NETWORK LEVEL PAVEMENT STRUCTURAL EVALUATION THROUGH THE USE OF THE ROLLING WHEEL DEFLECTOMETER

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ABSTRACT

One of the primary purposes of pavement management systems (PMS's) is to select maintenance and rehabilitation (M&R) treatments at the optimum time during the life of each pavement in a network of roads. The M&R selections are typically based on surface condition and other available historical data. Surface distress data provides a good indication of the functional condition of a pavement and some distresses (example-alligator cracking) provide an indication of structural problems. However, assignment of M&R treatments could be improved if pavement structural capacity was considered in the evaluations.

A falling weight deflectometer (FWD) is a common non-destructive testing tool used to assess structural capacity of pavements. However, the relatively slow rate of testing and the need for traffic control often precludes its use on a broad network level. In response to the need for rapid collection of structural data on a network level, the Rolling Wheel Deflectometer (RWD) was developed. The RWD is an innovative device that uses a series of lasers mounted beneath the bed of a custom-built 53-foot (16 meter) semi-trailer to measure a continuous profile of pavement deflections under the trailer's 18-kip (8,164 kg) single axle load while traveling at traffic speed.

This paper presents the results of a study that evaluated the structural capacity of a sampling of the Pennsylvania Department of Transportation's (PennDOT's) roads using the RWD and compares the results to other conventional methods. The use of structural data from the RWD for network level PMS is also demonstrated through the study.

INTRODUCTION

Pavement Management Systems (PMS's) have gained widespread use as a tool to help transportation agencies manage their network of roads. Essentially, roadway managers use objective data on pavement condition to assess the current state of their pavements and to proactively program maintenance and rehabilitation in such a way that benefit is maximized for the limited funds available. The primary input to the PMS is surface condition data. Some agencies supplement surface condition with measurements of ride quality, rutting and other geometrics. Objective data on structural strength (load carrying capacity) of the pavement is a very useful supplement to condition data, however, such information is often not available on a broad network level due to the time and cost required to collect it [1].

This paper presents the results of a study that evaluated structural capacity, on a network level, using the Rolling Wheel Deflectometer (RWD) that was developed for use in rapid collection of relative pavement strength. Data from the RWD is compared to conventional falling weight deflectometer (FWD) testing and to a simple algorithm used in PennDOT's Roadway Management system to estimate pavement strength.

BACKGROUND

The overall strength and load carrying capacity of a flexible pavement is commonly expressed in terms of a Structural Number (SN) as defined in the 1993 AASHTO Guide for Pavement Design [2]. The SN is determined by multiplying the structural layer coefficient (a measure of contributing strength from each layer) by the thickness of each layer, then summing them together. The AASHTO design method calculates the required SN based on several input parameters, including the volume and type of expected truck traffic expressed in terms of equivalent single axle loads (ESALs). Applying the same design principle in reverse it is possible to determine the remaining pavement design life (in terms of ESALs carried) for a pavement with known strength (i.e. - structural number, SN).

A common technique to determine the effective SN of an in-place pavement is to conduct non-destructive testing with a Falling Weight Deflectometer (FWD). In order to provide a rough estimate of SN without the expense of testing their entire network of roads, PennDOT has incorporated a simple algorithm into their Roadway Management System (RMS) to calculate SN. For each half-mile segment of road, RMS takes the pavement layer type and thickness from the inventory and multiplies each layer thickness by its structural coefficient. The structural coefficients are taken from PennDOT's design manual for pavement layers less than 9 years old, and from a table of reduced coefficients if the pavement layer is more than 9 years old (in recognition of the fact that pavements deteriorate over time).

SCOPE OF STUDY

The study consisted of: pavement coring and FWD testing of sixteen half mile (0.8 kilometer) segments of road comprised of a range of pavement thicknesses and ages based on RMS records, RWD testing of 288 miles (463 kilometers) of road including the FWD/coring sites, analysis of the data to estimate SN and remaining pavement life, and comparison of the results for the three methods (RWD, FWD and RMS).

PAVEMENT THICKNESS AND AGE

A review of RMS records indicated the test sites contained 3.5 to 13 inches (90 to 330 millimeters (mm)) of bituminous pavement, ranging in age between 5 and 16 years. Pavement coring indicated relatively close agreement with the RMS recorded pavement thickness except for 4 sites where the core thicknesses were 3 to 4 inches (75 to 100mm) greater than indicated by RMS.

FWD TESTING

Equipment Description- The FWD is a trailer-mounted deflection device that is towed and operated by a driver in the tow vehicle (see Figure 1). The FWD generates an impact load by dropping a mass onto a circular load plate lowered to the pavement surface. The resulting deflection basin is measured by an array of sensors positioned radially from the center of the load plate and extending forward in the direction of travel. The largest deflection (D_o) occurs at the center of the load plate and 8 deflections gradually decrease with distance from the load. A typical deflection basin is illustrated in Figure 2.

The FWD provides the full deflection basin and data suitable for detailed structural evaluations, such as backcalculation of pavement layer moduli; however, it is a stationary test that requires traffic control for the protection of the operator, equipment, and travelling public. For this study the FWD tested each of the selected 16 road segments at 100 to 200 feet (30 to 60-meter) intervals in the right wheel path and an impact load of 9,000 pounds (4,082 kilograms) was used to simulate the load of one tire of a single axle loaded to 18,000 pounds (8,164 kilograms).

FIGURE 1 Photograph of FWD *(courtesy of Applied Research Associates)*

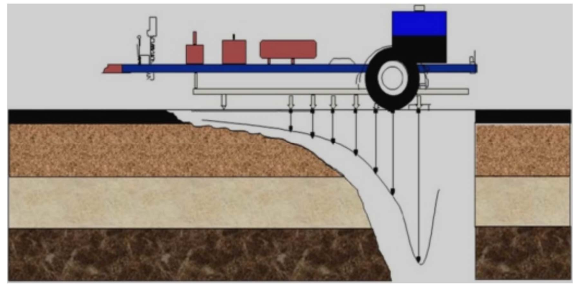

FIGURE 2 Schematic of FWD deflection basin *(courtesy of Applied Research Associates)*

Data Collection and Processing- An analytical technique referred to as "back calculation" was used to determine pavement properties by using pavement response models to predict deflections based on a set of given layer thicknesses and moduli. With pavement thicknesses determined from coring, the response models identify the set of subgrade and pavement layer moduli that give the same deflections as those measured in the field. This technique was used to calculate the overall pavement strength, expressed in terms of its stiffness modulus (E_p) and the strength of the subgrade soil expressed in terms of resilient modulus (M_r), at each test location. These parameters were then averaged for each test site. The results are summarized in Table 1.

TABLE 1 FWD Data Summary

Site #	County	SR No.	Max. Deflection	Average Modulus (MPa)	
			µm	Subgrade, Mr	Entire Pavement, Ep
1	Tioga	2027	792	48	234
2	Tioga	4017	536	40	549
3	Tioga	4002	391	59	833
4	Tioga	4017	286	37	1,660
5	Tioga	2005	234	70	1,163
6	Tioga	249	216	46	2,047
7	Tioga	4014	598	71	325
8	Tioga	4002	411	61	607
9	Tioga	2005	197	54	1,719
10	Tioga	1026	675	65	384
11	Tioga	4011	712	39	411
12	Clinton	144	386	59	781
13	Bradford	3027	157	77	1,972
14	Clearfield	453	160	66	2,649
15	Clearfield	53	108	108	3,249
16	Bradford	3017	510	38	651

RWD TESTING

Equipment Description- The RWD is an innovative device for the high-speed measurement of pavement deflections due to a 9,000 pound (8,164-kg), dual tire, single axle load, as shown in Figure 3. It uses a series of triangulation lasers mounted beneath a custom-built semi-trailer with the rearmost laser positioned above and between the trailer's rubber tires. As the RWD moves down the road the forward lasers measure the profile of the unloaded pavement surface and these readings are compared to the deflected pavement surface at the same location, once the RWD has moved forward. Because of the lasers' high-sampling frequency, the RWD can measure deflections at normal highway speeds (up to 50 miles/hour or 85 kilometers/hour). Typically, the RWD averages individual deflection readings over one tenth mile (160-meter) intervals, providing data suitable for network-level pavement structural evaluation [4]. For local roads, the RWD typically tests 80 to 150 miles (130 to 200 kilometers) per day.

FIGURE 3 Overview of RWD. *(courtesy of Applied Research Associates)*

Data Collection and Processing- The RWD tested 288 miles (463 kilometers) of roads that encompasses PennDOT's "Business Plans" 2, 3, and 4 (i.e.- National Highway System (NHS) roads, non-NHS roads with more than 2,000 Average Daily Traffic (ADT), and Non-NHS roads with less than 2,000 ADT, respectively). Deflection readings were taken with the lasers at 0.6 inch (15 mm) intervals. The random scatter of deflection readings is very high due to pavement surface texture, typically several orders of magnitude greater than the deflection being measured. To reduce this random error and to make file sizes manageable, data are typically averaged every 0.1 miles (160 meters), a suitable interval for network-level applications. For this study, the data was first averaged over 0.1 mile (160 meter) intervals, then groups of 0.1 mile (160-meter) averages were assigned to specific state routes and segments and an average determined for each segment.

REMAINING LIFE DETERMINATIONS

The primary output from this study is the projected remaining life of PennDOT pavements using 3 methods: structural testing with the RWD and FWD and an estimate based on calculations performed within PennDOT's Roadway Management System (RMS). The process used and the results for each method are presented in this section.

Falling Weight Deflectometer (FWD) Method-The remaining pavement life for each site tested was determined using the procedures from the 1993 AASHTO Pavement Design Guide [1]. First, the following formula was used to calculate the effective structural number of the pavements tested:

$$SN_{eff} = 0.0045D(E_p)^{1/3}$$

Where,

D= total thickness of all pavement layers above the subgrade soil (inches)
E_p= effective modulus of pavement layers above the subgrade soil (psi); determined from FWD back calculations.
SN_{eff} = effective structural number

Note- this empirical formula was developed in English units. The resulting calculations were converted to metric units.

Next, the average SN_{eff} for each site was used to determine the remaining pavement life using the nomograph on page II-32 of the AASHTO Guide [2]. Other parameters required in the nomograph include a reliability factor (R) and Standard Deviation (S_o) that account for the variability and degree of uncertainty associated with pavement design and the input parameters, and the Design Serviceability Loss, Δ PSI which is the difference between the serviceability of the pavement at the start and the end of its useful life. Values commonly used in the design process by PennDOT were used for these parameters. Additionally, the resilient modulus of subgrade soils is required in the nomograph. For this study, two different approaches were taken. First, a value of 7,500 pounds per square inch (52 Megapascals (MPa)) was used to be consistent with the assumed value used for the RMS estimate of remaining life. Second, M_r values determined from back calculation of deflection data obtained at each test site were used. The remaining life estimates based on the actual back calculated M_r's are considered to be more accurate than those that used the assumed value of 7,500 psi (52 MPa).

RMS Method- The process used to determine remaining pavement life from RMS data was identical to that described above for the FWD once the value of SN_{eff} is determined. The RMS software contains an estimated SN_{eff} based on the formula provided in the 1993 AASHTO Pavement Design Guide, which is repeated below.

$$SN_{eff} = \sum a_i \times d_i$$

Where,

$SN_{eff=}$ effective structural number;
a_i = structural layer coefficient for layer i;
d_i = thickness of layer i.

The structural layer coefficients used in the calculation come from a table in RMS. For flexible pavements, the layer coefficient for layers less than or equal to 9 years old are the same as those used in design for new pavements. If the layer is more than 9 years old, a reduced layer coefficient is used for most pavement layer types. Some coefficients remain unchanged as they age. Although use of this approach is practical and relatively easy to incorporate into PennDOT's RMS it is recognized that adjusting the relative pavement strength in one step at 9 years is very simplistic. A sample of layer coefficients for common flexible pavement layers is shown in Table 2.

TABLE 2 RMS Layer Coefficients

Pavement Layer Type	Structural Layer Coefficient (a)	
	Layer Age < or = 9 Years	Layer Age > 9 Years
Hot Mix Asphaltic Concrete Wearing Course	0.44	0.3
Hot Mix Asphaltic Concrete Binder Course	0.44	0.3
Hot Mix Asphaltic Concrete Base Course	0.4	0.3
Cold Recycled Asphaltic Base Course	0.3	0.3
Crushed Aggregate Base Course	0.14	0.14

Rolling Wheel Deflectometer (RWD) Method- The process used to determine remaining pavement life from RWD data was fundamentally different from that used for the FWD and RMS data. The RWD only measures the deflection directly under the load and, therefore, it is not possible to estimate the subgrade resilient modulus based on deflections further away from the load. Consequently, the effect of the subgrade soil and pavement structure cannot be separated and for this reason the SN of the pavement layers cannot be determined directly as it was for the FWD.

A method was developed by the Asphalt Institute in 1983 [3] that provides a rough estimate of remaining pavement life based on deflections measured with a piece of pavement testing equipment commonly used at that time called the Benkleman Beam (essentially, measured deflection of a beam placed on the pavement under a loaded truck). The pavement deflections measured by the FWD have been correlated to the Representative Rebound Deflection (RRD) measured by the Benkleman beam using the equation:

$$RRD = D_0 \text{ x } 1.6$$

Where,

RRD=Representative Rebound Deflection measured by Benkleman Beam, in micro-meters (µm).
D_o = Maximum deflection under load plate of FWD, in µm.

For this study, the RWD deflections were converted to RRD using the same conversion factor as that for the FWD and the relationship presented in the Asphalt Institute Manual Series MS-17 [3] Figure 8-2 was then used to estimate the remaining pavement life. The resulting remaining pavement life estimates, for each of the 3 methods, for the 16 test sites are summarized in Table 3.

TABLE 3 Structural Capacity Estimates

	Deflection, Do		FWD	Remaining Life (esals)				SN effective (mm)	
	FWD	RWD	Back-	FWD	FWD	RWD	RMS	FWD	RMS
Site #	(µm)	(µm)	Calculated Mr (Mpa)	(AASHTO eqns & assumed Mr=52 MPa)	(AASHTO eqns & Mr calc'd from FWD data)	(AI graphs)	(Layer thickness & age from RMS & AASHTO eqns)		
1	792	686.0	48.4	159,700	136,942	385,740	12,584	52	33
2	536	645	40.1	1,533,771	848,920	459,949	196,601	74	53
3	391	541	59.3	1,219,795	1,673,632	981,739	1,915,969	71	76
4	287	366	37.4	13,398,912	6,318,224	5,316,937	1,533,771	102	74
5	234	257	69.7	8,889,686	17,770,144	21,152,010	4,404,483	96	86
6	216	531	45.6	15,928,751	11,926,506	1,058,196	1,533,771	104	74
7	599	513	70.7	169,565	350,607	1,218,545	262,225	52	56
8	411	648	61.3	5,052,872	7,509,748	482,963	1,533,771	88	74
9	198	267	53.8	41,735,083	45,778,234	18,164,434	4,404,483	119	86
10	676	693	64.7	51,827	87,155	366,060	145,848	43	51
11	714	691	38.8	587,336	301,812	375,009	755,176	64	66
12	386	445	59.3	33,478,714	46,066,038	2,475,828	4,404,483	116	86
13	157	267	77.4	17,055,070	43,552,401	18,180,620	9,388,202	105	97
14	160	297	66.1	22,310,897	39,342,216	11,963,234	13,398,912	109	102
15	108	363	108.4	43,727,336	243,396,297	5,420,123	262,225	120	56
16	510	475	37.9	227,346	110,704	1,637,620	106,988	55	48

DATA ANALYSIS

Observations and assessments are presented separately for the 16 detailed test sites (where more comprehensive and accurate data was collected; i.e. - RWD and FWD testing, coring, and RMS estimates) and the more global network (where only RWD testing and RMS estimates are available).

Remaining Life Comparisons for Detailed Test Sites- A generally consistent trend was noted between the remaining life estimates by all 3 methods as illustrated in Figure 4. (i.e. - stronger or weaker pavements are detected by all 3 methods). It should be noted that the remaining life estimated from the FWD, presented in Figure 4, is based on the subgrade M_r back calculated from the deflection basin. This provides a more direct comparison to the RWD since the RWD estimates of remaining life are based on one deflection measurement directly under the applied load which is influenced by the pavement structure and the underlying subgrade soils.

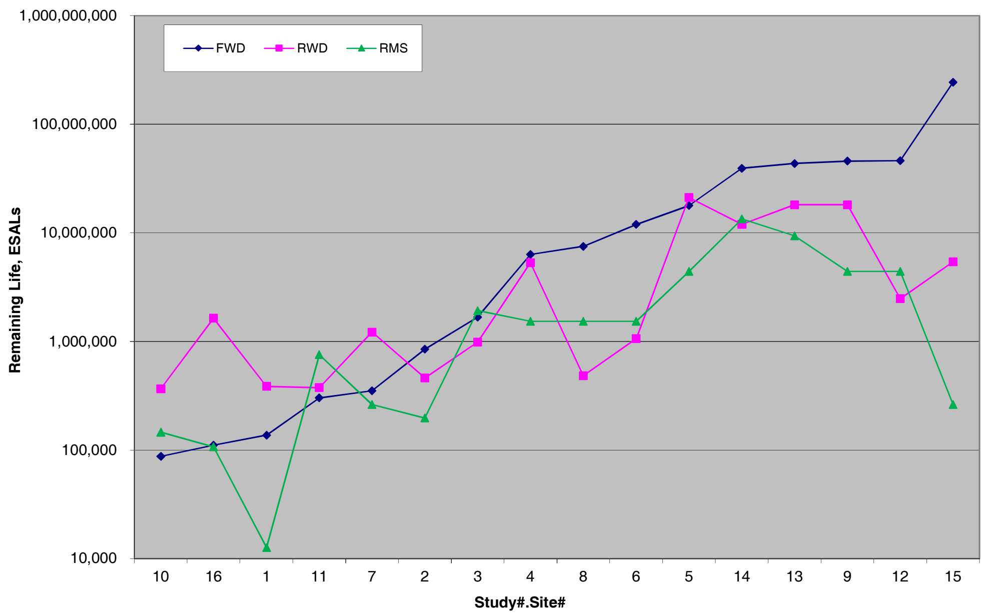

FIGURE 4 Remaining Life Comparison - 3 Methods.

In order to illustrate a more direct comparison between the remaining life predictions from the FWD and RMS, the remaining life from FWD data, using an assumed subgrade M_r of 7,500 psi (52 MPa) was used and the data plotted in Figure 5.

It should be noted that four of the sites had cored bituminous thicknesses significantly different than that recorded in RMS. Sites # 1, 12, and 15 had cored bituminous thicknesses greater than that in RMS which may explain why the remaining life estimates from RMS were significantly less than that from the FWD. Site #3 had cored bituminous thicknesses less than that in RMS, however, the remaining life estimates by both methods are comparable. If the four sites noted above are treated as outliers and removed from the data in Figures 4 and 5, the RMS predictions are in much better agreement with the other two methods.

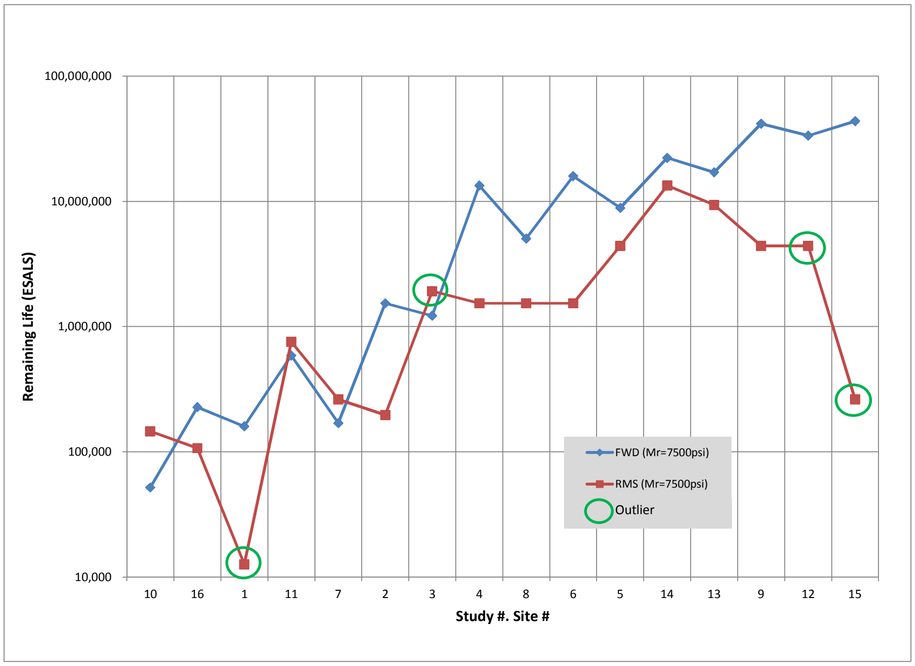

FIGURE 5 Remaining Life Comparisons- FWD and RMS.

Remaining Life Comparisons for Global Network- The global assessment of the entire 288-mile (463-km) network is based on many more data points, however, only RWD and RMS data are available. The plot of RMS versus RWD-estimated remaining pavement life, in Figure 6, indicates considerable scatter in the data as has been observed in other comparative studies of the FWD and RWD [4]. However, a one to one relationship between the RWD and RMS is apparent.

It should be noted that the remaining life based on the RWD is variable along the state routes, whereas the RMS predicts a uniform remaining life along several segments of many state routes (as evidenced by the series of points in a horizontal line in the graph) since the pavement history in RMS includes a uniform pavement section. Variability in pavement strength along a few miles of road is expected and the RWD is useful in identifying such variability. Two examples of variable remaining life (RWD) and uniform remaining life (RMS) are delineated by the areas circled in Figure 6.

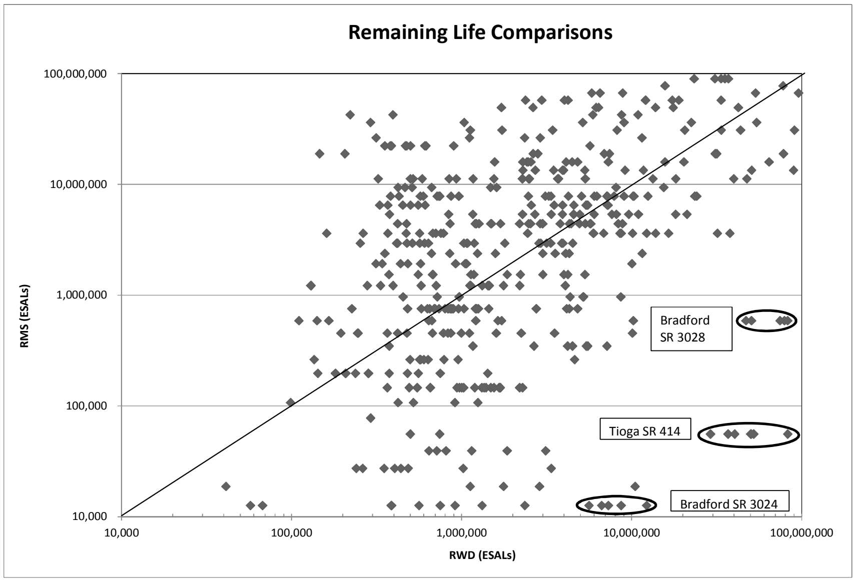

FIGURE 6 Remaining Life Comparisons- RWD vs. RMS- Global Network.

The remaining life predicted by the RWD and RMS was evaluated within each of PennDOT "Business Plans" 2, 3, and 4 since each of these classes of roads is expected to have significantly different strengths. The summary of remaining life predicted by each method, by business plan, in Table 4, shows that both the RWD and RMS clearly indicate that business plan 4 roads are the weakest (lowest remaining life) and that the strength increases from business plan 4 to 3 to 2.

TABLE 4 Average Remaining Life by PennDOT Business Plan

Business	Remaining Pavement Life (ESALs)		
Plan Group *	RWD	RMS	Log RWD/Log RMS
2	225 million	287 million	0.99
3	63 million	198 million	0.93
4	14 million	25 million	0.97

* See Page 5 for description of Business Plan Groups

The results also indicate close agreement in remaining life predictions by the RWD and RMS. It is useful to look at the results for business plan 4 since it represents 70 percent of the segments tested in this study and, therefore, contains the most data points. The average remaining life predicted for the 463 segments in business plan 4 was approximately 14 million by the RWD and approximately 25 million by RMS. Although the RMS is approximately double the RWD, the relationship between SN and remaining life is logarithmic. The ratio of log (remaining life RWD)/ log (remaining life RMS) is 0.97 indicating close agreement. Another way to put the difference between the two methods in perspective is to consider that the difference in average remaining life between the RWD and RMS for business plan 4 equates to an SN of 4.0 to 4.33 inches (100 to 110 mm) which can be accomplished with 0.75 inches (20 mm) of additional hot mix asphalt.

SUMMARY AND CONCLUSIONS

The primary purposes of this study were to determine the structural capacity of a 288-mile (463-km) subset of PennDOT's road network using the RWD and to compare the results to those obtained from the more accurate but slower testing FWD and to predictions from PennDOT's Roadway Management System (RMS).

The data collected in this study indicated relatively good correlation between the 3 methods, although significant scatter was observed in the RWD data. As was the case in previous studies, the RWD was found to be reliable in distinguishing between categories of pavement strength (strong, moderate, weak), making it a valuable tool for network level assessments and planning.

It was found that PennDOT's RMS, while it has limitations, is a relatively reliable method to estimate the structural number (SN) of a pavement, which can then be used to estimate the structural capacity provided that the historic pavement data stored in the system is accurate. An agency whose pavement management system contains historical data including the thickness and year of construction for each pavement layer may wish to consider an algorithm similar to that used in PennDOT's RMS to estimate structural number.

The data from this study indicated relatively good correlation between the RWD and FWD, although there was significant scatter in the RWD data. The number of data points for the FWD, in this study, were considerably less than that for the RWD and RMS and, therefore, it is recommended that more study of the RWD/FWD correlation be conducted. The RWD should be considered for broad, network level pavement management but is not considered accurate enough to replace the FWD for project level (pavement design) purposes.

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