknesses				
		Asphalt	Asphalt Treated base	Granular Subbase	Subgrade	Stiff Layer	Asphalt	Asphalt Treated base	Granular Subbase	Subgrade	Stiff Layer
C1	Thickness, in	11.5	-	15	36	-	10	-	12.7	66	-
	Modulus, ksi	845	-	47.5	16.5	46.5	822	-	38	17.8	60
C2	Thickness, in	10.5	4	17.5	-	-	10.2	5.1	16	54.5	-
	Modulus, ksi	2200	337	24.4	82.5	-	2070	395	38	17	1400
C3	Thickness, in	7.0	-	18.0	-	-	7.4	-	14.3	32.2	-
	Modulus, ksi	1460	-	7.4	36.3	-	1130	-	25.0	10.5	45
C4	Thickness, in	11.0	4.0	21.0	-	-	12.0	4.0	12.0	126.0	-
	Modulus, ksi	4080	1060	26.5	85.5	-	4300	920	50	16	80

CONCLUSIONS AND RECOMMENDATIONS

- A new forward calculation method called DELMAT has been developed to determine pavement layer moduli and thicknesses directly from FWD load and deflection measurements.
- This method does not require seed moduli and layer thicknesses to determine layer moduli. This gives the user more capability to determine structural condition.
- This method can detect the presence of a stiff layer and determine its location and modulus.
- It can also determine modulus and thickness of a PCC or asphalt/cement treated permeable base under the surface layer.



CONCLUSIONS AND RECOMMENDATIONS

- It includes a scheme to determine surface layer modulus and thickness less than 4 inch.
- However, a smaller FWD plate is needed to determine modulus and thickness of a surface layer less than 4 inch thick.
- All computations can be performed using a spreadsheet. However, these calculations can be automated for faster delivery of the results.
- A 3-D finite element method can be used to determine accurate $f(r)$ values for a layered-system.

