Estimating Load Transfer From Measured Joint Efficiency in Concrete Pavements

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Relationships between joint efficiency and load transfer for jointed plain concrete pavements have been established using the finite-element method ILLISLAB program. Efforts were made to show that the relationship depends not only on a/l but also on L/l, where L is the size of the square concrete slabs, a is the radius of the single-wheel load, and l is the radius of relative stiffness of the concrete slab. It is proposed that the relationship between joint efficiency and load transfer be developed based on L/l values. Four sets of curves were developed using L/l and for each set, the curves were separated for different ratios of a/l. The procedure of equivalent single-wheel radius for multiple-wheel gear loads is discussed and recommended.

The load transfer of jointed plain concrete pavements has been estimated on the basis of measured deflections across the joints (joint efficiency) using falling weight deflectometer (FWD) tests. The procedure is expedient and reliable. Review of the procedure indicated that the methodology can be improved, and this paper documents the proposed improvement.

Finite-element methods have been used to estimate load transfer from measured deflections of FWD tests. The results of an analysis conducted using the finite-element program WESLIQID in which a range of thicknesses, moduli of subgrade reaction, and joint stiffness parameters on 6.1-m (20-ft) square slabs were used to determine joint efficiency and load transfer for a variety of conditions were reported (*1*). These data were used (*2*) to determine a quadratic regression equation relating joint efficiency and load transfer. A relationship between load transfer and joint efficiency that closely parallels the Rollings regression equation by using the finite-element program ILLISLAB was developed (*3*).

LOAD TRANSFER ALONG JOINTS

Joints are placed in rigid pavements to control cracking and provide enough space and freedom for movement. Load is transferred across a joint principally by shear forces and in some cases by moment transfer. Shear force is provided by either dowel bars, keyed joint, or aggregate interlock. Moment transfer, on the other hand, is provided by the strength of the concrete slab or in-place thrust, or both, that is produced by heating the slab. When a joint has a visible opening, the transfer of moment across the joint becomes negligible. It is therefore justified to assume that there is no moment transfer across a joint (except in cases such as a tied joint where some moment transfer may be expected if the joint remains tightly closed).

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If moment transfer across a joint is neglected, the amount of load transfer at a joint is governed by the difference in deflection between the two slabs along the joint. At the U.S. Army Corps of Engineers, the load transfer is defined as the ratio of the strain on the unloaded side of the joint to that of the total strain (the sum of the strains on both unloaded and loaded sides) expressed as a percentage. The load transfer is 50 percent if deflections of both slabs are equal. The measured joint efficiency is defined as the ratio of deflections of the unloaded to the loaded slabs. Field measurements with strain gauges conducted by the Corps of Engineers in many military airfields (*4*) indicated that the dowel bars were not effective; their average load transfer across a joint was only about 25 percent.

ESTIMATE OF LOAD TRANSFER FROM FALLING WEIGHT DEFLECTOMETER

Finite-Element Analysis

The ILLISLAB program was used (*5*) to show that load transfer is a function of both the joint efficiency and the ratio of the radius of loaded area a to the radius of relative stiffness l, or an a/l ratio. The a/l ratio accounts for differences in the way the load is applied to the joint by considering a, and for the relative stiffness between the slab and foundation subgrade soil l, which accommodates the variables of slab thickness h, modulus of elasticity E, Poisson's ratio ν, and modulus of subgrade reaction k, as shown in Equation 1.

$$l = \{Eh^3/[12\,(1 - \nu^2)]k\}^{0.25} \quad (1)$$

By varying only the radius of loaded area a, and with the following conditions:

- Slab thickness h = 25.4 cm (10 in.), ν = 0.15;
- Slab length L = 4.58 m (15 ft), l = 91.8 cm (36.135 in.);
- Slab width W = 3.57 m (11.7 ft), E = 27,560,000 kPa (4,000,000 psi); and
- Modulus of subgrade reaction k = 3,204 kg/m^3 (200 pci).

A number of finite-element runs were conducted with varying joint stiffness (spring constant) for each of four a/l ratios—0.047, 0.156, 0.312, and 0.584. The slab thickness and slab size were kept constant at 25.4 cm (10 in.) and 4.58 m (15 ft) in length and 3.57 m (11.7 ft) in width, respectively, in the computation. The results are plotted in Figure 1.

Although the curves developed by Korovesis (*5*) and extended by Pittman (*6*) (Figure 1) account for differences in the way the load is applied to the slab by considering the ratio a/l, a constant slab size

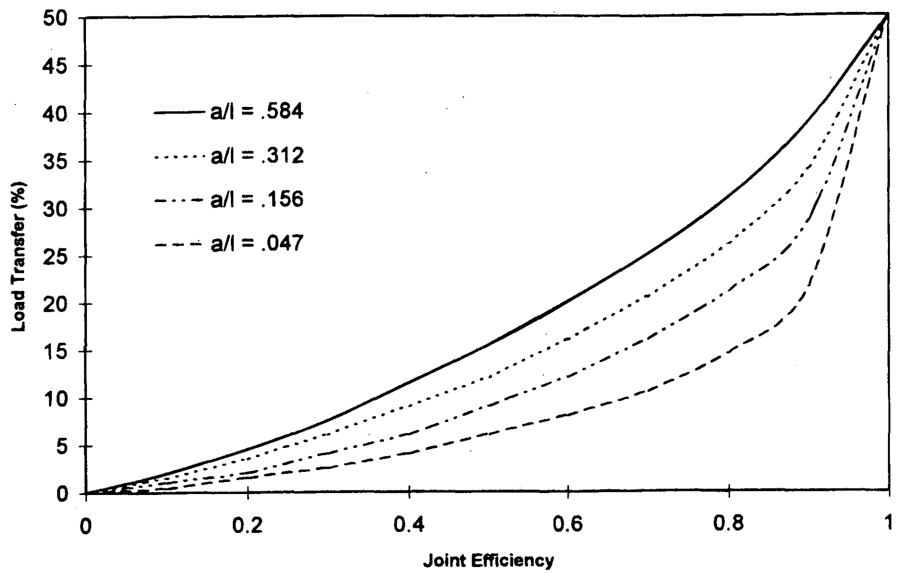

FIGURE 1 Relationship between joint efficiency and load transfer.

4.58 m (15 ft) long, 3.57 m (11.7 ft) wide, and 25.4 cm (10 in.) thick was used throughout that work developing the relationship between joint efficiency and load transfer. However, slab size is critical in problems involving deflections, which are discussed in the following paragraphs.

Westergaard's solution has been used for computing maximum edge stresses in concrete slabs. The slab is assumed to be infinite in length in the two directions. Field results indicated that computed stresses using Westergaard's solution were close to the measured values. By using the finite-element method ILLISLAB, it was found that slab size has much less effect on computed stress than on computed deflection. The computed results for single square slabs are presented in Table 1, which shows that as the slab size increases, deflection decreases and stress increases, but the rate of change is more significant in deflection than in stress.

Concrete pavement thickness design is based on the critical tensile stress, and when the finite-element method is used, it is generally believed that slab size is not critical as long as the slab is of rea-

TABLE 1 Computed Stresses and Deflections [E = 27,560,000 kPa (4,000,000 psi), k = 689 kPa (100 pci), ν = 0.15]

Slab Size L, m	L/l	Deflection mm	Stress kPa	Percent Change Deflection	Percent Change Stress
3.05	2.44	1.90	3,272.1	0	0
4.58	3.65	1.26	3,688.2	-33.8	12.7
6.10	4.87	1.13	3,801.2	-40.7	16.2
7.63	6.09	1.08	3,810.2	-43.3	16.4
9.15	7.31	1.05	3,809.5	-44.6	16.4

Notes:

The change in percentage is based on values computed for L=3.05m (10 ft). The single-wheel load is placed at the center of the slab edge. 1 m = 3.279 ft, 1 cm = 0.3937 in., 1 kPa = 0.1451 psi.

sonable size. For instance, a 4.58-m^2 (15- by 15-ft) slab is believed large enough for stress analysis under a single-wheel load on a 30.5-cm (12-in.) diameter area. This is correct in pavement thickness design in which the magnitude of critical tensile stress controls. It is particularly true for highway pavements where the slab thickness is relatively thin compared with airfield pavements. Based on the results of the analysis of this study, it was found that in the relationship between load transfer and joint efficiency in which deflections are involved, the slab size should vary depending on the following variables: slab thickness, subgrade strength, concrete modulus, and loaded area. A dimensionless factor *L/l* was introduced in which *L* is the size of the square slab and *l* is the radius of relative stiffness defined in Equation 1. Equation 1 shows that a larger slab is needed for thicker pavements, greater concrete moduli, or weaker subgrades. In other words, when a comparison is made involving deflection for two different slabs, the *L/l* values should be compatible. This may be demonstrated using the ILLISLAB program.

The analysis was made on a two-slab system under a single-wheel load placed at the slab edge at the center of the joint. Several values of joint stiffness, represented by spring constants, were used in the computation, and the *E*, *K*, and ν values were the same as shown for Table 1. Figure 2 shows the relationship between the joint efficiency and load transfer for two sets of *L/l* curves. For each *L/l* value, the slab thickness *h* and *l* are constants and the loaded area *a* varies, which results in varying *a/l* ratios. It needs to be pointed out that the slab size *L* in the two cases being nearly the same—4.64 and 4.61 m (15.2 and 15.1 ft)—is purely coincidental.

Figure 1 demonstrated that in the relationship between joint efficiency and load transfer, the curves with varying *a/l* ratios are plotted in descending order, with larger *a/l* at the upper position. The load transfer capability can be determined from the measured joint efficiency for a given *a/l* ratio. Figure 2 shows both Curves 3 and 5 having the same *a/l* ratio of 0.082, but the curves do not yield the same result, (i.e., for a given joint efficiency, different load transfer is obtained for different *L/l* value). Also, Curve 4 (*L/l* = 2.5), which has an *a/l* ratio of 0.415, is plotted below Curves 2 and 3 (*L/l* = 5), which have *a/l* ratios smaller than 0.415. Figure 2 demonstrated that when curves with different *L/l* values are plotted together, the curves will not be placed in order following the *a/l* ratios, which defeats the purpose of the relationship between the joint efficiency and load transfer. It is suggested that the curves be plotted separately based on the *L/l* value. Explaining it in a different manner, when conducting an FWD test, if the slab size *L* is 3.05 m (10 ft) and the slab thickness is 50.8 cm (20 in.), resulting in a *L/l* value of 1.7 [183.6 cm (*l* = 72.3 in.)], the load transfer should not be determined from the results of ILLISLAB analysis on a 6.1-m (*L* = 20-ft) slab (*L/l* = 3.4 and *l* = 72.3 in.) because a different load transfer will be obtained for the same *a/l* value.

The maximum stress and deflection in Westergaard's closed form solutions for a circular load at the slab edge are functions of *a/l*. However, it is of paramount importance to point out that this is true only for maximum stress and defection (i.e., at locations directly under the load).

Proposed Method

Figures 3 to 6 present the relationship between measured joint efficiency and load transfer for four different values of *L/l*. For each *L/l*, curves with varying *a/l* ratios are plotted. *L/l* ratios are determined

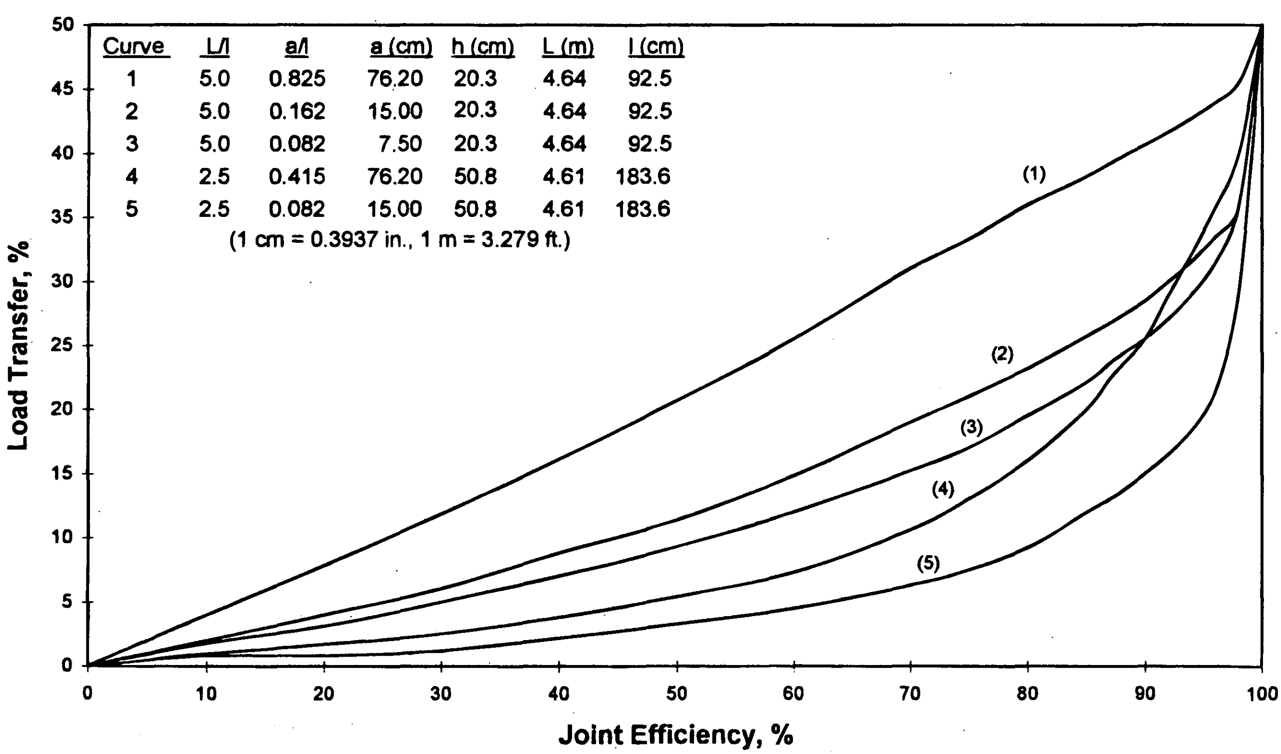

FIGURE 2 Relationship between joint efficiency and load transfer, L/l = 5.0 and L/l = 2.5.

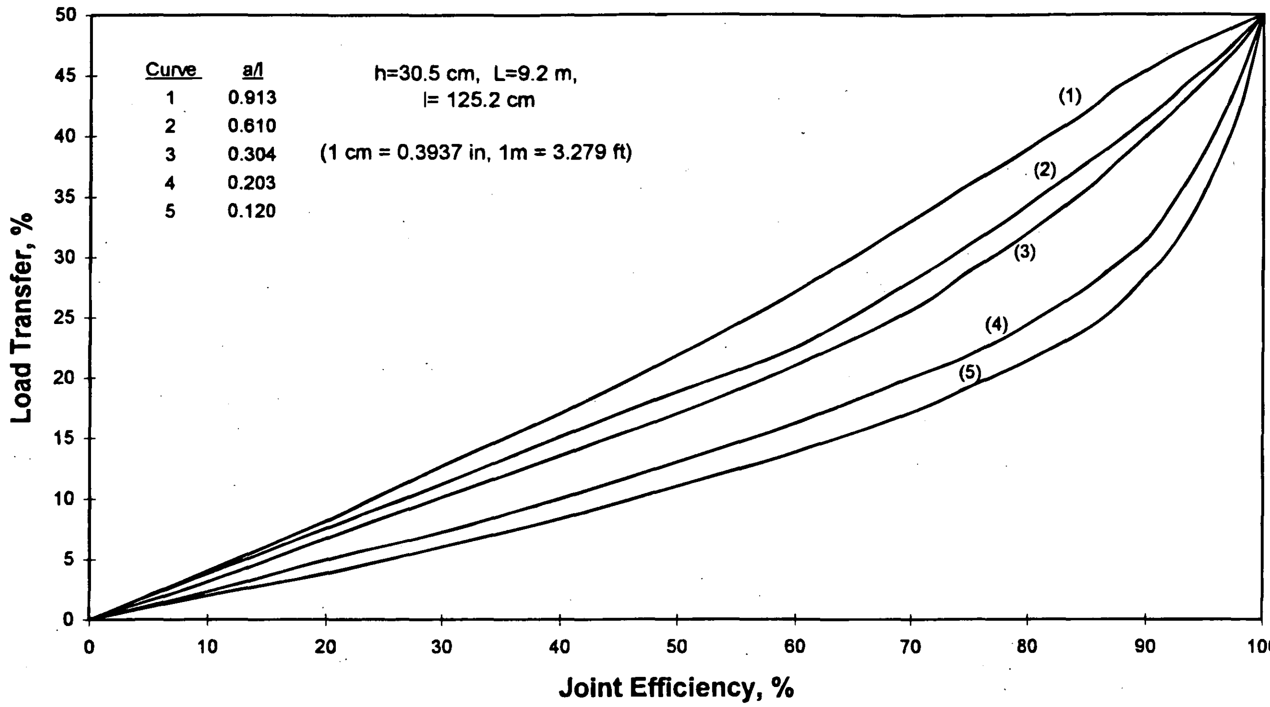

FIGURE 3 Relationship between joint efficiency and load transfer, L/*l* = 7.5.

with different slab size L and concrete slab thickness h. The E, k, and ν values are constants. Table 1 results in constant l for each L/l value. Figures 3 to 6 show that for L/l values less than 5, the difference between joint efficiency and load transfer is significant, but the difference becomes smaller in curves $L/l = 5$ (Figure 4) and 7.5 (Figure 3).

In using the ILLISLAB program, the following guidelines were used.

- Circular wheel loads were converted to square loads of the same area and same magnitude.
- The foundation was represented by the Winkler energy consistent uniform subgrade, not the springs subgrade used in the Westergaard's solution.
- Maximum tensile stress and deflection were selected in determining the joint efficiency and load transfer.

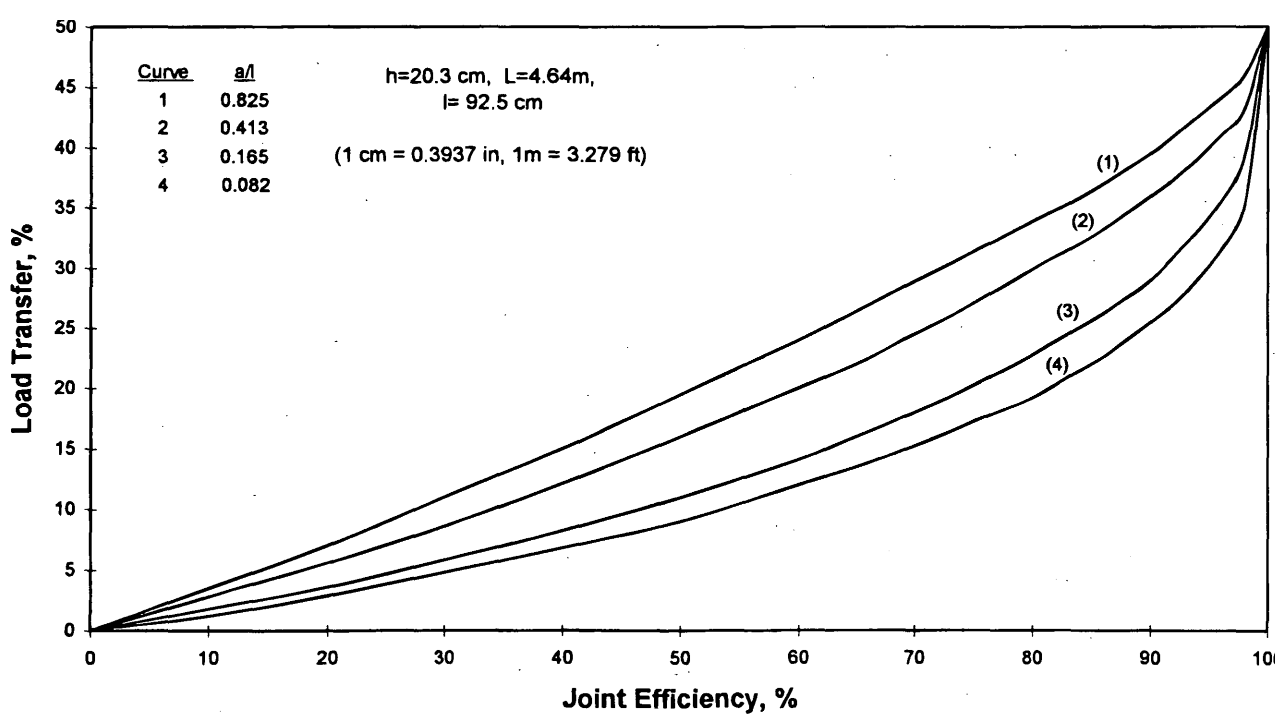

FIGURE 4 Relationship between joint efficiency and load transfer, L/*l* = 5.0.

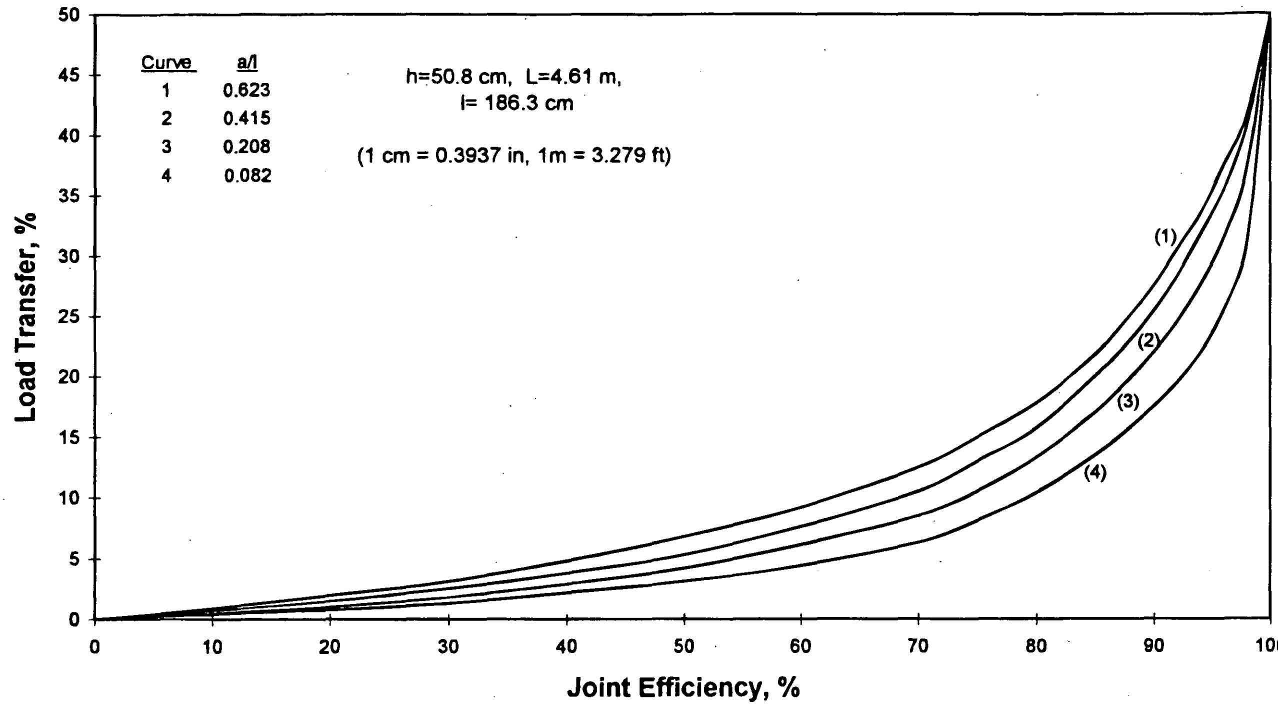

FIGURE 5 Relationship between joint efficiency and load transfer, L/*l* = 2.5.

• The total number of elements depends on the size of the slab *L*. A 25.4-cm (10- by 10-in.) grid is generally used in both directions of the slab, resulting in an element aspect ratio of unity. For smaller loaded areas, grid sizes smaller than 10 in. were used at and near the load, but the aspect ratio for elements near slab edges and locations away from the load were kept less than two. For thinner slabs [h = 20.3 cm (8 in.)], element sizes smaller than 25.4 cm (10 in.) were used.

To verify the correctness of the curves presented in the figures, additional computations were made and the results are presented in Figure 7. Curve 1 in Figure 4 (L/l = 5 and a/l = 0.082) is reproduced

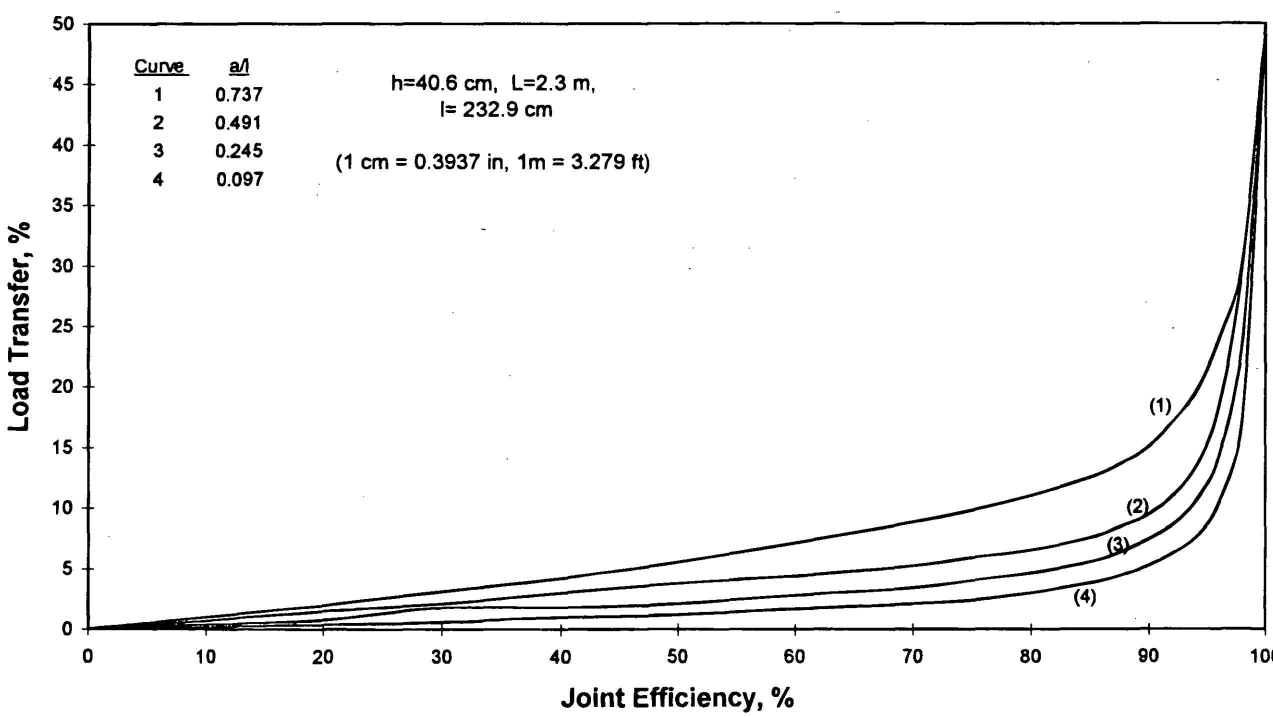

FIGURE 6 Relationship between joint efficiency and load transfer, L/*l* = 1.5.

in the figure in which the points on the curve were computed for the condition a = 7.54 cm (2.97 in.), h = 20.3 cm (8 in.), and L = 4.64 m (15.2 ft). For a completely different condition with slab size L = 30 ft, slab thickness h = 50.8 cm (20 in.), and loaded radius a = 15 cm (5.9 in.), that result in L/l = 5 and a/l = 0.082 satisfying the condition for using Curve 1, the joint efficiency and load transfer were computed and represented as the "crosses," which plot very close to Curve 1. It means that for an FWD test with a 30-cm (11.8-in.) diameter loading plate (a = 5.9 in.) and for a test pavement 50.8 cm (20 in.) thick and a slab size of 9.15 m (30 ft) (i.e., L/l = 5 and a/l = 0.082), the load transfer can be determined from the measured joint efficiency using Curve 1, which has L/l = 5 and a/l = 0.082.

Similarly, Curve 2 in Figure 5 (L/l = 2.5 and a/l = 0.415) is reproduced in the figure. The points on the curve were computed based on the condition a = 76.2 cm (30 in.), h = 50.8 cm (20 in.), and L = 4.61 m (15.1 ft). Similarly, assuming a condition L = 3.14 m (10.3 ft), h = 30.5 cm (12 in.), and a = 51.94 cm (20.45 in.), which resulted in L/l = 2.5 and a/l = 0.415 satisfying the condition for using Curve 2, the computed values of joint efficiency and load transfer are represented as the "dots," which also plot close to Curve 2. In other words, for a single-wheel load with a 152.4-cm (60-in.) diameter loaded area [a = 76.2 cm (30 in.)], a test pavement with a thickness of 30.5 cm (12 in.), and a slab size of 3.14 m (10.3 by 10.3 ft) (i.e., L/l = 2.5 and a/l = 0.415), the load transfer can be determined from the measured joint efficiency using Curve 2, which has L/l = 2.5 and a/l = 0.415.

The reason that the parameter L/l influences the relationship between joint efficiency and load transfer lies in deflections being involved in the relationship. When slab size is increased, deflections are reduced and stresses are increased, and the combination of the changes together with the possible interaction of loaded area can separate the curves having the same a/l ratio but having a different L/l value.

Computations were all made for the condition E = 27,560,000 kPa (4,000,000 psi), ν = 0.15, and k = 1,602 kg/m³ (100 pci). Attempts were made to vary E, h, and k to determine whether the change would affect the computed results. Curve 1 in Figure 7 was chosen for comparison. The following five sets of h, k, and E values were selected:

- h = 20.3 cm, k = 801 kg/m³, E = 13,583,483 kPa,
- h = 20.3 cm, k = 3,204 kg/m³, E = 54,333,933 kPa,
- h = 20.3 cm, k = 8,010 kg/m³, E = 135,834,834 kPa,
- h = 25.5 cm, k = 3,204 kg/m³, E = 27,560,000 kPa,
- h = 34.6 cm, k = 8,010 kg/m³, E = 27,560,000 kPa,
- (1 m = 3.279 ft, 1 kg/m³ = 0.0624 pci, 1 kPa = 0.1451 psi)

which result in the same radius of relative stiffness of the slab l [92 cm (36.22 in.)] and a/l = 0.082. The computed results are plotted along Curve 1 as squares marked with numbers. The squares are plotted on the curve, indicating the correctness of the method.

MULTIPLE-WHEEL GEAR LOADS

The procedure of equivalent single-wheel radius (ESWR) was proposed (7) to determine the load transfer in jointed plain concrete pavements. An ESWR is defined as the radius of a single tire that will cause an equal magnitude of edge stress in the pavement to that resulting from a multiple-wheel load. It was proven that the ESWR so determined can produce the same load transfer as the multiple-wheel load. The ESWR can then be used on curves similar to those shown in Figures 3 to 6 to determine the load transfer of the slabs under the multiple-wheel load based on the measured joint efficiency.

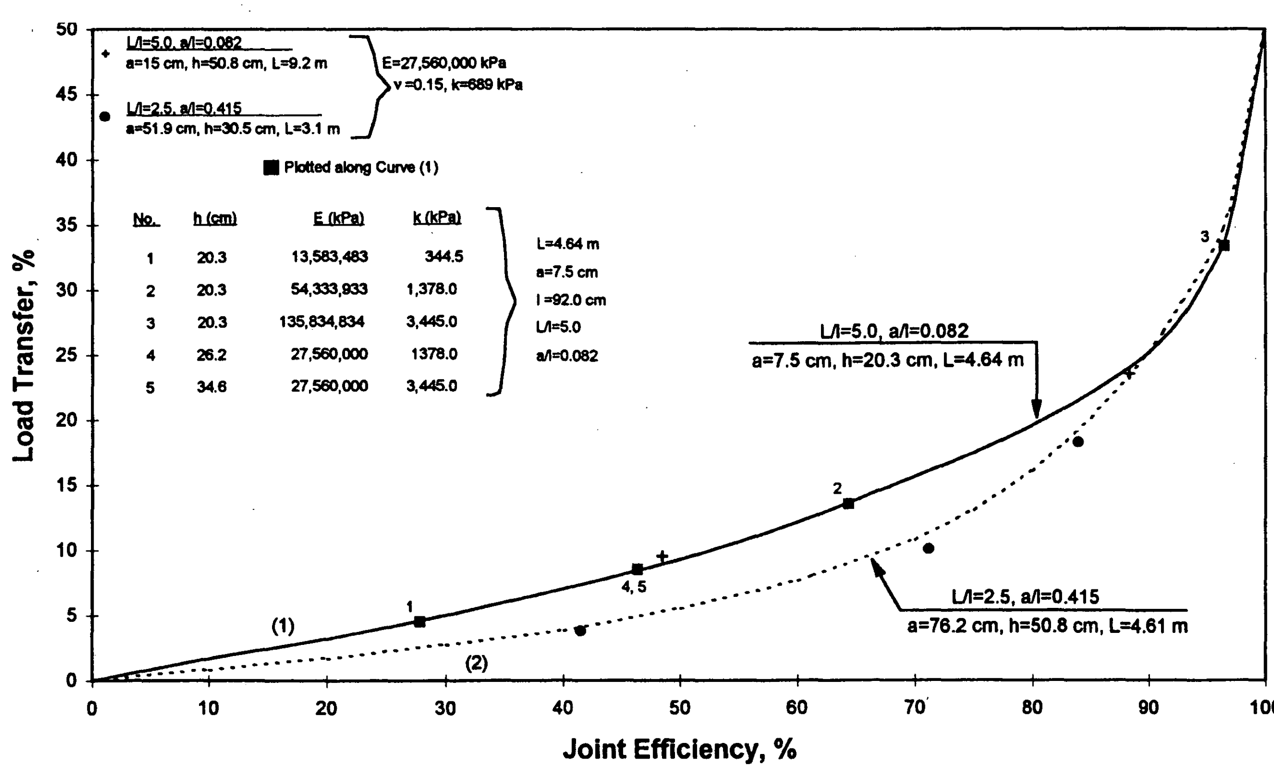

FIGURE 7 Verification of the proposed procedure.

TABLE 2 Computed Stresses and Deflections [E = 27,560,000 kPa (4,000,000 psi), k = 689 kPa (100 pci), ν = 0.15]

Radius of a Circular Loaded Area, cm 2.54 cm (1 in.)	Joint Efficiency, percent
7.5	59.9
15.0	65.0
38.1	62.5
76.2	64.5

Notes:

L = 4.58 m (15 ft), E = 27,560,000 kPa (4,000,000 psi)

k = 1,602 kg/cu m (100 pci), l = 93.35 cm (36.75 in.)

h = 20.32 cm (8 in.), L/l = 5.0

Joint spring constant = 55,120 kPa (8,000 psi)

It was assumed that the joint efficiency is independent of the loaded area during the measurement, that is, for the same slab the measured joint efficiency of the 30-cm (11.8-in.) loading plate FWD test (or other field measurements) is the same as the joint efficiency of the ESWR load. This assumption was verified with the computed results using ILLISLAB as shown in Table 2. The computed joint efficiency in jointed slabs is nearly the same under circular loaded area of different radius.

CONCLUSIONS

The relationships between measured joint efficiency and load transfer for jointed plain concrete pavements presented in Figures 3 to 6, as derived by the ILLISLAB program, may be used to determine the load transfer of concrete pavements based on the measured joint efficiency using FWD tests. The relationships depend not only on a/l but also on L/l, where L is the size of the square concrete slabs, a is the radius of the single-wheel load, and l is the radius of relative stiffness of the concrete slab. It is proposed that the relationship between joint efficiency and load transfer be developed based on L/l and a/l values. The ESWR proposed by Seiler's procedure (*6*) can be used to determine the load transfer of multiple-wheel gear loads.

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