Analysis of Concrete Pavements Subjected to Early Loading

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Even before a newly placed concrete pavement has achieved its specified design strength, it is often subjected to loading from construction traffic and equipment. Concrete trucks, haul trucks, and joint-sawing equipment are among several of the different types of construction traffic to which a young pavement may be subjected. Engineers have long speculated whether this early loading of the young pavement by construction traffic causes any significant damage to the pavement. In a research study for the Federal Highway Administration, the effects of early loading of a young pavement by construction traffic at different locations were investigated. Accumulated fatigue damage inflicted by an 18-kip single axle was calculated for the edge, interior, and transverse joint loading conditions for a slab of various concrete strengths. The results indicated that slab edge loadings were the most critical and, depending on their magnitude and the strength of the concrete at the time of loading, could reduce the life of the pavement. The interior and transverse joint stresses were comparable in magnitude, but much less than those produced at the slab edge. Joint-sawing equipment was shown to have a negligible effect on the fatigue life of the slab.

Newly placed concrete pavements are often subjected to traffic loading shortly after they have hardened but long before they have attained their design strength. For example, construction traffic may use the young pavement as a working platform to facilitate subsequent construction activities. Lighter construction equipment, such as joint-sawing equipment, may also load the pavement at a very early age.

The early trafficking of young concrete pavements raises several questions regarding the potential reduction in the service life of the pavement caused by the early loading. Although some argue that the pavement should not be loaded until it has achieved its design strength, others contend that light loads or a small number of heavy load repetitions will not cause any appreciable damage. A methodology for evaluating the effect of early loading is presented here with a demonstration of its use in practical applications.

APPROACH TO EARLY LOADING EVALUATION

In order to determine the damage caused by early loading, a fatigue analysis of concrete pavements subjected to early loading was conducted. The fatigue analysis compares the actual number of early traffic load applications with the allowable number of load applications that the pavement may sustain before cracking. This latter value depends on the critical stresses produced in the slab by the construction traffic and the existing strength of the slab. The greater the strength of the slab, the larger the number of load applications that the slab may sustain before cracking.

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Determining Stresses and Compressive Strength

The maximum tensile stresses occurring at the bottom of the slab, which are the critical stresses that can produce fatigue cracking, were determined for typical construction traffic loadings using the ILLI-SLAB finite-element computer program (*1–3*). The program was recently evaluated using field-measured strain data for newly constructed pavements and provided reasonable results (*4*).

In a laboratory evaluation of early-age concrete properties, the following relationship was developed between the concrete elastic modulus and the concrete compressive strength (*4*):

$$E_c = 62{,}000 * (f'_c)^{0.5} \qquad (1)$$

where E_c is the elastic modulus of the concrete in pounds per square inch and f'_c is the compressive strength of the concrete in pounds per square inch. This relationship was based on laboratory concrete mixes ranging in age from 1 to 28 days and is believed to be more reflective of early-age concrete strength properties than the more familiar American Concrete Institute (ACI) relationship. However, Equation 1 is used here for demonstration purposes only. The actual relationship for a given project is a function of cement type, cement source, and aggregate type; each agency should therefore develop relationships representative of their materials and conditions. Equation 1 can be used to relate the compressive strength of a concrete slab at any time to the elastic modulus, which is needed by the ILLI-SLAB program to obtain an estimate of the load stresses developing in the slab.

Determining Modulus of Rupture

The modulus of rupture represents the strength of the concrete slab in flexure. As such, it is an important parameter in the estimate of fatigue damage. Since this test typically is not performed by most agencies, it is recommended that each agency develop a relationship between the compressive strength of the concrete and the modulus of rupture. A general relationship between these factors is given below (4):

$$MR = [8.460 \times (f_c')^{0.5}] + (3.311 \times RH) - 155.91 \quad (2)$$

where

MR = concrete modulus of rupture (psi),
f_c' = concrete compressive strength (psi), and
RH = relative humidity during curing (%).

This model was derived for a number of different materials with different aggregate and cement sources, different relative humidities, and different cement contents. Although Equation 2 will be used here for demonstration purposes, it is recommended that agencies develop their own unique relationships for each individual mix design.

Estimating Concrete Fatigue Damage

The amount of fatigue damage occurring in a slab subjected to early loading was estimated by employing a fatigue-consumption approach similar to the one first proposed by Miner (5). This approach theorizes that a concrete pavement has a finite fatigue life and can withstand some maximum number of load repetitions, N, of a given traffic loading before fracture. Every individual traffic loading applied, n, decreases the life of the pavement by an infinitesimal amount. Damage is defined as

$$\text{Damage} = \Sigma (n/N) * 100 \quad (3)$$

where

Damage = proportion of life consumed when mean inputs are used (50 percent of slabs cracked when damage is 100),
n = applied number of applied traffic loadings, and
N = allowable number of traffic loadings to slab cracking.

This value provides the percentage of life that is consumed by the applied traffic loads up to a given time. Theoretically, when $\Sigma (n/N) = 100$, fracture of the concrete would occur for a given slab; however, because of variability in edge traffic loadings and concrete strength from slab to slab, fracture of some slabs can occur at values both less than and greater than 1. Thus, because mean values are used for all inputs in the fatigue damage analysis, 50 percent of the slabs should be cracked when the calculated fatigue damage is 100.

The allowable number of traffic loadings when 50 percent of the slabs are cracked can be estimated from the following fatigue damage model (6):

$$\text{Log}_{10} N = 2.13 (1/SR)^{1.2} \quad (4)$$

where

N = allowable number of traffic loadings at 50 percent slab cracking,
SR = stress ratio = σ/MR,
σ = critical stress in slab due to given loading (psi), and
MR = 28-day cured concrete modulus of rupture (psi) (from beam breaks).

The fatigue model was developed from 60 full-scale test sections built by the Corps of Engineers (6). As such, it is believed to be a more realistic model than fatigue models developed from laboratory beam testing since the field-developed model represents supported slab conditions, whereas laboratory beams do not. Furthermore, whereas in theory a crack can occur from one loading if the stress ratio is greater than or equal to 1, the fully supported slab in the field can sustain many more loadings before the crack progresses to the surface.

EARLY CONSTRUCTION TRAFFIC LOADING

An 18,000-lb single axle with dual tires was selected as a typical load for the evaluation of fatigue damage from early construction traffic loading. Tandem-axle loads were not considered, but generally the stresses produced by a tandem axle, which has twice the load of a single axle, are less than those for single axles. Furthermore, only one contact pressure (100 psi) was evaluated.

Five elastic modulus values (1 million to 5 million psi) were investigated, corresponding to a range in compressive strength of the concrete. Although the higher elastic modulus levels (4 million and 5 million psi) are not representative of early loading conditions, they were included to illustrate the effect of load-induced stresses on mature pavements.

Three loading conditions (edge, interior, and transverse joint) were evaluated. The critical stresses for each of these loading conditions were determined using the ILLI-SLAB program for a range of slab thicknesses, elastic modulus values, and effective k-values. The input variables used in the ILLI-SLAB evaluation of pavements subjected to early loading are given in Table 1.

Edge Loading Condition

The edge loading condition consists of the load placed at the slab edge midway between the transverse joints. This represents the most critical loading position because the largest stresses for a free edge develop at this location. On the basis of the relationship presented earlier between the concrete elastic modulus and concrete compressive strength, the critical edge stresses computed from ILLI-SLAB were related directly to the compressive strength. For example, with the previous relationship between elastic modulus and compressive strength (Equation 1), the compressive strength corresponding to a concrete elastic modulus of 2 million psi would be

$$f_c' = (2{,}000{,}000/62{,}000)^2 = 1{,}040 \text{ psi}$$

If the modulus of rupture corresponding to a given compressive strength could be estimated, the stress ratio (stress/modulus of rupture) would be known and an estimate of the fatigue damage done to the pavement by the given construction loading could be obtained. For purposes of illustration, the general relationship between modulus of rupture and com-

TABLE 1 Summary of Input Variables Used in ILLI-SLAB Evaluation of Early Construction Traffic Loading

PAVEMENT TYPE	JPCP
PCC SURFACE PROPERTIES	
Slab Thickness	8 in
	10 in
	12 in
Poisson's Ratio	0.15
Modulus of Elasticity	1,000,000 psi
	2,000,000 psi
	3,000,000 psi
	4,000,000 psi
	5,000,000 psi
SUBGRADE PROPERTIES	
Subgrade Model	Winkler
Subgrade *k*-value	100 psi/in
	300 psi/in
	500 psi/in
JOINT DATA	
Joint Spacing	15 ft
Lane Width	12 ft
Joint Width	0.125 in
Transverse Joint	
Doweled Joint	
Dowel Diameter	1.25 in
Dowel Spacing	12 in
Modulus of Dowel Support	1,500,000 psi/in
Dowel Modulus of Elasticity	29,000,000 psi
Dowel Poisson's Ratio	0.30
Dowel Concrete Interaction (Using Friberg's Analysis)	1,490,000 lb/in
Nondoweled Joint	
Aggregate Interlock Factor	0 (free edge)
WHEEL LOADING	
Type of Axle	Single, dual wheel
Gross Weight of Axle	18,000 lb
Tire Imprint	45 in^2
Contact Pressure	100 psi
TEMPERATURE GRADIENT	
Not considered	

pressive strength given in Equation 2 will be used, assuming 80 percent relative humidity.

The resulting modulus of rupture estimate was then used in the fatigue model to obtain the mean allowable number of load applications before slab fracture. For example, for a slab with a compressive strength of 1,000 psi and a curing relative humidity of 80 percent, the modulus of rupture would be

$$MR = [8.460 \times (1000)^{0.5}] + (3.311 \times 80) - 155.91 = 376 \text{ psi}$$

Using this modulus of rupture estimate and the 195-psi critical stress value previously obtained, the resulting allowable number of edge load applications is

$$N = 10^{2.13 \cdot (376/195)^{1.2}} = 48{,}242 \text{ applications}$$

This indicates that when the concrete attains a compressive strength of 1,000 psi, the pavement can sustain 48,242 edge load applications by an 18-kip single-axle load before 50 percent of the slabs are cracked. To calculate the damage done by 100 loads along the unsupported edge, the applied number of load applications (n) is divided by N, so that the percent life consumed is

$$\text{Damage} = (100/48{,}242) \times 100 = 0.21 \text{ percent}$$

This value indicates that the amount of damage from 100 applications of an 18,000-lb single axle with a tire pressure of 100 psi along an unsupported edge would reduce the pavement life by 0.21 percent at that point in time when the concrete possesses a compressive strength of 1,000 psi. The damage done by the same 100 loads for pavements with a compressive strength of 1,500 and 2,000 psi would be 0.05 and 0.014 percent, respectively.

Table 2 provides a summary of the edge load fatigue damage calculations for each combination of slab thickness (t), k-value, and elastic modulus value (E). Table 2 also shows the corresponding compressive strength (f'_c) and modulus of rupture (MR) values, the critical stress in the slab (σ), and the allowable number of load applications (N).

Selected fatigue damage results from Table 2 are plotted in Figures 1 through 3 for 8-, 10-, and 12-in. slabs with a k-value of 300 psi/in. Other cases in which significant fatigue damage occurred could also have been plotted. These charts allow for the immediate determination of the fatigue damage

TABLE 2 Summary of Fatigue Damage Determination for Edge Loading Condition

Pavement Characteristics				Calculated Values			Percent Fatigue Damage Consumed at Different Levels of Early Loading				
t (in)	k (psi/in)	E_c (psi)	f'_c (psi)	MR (psi)	σ (psi)	N_{all} (No. of loads)	1	10	100	1000	10000
8	100	1000000	260	245	290	5.54e+01	2	18	181	1806	18055
8	100	2000000	1041	382	333	3.24e+02	0	3	31	309	3087
8	100	3000000	2341	518	351	2.51e+03	0	0	4	40	398
8	100	4000000	4162	655	364	2.04e+04	0	0	0	5	49
8	100	5000000	6504	791	373	1.78e+05	0	0	0	1	6
8	300	1000000	260	245	243	1.43e+02	1	7	70	699	6990
8	300	2000000	1041	382	285	1.06e+03	0	1	9	94	942
8	300	3000000	2341	518	302	1.18e+04	0	0	1	8	85
8	300	4000000	4162	655	315	1.33e+05	0	0	0	1	7
8	300	5000000	6504	791	325	1.57e+06	0	0	0	0	1
8	500	1000000	260	245	222	2.53e+02	0	4	40	396	3959
8	500	2000000	1041	382	263	2.15e+03	0	0	5	47	465
8	500	3000000	2341	518	280	2.88e+04	0	0	0	3	35
8	500	4000000	4162	655	293	3.89e+05	0	0	0	0	3
8	500	5000000	6504	791	302	5.83e+06	0	0	0	0	0
10	100	1000000	260	245	206	4.25e+02	0	2	24	235	2355
10	100	2000000	1041	382	232	7.47e+03	0	0	1	13	134
10	100	3000000	2341	518	243	1.93e+05	0	0	0	1	5
10	100	4000000	4162	655	249	6.25e+06	0	0	0	0	0
10	100	5000000	6504	791	254	2.13e+08	0	0	0	0	0
10	300	1000000	260	245	174	1.65e+03	0	1	6	61	605
10	300	2000000	1041	382	201	3.99e+04	0	0	0	3	25
10	300	3000000	2341	518	213	1.56e+06	0	0	0	0	1
10	300	4000000	4162	655	221	6.95e+07	0	0	0	0	0
10	300	5000000	6504	791	227	3.39e+09	0	0	0	0	0
10	500	1000000	260	245	160	3.62e+03	0	0	3	28	276
10	500	2000000	1041	382	187	1.04e+05	0	0	0	1	10
10	500	3000000	2341	518	198	5.75e+06	0	0	0	0	0
10	500	4000000	4162	655	206	3.40e+08	0	0	0	0	0
10	500	5000000	6504	791	213	1.94e+10	0	0	0	0	0
12	100	1000000	260	245	156	4.66e+03	0	0	2	21	214
12	100	2000000	1041	382	171	3.85e+05	0	0	0	0	3
12	100	3000000	2341	518	177	5.40e+07	0	0	0	0	0
12	100	4000000	4162	655	181	9.23e+09	0	0	0	0	0
12	100	5000000	6504	791	183	2.20e+12	0	0	0	0	0
12	300	1000000	260	245	131	3.34e+04	0	0	0	3	30
12	300	2000000	1041	382	150	3.44e+06	0	0	0	0	0
12	300	3000000	2341	518	158	7.27e+08	0	0	0	0	0
12	300	4000000	4162	655	164	1.65e+11	0	0	0	0	0
12	300	5000000	6504	791	168	4.75e+13	0	0	0	0	0
12	500	1000000	260	245	122	8.47e+04	0	0	0	1	12
12	500	2000000	1041	382	140	1.26e+07	0	0	0	0	0
12	500	3000000	2341	518	148	3.85e+09	0	0	0	0	0
12	500	4000000	4162	655	154	1.25e+12	0	0	0	0	0
12	500	5000000	6504	791	158	5.27e+14	0	0	0	0	0

done by the standard truck loading (18,000-lb single axle, 100-psi contact pressure) on a pavement of known compressive strength. For simplification in graphing, the compressive strength values have been rounded off to the nearest 50 psi.

It is observed from Figure 1, which is for an 8-in. slab with a *k*-value of 300 psi/in., that 100 load applications of the standard truck loading will consume 70 percent of the concrete fatigue life if the slab is loaded when it has a compressive strength of only 250 psi. However, if the pavement is not loaded until the concrete has attained a compressive strength of 2,350 psi, then 100 load applications of the standard loading will reduce the fatigue life by only about 1 percent.

Interior Loading Condition

The interior loading condition calls for the wheels to be situated at some distance from the edge. The interior load was placed 2 ft from the edge to represent the case in which an 8-ft-wide truck would center itself in a 12-ft-wide lane. The

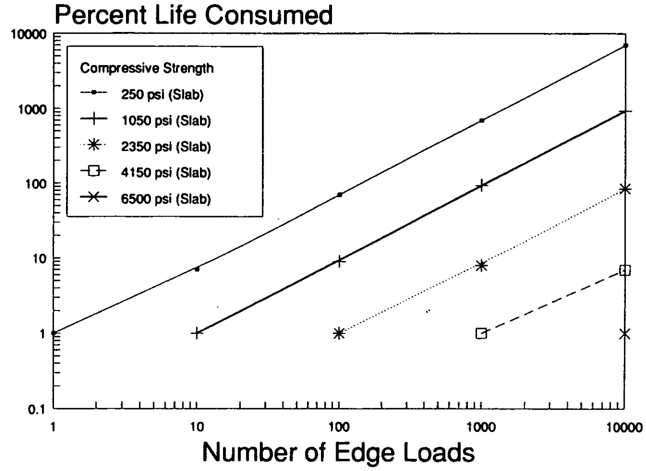

FIGURE 1 Percent life consumed versus number of 18-kip single-axle edge load applications for an 8-in. slab (k = 300 psi/in.)

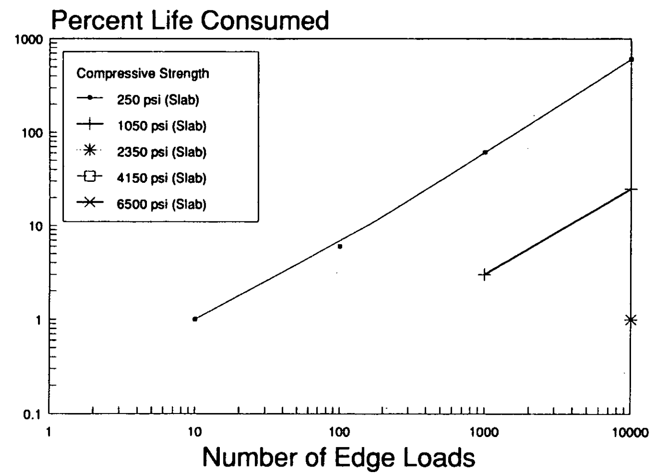

FIGURE 2 Percent life consumed versus number of 18-kip single-axle edge load applications for a 10-in. slab (k = 300 psi/in.).

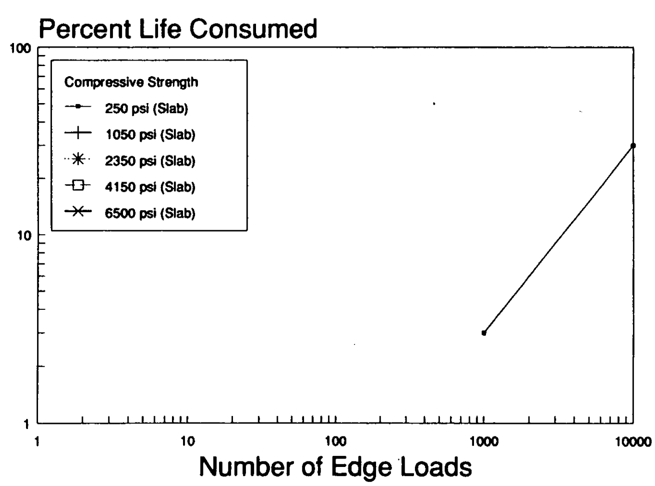

FIGURE 3 Percent life consumed versus number of 18-kip single-axle edge load applications for a 12-in. slab (k = 300 psi/in.).

ILLI-SLAB program again was used to determine the stresses occurring in the slab for the 18,000-lb single-axle load with a contact pressure of 100 psi.

The maximum stress in the slab was calculated as a function of the compressive strength of the concrete following the same procedure as that used in the edge loading analysis. Then, again for purposes of illustration, the modulus of rupture was estimated from the general relationship with compressive strength. These results were then evaluated using the fatigue damage model to obtain an estimate of the slab fatigue damage for a range of slab thicknesses and load applications. Table 3 summarizes the results of the fatigue damage evaluation for the interior loading condition.

An examination of Table 3 shows that the interior loading condition produces much less damage than the edge loading condition and indicates that if the trucks that load a pavement at an early age stay away from the edge (in this case, 2 ft from the edge), little damage may result. Charts could have been developed to illustrate the percent life consumed as a function of the number of load applications, but this was not done since the amount of fatigue damage was so small.

In the example cited for the edge loading condition, it was noted that 100 applications of the 18,000-lb single axle consumed 70 percent of the life of an 8-in. slab that had a k-value of 300 psi/in. and a compressive strength of 250 psi. However, if on that same pavement those 100 applications stay 2 ft away from the slab edge, Table 3 indicates that virtually no fatigue damage occurs.

Transverse Joint Loading Condition

The transverse joint loading condition was evaluated with the ILLI-SLAB program for a few selected cases. A 10-in. slab (with and without dowel bars) was evaluated for a k-value of 300 psi/in. and portland cement concrete (PCC) elastic modulus values of 2 million and 4 million psi. The tranverse joint was loaded with an 18,000-lb single-axle load 6 ft from the edge.

Doweled Transverse Joint

ILLI-SLAB was used to calculate the stresses occurring for the doweled transverse joint loading condition. The doweled transverse joint was analyzed assuming no aggregate interlock at the joint; that is, load transfer was provided only by the dowel bars. This provides a conservative estimate of the actual stresses because a portion of the load will be transferred through aggregate interlock. Typical stress load transfer efficiencies (LTE) for the doweled joints ranged between 46 and 58 percent.

Nondoweled Transverse Joint

ILLI-SLAB was also used to calculate stresses for the nondoweled transverse joint loading condition. The analysis was conducted assuming a "free edge" and then the various stresses

TABLE 3 Summary of Fatigue Damage Determination for Interior Loading Condition

Pavement Characteristics				Calculated Values			Percent Fatigue Damage Consumed at Different Levels of Early Loading				
t (in)	k (psi/in)	E_c (psi)	f'_c (psi)	MR (psi)	σ (psi)	N_{all} (No. of loads)	1	10	100	1000	10000
8	100	1000000	260	245	165	2.69e+03	0	0	4	37	372
8	100	2000000	1041	382	185	1.21e+05	0	0	0	1	8
8	100	3000000	2341	518	197	6.32e+06	0	0	0	0	0
8	100	4000000	4162	655	205	3.82e+08	0	0	0	0	0
8	100	5000000	6504	791	212	2.21e+10	0	0	0	0	0
8	300	1000000	260	245	139	1.64e+04	0	0	1	6	61
8	300	2000000	1041	382	155	1.93e+06	0	0	0	0	1
8	300	3000000	2341	518	165	2.58e+08	0	0	0	0	0
8	300	4000000	4162	655	173	3.32e+10	0	0	0	0	0
8	300	5000000	6504	791	179	4.72e+12	0	0	0	0	0
8	500	1000000	260	245	129	4.06e+04	0	0	0	2	25
8	500	2000000	1041	382	143	8.37e+06	0	0	0	0	0
8	500	3000000	2341	518	153	1.62e+09	0	0	0	0	0
8	500	4000000	4162	655	160	3.58e+11	0	0	0	0	0
8	500	5000000	6504	791	165	9.45e+13	0	0	0	0	0
10	100	1000000	260	245	118	1.35e+05	0	0	0	1	7
10	100	2000000	1041	382	131	4.90e+07	0	0	0	0	0
10	100	3000000	2341	518	139	2.16e+10	0	0	0	0	0
10	100	4000000	4162	655	144	1.29e+13	0	0	0	0	0
10	100	5000000	6504	791	147	1.13e+16	0	0	0	0	0
10	300	1000000	260	245	99	2.15e+06	0	0	0	0	0
10	300	2000000	1041	382	110	3.05e+09	0	0	0	0	0
10	300	3000000	2341	518	118	3.79e+12	0	0	0	0	0
10	300	4000000	4162	655	123	6.95e+15	0	0	0	0	0
10	300	5000000	6504	791	128	8.98e+18	0	0	0	0	0
10	500	1000000	260	245	91	1.01e+07	0	0	0	0	0
10	500	2000000	1041	382	102	2.42e+10	0	0	0	0	0
10	500	3000000	2341	518	108	9.75e+13	0	0	0	0	0
10	500	4000000	4162	655	114	2.26e+17	0	0	0	0	0
10	500	5000000	6504	791	118	7.89e+20	0	0	0	0	0
12	100	1000000	260	245	89	1.57e+07	0	0	0	0	0
12	100	2000000	1041	382	98	7.85e+10	0	0	0	0	0
12	100	3000000	2341	518	103	6.43e+14	0	0	0	0	0
12	100	4000000	4162	655	106	8.66e+18	0	0	0	0	0
12	100	5000000	6504	791	107	3.17e+23	0	0	0	0	0
12	300	1000000	260	245	75	6.84e+08	0	0	0	0	0
12	300	2000000	1041	382	84	1.28e+13	0	0	0	0	0
12	300	3000000	2341	518	89	4.42e+17	0	0	0	0	0
12	300	4000000	4162	655	93	1.44e+22	0	0	0	0	0
12	300	5000000	6504	791	96	5.86e+26	0	0	0	0	0
12	500	1000000	260	245	69	5.82e+09	0	0	0	0	0
12	500	2000000	1041	382	77	3.56e+14	0	0	0	0	0
12	500	3000000	2341	518	82	2.94e+19	0	0	0	0	0
12	500	4000000	4162	655	86	2.18e+24	0	0	0	0	0
12	500	5000000	6504	791	89	2.06e+29	0	0	0	0	0

corresponding to selected load transfer efficiencies were determined using the following relationship:

$$\sigma = \sigma_{fe} / (1 + LTE) \tag{5}$$

where

σ = calculated edge stress for a given LTE (psi),
σ_{fe} = maximum free edge stress (zero LTE) (psi), and
LTE = stress load transfer efficiency across transverse joint.

Comparison of Interior and Transverse Joint Stresses

The stresses for the doweled and nondoweled joints (assuming 50 percent LTE) are plotted in Figure 4 along with the corresponding interior stresses. Generally speaking, there is little difference in the magnitude of the stresses, indicating that the stresses occurring at the transverse joints are comparable with the stresses occurring in the interior portions of the slab. It is interesting to note that as the elastic modulus increases,

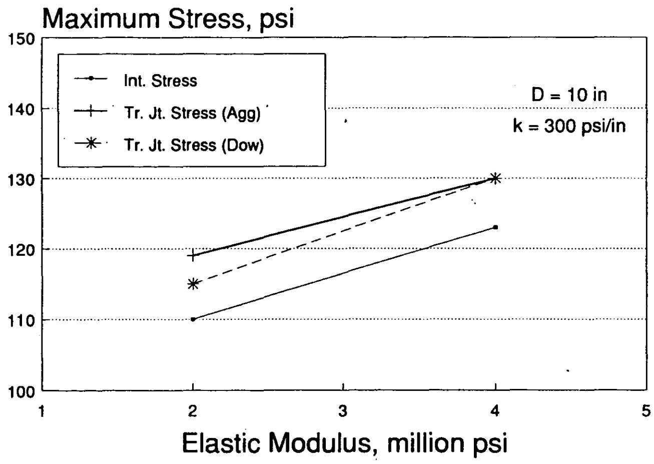

FIGURE 4 Comparison of interior and transverse joint stresses for a 10-in. slab (k = 300 psi/in.).

the doweled transverse joint stress approaches that of the nondoweled transverse joint stress.

The nondoweled transverse joint stresses were generally higher than those for the doweled joint or the interior loading condition. Again, however, the nondoweled transverse joint stresses were not substantially different from those for the interior loading condition.

For the purposes of this comparison, 50 percent stress load transfer was assumed for the nondoweled transverse joint. In actuality, this value may be much higher because of the high level of aggregate interlock that exists immediately after construction. As calculated from Equation 5, an increase in stress load transfer efficiency to even 75 percent greatly reduces the magnitude of the stress. The same type of argument can be made for the stresses developing in the doweled joint, because these neglected aggregate interlock load transfer and the actual stresses would probably be less.

DOWEL BEARING STRESSES

The maximum bearing stresses exerted by the dowels on the concrete are a critical aspect in the design of doweled concrete pavements. It has been shown that the magnitude of the bearing stresses has a great effect on the development of transverse joint faulting (*7*). If the bearing stresses due to early loading exceed the compressive strength of the concrete, fracture or crushing of the concrete around the dowel bar could occur.

The modified Friberg analysis was used to calculate the maximum bearing stresses (*7–9*). The maximum bearing stress is given by the following formula:

$$\sigma_{max} = K * \delta_0 \qquad (6)$$

where

K = modulus of dowel support (psi/in.),
δ_0 = deflection of the dowel at the face of the joint (in.),
= $P_t\,(2 + \beta z)\;/\;4\beta^3 E_s I$, in which
P_t = shear force acting on dowel (lb),
z = width of joint opening (in.),
E_s = modulus of elasticity of dowel bar (psi),
I = moment of inertia of dowel bar cross section (in.^{4}),
= $0.25 * \pi * (d/2)^4$ for dowel diameter d in inches, and
β = relative stiffness of the dowel concrete system (l/in.)
= $[(Kd)/(4E_sI)]^{0.25}$.

The analysis assumes a 9,000-lb wheel load placed at the corner, which will produce the maximum stress in the outermost dowel bar. Only dowel bars within a distance of 1.0 * l from the center of the load are considered to be active, where l is the radius of relative stiffness, defined as

$$l = [Eh^3/12k(1 - \mu^2)]^{0.25} \qquad (7)$$

where

E = concrete modulus of elasticity (psi),
h = slab thickness (in.),
k = effective modulus of subgrade reaction (psi/in.), and
μ = Poisson's ratio.

Finally, the modified Friberg analysis is based on the assumption that 45 percent of the *load* (not the stress) was transferred across the joint, which has been shown to provide conservative results (*7*).

The modulus of dowel support, K, has been suggested to range from 300,000 to 1,500,000 psi/in., with a value of 1,500,000 psi/in. typically assumed in design. However, this value is probably less than that when the concrete is newly placed and its compressive strength is low. One recent study showed that the modulus of dowel support increased with increasing compressive strength (*10*). Since K is a measure of the support provided to the dowel bar by the slab, it is intuitive that this support value will increase with increasing compressive strength. It would follow, then, that the parameter also increases with increasing concrete elastic modulus and that different K-values corresponding to increases in the concrete elastic modulus should be used in the evaluation of early-age bearing stresses.

Unfortunately, very little research has been done on the relation between the modulus of dowel support and PCC compressive strength or elastic modulus. Limited data from Tayabji and Colley (*10*) indicated that K increased with increasing compressive strength, and these data were used to develop some very crude approximations of the modulus of dowel support at various compressive strengths. Since only 28-day compressive strengths were measured in that study, strengths at earlier times were obtained using the concrete strength development model provided by Davis and Darter (*11*). The average modulus of dowel support values shown below were estimated for the corresponding elastic modulus values evaluated in this study.

PCC Elastic Modulus (psi)	*PCC Compressive Strength (psi)*	*Modulus of Dowel Support (psi/in.)*
1,000,000	260	375,000
2,000,000	1,041	650,000
3,000,000	2,341	1,000,000
4,000,000	4,162	1,750,000
5,000,000	6,504	2,500,000

It must be reiterated that the values shown above are based on very limited data, particularly in the area of early concrete strengths. Additional research is definitely needed to quantify this relationship more accurately.

Assuming the modulus of dowel support values given above, dowel bearing stresses were computed using ILLI-SLAB. Dowel bar diameters were assumed to be one-eighth of the slab thickness. The resulting bearing stresses are plotted in Figures 5 through 7 for a range of design factors. The diagonal line shown in Figures 5 through 7 represents the line of equality between the bearing stress and the compressive strength; those bearing stresses that fall to the left of the line are unacceptable (i.e., bearing stress exceeds compressive strength) and those that fall to the right of the line are acceptable (i.e., compressive strength exceeds bearing stress).

It is observed from Figures 5 through 7 that the bearing stresses decrease with increasing slab thickness (and dowel bar diameter, since larger dowels were assumed for thicker slabs). Because of this, thinner slabs are much more susceptible to bearing stress fracture from early loading than the thicker slabs.

Another observation from Figures 5 through 7 is that the bearing stress increases with an increase in the foundation support. However, the impact of the foundation support on the dowel bearing stresses is not as substantial for thicker slabs with larger dowel bars.

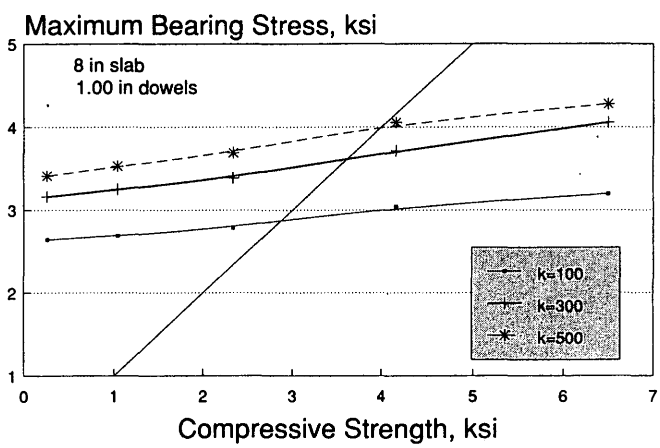

FIGURE 5 Maximum bearing stress versus compressive strength for 8-in. slab.

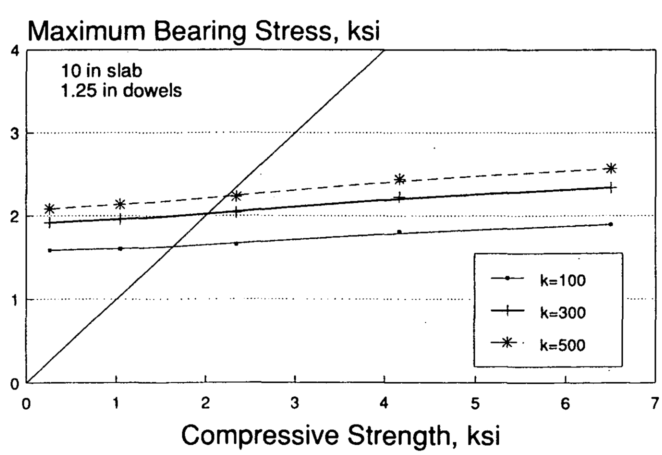

FIGURE 6 Maximum bearing stress versus compressive strength for 10-in. slab.

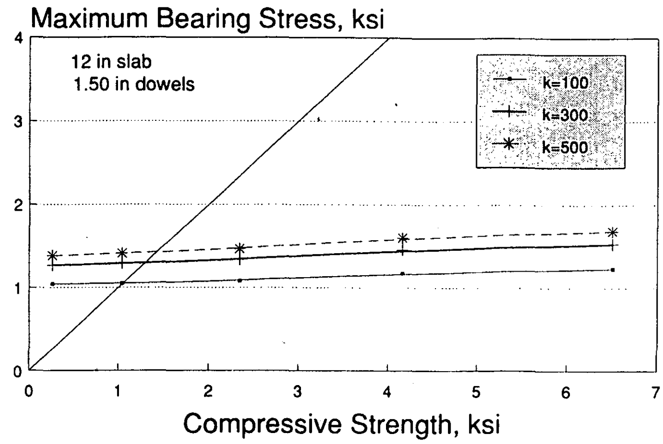

FIGURE 7 Maximum bearing stress versus compressive strength for 12-in. slab.

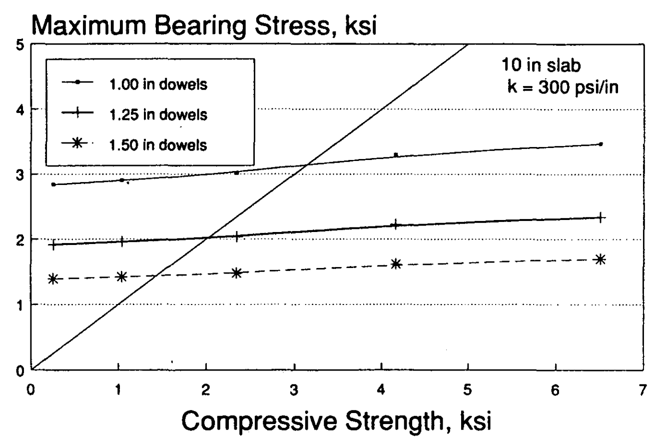

FIGURE 8 Maximum bearing stress versus compressive strength for 10-in. slab with varying dowel diameters.

It has been mentioned that dowel diameters are an important factor influencing the magnitude of the bearing stresses. To illustrate this, maximum bearing stresses were determined using ILLI-SLAB for a 10-in. slab with 1-, 1.25-, and 1.5-in. dowel diameters and assuming a foundation support of 300 psi/in. These bearing stresses are plotted in Figure 8. As would be expected, the larger-diameter dowel resulted in lower bearing stresses, with a particularly big reduction in bearing stresses obtained by moving from a 1-in. to a 1.25-in. dowel.

LOADING BY SAWING EQUIPMENT

Other than construction truck traffic, the spansaw, a piece of heavy equipment used to cut the transverse joint in the slab, could load a pavement at an early age. Hence, the fatigue damage done by the spansaw was also evaluated by placing it in the interior portions of the slab. The inputs for the ILLI-SLAB evaluation are given in Table 4.

TABLE 4 Summary of Input Variables Used in ILLI-SLAB Evaluation of Spansaw Interior Loading

PAVEMENT TYPE	JPCP
PCC SURFACE PROPERTIES	
Slab Thickness	8 in
	10 in
	12 in
Poisson's Ratio	0.15
Modulus of Elasticity	1,000,000 psi
	2,000,000 psi
	3,000,000 psi
	4,000,000 psi
	5,000,000 psi
SUBGRADE PROPERTIES	
Subgrade Model	Winkler
Subgrade *k*-value	100 psi/in
	300 psi/in
	500 psi/in
JOINT DATA	
Joint Spacing	20 ft
Lane Width	24 ft
WHEEL LOADING	
Gross Weight of Spansaw	14,500 lb
Number of Tires	4
Tire Imprint	48 in^2
Contact Pressure	75.5 psi
TEMPERATURE GRADIENT	
Not considered	

The spansaw configuration and input variables were analyzing using ILLI-SLAB. A fatigue damage analysis was conducted using the same relationships and procedures previously described. The results of that analysis indicated that no fatigue damage occurs for any combination, even up to a maximum of 10,000 load applications of the spansaw. Thus, it is believed that none of the lighter construction equipment causes any damage on the pavement after a minimum compressive strength of 250 psi (corresponding to an elastic modulus of 1,000,000 psi) has been obtained.

SUMMARY

A methodology has been presented that allows for the estimation of concrete fatigue damage due to early loading. The fatigue damage sustained by a slab of known compressive strength from a certain number of early load applications can be estimated or, conversely, the minimum compressive strength required to minimize the fatigue damage caused by those early load applications can be determined. The early loading analysis was conducted using relationships between compressive strength, flexural strength, and modulus of elasticity.

The longitudinal edge loading condition, in which the load is placed in the midpoint of the slab at the edge, was determined to be the most critical. The stresses that develop in the slab at this location are much larger than those that develop at the slab interior or at the transverse joint for the same loading. This indicates that a slab can be subjected to early loading with very little fatigue damage if the loads are located away from the longitudinal slab edge.

An evaluation of the transverse joint loading condition showed that the maximum slab stresses for both the nondoweled and doweled joints were compatible with the stresses developing for the interior loading condition, and both conditions yielded virtually no fatigue damage. If higher levels of aggregate interlock were assumed (which is not unrealistic for a newly placed concrete pavement), the critical transverse joint stresses would be even less than the interior stresses.

An evaluation of dowel bearing stresses at early ages indicated that thinner slabs, which typically use smaller-diameter dowel bars, may be more susceptible to early loading damage than thicker slabs. Indeed, larger-diameter dowels were observed to be very effective in reducing bearing stresses. All of the work evaluating bearing stresses was based on modulus of dowel support values that were assumed to change with compressive strength. Rough approximations of the modulus of dowel support value were made, but much more research on this topic is needed.

A fatigue damage analysis was also conducted for the use of spansaws. The evaluation indicated that this equipment causes no fatigue damage to a slab (for a minimum compressive strength of 250 psi).

If early loading of a concrete slab becomes desirable or necessary, it is important to identify the maximum amount of fatigue damage that the slab should sustain from early loading without sacrificing its design life. That maximum amount of early loading damage is ultimately up to the highway agency, but it is critical that the agency consider the design traffic and the performance period of the pavement.

As an illustration, consider a pavement that was designed for 10 million 18-kip equivalent single-axle load (ESAL) applications over a 20-year period. Of those 10 million ESAL applications, assume that about 6 percent (0.6 million) of these would be edge loads. If early edge loading consumed 10 percent of the fatigue damage, this would mean that about 60,000 edge load applications were consumed. This translates to a reduction in life of roughly 2 years, assuming a linear distribution of traffic loading over the 20-year period. For this particular example, with the unknowns in actual traffic loadings and the historic inaccuracies of past traffic projections, the loss of 2 years of service life is probably unacceptable. Thus, the design traffic and the performance period must be evaluated for each design in order to evaluate what may be an acceptable level of fatigue damage from early loading.

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REFERENCES

1. A. M. Tabatabaie and E. J. Barenberg. Structural Analysis of Concrete Pavement Systems. *Transportation Engineering Journal*, ASCE, Vol. 106, No. TE5, Sept. 1980.
2. A. M. Ioannides. Analysis of Slabs-on-Grade for a Variety of Loading and Support Conditions. Ph.D. dissertation. University of Illinois, Urbana-Champaign, 1984.
3. G. T. Korovesis. Analysis of Slab-on-Grade Pavement Systems Subjected to Wheel and Temperature Loading. Ph.D. dissertation. University of Illinois, Urbana-Champaign, 1990.
4. P. A. Okamoto, P. J. Nussbaum, K. D. Smith, M. I. Darter, T. P. Wilson, C. L. Wu, and S. D. Tayabji. *Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements*, Volume I—*Final Report*. Report FHWA-RD-91-079. FHWA, U.S. Department of Transportation, Oct. 1991.
5. M. A. Miner. Cumulative Damage in Fatigue. *Transactions, American Society of Mechanical Engineers*, Vol. 67, 1945.
6. M. I. Darter. *A Comparison Between Corps of Engineers and ERES Consultants, Inc. Rigid Pavement Design Procedures*. Technical Report. U.S. Air Force SAC Command, Aug. 1988.
7. K. W. Heinrichs, M. J. Liu, M. I. Darter, S. H. Carpenter, and A. M. Ioannides. *Rigid Pavement Analysis and Design*. Report FHWA-RD-88-068. FHWA, U.S. Department of Transportation, June 1989.
8. B. F. Friberg. Design of Dowels in Transverse Joints of Concrete Pavements. *Transactions of the American Society of Civil Engineers*, Vol. 105, 1940.
9. A. M. Ioannides, Y.-H. Lee, and M. I. Darter. Control of Faulting Through Joint Load Transfer Design. In *Transportation Research Record 1286*, TRB, National Research Council, Washington, D.C., 1990.
10. S. D. Tayabji and B. E. Colley. *Improved Rigid Pavement Joints*. Report FHWA/RD-86/040. FHWA, U.S. Department of Transportation, Feb. 1986.
11. D. D. Davis and M. I. Darter. Early Opening of PCC Full-Depth Repairs. Presented at the 63rd Annual Meeting of the Transportation Research Board, 1984.