Analysis of Concrete Pavement Performance and Development of Design Procedures

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A procedure to design concrete pavements based on local conditions and performance of existing pavements is presented. The procedure is used to develop design equations to determine required concrete thickness or terminal condition of the pavement for a number of design inputs. These inputs include subgrade support, concrete modulus of rupture, stress-to-strength ratio, traffic, concrete thickness, and the condition of the pavement at the end of the design period. The procedure utilizes the pavement condition index (PCI) survey procedures and nondestructive deflection testing to develop design equations for local conditions. Existing pavements are surveyed and evaluated to provide information for use in developing a design equation for local conditions.

A procedure to develop a performance-based concrete pavement design is described. In-service pavements with a range of traffic, age, thickness, and condition are used to develop design equations to determine the required thickness to adequately serve the projected traffic for the design period and desired terminal condition.

PROCEDURE

The steps involved in developing a performance-based design equation are shown in Figure 1. The primary steps to collect the necessary data and develop the equation include preliminary data collection, dividing the pavement into uniform sections, distress survey, nondestructive deflection testing (NDT), coring, and a traffic analysis. These steps are discussed in detail in the sections that follow.

Preliminary Data Collection and Pavement Identification

The first step is office data collection for information on construction history, design, materials and soils properties, and past and projected traffic. Any previous performance and maintenance data should also be obtained. Once this information has been collected, the pavements with the desired characteristics and range of variables such as thickness, traffic, or age are identified.

Division of Pavement Into Uniform Sections

After initial identification, the pavements are divided into uniform sections. A uniform section has consistent characteristics such as structural composition, construction history, traffic, and condition throughout its length. Once the uniform sections are identified, collection of additional information from coring, nondestructive deflection testing, and a distress survey can begin. As additional data are obtained from these activities, it may be necessary to modify the uniform sections. For example, if one uniform section has consistent construction history and structural composition but different levels of traffic or pavement condition, it is necessary to divide that section into two or more uniform sections. Definition of uniform sections is an iterative process throughout data collection.

Pavement Condition Survey

The condition of in-service pavements must be known to develop performance-based design equations. An objective measure of performance of existing pavement sections is the basis on which performance-based designs are developed. The pavement condition index (PCI) method developed by the U.S. Army Corps of Engineers (*1*) is used to determine the pavement section condition and provide a measure of its performance. The PCI is determined as a function of distress type, severity, and amount. The final calculated PCI is a number from 0 to 100, with 100 representing a perfect pavement. A summary of the PCI scale is shown in Figure 2.

Each uniform section is further subdivided into sample units for pavement inspection. Each pavement section may be surveyed in its entirety or by using sampling techniques. The PCI of each pavement section is determined and is used to develop a design equation.

Nondestructive Deflection Testing

NDT is used to measure the pavement system's structural response to simulated moving truck wheel loads, to evaluate subgrade support conditions, and provide information for use in materials characterization and fatigue analysis.

The NDT program is conducted using the falling weight deflectometer (FWD). The FWD is an impulse loading device capable of simulating a moving wheel load in both magnitude and duration of loading. The FWD is capable of producing loads from 1,500 to 24,000 lb force.

The NDT program should test slabs at both center slab and joint locations as shown in Figure 3. Results from center slab tests are used to determine the dynamic stiffness modulus of the concrete slabs and the dynamic modulus of subgrade reaction (*k*-value). Joint testing is used to determine load transfer efficiency. Load values used during testing should simulate the actual loadings expected for the pavement. A reference slab

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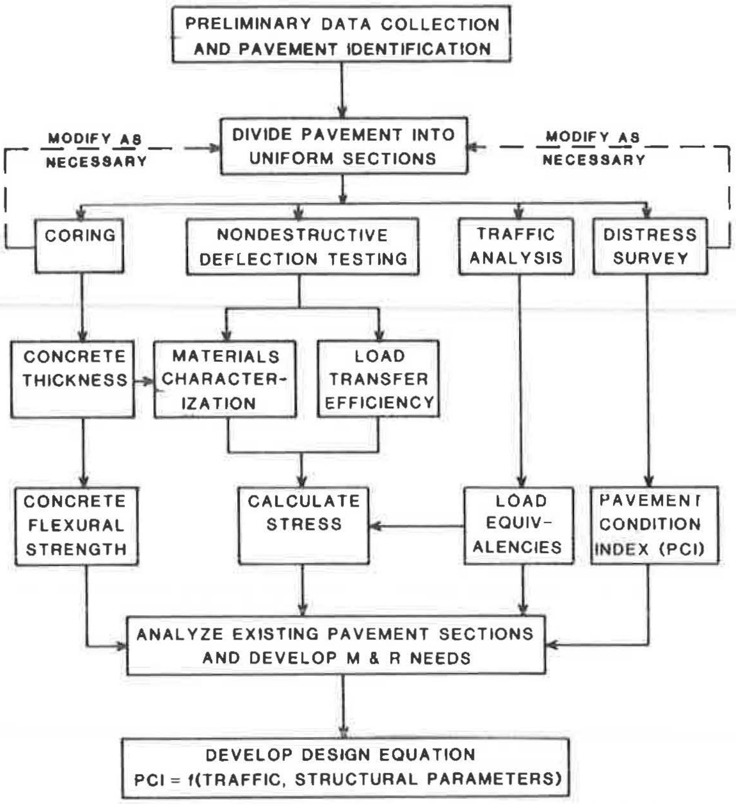


FIGURE 1 Steps to develop a performance-based concrete design equation.

should be chosen to measure the effects of temperature on deflection measurements. This is necessary to compensate for any environmental influences, such as slab curling, that may affect measured deflections or load transfer. Tests should be conducted at various times throughout the day at the same point at center slab and joint locations of the temperature reference slab.

Materials Characterization

Deflection data are used to evaluate the structural capacity of the pavement and subgrade properties. These properties include the dynamic modulus of elasticity of the concrete slab and the subgrade *k*-value. The NDT deflection basin results and layer thicknesses are used as inputs to a computer finite-element pavement model (*2*) to back-calculate the in-situ dynamic material properties. Both the dynamic slab modulus and subgrade modulus values are varied to obtain a grid such as that shown in Figure 4 for a given concrete pavement thickness and slab size. The basin area shown on the *x*-axis is obtained from deflection data as shown in Figure 5. Measured values obtained with the FWD are used as entrance points on this grid to determine both the dynamic subgrade *k*-value and the dynamic concrete modulus values simultaneously. Average values for the dynamic modulus of the concrete and subgrade *k*-value for each pavement section are determined in this manner. The existing concrete thickness must be known to develop

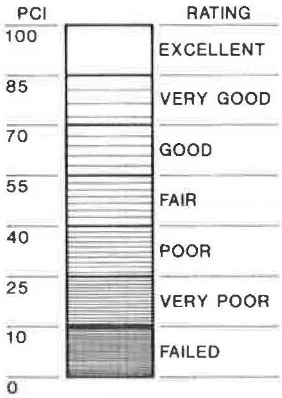


FIGURE 2 PCI rating scale.

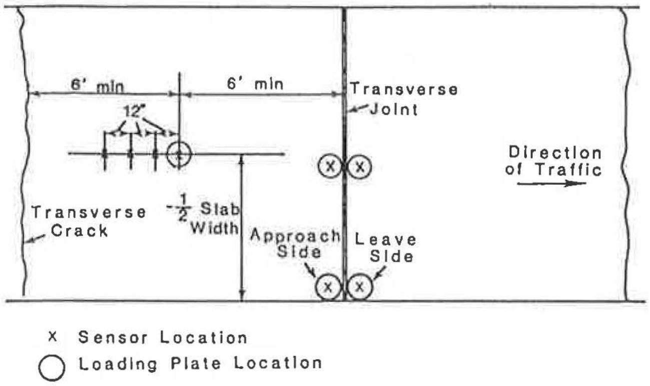


FIGURE 3 FWD test locations.

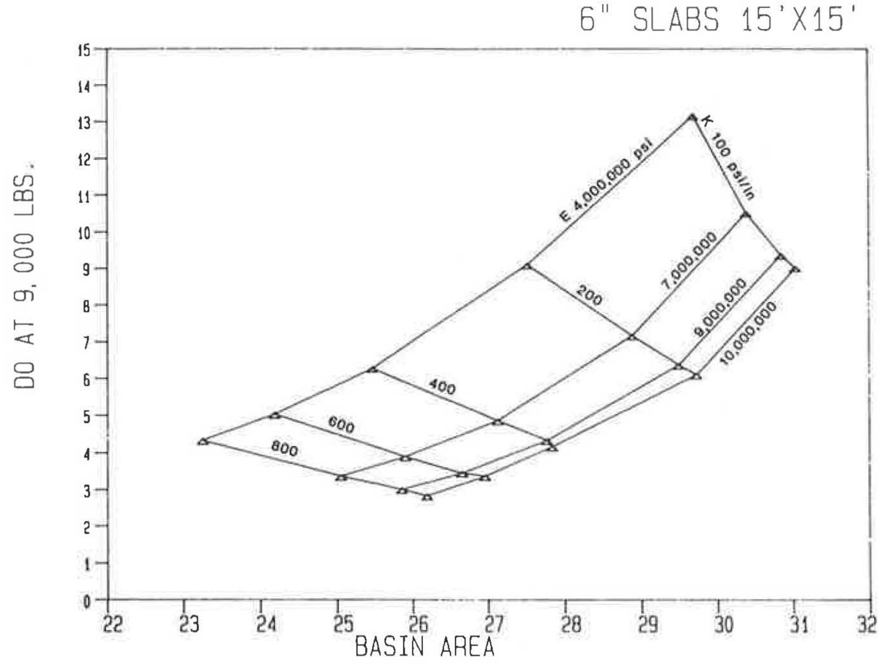


FIGURE 4 Example concrete modulus and k-value determination graph.

the grid system. Therefore, a coring program should be coordinated with the nondestructive deflection testing.

Load Transfer Across Joints

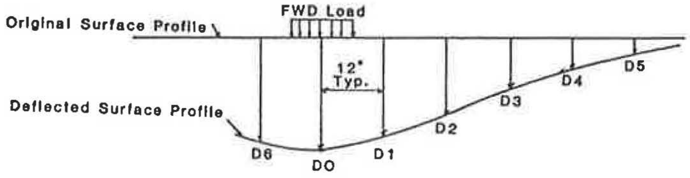
NDT is also used to determine the load transfer efficiency across joints. Load transfer efficiency is defined as the ratio of the deflection of the unloaded side of the joint to the deflection of the loaded side. Load transfer efficiencies in the range of 70 to 100 percent are considered good, whereas load transfer efficiencies below 50 percent are considered poor. A high degree of load transfer (greater than 70 percent) is effective in reducing the critical stress in the concrete slab due to the edge loading and corner loading conditions. Lower stresses will reduce the occurrence of load-related distresses such as corner breaks, spalling, and linear cracks.

Determination of Concrete Stresses

When material properties and the level of load transfer are determined, the stress in each pavement section is determined by using a number of models. The finite element program ILLI-SLAB (*2*), developed at the University of Illinois, is used to evaluate the structural response of the pavement and determine the concrete stresses. ILLI-SLAB is capable of analyzing jointed concrete pavements comprised of one or two layers with any specified level of load transfer at the joints or cracks and arbitrary loading conditions such as center, corner, or edge loading. The primary advantage of using ILLI-SLAB is that the actual load transfer conditions determined using nondestructive deflection testing are used when determining the concrete stresses for each pavement section under consideration. Required inputs to use ILLI-SLAB include slab size, thickness, modulus of elasticity, load transfer efficiency, dimensions of the loaded area, and amount of load. Therefore, traffic information and concrete thickness from a coring program are needed to determine the concrete stresses for each pavement section.

Coring

A limited destructive testing survey is necessary to determine the actual concrete thickness for each pavement section. The pavement thickness is used when back-calculating the dynamic concrete modulus of elasticity and dynamic subgrade *k*-value, and in determining the concrete stresses for each section.



Deflection basin AREA1 is calculated using the formula:

AREA1 = [6/DO] x [Do + D1 + D6 + 2D2 + D3]

FIGURE 5 Determination of deflection basin area.

The flexural strength of each pavement section is determined by taking cores or cutting beams from the pavement and testing to determine the concrete modulus of rupture. The concrete flexural strength is used in the development of the design equation to relate the stress ratio for each pavement section to performance or condition of each section.

If concrete cores or beams are not available, the flexural strength can be calculated based on a correlation with a concrete dynamic stiffness modulus.

Traffic Analysis

Traffic data are necessary to provide information on traffic volume and loadings. This information is needed to define the uniform pavement sections and develop the design equation. Once the traffic volume and loadings are determined, the number of load equivalencies, such as 18-kip equivalent single axle loads, for each pavement section is determined.

Analysis of Existing Pavement Sections

Once the aforementioned steps have been completed, the pavement sections surveyed are analyzed and maintenance and rehabilitation needs are developed for each section. Maintenance and rehabilitation alternatives should be specified both to repair existing distress and to retard or prevent future deterioration of the pavement section. Loss of subgrade support should be evaluated. Results of nondestructive deflection tests at corner locations are used to determine the areas that are exhibiting loss of support (*3*).

Development of a Design Equation

A design equation is developed to determine the relationship between PCI, stress ratio (concrete stress/modulus of rupture), and traffic (*4*). The best general form of the equation was found to be $\text{PCI} = 100 - 10^{a1} \times [\text{traffic} \times (\text{stress ratio})^{b1}]$.

Regression techniques are used to determine the coefficients $a1$ and $b1$. Once these coefficients are determined, the correlation between predicted PCI from the above equation and the measured PCI is determined. This equation is then used as a design equation to determine the required concrete slab thickness for some terminal PCI value at the end of the design period. The equation can also be used to predict the future PCI of existing pavements as a function of traffic and stress ratio.

EXAMPLE APPLICATION

The foregoing procedure to develop a design equation based on local conditions and pavement performance can be used in many applications. This example considers a large truck terminal. One-half of the truck terminal consists of a concrete pavement in various conditions. The other one-half of the terminal is currently asphalt concrete that is to be removed and replaced with a concrete pavement.

Preliminary Data Collection

The initial office data collection effort showed that the concrete pavements at the terminal could be categorized as follows:

1. A 6-in. jointed reinforced concrete pavement with Number 4 reinforcing bars in both directions placed on 6–9 in. of lime-modified subgrade. These areas were constructed in 1982.
2. An 8-in. jointed reinforced concrete pavement with Number 4 reinforcing bars in both directions on recompacted subbase material. These areas were constructed in 1982.
3. A 6-in. jointed reinforced concrete pavement constructed directly on top of 6–8 in. of lime-modified subgrade. This area was constructed in 1965.
4. A 6-in. jointed reinforced concrete pavement constructed directly on top of recompacted subbase. These areas were constructed in 1977.

Available traffic information included the number and weight of trucks that entered the terminal.

Results of the PCI Survey

Before conducting the PCI survey, the concrete pavement network was divided into uniform pavement sections and sample units. Sections were divided based on pavement areas that had consistent characteristics such as structural composition, construction history, traffic pattern, and function. Each section was further subdivided into sample units for pavement inspection. For pavements with joint spacings less than or equal to 30 ft, a typical sample unit consists of an area of approximately 20 slabs (± 8 slabs).

The PCI was determined from a visual survey in which distress type, severity, and quantity were recorded for the concrete areas. The PCI value calculated for each sample unit and the section PCI are shown in Figure 6. The PCI for each section was calculated by averaging the sample unit PCIs.

Nondestructive Deflection Testing

The program was conducted on pavement Sections 1 through 22. The objective of the NDT program was to (*a*) measure the pavement system's structural response to simulated moving truck wheel loads, (*b*) evaluate subgrade support conditions, and (*c*) provide information for use in materials characterization and fatigue analysis.

The NDT program was conducted using the FWD. Slabs were tested at both center slab and joint locations as shown in Figure 3. Results from center slab tests were used to determine the dynamic stiffness modulus of the concrete slabs and the dynamic subgrade *k*-value of the foundation.

Emphasis was placed on testing areas to provide information to evaluate the concrete and subgrade strength properties. A reference slab was chosen to evaluate the effects of temperature on deflection measurements. This is necessary to compensate for any environmental influences, such as slab curling, that may affect measured deflections or load transfer.

SECTION PCI SUMMARY

SECTION	PCI	SECTION	PCI
01	98	12	75
02	83	13	75
03	98	14	70
04	74	15	97
05	92	16	75
06	98	17	99
07	62	18	80
08	96	19	75
09	90	20	94
10	61	21	96
11	96	22	100

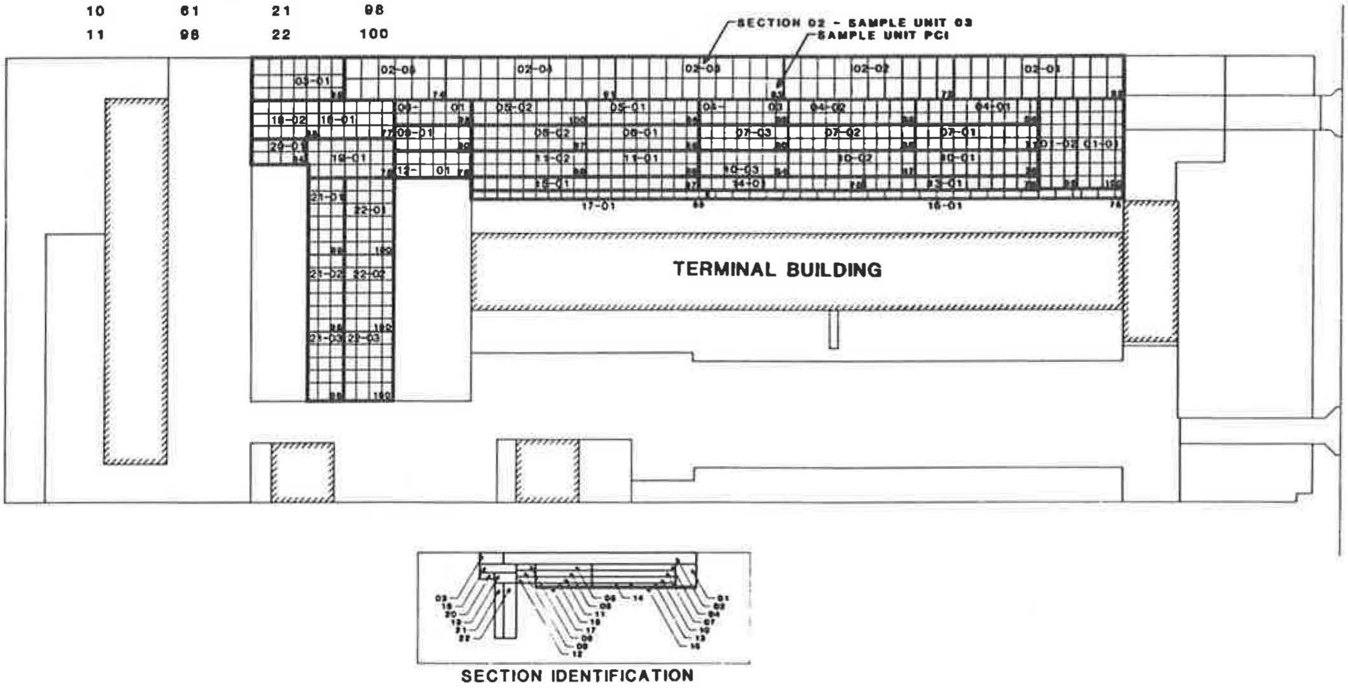


FIGURE 6 Section and sample unit PCI summary for truck terminal example.

Materials Characterization

Both the dynamic slab modulus and subgrade modulus values were varied to obtain a grid as shown in Figure 4. A grid was developed for both the 6-in. and 8-in. concrete sections. Measured values obtained with the FWD were used as entrance points on the grid to simultaneously determine the dynamic subgrade *k*-value and concrete modulus values. The average concrete modulus and *k*-values for each section are summarized in Table 1. The subgrade moduli values shown are dynamic moduli values that are approximately double the conventional static moduli values used in pavement design. The concrete moduli values are also dynamic moduli values that are approximately 1.4 times the conventional static moduli values.

The wide variance in back-calculated concrete moduli values suggests a significant slab thickness variation along the project in addition to varying strengths. The variation in concrete thicknesses and compressive strengths obtained from limited coring at the site support this. Results of test cores are given in Table 2. As the concrete thickness increases, the curves in Figure 4 will shift to the right along the subgrade *k*-value lines. Therefore, if the calculated slab modulus is 8 × 10^6 based on a grid system for a 6-in. thick slab, and the actual slab thickness is 7 in., the actual slab modulus would be reduced to 6 × 10^6,

TABLE 1 SUMMARY OF SLAB AND SUBGRADE MODULI VALUES

SECTION		Dynamic E_{pcc} $(x10^6)$	Dynamic k -value
1		7.83	373
2		8.76	224
3		6.80	223
4		8.42	347
5		7.73	219
6		8.87	290
7		7.36	282
8		9.50	400
9		7.30	337
10		7.12	288
11		7.85	405
12		8.00	350
13		9.25	305
14		7.50	285
15		8.00	377
16		6.37	217
17		7.70	330
18		6.36	306
19		7.80	333
20		8.40	340
	Average	7.85	311
	Standard Deviation	0.86	59
21*		6.65	278
22*		6.50	270
	Average	6.58	274
	Standard Deviation	0.11	6

* 8 inch slabs

TABLE 2 RESULTS OF TEST CORES

CORE NUMBER	PAVEMENT THICKNESS	UNCONFINED COMPRESSIVE STRENGTH	SLAB CONDITION
1	5.29 inches	6460 psi	Shrinkage Crack
2	7.38	6530	No Distress
3	5.96	4560	Failed
4	5.35	--	Linear Crack
5	5.97	4440	Failed
6	6.32	--	At Joint
7	6.44	7100	No Distress

--Could not be tested

for example, if the grid system with the proper thickness had been used. The variation in *k*-values due to the thickness effects was found not to be significant. No attempt was made to correct the concrete modulus values for the variation in concrete thickness due to the wide range of thicknesses obtained during coring. Extensive coring would be required to accurately define the concrete thickness throughout the site. Ideally the concrete modulus and subgrade *k*-values should be back-calculated using center slab deflection data from slabs where the exact concrete thickness is known because the grid shown in Figure 4 is a function of concrete slab thickness. Therefore, center slab deflections should be taken at all slabs selected for coring.

Load Transfer Across Joints

The average load transfer for each section tested ranged from 32 to 100 percent and is given in Table 3.

TABLE 3 AVERAGE LOAD TRANSFER ACROSS JOINTS

	PERCENT LOAD TRANSFER JOINT CONDITION		
SECTION	LONGITUDINAL	TRANSVERSE	CORNER
01	95	68	66
02	40	66	55
03	*	94	98
04	89	90	64
05	96	95	*
06	82	*	*
07	83	96	*
08	91	*	*
09	78	*	*
10	32	83	*
11	80	50	*
12	71	*	*
13	64	76	82
14	47	79	41
15	94	100	*
16	56	43	*
17	90	95	*
18	81	*	*
19	60	*	*
20	70	94	*
21	67	*	*
22	*	75	*

* Not Tested

Development of Design Equation

A design equation was developed based on the results of the PCI survey, deflection testing, and available traffic information. This information was used to develop a relationship between PCI, the stress ratio (concrete stress/modulus of rupture), and traffic for Sections 1 through 22. The procedure followed to develop this relationship is described in the following sections.

Concrete Modulus of Rupture

The concrete modulus of rupture (MR) for each of the 22 pavement sections was determined using the average dynamic concrete modulus of elasticity (*E*) from each section as determined from deflection testing and the empirical relationship (*5*): $MR = 200E^{0.736}$. The modulus of rupture calculated using this equation is the dynamic modulus of rupture. This value is approximately 1.4 times the static modulus of rupture as determined from flexural tests of concrete beams. The dynamic modulus of rupture for each section is given in Table 4. Ideally, concrete cores or beams would have been taken to determine the concrete modulus of rupture. However, because of project constraints, this was not possible.

Determination of Concrete Stresses

The concrete stress for an edge loading condition with an 18-kip axle load and existing load transfer efficiency was determined for Sections 1 through 22. The concrete slabs were assumed to be 6-in. for Sections 1 through 20, and 8 in. for Sections 21 and 22, although the limited test cores show that this thickness may vary appreciably. The concrete stresses for each section are given in Table 4.

Traffic Analysis

The number of past and future traffic movements were estimated based on information from a typical 99-hr count that provides the number and weight of trucks due to arrive at the terminal during the next 99 hr. The same number of trucks were assumed to be leaving the terminal during this time span. This information was extrapolated over a period of 1 year to arrive at a total number of trucks entering and leaving the terminal during the year. Truck weights were also obtained from a 99-hr traffic count and extrapolated over the period of 1 year. The number of trucks was then converted to a number of 18-kip equivalent single axle loads (ESALs). Equivalent single load applications were determined to be approximately 33,200 per year. This number, along with a traffic factor, was used to calculate the past 18-kip ESAL applications for each uniform section.

A traffic factor was assigned to various sections of the terminal based on the terminal operations and the traffic patterns observed during on-site visits. Areas that were observed to carry the greatest number of traffic repetitions were assigned a traffic factor of 100 percent, areas that carried one-half of the greatest number of repetitions were assigned a traffic factor of 50 percent, and so on. This traffic information is an estimate, as several factors, such as the degree of traffic channelization and the number of interfacility movements, could not be adequately addressed. Past traffic information is given in Table 5.

TABLE 4 SUMMARY OF MATERIAL PROPERTIES

SECTION	DYNAMIC MR (psi)	DYNAMIC SLAB MODULUS (X 10^6)	DYNAMIC K-VALUE (pci)	EDGE STRESS (psi)
01	910	7.8	375	365
02	988	8.8	225	449
03	820	6.8	225	280
04	960	8.4	350	378
05	901	7.7	220	286
06	997	8.9	290	338
07	869	7.4	280	327
08	1049	9.5	400	293
09	864	7.3	340	330
10	848	7.1	288	442
11	911	7.9	405	398
12	924	8.0	350	369
13	1028	9.3	305	382
14	881	7.5	285	423
15	924	8.0	380	266
16	781	6.4	220	416
17	898	7.7	330	310
18	781	6.4	310	336
19	907	7.8	335	380
20	958	8.4	340	367
21	807	6.7	280	303
22	793	6.5	270	289

Note: All stresses in psi

Model Development

A linear regression was performed to determine the coefficients $a1$ and $b1$ in the regression equation. A second linear regression was then performed using the measured PCI values from the condition survey and the calculated PCI values from the aforementioned equation in the section on the development of a design equation. Results of this first regression indicated that several sections (Sections 05, 07, 16, and 17) could not be modeled with the equation. This was attributed to inaccuracies in estimating the traffic factor. These sections were omitted and the regression analysis was repeated. The final equation to predict PCI at the terminal is $\text{PCI} = 100 - 10^{-2.373}[\text{traffic (stress ratio)}^{3.7285}]$. The measured PCI versus the PCI predicted from the regression is plotted in Figure 7.

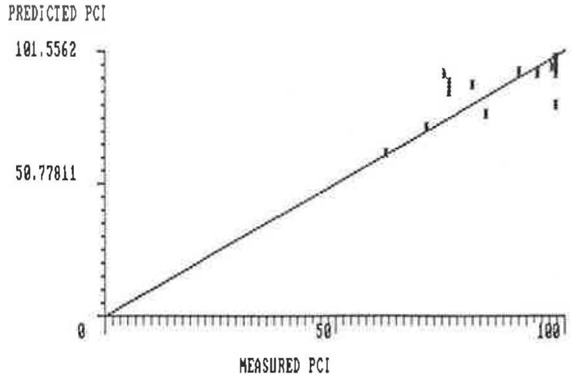


FIGURE 7 Relationship between measured PCI and predicted PCI.

The effect of the stress ratio and traffic on PCI is shown in Figure 8. This graph was plotted using the preceding equation. Increasing traffic or stress ratio will greatly reduce the predicted PCI.

TABLE 5 PAST TRAFFIC INFORMATION

SECTION	AGE (YEARS)	TRAFFIC FACTOR %	18-kip ESAL's
01	3	15	14,951
02	20	15	99,672
03	3	15	14,951
04	3	50	49,836
05	3	50	49,836
06	3	50	49,836
07	3	50	49,836
08	3	50	49,836
09	3	50	49,836
10	3	100	99,672
11	3	100	99,672
12	3	100	99,672
13	3	100	99,672
14	3	100	99,672
15	3	100	99,672
16	8	100	265,792
17	8	100	265,792
18	3	60	59,803
19	3	60	59,803
20	3	60	59,803
21	3	60	59,803
22	3	60	59,803

Thickness Design for a New Pavement

The west half of the terminal is currently asphalt concrete and was in need of pavement reconstruction. A concrete pavement thickness was determined for this area based on deflection testing and the PCI equation developed for the east half of the terminal.

Nondestructive deflection testing was used to evaluate the existing subgrade support conditions on the west half of the terminal. The design subgrade k-value was 225 pci.

The PCI equation was used to determine the required concrete thickness, for a range of terminal PCI values, after a 20-year period. The design inputs selected are as follows:

- Traffic: 35,000 ESALs/year with 20 years = 700,000 ESALs,
- Design modulus of rupture = 700 psi,
- Design concrete modulus of elasticity = 5.9×10^6 psi,

- Subgrade *k*-value = 225 pci, and
- Pavement thickness ranged from 6–12 in.

The concrete stresses for the edge loading condition were determined for each pavement thickness. A deflection load transfer of 40 percent was selected for an undowelled design, and deflection load transfer of 70 percent was selected for the dowelled pavement design. The concrete stresses are summarized in Table 6 and the stress ratio as a function of concrete thickness is shown in Figure 9. The concrete stresses, traffic, and design modulus of rupture were then used to determine the terminal PCI for each pavement thickness after 20 years. The terminal PCI after 20 years as a function of concrete thickness is shown in Figure 10 for both the dowelled and undowelled pavement sections. Figure 10 presents a performance-based design chart for the pavement conditions under consideration. For example, if a terminal PCI of 60 is desired after 20 years, a minimum concrete thickness of 8.5 in. dowelled or 9.5 in. undowelled will be required.

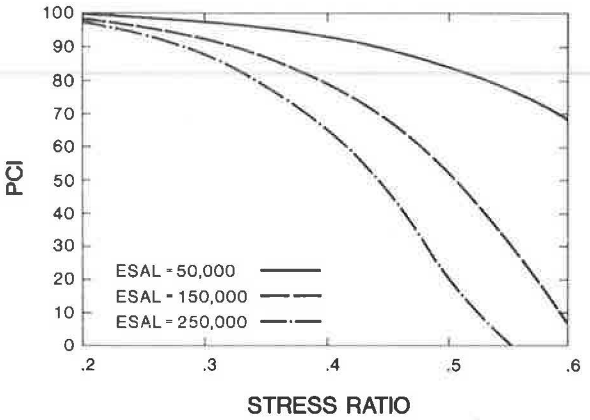


FIGURE 8 Effect of stress ratio and traffic on PCI.

TABLE 6 SUMMARY OF CONCRETE STRESSES FOR WEST HALF THICKNESS DESIGN

CONCRETE THICKNESS (in.)	EDGE STRESS NO DOWELS (psi)	EDGE STRESS WITH DOWELS (psi)
6	430	371
8	290	250
9	237	204
10	205	177
12	146	126

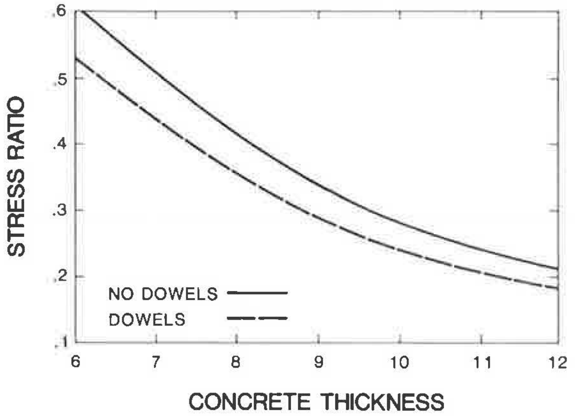


FIGURE 9 Stress ratio versus concrete thickness.

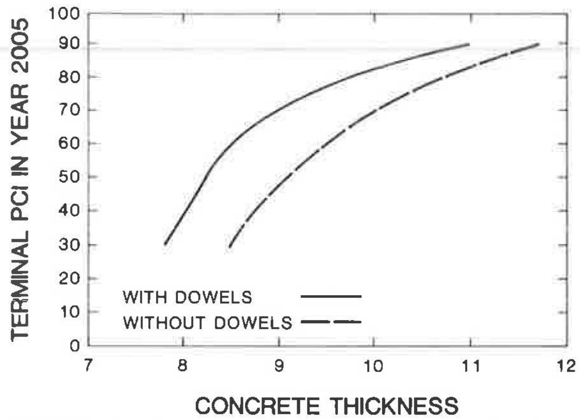


FIGURE 10 Terminal PCI after 20 years as a function of concrete thickness.

SUMMARY

Design equations can be developed based on local conditions to account for subgrade and material properties, traffic, and environment. Performance-based design equations based on local conditions provide the engineer with a tool to aid in the design of new pavements and the prediction of future performance of existing pavements. Equations developed using these procedures must be used within the range of variables from which they were developed. The models must not be used in some unusual situation caused by construction or materials problems that could invalidate the use of the design equation.

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