OPTIMIZED PERFORMANCE AT CONCRETE PAVEMENT JOINTS

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Results of an investigation conducted to develop improved performance at concrete pavement joints are presented in this paper. The investigation included development of a finite element analysis computer program, laboratory testing, and evaluation of techniques to improve structural response at joints. The computer program, Program JSLAB, can analyze a large number of jointed concrete slabs consisting of a one- or two-layer concrete pavement system resting on a Winkler (spring) foundation. Program JSLAB was used to evaluate the effect of the use of fewer nonuniformly spaced dowel bars, tied-concrete shoulders, and widened lanes on joint performance. Theoretical analysis indicates that maximum deflections and stresses at a transverse joint with six or seven nonuniformly spaced dowels are similar to those for a conventional joint with twelve uniformly spaced dowels. No new load transfer devices (LTD) were developed as part of this study. After a review of various patented devices and a study of various LTD shapes, configurations, and placement requirements, it was concluded that solid round dowel bars are the most cost-effective mechanical load transfer device for new construction.

Joints are provided in concrete pavements to control transverse and longitudinal cracking that results from restrained deformations caused by moisture and temperature variations in the slab. Without some form of control, concrete pavements would exhibit random cracking that could result in premature functional and structural failure of the pavement. By providing joints, pavements can be constructed so that cracks either do not develop or develop only in a controlled manner related to the location of the joint. In either case, a joint is superior to an uncontrolled crack as provisions for load transfer and sealing can be effectively made at a joint.

Because of the discontinuity, the use of joints may reduce load carrying capacity of the pavement at the joint. In addition, the joint creates an area of weakness in the pavement where potential for development of distress is high. Therefore, joint design must consider methods that will provide and maintain adequate structural integrity at the joint as well as ensure joint durability. Poor joint designs often result in joint related distress that adversely affect pavement performance and ride.

A concrete pavement develops early cracking as follows. Soon after the pavement is placed, drying shrinkage of the concrete begins. In addition, due to the heat of hydration, concrete generally sets at a temperature higher than ambient. Subsequent cooling results in a reduction in concrete volume. This early drying shrinkage and volume reduction of concrete is restrained by subgrade friction. If restraint exceeds concrete tensile strength, cracking occurs.

Subsequent cracking may occur due to stresses caused by restrained curling and warping and traffic loading. The restraint stresses are a result of temperature and moisture differential between slab top and bottom. Curling refers to effects of temperature differentials and warping refers to effects of moisture differentials.

Jointing systems for concrete pavements should be designed to ensure pavement structural integrity and riding quality at the lowest annual cost. A significant portion of concrete pavement construction and rehabilitation dollars are spent on joints and load transfer devices. Considering the high cost of providing effective "retrofit" load transfer devices and maintenance and repair costs of joint related distress, provision of dowels for plain pavements at the time of construction is considered cost-effective when high volume of truck traffic is anticipated.

This paper summarizes results of a study that was conducted to develop new or improved joint systems and load transfer devices for concrete pavements (1). As part of the study, the state-of-the-art of joint design practices was reviewed, a finite element computer program for analysis of jointed concrete pavement was developed, several areas were identified that would potentially improve joint performance, and laboratory testing of joint systems was conducted.

Functions of Joints

As stated previously, joints are controlled crack locations that create areas of weaknesses if not designed properly. Proper transverse joint design for jointed concrete pavements requires the following:

1. Provision of adequate load transfer
2. Allowance for slab end movements
3. Selection of proper joint sealant

Load transfer across joints results in reduced loaded slab deflections, reduced loaded slab stresses, and reduced relative deflections between adjacent loaded and unloaded slabs. Slab deflections at the joint are greatly influenced by loss of support along the joint due to upward warping and curling of the slab. If slab deflections are not reduced, high deflections may result in joint related distress such as pumping, faulting, and corner breaks. Slab deflections and problems associated with deflections may also be reduced by use of high quality subbases.

Pavement slabs should be free to expand and contract with changes in slab temperature and moisture. Restraint to slab movement is provided by subbase friction and locked (or frozen) dowels. For short slabs, resistance due to subbase friction is not as significant. The magnitude of restraint due to locked joints depends on the degree of load transfer device misalignment and corrosion. Excessive restraint to slab movement may result in transverse cracking and spalling at the concrete face around the dowel.

Finally, to ensure good performance at joints, steps must be taken to prevent infiltration of water and incompressible material. This is usually done by use of poured or preformed sealants in properly shaped joint sealant reservoirs.

Background

Highway pavement joints are broadly classified as being transverse or longitudinal. For transverse joints, contraction joints are the predominant type. For longitudinal joints, the shoulder joint is of primary concern. A longitudinal shoulder joint may be a construction or a contraction type joint. This section presents a background on several items of importance to joint performance.

Transverse Joints

Over the years, two design approaches have been used for jointed concrete pavements. The first approach considers plain concrete pavements. Joint spacing is about 12 to 20 ft and no midslab cracking is expected to occur. Many highway agencies use "randomized" joint spacing. A representative random spacing pattern used is 13, 19, 18, and 12 ft. California has recently instituted the practice of specifying joints at 12, 15, 13, and 14 ft.(2)

The second approach considers jointed concrete pavements with distributed steel. Joint spacing used in this case is generally about 25 to 60 ft. One or more cracks may be expected to occur in these slabs between joints. However, the distributed steel prevents the cracks from opening widely. The amount of steel used is about 0.1 percent of the pavement cross-sectional area.

Transverse construction joints are used when it is necessary to halt construction. These joints are usually located at planned locations for contraction joints. Use of load transfer devices at these locations is essential as there is no effective aggregate interlock.

Transverse expansion joints are only used at structures or at intersections. These joints are used to accomodate larger slab end movements due to concrete slab expansion and contraction.

Longitudinal Joints

Longitudinal joints are located between lanes or at the pavement edge. These are weakened-plane or construction joints. Weakened-plane joints are formed by sawing or by use of a plastic insert. Recommended depth of saw-cut or insert is one-third the slab thickness. Tie-bars are used at these joints to prevent lateral migration of the slabs and to assure positive keyway or aggregate interlock action. Use of tied-concrete shoulders is becoming widely accepted. The shoulder may be paved at the same time as the outside lane or paved later. A keyway may be used with a tied shoulder if the shoulder is paved separately.

Load Transfer Devices

As the name implies, load transfer devices (LTD) are used to transfer load from the pavement on the loaded side of the joint to the pavement on the unloaded side. The effectiveness of load transfer is determined by the deflection of the pavement on the unloaded side of the joint. The closer this deflection value approaches the deflection of the loaded side of the joint, the better the effectiveness of the joint in transferring load across the joint. A perfect joint would ensure equal deflection on both sides of the joint when only one side is loaded.

A check of patented joint systems and load transfer devices shows that many innovative systems have been proposed. However, most of these devices either did not perform well in the field or were impractical from construction and cost aspects. Major drawbacks to development of workable and effective load transfer devices are problems associated with construction and cost. For example, positioning and alignment of the LTD is critical. For two component devices, positive contact between the two components needs to be ensured over a long period. In addition, corrosion is a significant problem in areas where road salt is used during winter months.

Mechanical load transfer devices should possess the following properties: (3)

1. They should provide adequate load transfer across the joint
2. They should be simple in design to allow proper installation or placement without difficulty
3. They should offer little restraint to joint opening
4. They should be corrosion resistant

Current practice for load transfer devices at joints has evolved over a period of time. For plain concrete pavements, load transfer may be achieved by use of aggregate interlock or dowels. For reinforced concrete pavements, mechanical load transfer devices are always specified. Although many types of mechanical load transfer devices have been tried, round steel dowel bars have proven to be the most widely used device.

Current practice for doweled joints requires dowel diameters to be one-eighth of slab thickness, dowel spacing to be 12 in. and dowel length to be

15 to 18 in. Coated dowels are often used to provide resistance to corrosion. The coating may be a zinc or lead based paint or an epoxy coating. Recently, vertically installed load transfer devices have been used on an experimental basis to restore load transfer at joints of existing pavements.

Dowel Corrosion and Coatings

Corrosion is one of the major concerns with doweled joints. Steel corrosion results in an increase in dowel volume. The magnitude of the increase in volume varies but is in the range of 2 to 3 times the volume of steel removed. The increased volume prevents free movement of dowels within the dowel slot. When the restraint to movement is excessive, transverse cracking can occur.

Corrosion Mechanism. A steel bar surrounded by concrete is normally protected from corrosion by the alkaline (pH < 12) nature of the concrete which renders the steel passive (4). Corrosion occurs if this passivity is destroyed. Passivity may be destroyed by carbonation of the concrete, which reduces the alkalinity or the ingress of chlorides that can cause localized disruption of the passive layer. Once the passivity has been destroyed, corrosion can take place, though it only will occur if oxygen and sufficient moisture are present at the steel bar.

In the case of dowels at joints, there is easy access for chlorides from road salt because of the joint opening. Therefore, unless dowels are coated, corrosion can take place.

Restraint to Slab End Movement. The magnitude of restraint to slab end movement depends on the degree of load transfer device misalignment and corrosion. Excessive restraint to slab movement may result in transverse cracking and spalling at the concrete face around the dowel. Examples of calculated of restraint to cause midslab cracking are presented in Table 1.

Restraint stresses can also develop at a joint face around a properly aligned but completely "frozen" dowel. The development of these restraint stresses that lead to spalling of concrete around a dowel is probably of a progressive nature. Spalling may initiate at a lower temperature drop, especially when concrete has not attained sufficient strength.

Anti-Corrosion Measure. Dowel corrosion can be reduced or eliminated by use of noncorrosive materials for dowels or by use of coatings. Of the noncorrosive materials, stainless steel has been used on a few projects in the past. However, the high cost of noncorrosive materials restricts their use.

Coatings commonly used include lead and zinc based paints and epoxy. Stainless steel cladding and nickle molybdenum coatings have also been used. Epoxy coated dowels in present use have a coating of about 10 mils. Epoxy coated dowels need to be coated with grease or oil at the time of placement.

Slab End Movements

Slab end movements result from daily and seasonal temperature variations and changes in moisture content of the concrete.

Slab end movements affect joint design and performance as follows:

1. Slab end movements govern sealant design and selection. Further discussion on sealant design and practice is given in the next section.
2. Slab end movements affect load transfer at joints in plain concrete pavements without load transfer devices.
3. The effect of slab end movements on load transfer is not significant for doweled joints. However, for misaligned dowels, a greater potential would exist for spalling around dowels for large slab end movements.

Joint Construction

Proper joint construction is essential to the long term performance of concrete pavements. Construction items of importance include dowel placement, formation of weakened plane joints, and installation of joint sealant.

Dowel Placement. Dowels may be placed using wire basket (cage) assemblies or other forms of supporting assemblies. The assembly must be rigid and must be fastened firmly to the subbase by special nails, stakes, or clips. As the paving machine travels over the dowel basket assembly, the assembly must maintain its location so that the drowels remain parallel to the roadway in both the horizontal and vertical directions. Alternate ends of the dowels are welded or securely fastened the basket assembly. For coated dowels, welding may result in burnt out areas on the dowel surface.

Round steel dowel bars may also be implanted in plastic concrete by an implanting machine that follows the paver. For implanted dowels, different paving sequences have been used to achieve proper placement of dowel bars. Some paving sequences used strike-off and concrete consolidation (internal vibration) operations following dowel placement (6). In other paving operations, concrete consolidation after dowel placement was not used (7). However, degree of compliance with allowable dowel placement tolerances has been reported as being not satisfactory for any of these procedures (6,7). In some states, use of implanting machines has been discontinued because of concern with dowel placement tolerances.

Dowel Installation and Placement Tolerances. It is required that dowels be placed as parallel as practical to the longitudinal axis and the horizontal plane of the pavement. Generally, limits on permissible tolerances are specified by state highway agencies. The different categories of dowel misalignment and their possible effects on pavement behavior are illustrated in Fig. 1.

The following factors affect level of dowel misalignment when basket assemblies are used:

1. Basket rigidity
2. Quality control during basket fabrication
3. Care during basket assembly, transportation, and placement
4. Fastening of basket to subbase
5. Location of saw-cut over basket
6. Paving operation - the large roll of concrete ahead of paver may displace individual dowels or the basket assembly
7. Field inspection during construction

The following factors affect level of dowel misalignment when dowels are implanted:

1. Implanting machine operation
2. Strike-off after dowel placement

3. Consolidation (vibration) after dowel placement
4. Location of saw-cut over implanted dowels
5. Field inspection during construction

A recent FHWA technical advisory on rigid pavement joints does not specify any limits on misalignment but cautions that "close tolerances for dowel placement are extremely important for proper functioning of the slab and for long-term performance" (8). This advisory also states that "care must be exercised in both specifying dowel placement tolerance and in evaluating the adequacy of construction placement" (8).

No clear concensus exists as to the level of practical limits on dowel placement tolerances. When limits are specified, contractors often state that they are neither practical nor realistic. In addition, it is a very slow process to determine levels of misalignment once the pavement is constructed. Attempts have been made to measure levels of misalignment by using a pachometer and taking partial depth or full depth cores near the ends of the dowel.

Placement Tolerances Studies. Recent investigations have concentrated on comparing misalignment levels and performance of joints having machine implanted dowels and pre-set basket assemblies (9, 10,11). These studies have been conducted because of concern about dowel placement accuracy using machine implanters. In the Pennsylvania study, (9) sixty percent of the implanted dowels and 40 percent of conventionally placed dowels were outside specified limits of tolerances.

In an investigation conducted for the American Concrete Pavement Association, visual surveys and misalignment determinations were made at several sites to compare joints with mechanically implanted and conventionally placed dowels (10). However, no statistically valid conclusions could be drawn from the misalignment data.

In a Tennessee investigation, (11) misalignment levels were determined at several sites by uncovering dowels in freshly placed plastic concrete and by core drilling in hardened concrete. Based on findings, it was recommended that horizontal and vertical skew tolerances be 1/2 in., vertical tolerance be ± 1 in., and the longitudinal tolerance be ± 1-1/2 in.

However, based on poor experience at projects in Florida where mechanical implanters were used, FHWA informed Florida Department of Transportation during 1980 that, "the implanting machine method currently in use is not acceptable for constructing PCC pavement on Federal-aid projects," in Florida (6).

In a study conducted during 1982 by the Georgia Department of Transportation, dowel bar placement was investigated at five highway projects (7). Three projects had implanted dowels and two projects had used dowel basket assemblies. A substantial amount of non-compliance with placement specification requirement was found for the projects with implanted dowels. However, no dowel related distress was found in any of the hundreds of joints that were examined. In addition, it was reported that joints at all of the five projects had started "working" within few days of construction. However, because of the non-compliance problem with implanted dowels, the study recommended that implanting of dowels should not be allowed (7).

Joint Sealing

As discussed before, an important function of joints in rigid pavements is to eliminate or minimize infiltration of water and incompressible materials. It has long been recognized that proper joint sealing can contribute to improved pavement performance. Joints that are not sealed or not properly sealed allow infiltration of water and incompressible materials into the joint. Joints filled with incompressibles may result in joint spalling and pavement buckling as the pavement expands. The presence of water at joints weakens the subbase and subgrade and also results in erosion of subbase/subgrade material leading to pumping and faulting at joints. Therefore, in wet areas adequate sealing of joints is strongly recommended.

Many state highway agencies regularly conduct field evaluations of joint sealant performance. A listing of sealant materials evaluated by these agencies is contained in the AASHTO-FHWA publication entitled, "SPEL-Special Product Evaluation List" (12). An effectiveness rating of sealant materials used by various highway agencies is given in Table 2.

Joint Effectiveness Characterization

There are several methods available to characterize joint effectiveness (14,15). An expression that is popular currently is as follows:

$$JE_d = \frac{du}{dl} \times 100 \qquad (1)$$

where: JE_d = joint deflection efficiency, percent

du = deflection of the unloaded slab

dl = deflection of the loaded slab

In this equation, JE is zero if du is zero and JE is 100 percent if du equals dl. Because of the simplicity of the equation, it is simple to visualize joint effectiveness. Because of recent concern about deflection related distress at joints, use of this equation to characterize joint effectiveness will continue to be popular. It should be noted that knowledge of joint deflection efficiency alone is not sufficient to evaluate performance of a joint. The deflection of the loaded slab should always be considered in evaluating joint performance.

A stress based equation in a form similar to the joint deflection efficiency equation is as follows:

$$JE_s = \frac{\sigma_u}{\sigma_\ell} \times 100 \qquad (2)$$

where: JE_s = joint stress efficiency, percent

σ_u = stress at the unloaded side of the joint

σ_ℓ = stress at the loaded side of the joint

The concept behind JE_s is similar to that for JE_d.

Joint Analysis

Development of analysis procedures for jointed concrete pavements have basically followed two directions. One direction has involved analysis techniques for slabs on elastic foundation to evaluate response of concrete pavements. The second direction has involved studies of individual joint systems. Recent efforts, using finite element analysis techniques, have considered the entire jointed concrete pavement system as a single entity. Several computer programs have recently been developed to conduct analysis of jointed concrete pavements. Two of the recently developed programs are WESLIQUID (16) and ILLI-SLAB (17) developed at the U.S. Army Engineer Waterways Experiment Station and the University of Illinois, respectively. The two programs are similar in capabilities. Both can evaluate joints with dowels, aggregate interlock, and keyways. Dowels are simulated by beam elements and aggregate interlock and keyways by spring elements. Program outputs include stresses and deflections in the slab and load transferred by the load transfer devices.

A comprehensive finite element computer program for analysis of jointed concrete pavement has also been developed as part of the investigation being reported. The program, designated as JSLAB, is discussed in detail in Reference 18.

Detailed analysis at the joint can also be conducted by using multi-purpose finite element computer programs. A commonly used program includes the SAP4 program developed at the University of California, Berkeley (5).

Attempts have also been made to analyze joint systems containing interface contacts, such as keyways. Such an analysis requires use of a "joint" element that permits debonding (separation) of and slippage along interfaces. Development and use of joint elements is still a new area of study. A two-dimensional finite element computer program developed by the Naval Civil Engineering Laboratory incorporated a simple joint element (19). The program was used to study response of keyway joints.

Joint-Related Distress

This section presents a discussion of distress that may develop due to improper design, construction, or maintenance practices related to joints. The distress is evident primarily at or near joints but may occur away from joints as in the case of midslab cracking due to locked joints. Good jointing practices must consider ways to minimize, eliminate, or control the different types of distress.

Some of the principal causes of distress that require remedial action include the following:

1. Poor slab support
2. Erodible support
3. Excessive water
4. Particle infiltration into joints
5. Poor load transfer
6. Excessive traffic loads
7. Sealant failure
8. Long slabs
9. Dowel misalignment
10. Dowel corrosion
11. Soil movements
12. Poor concrete aggregate performance (expansive concretes)

The primary types of distress that are related to joints are cracking, faulting, pumping, spalling, and ravelling. A detailed discussion of joint-related distress in concrete pavements is given in Reference 20.

Pumping in Concrete Pavements

Because a large amount of distress at joints is related to pumping, a separate discussion on pumping is presented.

Pumping is the ejection of water and subgrade or subbase material through joints and cracks or along slab edges due to the action of traffic. When pumping occurs, it leads to faulting and broken slabs. Measures to correct these problems are costly. In addition, they often involve lane closures and traffic disruptions. Thus, the best approach is to ensure that adequate consideration is given to the potential for development of pumping and that necessary measures are taken during design and construction to guard against such an eventuality. For pumping to occur, three factors are necessary. These are:

1. Presence of free water
2. Heavy axle loading
3. Erodible support material

For free water to exist under a slab, void space under the slab has to be present. The void space initially develops due to upward slab warping. Warping results from moisture differentials between slab top and bottom. Warping is almost never recoverable. Curling due to temperature differentials between slab top and bottom modifies warping behavior. Along edges and joints, loss of support due to warping and curling may extend inward 18 to 36 in. depending on slab dimensions. Additionally, under heavy loading permanent subbase/subgrade deformation may take place, thus aggravating an already serious condition. Warping and curling deformation and extent of loss of support can be estimated using finite element analysis. An example is shown in Fig. 2.

Under very heavy loading resulting in large deflections and in the presence of free water, water escapes through joints and cracks and along edges at high velocity. Over a period of time, the high velocity water begins to erode the surface of the subbase/subgrade.

Surface erosion begins as a particle by particle phenomenon, due to the relative instability of a given particle as compared to the remainder of the surface. This instability can arise from orientation, poor bonding, or particle structural matrix defects.

Another action that may occur is the development of high pore pressure in the subbase/subgrade material. If the pore pressure is high, it may create a condition similar to liquification in that the material possesses no strength. The pore pressure magnitude may be sufficient to break the bond that holds the soil or subbase matrix together. In addition, channeling or piping may be created due to movement of fine material in the subbase and subgrade.

Pumping can be eliminated or controlled by giving adequate considerations to the following items:

1. Subsurface drainage
2. Load transfer at joints to reduce slab deflections
3. Nonerodible high quality subbase
4. Positive joint sealing

As stated before, for pumping to occur free water has to be present. Pumping does not occur in pavements that incorporate a properly designed subsurface drainage system. Field permeability tests at pavement sites show that drainage is almost nonexistent under many old concrete pavements. The use of open-graded drainage layers together with collector drains is being incorporated in new construction by many highway agencies to provide effective drainage.

Analysis of Jointed Concrete Pavement

As discussed previously, recent efforts to understand the behavior of jointed concrete pavements has involved the use of the finite element method for structural analysis. As part of the present study, a finite element computer program, Program JSLAB, has been developed to analyze jointed concrete pavement sections. Details of the program are given in Reference 18.

Program JSLAB can analyze concrete pavement sections consisting of a large number of slabs. In addition, a two-layer pavement system can be considered. Layers may be bonded or unbonded. Slab sections are represented by rectangular plate elements. Joints are modeled as doweled, aggregate interlock, or keyed. Other types of shear type load transfer devices can also be modeled with minor modifications to the program. Dowels are represented as thick beams. Aggregate interlock and keyways are represented by springs. Load input is in terms of wheel loads placed at any location on the slabs. A rectangular tire imprint is used.

The subgrade is modeled as a Winkler (spring) foundation. Loss of support, variable support conditions, as well as variable material properties can be considered. Also, curling due to linear temperature gradient through the slab thickness can be analyzed for a single layer system.

For doweled joints, dowel properties such as diameter, modulus of elasticity, and modulus of dowel/concrete reaction are inputs. For aggregate interlock and keyway joints, a spring stiffness value is required. This value represents the load deflection characteristics of the joint. The stiffness value can be determined from field or laboratory tests. The computer program considers allocation of stiffness parameters of the LTD at actual locations. This feature is very useful for analysis of jointed slabs incorporating nonuniformly spaced LTDs at joints.

Analysis of Pavements with a Tied-Concrete Shoulder

An analysis was conducted for a 36,000 lb tandem axle load (TAL) placed at a corner of a transverse joint and 20 in. inward from the corner. The keyway of the tied shoulder is represented as a spring having a stiffness of 25,000 lb/in. per in. length of joint. Figure 3 shows the effect of a tied shoulder on magnitudes of dowel shear. For the TAL placed 20 in. inward from the corner, the effect of a tied shoulder on dowel shear is negligible. However, for the TAL placed at the corner location, use of a tied shoulder results in a reduction of dowel shear to 2000 lb from 2700 lb without a tied shoulder. This is a significant reduction. Also, slab corner deflections are considerably reduced when a tied shoulder is used. Thus, use of tied shoulders is expected to result in significantly improved pavement performance.

In a recent field study conducted for the Minnesota Department of Transportation, strain and deflection measurements were obtained at two projects incorporating a tied concrete shoulder (21). Study results indicated that strains and deflections under truck loading along a tied-shoulder joint were less than those along a free edge. Based on an analysis using the AASHTO traffic equivalence factors, the study concluded that a pavement with a tied-shoulder can conservatively carry twice the truck traffic compared to a pavement without a tied-shoulder (21). Thus, performance at a joint can be expected to be better when a tied-shoulder is incorporated as part of pavement design.

Nonuniformly Spaced Doweled Joints

As part of the study to improve rigid pavement joints, the use of fewer nonuniformly spaced dowels was investigated. Reducing the number of dowels used per joint can result in significant economy. Three cases of nonuniformly spaced doweled joints were analyzed.

Case 1 considers seven dowels positioned at the joint as shown in Fig. 4(a). The seven nonuniformly spaced dowels were located at 6, 18, 30, 60, 90, 120, and 138 in. from the shoulder edge. Calculated dowel shears are shown in Figs. 4(b) and 4(c) for a 36,000 lb TAL placed at a joint and at a corner, respectively. Results are compared in Fig. 4(a) and 4(b) to the case of a joint with twelve uniformly spaced dowels.

Maximum dowel shears for the 7-dowel joint and the 12-dowel joint are about the same for the TAL placed at the corner. Maximum dowel shear for the 7-dowel joint is higher than that for the 12-dowel joint when the TAL is positioned at the joint but away from the corner. However, the maximum dowel shear at the corner dowel when the TAL is placed at the corner controls the doweled joint design.

Case 2 considered six dowels positioned at the joint as shown in Fig. 5(a). The six nonuniformly spaced dowels were located at 6, 18, 36, 81, 105, and 135 in. from the shoulder edge. Calculated dowel shears are shown in Figs. 5(a) and 5(b) for a 36,000 lb TAL placed at a joint and at a corner, respectively. The response is similar to that obtained for the 7-dowel joint.

Case 3 also considered six dowels, but located at 6, 24, 42, 90, 117, and 135 in. from the shoulder edge. Results for Case 3 were similar to those obtained for the 7-dowel joint. In all three cases, stresses and deflections for the nonuniformly spaced doweled joints are similar to those obtained for the twelve dowel joints with uniform spacing. Use of fewer dowels per joint would reduce problems associated with misaligned dowels as the total number of possibly misaligned dowels would decrease in proportion to the number of dowels used.

Analysis of Widened Lanes

Performance along both transverse and longitudinal joints can be improved by use of a widened outside lane. When a widened outside lane is used, the corner region effects are eliminated since the slab corner is far removed from the wheel paths of most of the truck traffic. Similarly, the shoulder joint is also far removed from the traffic wheel path.

The case of a 3-ft outside lane widening was analyzed for an 18,000 lb SAL and a 36,000 lb TAL at a lane corner and along a lane edge as shown in Fig. 6. Analysis results for a 9-in. thick pavement are presented in Table 3 for lane corner loading. It is seen from Table 3 that for the case of lane corner loading, a 3-ft lane widening with doweled transverse joint is comparable to a 12-ft wide pavement with tied-concrete shoulder and doweled transverse joints. Also, a 3-ft lane widening with no load transfer at transverse joints is comparable to a conventional pavement with doweled transverse joints.

For the case of lane edge loading, the lane widening also results in significantly lower magnitudes of deflections and stresses along the edge. Thus, it is seen that lane widening can significantly improve pavement performance by lowering slab deflections and stresses.

Results of analysis using a 20-in. lane widening also indicate that pavement responses along the longitudinal joint and corner locations are greatly improved.

Summary and Recommendations

This section discusses improvements in concrete pavement jointing system by means of improving structural performance at joints. Other improvements such as those related to dowel placement, joint forming, dowel corrosion, and joint sealing are also important. However, these improvements can generally be controlled by better construction specifications, techniques, and materials.

At properly controlled paving projects, problems related to late sawing or poor quality control do not develop. As discussed, there is no definitive consensus regarding acceptable levels of dowel misalignment. At the same time, it is not practical to precisely position dowels as sometimes specified. Therefore, until more field data are obtained, the FHWA directive on dowel placement should be followed. This directive states that, "close tolerances for dowel placement are extremely important for proper functioning of the slab and for long-term performance," (8) and that, "care must be exercised in both specifying dowel placement tolerance and in evaluating the adequacy of construction placement" (8)

To ensure long-term durability of doweled joints, coated dowels should be used in areas where deicing salt application is common during winter months. Epoxy coating or other coatings that have shown good performance should be specified for use in these areas.

Proper specifications for sealant materials and installation procedures are critical to long-term performance of joints. Properly installed neoprene or low-modulus silicone sealants show potential for long lasting performance. In addition, use of sealants that have a performance warranty should also be considered. It must be stressed that the ability of the selected sealant to perform under local service conditions must be carefully checked. For example, certain cold-poured sealants will lose adhesion to concrete if the sealant remains completely submerged in water for a short period of time.

Improvements in the structural performance at joints can be achieved by reducing pavement deflections and stresses. An ideal joint is one at which relative deflections across a joint approaches zero and the absolute deflection under load at the joint approaches that at the slab interior for the same load. It should be noted that if deflection improvements are obtained, then improvements in stress responses will also be attained.

Two types of improvement in the structural performance at joints are discussed. These relate to improvements that result in better performance and those that provide the same performance at lower cost.

Nonuniformly Spaced Dowels

Conventional doweled joints incorporate dowels uniformly spaced at 12 in. However, dowel location is critical only in the vicinity of the outside slab corner. Therefore, use of a large number of dowels along the joint away from the outside corner is not warranted. Dowel use can be optimized by locating more dowels at the wheel path near the outside corner and fewer at interior portions of the joint.

Based on results of the analysis presented earlier in this paper the following patterns of dowel placement are recommended for use at outside lanes.

1. Six dowels located at 6, 18, 36, 81, 105, and 138 in. from the shoulder edge
2. Seven dowels located 6, 18, 30, 60, 90, 120, and 138 in. from the shoulder edge

However, many dowel basket fabrication processes are set for baskets with dowels spaced at 12 in. Therefore to achieve cost savings it is desirable that this fact be taken into account when specifying use of nonuniformly spaced dowels.

The following dowel spacing is recommended to incorporate the constraints of the fabrication process requiring dowels spaced at intervals that are multiples of twelve:

1. Six dowels located at 6, 18, 30,78, 102, and 126 in. from the shoulder edge
2. Seven dowels located at 6, 18, 30, 66, 90, 114, 138 in. from the shoulder edge

With the above spacings, no major changes would be required in the existing fabrication process designed for twelve uniformly spaced dowels. The only change required is the elimination of some of the interior dowels.

It should be noted that exact lateral location for only the first three outside dowels is important and some lateral placement variations in the interior dowels may be permissible. For 20 ft joint spacing, the number of dowels eliminated by using six dowels per joint is 6,336 for a 4-lane mile. Thus, substantial savings can be achieved by use of fewer, nonuniformly spaced dowels. Use of fewer dowels per joint would also reduce problems associated with misaligned dowels as the total number of possibly misaligned dowels would decrease in proportion to the number of dowels used.

Tied-Concrete Shoulder

Tied-concrete shoulders have been used adjacent to mainline concrete pavements in the United States for almost 20 year. Use of tied-concrete shoulders improve mainline pavement performance by reducing edge and corner deflections and edge strains. In addition, there is less water infiltration along pavement edges due to better pavement shoulder joint sealing.

Analyses made using Program JSLAB show that calculated corner and edge deflections are greatly reduced when a tied-concrete shoulder is used. Use of a tied-shoulder improves pavement response along the shoulder joint and also at transverse joints. In addition to lower corner deflections, use of a tied-shoulder also results in reduced dowel shears for dowels located in the vicinity of the corner at a joint. Thus, performance of a doweled joint can be further improved by using tied-concrete shoulders. The following options for tied-shoulder use are recommended and are listed in a descending order of priority:

1. Shoulder thickness same as mainline slab across entire width

2. Shoulder tapered from thickness of the mainline to not less than 6 in. at outside edge of shoulder
3. Shoulder thickness less than mainline slab thickness but not less than 6 in

Shoulder width and geometrics should follow the normal practice of the highway agency. However, shoulder width should be at least 6 ft to derive maximum structural benefit. It should be noted that if shoulder thickness is less than mainline slab thickness, then a well draining subbase should be used under the shoulder. Otherwise, a "bath-tub" type condition may be built into the pavement that could lead to future problems with pumping and weak support under the pavement.

Widened Lanes

Use of widened lanes has been suggested as an efficient means of improving pavement response under load. When a widened lane is used, the corner region effects are eliminated since the corner region is far removed from the wheel paths of most of the truck traffic. Similarly, the shoulder joint is also far removed from the traffic wheel path. Thus, critical pavement responses under load are less severe when a widened lane is used.

In addition to reduced levels of pavement responses to load, lane widening also makes these responses less sensitive to the effects of slab warping and curling. Slab warping and early morning slab curling result in lifting of the slab from the subbase at edges and corner. Warping and curling may leave slabs unsupported for distances of 4 to 5 ft at slab corners, and 2 to 3 ft at slab edges.

Because of warping and curling, slab deflections under load are influenced by time of loading with higher deflections during early morning and lower deflections during the period after noon. However, with widened lanes, since primary traffic loading is away from the slab edges, the effect of loss of support along edges would not be as detrimental. Analyses made using program JSLAB show that a 3-ft lane widening without dowels at transverse joints produces corner deflections equivalent to those for no widening but with a doweled joint. If lane widening is used in addition to doweled joints, corner deflections are even more reduced. The reduced deflections would minimize problems of pumping and faulting at joints.

Lane widening may be used by itself or may be incorporated with a tied-concrete shoulder. Use of lane widening requires that more attention be paid to concrete curing and timing of sawing of longitudinal joints. At some projects, isolated cases of longitudinal shrinkage cracking has been reported a few feet from the edge of the widened lane.

The following lane widening options are listed in order of decreasing preference:

1. 3-ft widening
2. 2-ft widening
3. 1-ft widening

Lane widening greater than 3 ft is not recommended because of potential for longitudinal cracking.

Shorter, Smaller Dowels

Adequate structural performance under highway type loading can be obtained by using dowels with a length of 16 in. as compared to conventionally used 18-in. long dowels. Use of shorter dowel length is recommended because shorter dowels also develop lower restraint to slab end movement in case of dowel misalignment or dowel corrosion. As for dowel size, use of 1, 1-1/8, or 1-1/4 in. diameter dowels may be specified for 8 to 10 in. thick pavments.

Improved Subbase Support

Performance of rigid pavement joints is greatly influenced by the quality of subbase and subgrade support. The quality of subbase and subgrade determines the level of deflection under traffic load. If slab deflections are large, then pavement performance is adversely affected. The subbase type and thickness should be selected to ensure that permanent deformation under repeated loading is kept at a minimum.

In addition to the requirement of improving the structural response of a pavement, the subbase selected should also be free draining and non-erodible to minimize problems related to pumping.

New Load Transfer Devices

As part of the present study, an attempt was made to develop new load transfer devices that would be an improvement over currently used solid round steel dowel bars. The main area of weakness associated with use of round steel dowel bars is the care required to ensure proper alignment of the bars.

Therefore, in the investigation to develop new load transfer devices, the primary requirement established was that the new load transfer device be not sensitive to construction or installation requirements. It is not considered difficult to develop a device that can provide the load transfer capabilities across a joint. However, development of a practical device that ensures minimum problems with construction and allows unrestrained slab end movements is not simple.

Several configurations and shapes of single-component and two-component devices were studied. For two-component devices, the amount of gap between the two components is of major concern. Because load transfer for two-component devices is by shear only, only a small bearing area is required between the two components. However, because cracking cannot be ensured through the middle of the two component devices, the effectiveness of the two-component devices cannot be guaranteed.

After a review of various patented devices and a study of various shapes and configurations, the project staff came to a conclusion that solid dowel bars were the most cost-effective mechanical load transfer devices. Cost of fabricating and installing any other newly developed load transfer device would be prohibitive for new construction.

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Table 1. Calculated Restraint to Cause Midslab Cracking in a 10-in. Thick Slab.

Age (Days)	Tensile Strength, psi	Compressive Strength, psi	Concrete Modulus, million, psi	Allowable Strain, millionth	Restraint to Cause Cracking, lb per foot width
1	87	700	1.5	58	10,400
3	184	1800	2.3	80	22,100
7	258	2750	2.9	89	31,000
28	333	3800	3.4	97	40,000
365	425	5250	4.2	102	51,000

Notes:
1. Before midslab cracking occurs, spalling may take place around load transfer device.
2. Tensile stress in the form of curling restraint stress and load stress also exist. Therefore, even a reduced level of restraint can contribute significantly to crack formation.
3. Age, strength, and modulus relationships are general and are used for illustration only.

Table 2. Effectiveness Rating of Sealant Materials (Ref. 13).

Material Type	Number Listings by Agencies	Effectiveness Rating Range	Average Effectiveness Rating[a]	Comments
Asphalt Cement	11	Poor-Good	3.15	Does not penetrate; must be resealed often.
Cutback Asphalt	17	Very Poor-Good	2.29	Generally requires blotter; relatively short life.
Emulsion	10	Very Poor-Good	3.22	Seasonal. Generally must be resealed often.
Rubberized Asphalt, Cold Applied	1	Good	4.00	Labor intensive.
Rubberized Asphalt, Hot Applied	36	Very Poor-Very Good	4.12	Relatively long life.
Cutback Asphalt with Rubber	2	Good-Very Good	4.75	Limited data; good performance.
Asphalt Emulsion with Rubber	1	Good-Very Good	4.50	Limited data; good performance.
Performed Filler	2	Fair-Good	3.50	
Silicone Dow 888	7	Good-Very Good	4.60	Relatively limited data but good performance to date.
Preformed Joint Seal	5	Poor-Very Good	3.60	Costly.
Other (PVC, Polyure-thane, (Vulken)	6	Very Poor-Good	3.25	Vulken rates very poor.
Tar	2	Very Poor	1.00	Short life, too rigid.
Catalytically Blown Asphalt	1	Good	4.00	

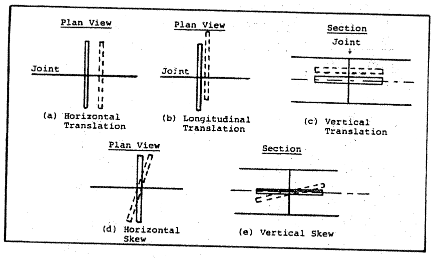
[a]Rating Scale: Very Good - 5.00; Good - 4.00; Fair - 3.00; Poor - 2.00; Very Poor - 1.00

Table 3. Results of Lane-Widening Analysis for Corner Loading.

Load	Subgrade Modulus, pci	Corner Load Deflection, in.			
		Conventional Pavement	Pavement with Tied Shoulder	3-ft Lane Widening, Undoweled Joints	3-ft Lane Widening, Doweled Joints
18 kip SAL	100	0.032	0.023	0.036	0.019
	150	0.023	0.016	0.027	0.014
	200	0.017	0.012	0.019	0.010
36 kip TAL	100	0.042	0.027	0.045	0.025
	150	0.032	0.020	0.033	0.018
	200	0.022	0.014	0.022	0.012

Notes:
1) Slab thickness = 9 in.
2) Conventional pavement is 12 ft wide with doweled transverse joints.
3) Pavement with tied shoulder has doweled transverse joints.

Figure 1. Effects of dowel misalignment.



Type of Misalignment	Effect on		
	Spalling	Cracking	Load Transfer
a	-	-	(Yes)*
b	-	-	(Yes)*
c	Yes	-	(Yes)*
d	Yes	Yes	Yes
e	Yes	Yes	Yes

*Effect will depend on amount of translation

Figure 2. Calculated warping deformation.

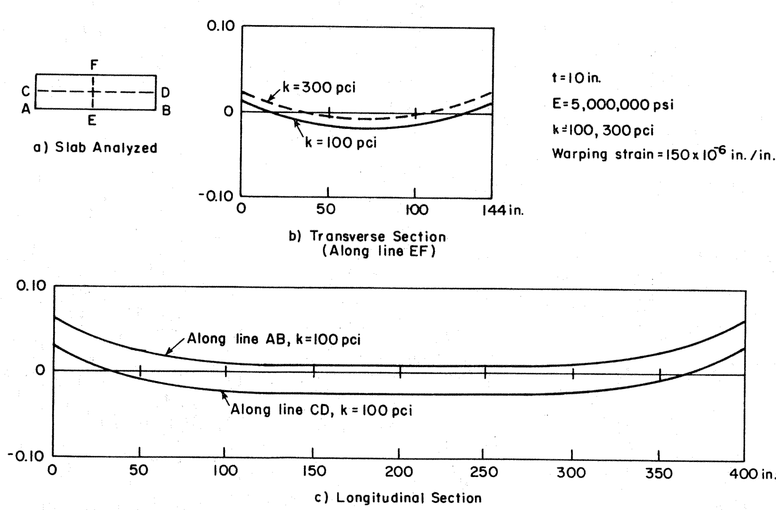


Figure 3. Calculated effect of tied shoulder on dowel shear.

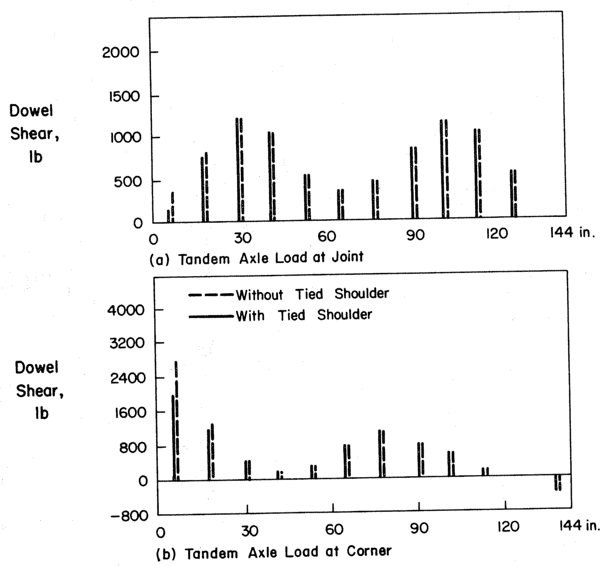


Figure 4. Calculated responses for joint with seven non-uniformly spaced dowels.

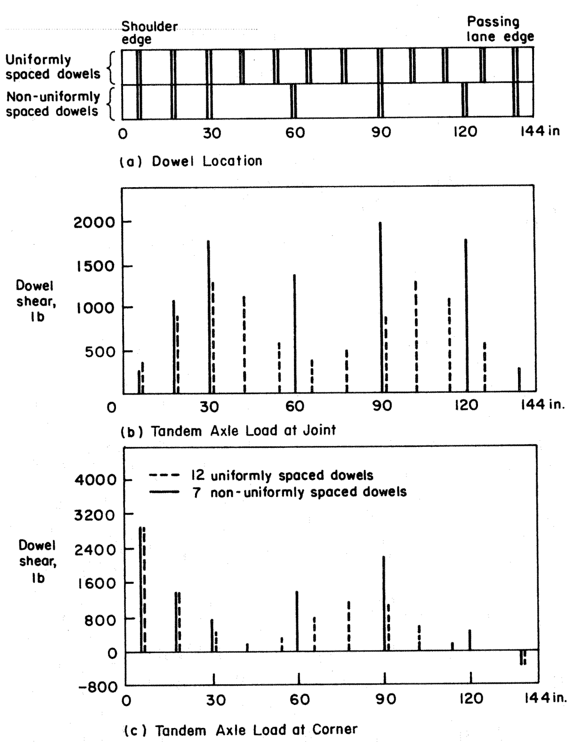


Figure 5. Calculated responses for joint with six non-uniformly spaced dowels - Pattern 1.

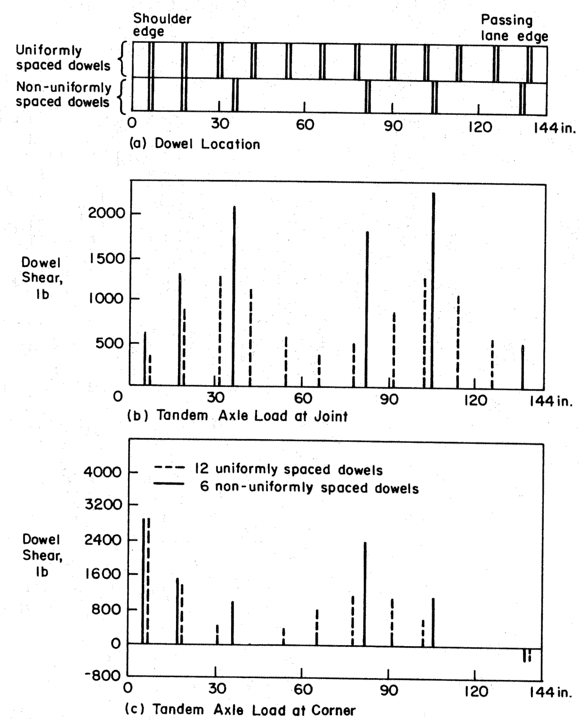


Figure 6. Load layouts for pavements with 3-ft lane widening.