Case Study: The Falling Weight Deflectometer (FWD) as a Multifunctional Analysis Tool

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ABSTRACT

While the utility of the Falling Weight Deflectometer (FWD) in assessing pavement condition is well-established, the usefulness of this device in identifying the factors that affect pavement condition and monitoring the effectiveness of pavement rehabilitation efforts has been much less publicized. This paper intends to demonstrate the multifunctional nature of the FWD through a case study example – a real-life project. The case study project involved an eighteen (18)-mile stretch of Route I-287 in New Jersey. In this project FWD testing and analysis were used for a variety of functions – assessing the existing condition of the mainline pavement (a jointed reinforced concrete pavement), investigating the causes of premature distresses in the mainline pavement, and monitoring the effectiveness of slab undersealing at joint locations.

The initial investigation for the case study project involved a pavement evaluation to determine the causes of premature transverse cracking and other distresses on I-287. FWD test results proved to be very useful during this investigation – both in evaluating the pavement condition and investigating the causes of the transverse cracking. Pavement cores at transverse crack locations indicated that the cracks were initiating at the pavement surface and propagating downwards, suggesting a history of large negative moments within the slab layer. FWD test results were used to investigate the causes of these moments. The results from FWD testing and other test methods indicated that the Portland cement concrete layer and the support to this layer were adequate at midslab locations. However, FWD joint test results revealed high joint deflection (i.e., the deflection directly beneath the center of the FWD load plate during joint testing) and joint intercept (which is a measure of slab support and indicative of the presence of voids under the slab at joint locations) values, indicating the likely presence of voids beneath the slabs at joint locations. Furthermore, the FWD results indicated that the ratio of the joint deflection to the midslab deflection varied with the test temperature. This ratio was also found to be very high compared to the ratios recorded for other roadways that utilized a dense-graded base layer rather than the non-stabilized open-graded (NSOG) base layer used for I-287. These findings led to the conclusion that the slabs were experiencing significant upward slab curling due to differences between the daytime and nighttime temperatures and the presence of an NSOG base layer. The application of dynamic truck loads to the curled slabs likely caused densification of the NSOG layer and a loss of slab support. The curling and associated lack of slab support were identified to be the likely causes of the transverse cracking, as the resulting cantilever condition of the slabs near the joints subjected the top portion of the slabs to large negative moments (and thus tensile stresses) when truck loads were applied.

More than a year after the initial investigation, a slab undersealing operation is currently (at the time that this paper was prepared) being performed at joint locations on I-287. FWD joint testing is being performed before and after the undersealing operation to monitor the effectiveness of the repairs. Only a limited amount of undersealing and FWD testing (part of a preliminary test grouting program), using a fly ash-cement grout and a high-density polyurethane (HDP) grout, had been performed at the time that this paper was prepared. The results indicated that both types of grout were effective in reducing the joint intercept values. The post-grouting testing is also being used in this project as a quality control measure by the New Jersey Department of Transportation (via a specification requiring the post-grouting joint deflection to be less than 10 mils) to help ensure that the desired product is achieved.

INTRODUCTION

The Falling Weight Deflectometer (FWD) is a readily available, industry-accepted testing instrument that measures the pavement response (i.e., deflection) to a load that simulates the in-service truck loads applied to the pavement. The FWD is a multifunctional tool that can be used in various facets of a pavement project. In addition to its conventional, well-established use for evaluating pavement condition, FWD testing (and the associated analysis) can also be used to identify the factors that affect pavement condition and to monitor the effectiveness of pavement rehabilitation efforts. This paper intends to demonstrate the multifunctional nature of the FWD through a case study example – a real-life project involving an eighteen (18)-mile stretch of Route I-287 in New Jersey. In this project FWD testing and analysis were used as a means for assessing the existing condition of the mainline pavement (a jointed reinforced concrete pavement), investigating the causes of premature transverse cracking in the mainline pavement, and monitoring the effectiveness of slab undersealing at joint locations. An overview of the case study project is first presented. The usefulness of FWD data for evaluating pavement condition, identifying factor effects on pavement condition, and monitoring the effectiveness of pavement rehabilitation efforts is then explained – both in general terms and in terms of the case study.

OVERVIEW OF CASE STUDY PROJECT (ROUTE I-287)

The case study project concerned an eighteen (18)-mile stretch of I-287 in New Jersey, which had been in-service for less than nine years at the time of the initial investigation for this project. The initial investigation involved a pavement evaluation to determine the causes of premature transverse cracking and other distresses that plagued the I-287 mainline pavement (a jointed reinforced concrete pavement). Nine (9) discrete areas of I-287, which were identified as Sections A through I, were initially investigated for this project. Table 1 provides the milepost (MP) limits for these pavement sections.

TABLE 1 Milepost Limits for the Pavement Sections Used in the Case Study Project

Section	Southbound	Section	Northbound
I	MP 64.0 to 65.5	–	–
H	MP 56.8 to 58.3	G	MP 57.0 to 58.1
F	MP 54.8 to 56.0	E	MP 54.8 to 56.0
D	MP 52.8 to 54.7	C	MP 52.1 to 53.8
B	MP 50.8 to 52.1	A	MP 50.7 to 52.1

There were three mainline lanes throughout the project area with the exception of Section I (where there were two lanes). The existing mainline pavement was comprised of an 11 in.-thick Portland cement concrete (PCC) layer, a 4 in.-thick non-stabilized open-graded (NSOG) base layer, a 6 to 8 in.-thick dense-graded aggregate base course (DGABC) layer, and an 8 in.-thick subbase layer. This pavement utilized dowel and tie bars across the transverse and longitudinal joints, respectively. The PCC slabs were approximately 78 ft. in length. The shoulders were constructed of flexible pavement.

Various types of testing were performed as part of the pavement evaluation for the initial investigation. FWD testing was performed at midslab and joint locations in the left and right mainline lanes. The midslab testing was performed to obtain data that could be used to backcalculate the elastic modulus values of the various pavement layers. FWD testing was also performed at joint locations to determine load transfer efficiency (which is a measure of the ability of a joint to transfer load from one side to the other) and joint intercept (which is a measure of slab support and indicative of the presence of voids under the slab at joint locations) values. In addition to the FWD testing, pavement cores were extracted from the roadway to determine the thickness of the PCC layer. Some of the cores were tested for compressive strength. The thicknesses and stiffnesses of the subsurface pavement layers were estimated based on the results from Dynamic Cone Penetrometer (DCP) testing, which was performed in some of the core holes. A visual pavement condition survey was also conducted to determine and catalog the existing pavement distresses on I-287.

More than a year after the initial investigation, a slab undersealing operation is currently (at the time that this paper was prepared) being performed at joint locations on I-287. FWD joint testing is being performed before and after the undersealing operation to monitor the effectiveness of the repairs. Only a limited amount of undersealing and FWD testing (part of a preliminary test grouting program), using a fly ash-cement grout and a high-density polyurethane (HDP) grout, had been performed at the time that this paper was prepared. The results from that testing are discussed later in this paper.

EVALUATION OF PAVEMENT CONDITION

General

The primary function of the FWD is to provide deflection data for evaluating the in-situ structural condition of pavement structures. A complement of FWD testing and other test methods provides the necessary information for evaluating pavement condition in a reliable, mechanistic manner. When testing is conducted away from cracks and joints, FWD data can be used to determine the elastic moduli of the various pavement layers. The results of FWD testing at joint locations (in PCC and composite pavements) enable joint performance to be assessed through calculation of the load transfer efficiency and joint intercept values. Since the structural condition of a pavement is primarily dependent on the moduli of the pavement layers and the condition of the joints (in PCC and composite pavements), it can be concluded that FWD testing is an effective means for evaluating pavement condition.

Case Study

As noted previously, a full complement of testing (FWD midslab and joint testing, coring, compressive strength testing, DCP testing, and a visual pavement condition survey) was performed during the initial investigation in the case study project to evaluate the existing condition of the I-287 mainline pavement. The visual survey results confirmed the presence of the distresses that prompted the case study investigation. Low- to medium-severity transverse cracks (i.e., cracks with a width < 3 in.), located approximately 20 ft. from the joints, were found throughout the project area. This cracking was the only distress that was commonly found throughout the project area. A few other localized distresses were also observed during the visual survey. Pavement settlement could be found in a few, isolated areas, while Section D was plagued with severe transverse cracking (i.e., cracks with a width ≥ 3 in.). Section I was marked by longitudinal cracking along the joint between the two mainline lanes.

The FWD, DCP, and compressive strength test results were used to evaluate the condition of the various pavement layers. A normalization load of 9000 lb. was used for the analysis of the FWD test results. That is, the FWD deflections from the actual applied loads were normalized or adjusted to the values that would have resulted if a 9000 lb. loading had been applied. The average FWD midslab and joint test results for each pavement section of the case study project are summarized in Table 2. The FWD and compressive strength test results revealed that the PCC layer was in fair-to-good condition. The average backcalculated PCC layer modulus (E_{PCC}) was almost 5000 ksi, while the average compressive strength of the PCC layer was 8700 psi. The FWD results also indicated that the support to the PCC layer was adequate at midslab locations, as the average backcalculated modulus of subgrade reaction (k) value was 200 pci, a fair value. However, the DCP test results indicated low California Bearing Ratio (CBR) values (average CBR = 46%) for the NSOG layer. Notwithstanding the load transfer efficiency values (92% on average), the FWD joint test results indicated that the pavement was not performing well at joint locations. The joint deflection (i.e., deflection directly beneath the center of the FWD load plate during joint testing) and joint intercept values were fairly high (average values of 9.6 mils and 2.1 mils, respectively). These results suggest that voids likely exist beneath the slabs near joints and excessive vertical slab movement consequently occurs at these locations.

The above discussion regarding the case study project illustrates the usefulness of FWD data in evaluating pavement condition and how other test results complement the FWD findings. The FWD data provided a mechanistic means for determining E_{PCC} and k as well as assessing the condition of the joints. The core results provided required thickness information for the FWD data backcalculation, the compressive strength test results acted as a second source of information regarding the PCC layer strength, the DCP test results provided information on the base layer stiffness (which is not determined for PCC and composite pavements using the FWD data), and the visual survey results yielded an overall indication of the functional and structural condition of the pavement.

IDENTIFICATION OF FACTOR EFFECTS ON PAVEMENT CONDITION

General

Besides providing information for evaluating the pavement condition, FWD data can also function as a source of information for identifying the factors that affect that pavement condition. The deflection data recorded by the FWD represents the actual response of the pavement to a load that simulates the in-service truck loads applied to the pavement. Accordingly, FWD data provides insight into how the pavement behaves (or performs) under a certain set of conditions (or factors). The effects of the governing factors on pavement performance can thus be analyzed using FWD data.

Case Study

The primary objective of the initial investigation for the case study project was to investigate why the I-287 pavement was experiencing premature transverse cracking and other distresses. FWD data served as a very useful tool in investigating the causes of the predominant distress in the mainline pavement – low- to medium-severity transverse cracking. Pavement cores taken at transverse crack locations indicated that these cracks were actually initiating at the pavement surface and propagating downwards. This “top-down” cracking suggested that the cracks

TABLE 2 Average FWD Test Results for the Pavement Sections Used in the Case Study Project

Section	**Lane**	**Joint Deflection[a] (mils)**	**Load Transfer[b] (%)**	**Joint Intercept[c] (mils)**	**Midslab Deflection[d] (mils)**	**Slab Modulus (ksi)**	**Modulus of Subgrade Reaction (pci)**
A	**Left** MP 50.7-52.1	5.1	93	0.6	2.4	4460	252
	Right MP 50.7-52.1	6.5	85	1.3	3.0	5010	146
B	**Left** MP 50.8-52.1	10.4	99	2.6	2.3	3890	256
	Right MP 50.8-52.1	3.2	80	0.1	3.5	4150	104
C	**Left** MP 52.4-53.8	8.0	99	1.1	2.8	4640	189
	Right MP 52.1-53.1	11.3	99	2.6	4.0	6110	113
D	**Left** MP 52.8-53.8	13.2	100	3.0	2.7	5000	228
	Right MP 53.6-54.7	8.4	95	1.2	2.7	5640	199
E	**Left** MP 54.8-56.0	4.9	94	1.0	2.3	4580	234
	Right MP 54.8-56.0	6.6	93	1.0	2.8	4650	170
F	**Left** MP 54.8-56.0	13.5	99	3.3	2.3	4160	278
	Right MP 54.8-56.0	9.7	99	2.3	2.7	4550	186
G	**Left** MP 57.0-58.1	4.5	82	0.4	2.6	3950	224
	Right MP 65.5-64.0	6.9	65	1.5	2.9	4480	177
H	**Left** MP 57.1-58.3	9.5	87	2.1	2.2	4240	282
	Right MP 56.8-57.8	9.8	89	2.3	2.9	5080	151
I	**Left** MP 65.5-64.0	13.9	99	2.6	2.5	4750	207
	Right MP 65.5-64.0	20.2	91	7.0	2.8	5000	179

[a] Joint deflection is the deflection directly beneath the center of the FWD load plate during joint testing.
[b] Load transfer [efficiency] is a measure of the ability of a joint to transfer load from one side to the other.
[c] Joint intercept is a measure of slab support and indicative of the presence of voids under the slab at joint locations.
[d] Midslab deflection is the deflection directly beneath the center of the FWD load plate during midslab testing.

were not caused by the conventional critical fatigue load situation. The conventional fatigue model considers the critical load position to be the midslab edge position, where the slab does not benefit from the support provided by the joints and the stresses are concentrated at the edge of the pavement. In this situation large positive moments occur in the slab, eventually leading to a fatigue crack that initiates at the bottom of the slab and propagates upward. Contrary to the conventional model, the top-down cracks observed in this project suggested that large negative moments were developing within the slab. The FWD data was thus examined to investigate the causes of these large negative moments.

The investigators in this project eventually reached their conclusions regarding the causes of the negative moments by considering the ratio of the joint deflection to the midslab deflection. This ratio provides insight into the relative pavement behavior between the midslab and joint locations. The first finding was that this ratio varied with the ambient test temperature, which indicated that the slabs were curling due to differences between the daytime and nighttime temperatures. Based on the experience of the investigators, pavements utilizing an NSOG base layer (which was used in the I-287 pavement) tend to be more prone to slab curling than pavements utilizing a dense-graded base layer. It is believed that the NSOG layer, which contains a large amount of air voids, acts as an insulator and thus causes a magnified variation in temperature throughout the slab depth as the temperature changes from daytime to nighttime and vice versa. This temperature variation causes the slabs to curl. The second finding in this project, which was that the joint deflection to midslab deflection ratio was very high for I-287 compared to the ratios recorded for other roadways that utilized a dense-graded base layer (see Table 3), supported this theory. It can also be seen in Table 3 that another roadway (I-80) that utilized an NSOG layer also demonstrated a high joint deflection to midslab deflection ratio compared to the other roadways. Based on the findings from this project, it was concluded that the slabs were experiencing significant upward slab curling due to the temperature variation from daytime to nighttime and the presence of the NSOG layer.

A connection was then made between the high joint deflection and joint intercept values in this project (which suggested that voids likely exist beneath the slabs at joint locations) and the slab curling. It is believed that the application of dynamic truck loads to the curled slabs near the joints likely caused densification of the NSOG layer and a loss of slab support. The combination of curling and lack of slab support created a cantilever condition, where the slabs were supported at the midslab location and curled upward towards the joints. It is believed that this cantilever condition created large negative moments within the slab when large axle loads (such as from trucks) were applied near the joints. Such moments cause large tensile stresses in the top portion of the slabs. It seems that these stresses eventually led to the observed top-down transverse cracking in the slabs. A schematic that depicts the induced negative moments and resulting transverse cracking is provided in Figure 1.

It was recommended that slab undersealing be performed at joints having intercept values greater than 3 mils (*1*). The purpose of this rehabilitation technique would be to fill the underlying voids and help reduce the slab deflections at the joint locations. It was also recommended that dowel bar retrofitting be performed for joints having a load transfer efficiency less than 70% (*2*). Crack stitching was also suggested to prevent growth of the existing cracks. A 3 in.-thick asphalt concrete (AC) overlay was also recommended to prevent further deterioration of the pavement. Such an overlay would also help to reduce upward slab curling.

The causes of the other, localized distresses (i.e., pavement settlement, severe transverse cracking, and longitudinal cracking) were also investigated in this project. FWD data was not used directly to determine the causes of these distresses, but it was used to help identify the locations of the distressed areas. Hence, the results from the investigation of these distresses is not discussed herein.

The utility of FWD data in identifying the factors affect pavement condition was illustrated in the case study project. As discussed above, FWD test results from this project provided information on the behavior of the pavement at midslab and joint locations under simulated in-service load applications. Such information played a critical role in determining the causes of the transverse cracking.

MONITORING THE EFFECTIVENESS OF PAVEMENT REHABILITATION EFFORTS

General

FWD testing is commonly utilized at the evaluation and design (pre-construction) phases to determine the existing structural capacity of the pavement and to identify joints and cracks that are in need of repair. Such testing is not often utilized at the post-construction phase, however, to monitor the effectiveness of the pavement work that was designed and recommended. FWD testing and the associated analysis can be performed after the rehabilitation work has been completed to determine if the work actually achieved the desired results. Use of FWD testing at the post-

TABLE 3 Comparison of Deflections for Rigid Pavements with Dense-Graded versus NSOG Base Layers

Roadway	**Direction**	**Lane**	**Base Type**	**Avg. Joint Deflection (mils)**	**Avg. Midslab Deflection (mils)**	**Joint Deflection/ Midslab Deflection Ratio**
I-80 Express	WB	Left	Dense-Graded	4.93	3.58	1.38
		Center	Dense-Graded	8.96	3.52	2.55
		Right	Dense-Graded	9.22	2.50	3.69
	EB	Left	Dense-Graded	4.90	3.71	1.32
		Center	Dense-Graded	13.99	3.94	3.55
		Right	Dense-Graded	6.85	3.36	2.04
I-80 Local	WB	Left	Dense-Graded	5.25	3.10	1.69
		Right	Dense-Graded	9.03	3.74	2.41
	EB	Left	Dense-Graded	6.03	4.31	1.40
		Right	Dense-Graded	7.01	4.67	1.50
I-78 Express	WB	Left	Dense-Graded	4.99	4.39	1.14
		Right	Dense-Graded	5.09	3.71	1.37
Route 24	WB	Left	Dense-Graded	5.99	3.07	1.95
		Right	Dense-Graded	11.55	5.44	2.12
	EB	Left	Dense-Graded	5.15	3.64	1.41
		Right	Dense-Graded	13.41	3.10	4.32
JFK Expressway	NB	Left	Dense-Graded	4.28	3.06	1.40
		Right	Dense-Graded	3.76	3.17	1.18
	SB	Left	Dense-Graded	4.54	2.68	1.70
		Right	Dense-Graded	3.70	2.65	1.40
			Average	**6.93**	**3.57**	**1.98**
I-287 (Case Study Project)	NB & SB	Left	NSOG	9.81	2.44	4.03
		Right	NSOG	9.46	3.05	3.20
I-80	WB	Right	NSOG	7.22	1.98	3.65
			Average	**13.43**	**2.43**	**3.63**

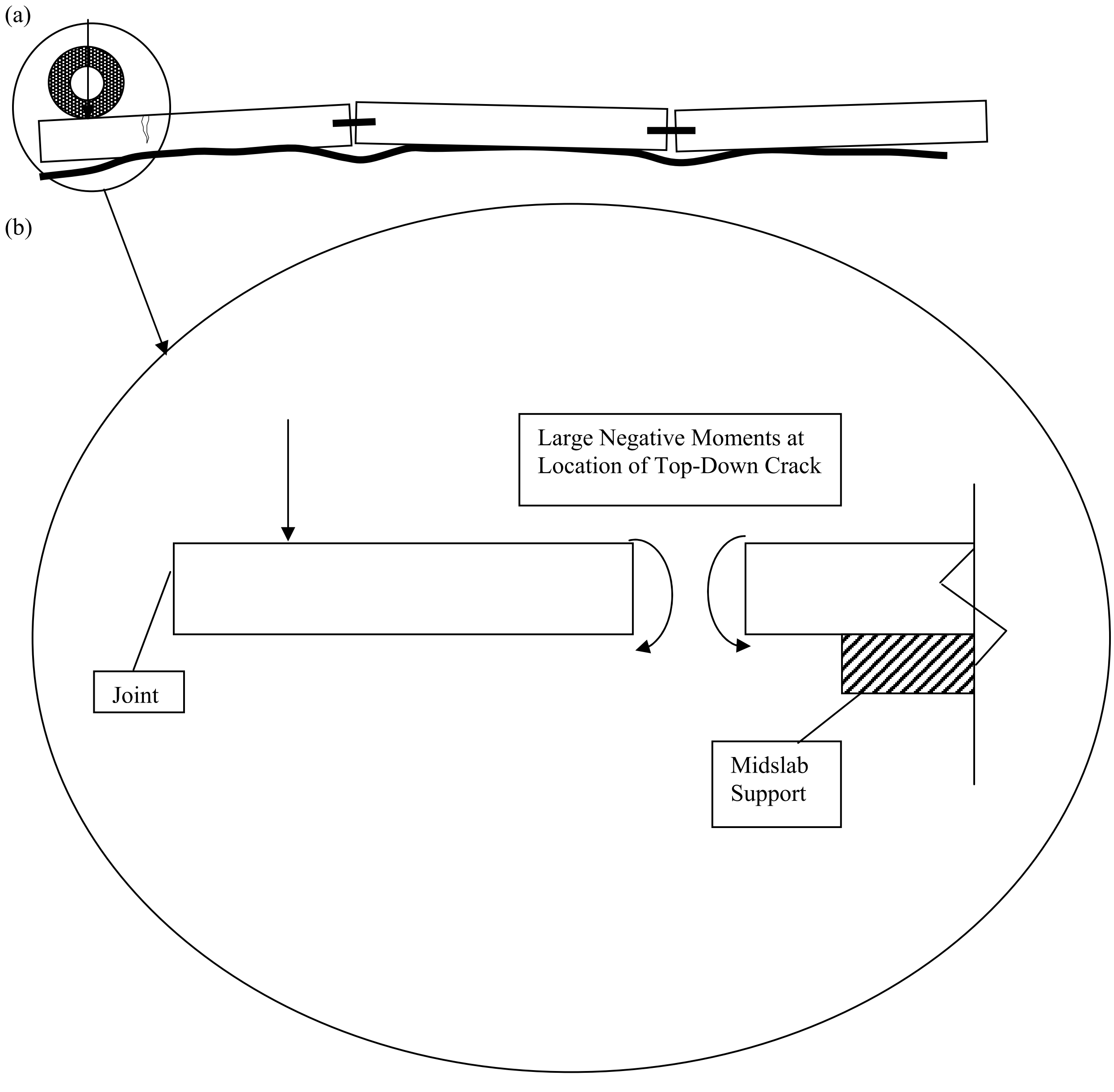

FIGURE 1 (a) Schematic of Unsupported Slab Being Loaded near a Joint and a Typical Top-Down Crack on I-287; (b) Schematic of Induced Negative Moments that Result from Such Loading near Joints and Are Believed to Have Lead to Top-Down Cracks in the I-287 Mainline Pavement.

construction phase could even be incorporated into the specification requirements for the work as a means of quality control.

Case Study

FWD testing was used in the case study project to monitor the effectiveness of slab undersealing at joint locations. As noted in the previous section of this paper, the densification of the NSOG layer is believed to have caused voids beneath the slabs at joint locations on I-287. It was recommended that slab undersealing be performed at joint locations to fill these underlying voids and help reduce the slab deflections at such locations. Based on these recommendations, a slab undersealing operation was initiated on I-287. Only a limited amount of the project area had undergone the undersealing operation at the time that this paper was prepared. The limited amount of undersealing that was conducted prior to preparation of this paper was actually performed as part of a preliminary test grouting program to determine what type of grout to use for the remainder of the grouting operation. Two different types of grouting were used during this test grouting program - a fly ash-cement grout and a high-density polyurethane (HDP) grout. The HDP grout undersealing was performed in Sections B and D, while the fly ash-cement grout undersealing was performed in Section I. The results from the FWD testing during the test grouting program are discussed below.

FWD joint testing was performed before and after the undersealing operation to monitor the effectiveness of the repairs. A normalization load of 8000 lb. was used for the analysis of these joint test results. The FWD test results indicated improved pavement support after grouting with both types of grout. For the joints that were grouted with HDP the FWD results indicated that the average joint intercept value was reduced from approximately 4 mils to 0 mils. FWD test results for the fly ash-cement-grouted joints indicated that the average intercept value was reduced from approximately 8 mils to 0.6 mils. Hence, both types of grout seemed to be effective in filling the voids, according to the FWD results. It was ultimately decided to use the HDP grout for the remainder of the slab undersealing operation, as this grout demonstrated more widespread penetration and distribution beneath the slab layer based on cores taken in the grouted slabs.

The New Jersey Department of Transportation (NJDOT) is also using the post-grouting FWD test results as a quality control tool for the slab undersealing operation. The NJDOT specification for the slab undersealing operation requires that grouted joints have a normalized joint deflection (i.e., deflection directly beneath the center of the FWD load plate during joint testing) less than 10 mils, based on a normalization load of 8000 lb. Any joints with deflection values greater than this threshold must be regrouted one additional time in an attempt to reduce the deflection below 10 mils.

The use of FWD joint testing for the slab undersealing operation in the case study project illustrates the utility of this device in monitoring the effectiveness of pavement rehabilitation efforts. NJDOT's specification regarding post-grouting FWD test results illustrates how the FWD can even be used as a quality control measure for pavement projects.

SUMMARY AND CONCLUSIONS

The FWD is a readily available, industry-accepted testing instrument that measures the pavement response to a load that simulates the in-service truck loads applied to the pavement. This paper has demonstrated the multifunctional nature of the FWD. Besides its conventional use for evaluating pavement condition, FWD testing (and the associated analysis) can be used to identify the factors that affect pavement condition and monitor the effectiveness of pavement rehabilitation efforts, as illustrated by the case study project. The FWD can thus act as an evaluative and investigative tool during the early stages of a project and as a quality control instrument to ensure that the desired final pavement product is achieved after the pavement work has been performed.

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