Factors Affecting Deterioration of Transverse Cracks in Jointed Reinforced Concrete Pavements

ZAFAR I. RAJA AND MARK B. SNYDER

Jointed reinforced concrete pavement (JRCP) develops transverse cracks as the drying and thermal shrinkage of the concrete is resisted by friction with the supporting layers. These cracks deteriorate with time and traffic because of loss of load transfer capacity. However, rapid deterioration of these cracks has been observed on some recently constructed projects. This rapid crack deterioration leads to accelerated maintenance requirements and shortened service lives. A synthesis of factors that may reduce aggregate interlock load transfer is presented, and research efforts currently under way at Michigan State University aimed at evaluating the relative effects of several of these factors on transverse crack deterioration in JRCP are described. The ongoing work involves the collection and analysis of load transfer data from the testing of a series of large-scale pavement test specimens that are subjected to repeated applications of loads simulating the passage of heavy-truck traffic. The test variables selected for the study include type of coarse aggregate, gradation of coarse aggregate, treatment of coarse aggregate (virgin, recycled, and blend), source of coarse aggregate, foundation support, reinforcing steel quantity and type, and amount of slab tension.

Jointed reinforced concrete pavement (JRCP) typically develops transverse cracks over the first several years of its service life as contractions of the slab (caused by combinations of drying and thermal shrinkage) are restrained by friction between the slab and supporting layers. Transverse cracks may also be initiated by combinations of curling, warping, and load-related stresses. Most JRCP designs rely on aggregate or grain interlock to transfer shear loads across these cracks. The loss of aggregate interlock due to opening of these cracks permits increased slab deflections, as well as the infiltration of water and intrusion of incompressibles into the cracks. These factors, in turn, lead to pumping and crack deterioration through faulting and spalling. Continued pumping eventually leads to a loss of support beneath the slabs, which greatly increases load-related stresses in the slab and can result in fatigue cracking. Thus, the transverse cracks must exhibit good long-term load transfer characteristics to minimize the development and severity of distresses. The concept of aggregate interlock is described in the following paragraphs, and factors that may accelerate the loss of aggregate interlock load transfer are discussed. Research being conducted at Michigan State University to evaluate the relative impacts of selected factors on JRCP transverse crack performance is also described.

Department of Civil and Environmental Engineering, Michigan State University, E. Lansing, Mich. 48824.

LOAD TRANSFER ACROSS TRANSVERSE CRACKS

The ability of transverse cracks and joints to transfer load is a major factor in the structural performance of the crack or joint and the surrounding slabs. This ability, typically referred to as load transfer efficiency, can be described in different ways, including deflection load transfer efficiency and stress load transfer efficiency. Several formulas for computing load transfer efficiency have been adopted by various researchers; the definitions used here are as follows:

$$\%LT = d_{UL}/(d_{UL} + d_L) \times 100 \quad (1)$$

where

$\%LT$ = percent load transfer,
d_{UL} = deflection of the unloaded side of the crack or joint, and
d_L = deflection of the loaded side of the crack or joint (*1*).

In Equation 1, the maximum load transfer that can be achieved is 50 percent. This value is obtained when the two slabs deflect an equal amount. Other deflection-based formulas include the one first proposed by Teller and Cashell (*2*):

$$\%LT = 2 \times d_{UL}/(d_{UL} + d_L) \times 100 \quad (2)$$

where d_{UL} is the deflection of the unloaded slab and d_L is the deflection of the loaded slab (*2–4*).

Load transfer efficiency can be computed on the basis of stress using formulas similar to those just described for load transfer based on deflection. Sutherland and Cashell (*5*) used the following definition to compute load transfer efficiency on the basis of stress:

$$E = (f_f - f_j)/(f_f - f_i) \quad (3)$$

where

E = joint efficiency,
f_f = stress for a given load applied at a free edge,
f_j = stress for a given load applied at the crack or joint edge, and
f_i = stress for a given load applied at the slab interior.

Most JRCP designs rely on aggregate or grain interlock to achieve the necessary load transfer capacity across transverse cracks. Deterioration of these cracks has been found to be strongly related to loss of load transfer efficiency. Therefore, a discussion on the mechanisms, models, performance, and endurance of aggregate interlock is presented in the succeeding paragraphs.

Aggregate Interlock Mechanism

Aggregate interlock is the simplest means of load transfer; the protrusions in one fractured face mesh with the recesses in the other to provide shear resistance along the fractured face. At the time of crack development, the vertical surfaces of the crack are usually rough and irregular. The majority of the coarse aggregate particles typically remain embedded in either of the crack faces. As a wheel approaches a crack, differential vertical displacement of the two slab fragments takes place, causing the particles of one face of the crack to come into contact with the matrix of the other face. Further differential vertical movement is then restricted by the bearing and friction of the aggregate particles along the crack surface. A portion of the wheel load is transferred from one side of the crack to the other through the shear developed by the interlocking action of the aggregate particles at the fractured faces of the crack. This action is commonly referred to as aggregate, or grain, interlock.

Substantial shear forces can be transmitted through this mechanism if the cracks remain tight. JRCP typically contains a small amount of longitudinal reinforcement, often referred to as temperature and shrinkage reinforcement, to help ensure that these cracks do not open appreciably.

Aggregate Interlock Models

Several models have been proposed to explain the aggregate interlock mechanism. One model (*6*) distinguishes between interlock due to local roughness and that due to global roughness of the crack face (see Figure 1). It is postulated that local roughness (or micro texture) causes interlocking of the fine aggregate particles, which is principally a bearing or crushing action, and that global roughness (or macro texture) causes interlocking of coarse aggregate particles, principally a sliding and overriding action. Local roughness is believed to be responsible for most aggregate interlock effects when crack widths are less than 0.01 in. It is further postulated that the effects of local roughness predominate in the early loading cycles and that global roughness predominates in later cycles as crack widths increase and local roughness is reduced.

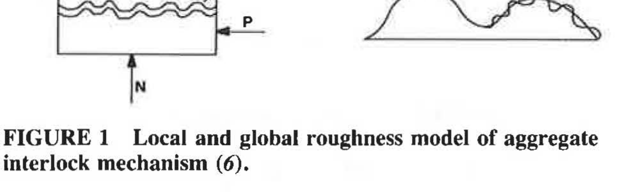

FIGURE 1 Local and global roughness model of aggregate interlock mechanism (*6*).

An alternative model proposes that aggregate interlock is caused by the sliding resistance of two rigid surfaces. These surfaces have been represented by a sawtooth shape (see Figure 2) (*7*,p.357) and by a series of parabolic segments (*8*).

A more recent model (*9*) suggests that concrete is a two-phase material of aggregate and cement matrix that can be modeled as a distribution of rigid spheres of a range of sizes embedded to various depths within a deformable rigid-plastic matrix (see Figure 3). In this model, shear forces are resisted by a combination of crushing and sliding of the rigid spheres into and over a softer cement matrix; contact and interaction between spheres projecting from opposite crack faces are not considered.

Millard and Johnson (*10*) devised a laboratory test to examine aggregate interlock and to determine whether any of the theoretical models could be verified. Their test results do not support the local and global roughness and frictional sliding models. However, they found a fairly consistent agreement between the test results and the two-phase model. These researchers concluded that "the aggregate interlock test results show that the two-phase model, involving a combination of crushing and sliding of the crack faces, is the most realistic one" (*10*).

Aggregate Interlock Performance

An extensive review of the literature reveals that the development of load transfer through aggregate interlock has been studied by several researchers since the early 1900s. However, with the exception of a field study conducted by the Michigan State Highway Department (*1*) to evaluate the aggregate interlock load transfer across reinforced transverse cracks, most of these previous studies were concerned with weakened-plane transverse joints. The studies have shown that a few variables

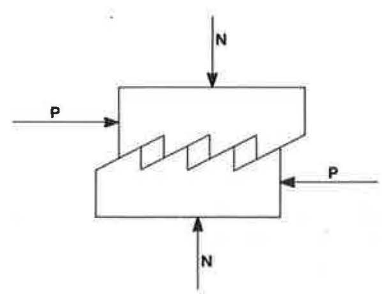

FIGURE 2 Frictional sliding model of aggregate interlock mechanism (*7,8*).

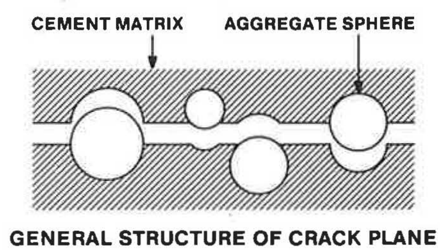

FIGURE 3 Two-phase model of aggregate interlock mechanism (*9*).

predominantly affect development and endurance of load transfer through aggregate interlock. These variables include width of crack opening and texture of the crack face.

Effect of Width of Crack Opening

The results of previous investigations have clearly established that the width of the crack opening has the most pronounced effect on the load transfer capacity of transverse cracks and joints through aggregate interlock. Benkelman (*1*) showed that opening these cracks by as little as 0.03 in. produces a loss of load transfer of 50 percent (see Figure 4). Colley and Humphrey (*3*) observed a similar trend in their studies of aggregate interlock behavior (see Figure 5). These researchers found that "when test load, slab thickness, and subbase were held constant, joint effectiveness decreased as the joint opening was increased" (*3*). Nowlen (*4*) reported a loss of 45 to 55 percent for the same amount of opening, depending on maximum size of aggregate. Similarly, studies by Darter (*11*) have shown that the drop in load transfer is from 20 to 60 percent for 0.03-in. openings, depending on the level of support provided by the foundation. A numerical study by Soroushian et al. (*12*) also indicated that the stiffness and ultimate strength of aggregate interlock decreases significantly with increases in crack width. This loss of load transfer capacity results from a loss of contact between the two slab fragments, requiring some differential vertical movement of the slab fragments before contact and bearing can take place.

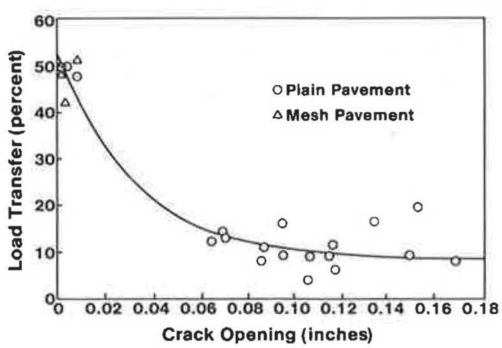

FIGURE 4 Relationship between crack opening and percentage of load transferred (from Equation 1) (*1*).

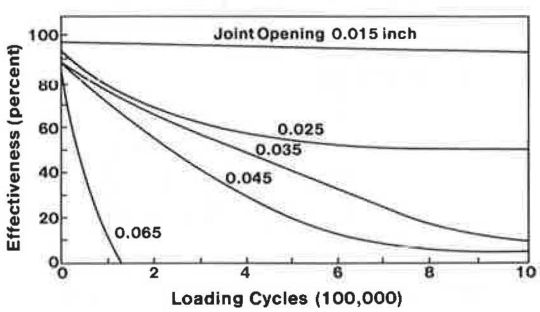

FIGURE 5 Influence of joint opening on effectiveness percentage (from Equation 2) (*3*).

Thus, for these cracks to exhibit good load transfer characteristics, it is imperative that reinforcement serve its intended purpose, that is, to hold the fractured concrete in close interlock.

The results of Benkelman's study (*1*) effectively illustrated the impact of reinforcement on load transfer capacity of transverse cracks (see Figure 6). This figure shows that a smaller percentage of load is transferred across cracks in plain concrete than across those in pavement containing reinforcement, even during the summer months. Moreover, plain concrete cracks undergo a significant drop in load transfer from summer to fall because of the seasonal opening of these cracks, whereas properly reinforced sections experience practically no loss of load transfer during the cold months. Benkelman attributed the small increase in load transfer between fall and winter to higher temperatures at the time of winter loadings compared with the tests made in autumn. Thus, Benkelman concluded that "when roughened edges of two slabs are held firmly together the aggregate interlock may be expected to function perfectly and permanently as a load-transfer medium" (*1*).

Effect of Texture of Crack Face

The aggregate interlock load transfer capacity of transverse cracks and joints has been found to be related to the texture of the crack face. The crack face texture is primarily a function of the type and size of the coarse aggregate, the maturity of the concrete at the time of fracture, and the strength of the concrete. Angular, rough-surfaced aggregates (such as crushed stone) generally provide better interlock and load transfer over narrow crack openings than do rounded, smooth-surface aggregates (such as natural gravels). This contention is supported by Colley and Humphrey (*3*), who contend that con-

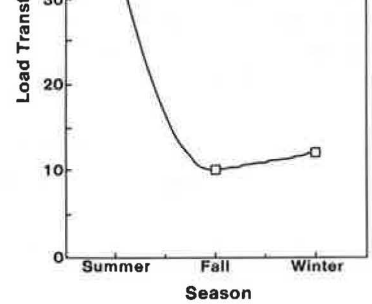

FIGURE 6 Restraining effect of reinforcement on load transfer capacity of transverse cracks (*1*).

cretes made using crushed limestone and crushed gravel coarse aggregates had higher load transfer effectiveness values than those made with natural rounded gravels.

The key factor that determines the texture of the crack face is the mode of concrete fracture. Depending on the bond strength, concrete may fracture in two different ways: (a) around the aggregate or (b) through the aggregate. When concrete fractures around the aggregate, many pullouts of aggregate particles exist, resulting in a rough interface. The results of the Nowlen study (*4*) show that early fracture (i.e., when the aggregate-paste bond is relatively weak) results in many pullouts. However, at later times of cracking, concrete strength has increased and pullouts are diminished because of higher aggregate-paste bond strengths, resulting in more numerous aggregate fractures. The study concluded that "for equal joint openings early fracture of the joint faces with resulting aggregate pullouts contributed to high effectiveness initially, and also to endurance of good effectiveness under repeated loads" (*4*).

When coarse aggregate fractures occur during crack formation, the advantages of angular, rough-surfaced aggregate are largely lost because fracture of aggregate results in a smoother crack face. Sutherland and Cashell (*5*) found that concretes made using natural round gravel had better aggregate interlock load transfer characteristics than concretes made using similarly graded crushed limestone. They attributed the greater load transfer efficiency of the joints in concrete made using rounded gravel to the development of aggregate projections along the crack face. These projections resulted from the poorer aggregate-paste bond, which allowed aggregates to pull out of the matrix rather than fracture. Concretes made using crushed stone tended to crack through the aggregate, producing a smoother crack face and lower levels of interlock load transfer efficiency.

Sutherland and Cashell (*5*) and Nowlen (*4*) also studied the effect of coarse aggregate size on the performance of load transfer through aggregate interlock. The results of these studies agree that large coarse aggregates provide more interlock and higher load transfer efficiencies than small coarse aggregates, particularly for large joint openings (see Figures 7 and 8). However, these figures also show that, although load transfer efficiency generally increases with increasing aggregate size, load transfer efficiency decreases rapidly with increasing joint width, regardless of aggregate size. Sutherland and Cashell concluded that "aggregate interlock was effective in stress

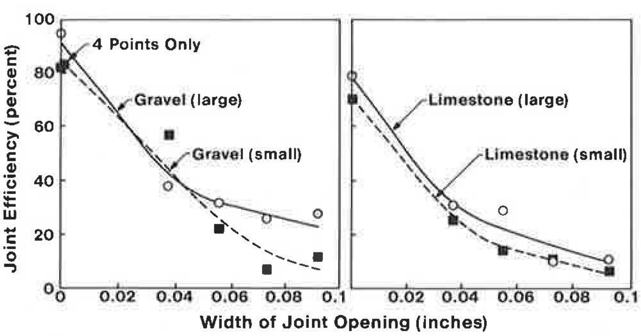

FIGURE 7 Effect of size of coarse aggregate on relationship between joint opening and joint efficiency (*5*).

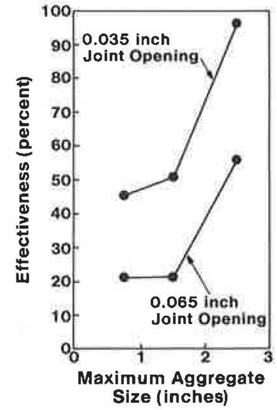

FIGURE 8 Influence of aggregate size on joint effectiveness (*4*).

control when the joints were closed or under compression, but that it was not dependable when the joints opened 0.037 in. or more irrespective of the type or maximum size of aggregate in concrete" (*5*).

The resistance of the crack faces against shear displacements is also affected by the compressive strength of concrete. Studies have shown that increasing the concrete compressive strength considerably increased the aggregate interlock stiffness and ultimate strength (*10,12*). It was suggested that, when increases in concrete compressive strength are due at least in part to increases in the matrix strength, resistance against contact area deformations is also larger so that higher shear stiffnesses are obtained.

Aggregate Interlock Endurance

Maintenance of adequate load transfer through aggregate interlock over a large number of heavy-truck load applications is critical to the satisfactory long-term performance of JRCP. The interlocking features of cracks and joints can be worn through repeated slippage and abrasion of the two vertical faces under accumulated load applications. It follows that hard materials, which are resistant to abrasion, should provide good load transfer effectiveness longer than soft materials, which abrade easily. Nowlen (*4*) confirmed this contention. He found that slabs built with aggregates with good abrasion resistance [Los Angeles abrasion loss values (LA) = 17 and 28] were superior in effective endurance to those built with aggregates having poor abrasion resistance (LA = 46).

Colley and Humphrey (*3*) found that load transfer effectiveness decreases as the number of load applications increases. They noted, however, that 90 percent of the decrease occurs during the first 500,000 load repetitions. These researchers introduced the concept of an endurance index (EI), which represents the ability of a joint or crack to retain load transfer effectiveness under load repetitions. The following model was developed to predict the EI as a function of the most significant variables in their test program:

$$EI = 230hk^{1/2}/Pw \qquad (4)$$

where

EI = endurance index,
h = depth of roughened interface (in.),
k = foundation modulus (psi/in.),
P = wheel load (lb), and
w = joint opening (in.).

The EI is particularly sensitive to variations in foundation strength and joint openings, as shown in Figures 9 and 10. For example, increasing the k value of the foundation from 90 to 450 psi/in. increases the EI by a factor of about 2.6 times for a 7-in. slab and about 2 times for a 9-in. slab. This increase in EI results because strong foundation support reduces the magnitude of the differential vertical deflections, thereby allowing the application of more load cycles to produce a given loss of interlock and load transfer. This finding was verified numerically by Ioannides and Korovesis (*13*). Figure 10 shows that EI decreases as the joint opening increases. For example, increasing the joint opening from 0.025 to 0.065 in. decreases the EI by a factor of about 6 for a 7-in. slab and about 3 for a 9-in. slab.

CURRENT RESEARCH NEEDS

As described previously, studies conducted to date have revealed a large number of variables that may have some impact on the rate of deterioration of load transfer capacity through aggregate interlock of transverse cracks and joints in JRCP. Variables that significantly affect load transfer through aggregate interlock include (but may not be limited to) the following:

- Width of crack opening,
- Restraining impact of reinforcement (percent steel),
- Type of coarse aggregate,
- Size of coarse aggregate,
- Paste-aggregate bond strength,
- Compressive strength of concrete,
- Hardness of coarse aggregate (abrasion resistance),
- Applied load magnitude,
- Applied load repetitions,
- Foundation support, and
- Depth of roughened interface (interlocking area).

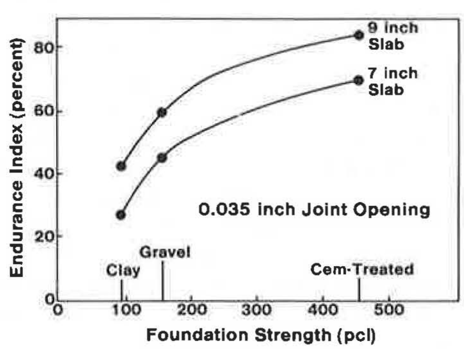

FIGURE 9 Effect of foundation strength on endurance index (*3*).

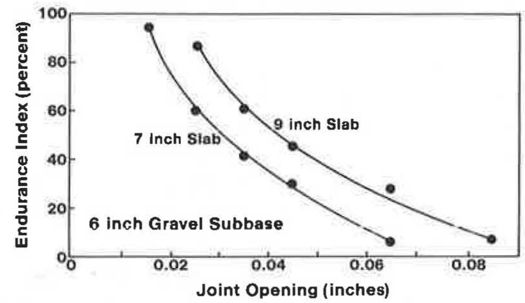

FIGURE 10 Effect of joint opening on endurance index (*3*).

Past research efforts, with the exception of the Benkelman study (*1*), have been directed only at the evaluation of weakened-plane transverse joints. Transverse joints are designed to allow horizontal slab movements and are thus different in design and function than transverse cracks in JRCP, which contain steel reinforcement that is intended to hold these cracks tight and resist any horizontal movement. Because of these design and functional differences, different variables affect the performance of joints and cracks. For example, the opening and failure of reinforced cracks are influenced by the design and performance of the reinforcing steel. Abrasion and attrition of the aggregates, daily and seasonal temperature variations, the presence of nonfunctional transverse joints (because of misaligned or corroded dowels or malfunctioning dowel assemblies), and the presence of expansion joints can also produce excessive crack movements. Many of these factors have not been evaluated in the context of transverse crack performance.

The performance of steel reinforcement in keeping JRCP transverse cracks from opening has historically been quite variable. Although many JRCP cracks remain tight throughout the pavement design life, there have been many documented cases of steel rupture, suggesting that the coefficient of friction or interlock between the slab and subbase may be much higher than traditionally assumed values. For example, temperature reinforcement is typically designed to withstand the stresses that would be produced in the presence of a subbase friction coefficient of 1.5 to 2 without allowing excessive crack opening. However, some types of granular and stabilized bases have been found to produce much higher levels of friction or interlock with the paving slab. This higher friction increases the slab and steel tension, which may cause permanent elongation or rupture of the steel and opening of the transverse cracks. These facts suggest that research efforts should be directed toward better characterization of the effects of slab tension and reinforcement on the performance of reinforced transverse cracks that are subjected to repeated heavy loads.

Another variable that merits further research is the effect of foundation support on crack load transfer capacity and endurance. A cracked slab supported on a fairly stiff foundation will experience little differential vertical movement across the cracks, even if they open substantially. However, pavements built on softer or unstable foundations can be expected to exhibit poor crack load transfer efficiency endurance. This factor is suspected of playing a major role in the rapid deterioration of cracks on at least one construction proj-

ect (*14*). Further research will help to quantify the role that foundation support plays in JRCP crack deterioration.

Previous research has not addressed some key issues currently facing pavement engineers. For example, current pavement design often calls for the use of smaller top-size aggregates (e.g., $\frac{3}{4}$ in. or less) as part of an effort to improve pavement durability. However, rapid deterioration of transverse cracks has been observed in recently constructed JRCP containing small-sized coarse aggregate. Cores taken at some of these projects have exhibited straight vertical crack faces with little roughness or meander. In many cases, the crack face has been ground almost to a sandpaper finish, indicating that little, if any, mechanical interlock will exist across even a tight crack (*14*). Such conditions reduce the vertical shear capacity of these cracks to near zero and can result in accelerated crack deterioration (i.e., spalling, faulting, and pumping) under repeated heavy-traffic load applications. Additional research must be devoted to determining the role of aggregate top size and gradation in the deterioration of reinforced transverse cracks.

High-quality aggregates suitable for use in highway construction are in short supply at many locations. One source of potentially high-quality aggregates is the recycling of concrete pavements that are in need of reconstruction. Coarse aggregates produced by recycling old pavements are often crushed to smaller sizes to improve the durability of the new pavement (especially if the old pavement exhibited durability-related distresses). These aggregates may also exhibit very different bonding characteristics with the cement paste due to local variations in the water-cement ratio caused by their nonuniform (and sometimes high) moisture absorption characteristics. Furthermore, these aggregates may fracture differently (and more readily) than natural aggregates, producing unusual crack face textures. A number of projects constructed using small-sized, recycled coarse aggregate have developed transverse cracks that deteriorated rapidly. Further study is needed to determine the effects of using various quantities of recycled concrete containing different types and gradations of virgin aggregate.

CURRENT RESEARCH

In light of the previously described research needs, a laboratory experimental research effort is under way at Michigan State University to evaluate the relative impacts of the following selected factors on JRCP transverse crack performance:

1. Coarse aggregate top size (1.0 versus 1.5 versus 2.5 in.),
2. Coarse aggregate treatment (virgin versus recycled versus recycled-virgin blend),
3. Coarse aggregate type (gravel versus limestone versus slag),
4. Coarse aggregate source (Gravel 1 versus Gravel 2, Limestone 1 versus Limestone 2),
5. Pavement support conditions (low versus medium versus high),
6. Reinforcing steel quantity (typical versus high),
7. Reinforcing steel type (smooth versus deformed), and
8. Slab tension (typical versus high).

The focus of this research is the development, execution, and analysis of a laboratory experiment involving the collection and analysis of load transfer data from the testing of a series of large-scale test specimens that are subjected to repeated applications of loads simulating the passage of heavy-truck traffic (see Figure 11). The test specimens are PCC-reinforced slabs, approximately 4.5 ft wide by 10 ft long and 9 in. thick at the transverse crack. The crack is forced near midslab after approximately 18 hr of curing. The test apparatus provides approximately uniform support for the specimen through the use of an artificial foundation (vibration isolation padding rated at specific *k*-values). Desired levels of foundation support are achieved by providing various thickness and type combinations of artificial foundation materials. The test equipment allows placement of slabs in tension before and during testing to simulate thermal and drying shrinkage in the field, which may exacerbate the effects of heavy-vehicle loads.

The application of traffic loads is accomplished using a pair of hydraulic actuators, of 11-kip capacity, which are mounted on the test frame. These actuators apply a sequence of load pulses to contact pads (simulating tire imprint areas) on the approach and leave sides of the crack to simulate field loading conditions for the outer wheel path of Interstate highway pavements. The maximum applied load is 9,000 lb (one-half of a standard 18,000-lb single-axle load). Most specimens are subjected to 600,000 load applications in a sequence simulating a wheel crossing the crack at 55 mph.

All testing and data collection are controlled by a 286-based personal computer that has been equipped with a high-speed, high-resolution data acquisition system. This system allows the coordinated control of both actuators as well as the collection of load and deflection data. All test data are collected following the completion of 1, 2,000, 5,000, 10,000, 20,000, 50,000, 100,000, 300,000, and 600,000 load applications.

The study is designed to estimate the main effects of each of the test variables being considered and to identify general single- and multivariable influences on crack deterioration. This information will be used to develop preliminary design guidelines and guide specifications for future JRCP design

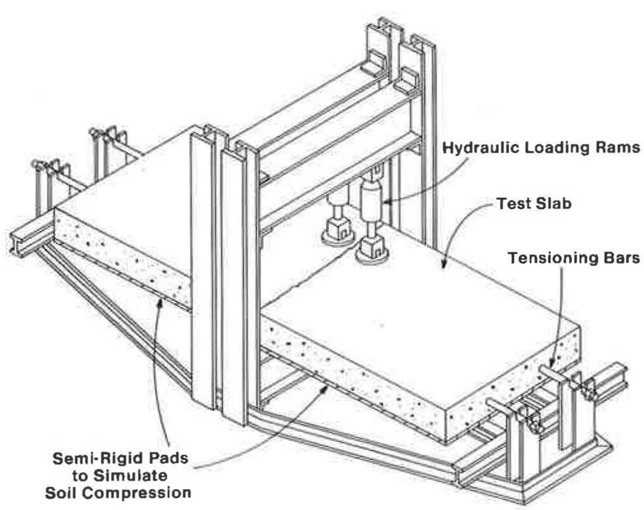

FIGURE 11 Isometric view of test frame.

and construction. It will also be used to suggest avenues of study for future research. The study is scheduled for completion in 1991.

SUMMARY

JRCP develops transverse cracks as the drying and thermal shrinkage of the concrete is resisted by friction with the supporting layers. Most JRCP designs rely on aggregate, or grain, interlock to achieve necessary load transfer capacity across these cracks. The cracks must exhibit good long-term load transfer characteristics to minimize the development and severity of various distresses (such as spalling, faulting, and pumping). However, the cracks deteriorate with time and traffic due to loss of aggregate interlock load transfer capacity.

Some of the significant factors that affect aggregate interlock load transfer capacity include width of the crack opening and texture of the crack face. Several other factors that may affect the performance of JRCP transverse crack and, hence, merit evaluation include coarse aggregate type and gradation, coarse aggregate treatment (virgin, recycled, and blend), coarse aggregate source, foundation support, reinforcing steel type and quantity, and amount of slab tension.

A research effort is under way at Michigan State University to evaluate the relative impacts of these factors on transverse crack deterioration in JRCP.

REFERENCES

1. A. C. Benkelman. Tests of Aggregate Interlock at Joints and Cracks. *Engineering News Record*, Vol. III, No. 8, Aug. 1933, pp. 227–232.
2. L. W. Teller and H. D. Cashell. Performance of Dowelled Joints Under Repetitive Loading. *Bulletin 217*, HRB, National Research Council, Washington, D.C., 1959.
3. B. E. Colley and H. A. Humphrey. Aggregate Interlock at Joints in Concrete Pavements. In *Highway Research Record 189*, HRB, National Research Council, Washington, D.C., 1967, pp. 1–18.
4. W. J. Nowlen. Influence of Aggregate Properties on Effectiveness of Interlock Joints in Concrete Pavements. *Journal of the PCA, Research and Development Laboratories*, Vol. 10, No. 2, May 1968, pp. 2–8.
5. E. C. Sutherland and H. D. Cashell. Structural Efficiency of Transverse Weakened-Plane Joints. *Public Roads*, Vol. 24, No. 4, April-June 1945.
6. J. P. Laible, R. N. White, and P. Gergely. Experimental Investigation of Seismic Shear Transfer Across Cracks in Concrete Nuclear Containment Vessels. In *Reinforced Concrete Structures in Seismic Zones*. ACI Special Publication SP-53. American Concrete Institute, Detroit, Mich., 1977, pp. 203–226.
7. R. Jimenez, P. Gergely, and R. N. White. *Shear Transfer Across Cracks in Reinforced Concrete*. Report 78-4. Cornell University, Ithaca, N.Y., Aug. 1978.
8. M. N. Fardis and O. Buyukozturk. Shear Transfer Model for Reinforced Concrete. *Proc., American Society of Civil Engineers*, Vol. 105, No. EM2, April 1979, pp. 225–275.
9. J. C. Walraven. Fundamental Analysis of Aggregate Interlock. *Journal of the Structural Division, ASCE*, Vol. 107, No. 11, Nov. 1981, pp. 2245–2270.
10. S. G. Millard and R. P. Johnson. Shear Transfer Across Cracks in Reinforced Concrete Due to Aggregate Interlock and to Dowel Action. *Magazine of Concrete Research*, Vol. 36, No. 126, March 1984.
11. M. I. Darter. *Design of Zero-Maintenance Plain Jointed Pavements: Volume 1.1—Development of Design Procedures*. FHWA, U.S. Department of Transportation, June 1977.
12. P. Soroushian, K. Obaseki, and K. Choi. Analysis of Aggregate Interlock Behavior at Cracks in Reinforced Concrete. *Magazine of Concrete Research*, Vol. 40, No. 142, March 1988, pp. 43–49.
13. A. M. Ioannides and G. T. Korovesis. Aggregate Interlock: Pure-Shear Load Transfer Mechanism. Presented at 69th Annual Meeting of the Transportation Research Board, Washington, D.C., 1990.
14. M. I. Darter. *Initial Evaluation of Michigan JRCP Crack Deterioration*. Michigan Concrete Paving Association, Mahomet, Ill., Dec. 1988, rev. Feb. 1989.

Publication of this paper sponsored by Committee on Rigid Pavement Design.