The Design of Plain Doweled Jointed Concrete Pavement

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INTRODUCTION

The use of dowel bars as a method of load transfer in jointed concrete pavements has been a controversial topic among highway engineers for years. Today many engineers agree to the use of dowels for expansion joints and for long reinforced slabs. However, there is still disagreement as to the use of dowels for heavily trafficked shorter slabs. Too often in the past, inadequate consideration has been given to the design of the concrete pavement structure as a complete structural system. All the components of a rigid pavement must be able to function adequately together as a structural system as well as being able to function successfully by themselves.

The rigid pavement design procedure has normally consisted of either a fatigue analysis or serviceability (roughness) analysis to determine the slab thickness required for a certain traffic level. This design procedure was sometimes inadequate because it didn't take into consideration other components of the complete structural system and their interaction within the system. Too much emphasis was often placed on the thickness. These inadequacies have led to the premature failure of some pavements, particularly when combined with the effects of heavy traffic and poor drainage conditions.(1)

The significant deterioration observed over the decades in many pavements that were designed and constructed in accordance with the conventional codes of practice have resulted in a considerable amount of research. A uniform design and construction manual for all States on load transfer for concrete pavement joints is impractical due to the wide variety of environmental and other conditions. However, there are uniform factors each State should take into account when deciding whether or not to use load transfer devices.

As dowels cannot be economically retrofitted on short slab pavements, they should be installed initially to prevent undesirable pavement faulting or differential slab elevations due to foundation settlements, consolidation of base or subbase under traffic, frost heave, or swelling soils. Until an improved design procedure for undoweled pavements is available that can reliably predict performance on an individual project, the use of dowels and short slab lengths should be considered for most pavements with other than light truck traffic.

REPORT OBJECTIVE

The main objectives of this report are to summarize the findings of past reports, to communicate the experiences of the various States and foreign countries, and to emphasize the need for dowels as a positive method of load transfer on most, if not all, medium and heavy truck traffic routes with plain jointed concrete pavements. Of the three basic types of concrete pavements--jointed plain concrete pavement (JPCP-doweled or undoweled), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP), this report will concentrate on the transverse joint design for JPCP. However, much of the information would apply to doweled joints in JRCP also.

JOINT FUNCTIONS AND DISTRESSES

Joints are provided in concrete pavements to relieve internal stresses caused by initial shrinkage due to moisture loss during curing, restraint by base or subbase friction during longitudinal expansion and contraction caused by temperature changes, and thermal and moisture gradients between the top and bottom of the slabs. Joints are the weakest parts of the system. If internal stresses are not relieved by transferring loads adequately from one slab to the next, critical distresses such as faulting, pumping, spalling, and corner cracking will occur. Figure 1 illustrates typical types of distress at pavement joints.(2)

Procedures for preventing joint problems should be developed with a full awareness of their causes. Infiltration of incompressible material into joints reduces the space available for expansion of the slabs, causes stresses to develop, and leads to spalling, restraint cracking, blow-ups, and compression failures. Late or inadequate depth of sawing of joints causes cracks to occur at other than designed locations. D-cracking is caused by low resistance to freeze-thaw cycles and is associated with the use of unsound aggregates. Alkali-aggregate reaction is also a material-related cause of distress in a number of pavements. The use of unsound aggregates will cause premature failure of even well-designed pavements and must be avoided. Pumping is caused by the slab rocking/pumping action of traffic loads on pavements with free water above or within an erodible base or subgrade. The pumping action reduces the slab support by the displacement of fine solids from beneath the leave slab to beneath the approach slab (figure 2). This pumping action usually results in faulting (an elevation difference between the leave and approach slabs) and subsequent cracking of the slab if positive load transfer is not provided. Faulting may also be caused by the consolidation of the material beneath the leave slab. This is considered to be a significant factor for satisfactory long-term performance (30 to 40 years) in pavements with open-graded subbases, even though pumping and faulting should not be a problem. Unless conditions causing the faulting are corrected, elevation differences between adjacent slabs will become progressively greater. However, in many cases, it is uneconomical or impossible to correct the causes of the problem without reconstructing the pavement. These differences in elevation contribute to the failure of joint seals through shearing action as the joint faces move vertically, allowing water and solids to enter the joints and further aggravate conditions.(2,3,4)

Prevention of these and other causes of joint related distress can be accomplished by using sound materials and good joint design and construction procedures. Proper transverse joint design requires the provisions for adequate load transfer (usually by the use of round dowel bars); well-compacted drainable, nonerodible or dense-graded impermeable bases; and selection of appropriate slab lengths and joint shape factor so joint sealants can be maintained and intermediate slab cracking prevented. The use of corrosion-resistant dowel bars and tie bars between adjacent slabs is also critical to long-term pavement performance. Some doweled joints have stopped functioning in as few as 5 years due to corrosion of the dowel. Dowel bar corrosion was the primary cause of joint lockup in the rigid pavement test sections of the extended AASHO Road Test.(5)

METHODS OF LOAD TRANSFER

Load transfer across transverse joints is provided by several mechanisms: subbase support, aggregate interlock (if the joint opening is sufficiently small), and mechanical load transfer devices, such as dowel bars.(3) The use of well-compacted dense-graded granular or stabilized bases with load transfer by aggregate interlock is normally sufficient to prevent pumping of plain concrete pavements having joint spacings less than 15 ft in dry arid climatic areas with limited temperature variations and carrying low truck volumes. Where medium or heavy truck traffic is involved, it is almost always necessary to provide more positive load transfer with dowels to prevent or minimize pumping and loss of support resulting in faulting of the slabs.

Stabilized bases produce greater slab support thereby reducing joint deflections and providing some protection against pumping. Rigid subbases or asphalt-treated bases which adhere to the concrete during the first 10 days reduce the variability of the joint openings whereas a more flexible material or an untreated material may lead to large openings on some joints particularly during the first few months of the pavements life. However, adherence of the concrete slab to the base or subbase may result in undesirable longitudinal or transverse cracking early in the pavements life. The use of a cement-treated material appears to reduce joint openings by about 20 percent compared with an untreated material.(6) Also, there is generally less loose material available for movement in stabilized than unstabilized materials. However, without proper construction practices, such as good surface material compaction and cementing after the trimming operation, uncemented particles can develop even in stabilized bases.(2) For example, Pennsylvania recently reported on the 15-year performance of a 7-in plain undoweled portland cement concrete pavement (15-ft joint spacing) with skewed joints on 4-in of aggregate-cement base course. The traffic increased from 1750 ADT with 9 percent trucks in 1969 to 2946 ADT with 4 percent trucks in 1987. By 1987, 13 percent of the joints were faulted less than 1/4-in. As a result, the report recommends the consideration of use of dowels on all JPCP regardless of ADT.(7) Pumping and faulting can be minimized by using lean concrete rather than cement treated bases. However, when poorly drained, the stabilized bases and/or the concrete slab itself is erodible and subject to deterioration under these adverse conditions. The use of lean concrete bases will reduce the rate but not the occurrence of faulting in undoweled slabs with medium or heavy truck traffic. Granular subbases are required beneath the lean concrete bases to prevent pumping of the fine-grained subgrade under these traffic conditions, particularly when undoweled slabs are used. Here again, the total pavement system must be considered to assure satisfactory long-term performance.(8)

Aggregate interlock results from the coarse aggregates interlocking across the width of the joint. Larger maximum size coarse aggregate may improve aggregate interlock, but might be more susceptible to D-cracking. Aggregate interlock depends on the angularity and durability of the coarse aggregate and the width of the joint opening. It is only effective if joint openings are very small, which suggest that joint spacings be very short. Research results indicate as long as a joint opening is less than .045-in, the initial efficiency of the joint will be high. As joint openings increase to more than about .05-in, the joint efficiency decreases. However, for long-term efficiency, an average joint opening of only about .025-in or less must be maintained. Figure 3 shows the influence of joint opening on load transfer effectiveness for gravel and cement treated subbases. If the joint has a greater opening, the aggregate wears away due to deflection caused by truck traffic, resulting in increased deflections and a decrease in joint efficiency. Also, some joints open wider than others and are much more susceptible to pumping and faulting. Investigations of load transfer efficiencies have indicated that aggregate interlock does not provide adequate load transfer in heavily trafficked highway pavements in most situations. (1,7,9,10)

The use of recycled D-crack susceptible aggregate is often possible if the pavement is crushed to pass the 3/4-in sieve so it will meet freeze/thaw durability test requirements. However, the smaller size coarse aggregate may not provide adequate aggregate interlock, so short joint spacing and dowel bars for load transfer should be considered under these conditions also.

LOAD TRANSFER IN DOWELED SLABS

Typically, dowels are round, solid, black steel bars which may be coated with epoxy or plastic or clad or wrapped with monel or stainless steel to prevent or reduce corrosion. Dowel bars serve two principal purposes. First, they maintain horizontal and vertical slab alignment so thermal and moisture expansion and contraction will not misalign the slab. Second, provided the conditions concerning their characteristics and utilization are complied with, dowel bars provide good load transfer. This positive load transfer reduces deflections which prevent or significantly reduce pumping of the fine material from under the slab, base or subbase, or shoulder, which would eventually lead to faulting. Dowels not only improve load transfer quality and durability but also make load transfer variation less sensitive to joint opening. If dowels are properly positioned, well-dimensioned, and durable, they will prevent the faulting process or inhibit it significantly. Provided the dowels are not overstressed and deformed or misshaped, the vertical displacement of the approach and leave slabs cannot be greater than the free space in the cavity of the concrete around the ends of the dowels. The vertical displacements at the joints of numerous doweled pavements indicate a certain amount of faulting will eventually occur on some sections. It must be noted the amount is greatly reduced by the combined effects of reduced sensitivity to joint opening and good durability. A bond breaker is needed on most dowels so the slabs are free to move horizontally due to temperature and slab moisture variations. This bond breaker should be uniformly thin so voids around the dowel or other looseness is not built into the joint system.(3)

The Proceedings of the 1987 Brussels World Road Congress report:

Tests have been performed on the NARDO (Italy) track where different modes are being tested: 18-cm (7.1-in) and 24-cm (9.5-in) slab thickness, 4- and 5-meter (13.1-ft and 16.4-ft) slab length, doweled and non-doweled joints, all of it lying on 15-cm (5.9-in) of cement-treated gravel. The use of dowels multiplied its life by 4.5. According to overloads, that may reach 50 percent of the authorized weight in case of heavy traffic, the pavement should not be less than 24-25 cm (9.5-in - 9.9-in).(11)

Based on a 1985 reevaluation of their concrete design procedure, the Minnesota Department of Transportation made the following recommendation:

For the present time, dowel bar placement on mainlines, ramps and loops should meet the following criteria using the 20th year design lane daily count of tractor semi-trailers (TST's):

a) 120 TST's for a granular subgrade when high quality concrete aggregate is used.
b) 100 TST's for a plastic subgrade when a high quality concrete aggregate is used or for a granular subgrade when carbonate aggregate is used.
c) 80 TST's for a plastic subgrade when carbonate aggregate is used.

This recommendation was also supported by the Minnesota concrete industry because of the adverse publicity received when some recently constructed undoweled pavements faulted severely in less than 10 years.(12)

DESIGN PROCEDURES

Although a significant amount of practical experience and research has been conducted over the years, no comprehensive uniform design and construction procedure exists to date for doweled joints. However, a microcomputer program PFAULT has been developed to predict the faulting of doweled and undoweled pavement. This program can assist designers by providing a procedure to check proposed designs to see if the faulting predicted is acceptable. A modified version, PFAULT 1.2, has been developed and is undergoing additional testing. The development of this procedure is described in reference 10.

Existing design procedures do not provide adequate guidance on the design of jointed plain PCC pavements to assure that harmful pumping and faulting will not occur. The widely varying climatic and geologic conditions from State to State and country to country, the variations in numbers and magnitudes of applied traffic loadings in each locality, and the simple theoretical treatment of the problem (still fairly elementary and only applicable to highly idealized conditions) has resulted in a large degree of empiricism derived from local experience to enter the design and construction approaches of each agency.(10) An excellent summary of international literature regarding "Load Transfer at the Contraction Joints and Design of Concrete Pavements" was prepared in 1979 by Subcommittee No. 1 of the PIARC Technical Committee on Concrete Roads.(13)

Design of dowels is dependent upon several factors: pavement design loads and repetitions, dowel shear and bearing stresses, slab thickness, size and durability of coarse aggregates, concrete flexural or compressive strength, concrete bearing strength, subbase support value, climatic effects, stresses induced by curling and warping, and loss of subbase support usually due to poor drainage conditions. The type of bar most frequently used today for load transfer is the round black steel dowel bar. They are commonly alternately embedded in the concrete on one side of the joint, while the other side is allowed to move along its axis by the use of grease and similar debonding coatings. Expansion caps or sleeves must be provided at all expansion joints. Design factors that must be considered for dowels include diameter, length, spacing, type of bond breaker and corrosion protection, and the required spacing of the contraction joints in order to limit and control the magnitude of stresses developing in each bar and in the surrounding concrete. Construction requirements include proper installation of the dowels by the use of wire baskets or dowel implanters and procedures to verify the accuracy of placement. Similar verification procedures are needed to assure tie bars are placed according to plan requirements.(3)

DOWEL DIAMETER

Rigid pavement design procedures used in the past have been based on mechanistic concepts (e.g. calculating critical stresses and fatigue damage). These previously used procedures have often resulted in dowels of too small diameter to perform satisfactorily. Today, for a proper design, both the mechanistic and empirical approaches should be employed to design a pavement that will perform adequately under the increasing truck traffic.(1) Recently completed research has improved guidance on the design of doweled pavements.(10)

One of the highly overlooked aspects of rigid pavement design was the effect dowel bar stresses had on the faulting of transverse joints. When loads are applied at a joint, a portion of that load is transferred through the dowel bar to the next slab. The dowel bar immediately under the load carries the major portion of the load with the other dowels assuming progressively lesser amounts. Tabatabie et al. concluded that "only the dowels within a distance 'L' (radius of the relative stiffness of the slab-foundation system) from the center of the load are effective in transferring the major part of the load." They proposed that a linear approximation to the dowel shear force diagram be used, beginning with a maximum under the load and diminishing to zero at a distance of "L" from this point.(10) In 1986, an instrumented 11-in thick JPCP, with skewed joints spaced 20-ft apart (with varying numbers of dowel bars in each traffic lane) on an open-graded recycled concrete subbase with deep longitudinal underdrains was constructed on I-80 in western Iowa. This data should provide valuable data to verify these assumptions under actual heavy truck traffic.(14)

Finite element studies by Tabatabie et al. also led to the conclusion that the dowel diameter and concrete modulus of elasticity have a very significant effect on the maximum dowel deflection and concrete bearing stress. Slab thickness and base, subbase and subgrade modulus play a much lesser role. A graph of concrete bearing stress versus dowel diameter for various dowel spacings is provided in figure 4. The enormous effect that dowel diameter has on bearing stress is evident. In a sensitivity analysis of the proposed model PFAULT for determining the maximum bearing stress, the dowel diameter clearly emerged as the most important of the variables considered. The reduction of bearing stress using dowels of 1.5 to 2.0 inches in diameter was dramatic. The sensitivity of the rest of the parameters used to determine the maximum bearing stress was considerably smaller. It was found that "the solution is more sensitive to those variables related to the dowel bars used (i.e., dowel diameter, spacing and modulus of support) than to the pavement system characteristics (e.g., slab modulus and thickness, subgrade modulus, and joint width)." The dowel spacing was found to have a smaller effect on bearing stress with larger diameter dowel bars.(10) The diameter of the dowel is commonly 1/8 of the pavement thickness, but, observing these results, it may be more economical in the long run to use the larger diameter dowels.

Recent FHWA research has indicated that Type 316 stainless steel pipe with .109-in wall thickness filled with concrete (1.66-in outer diameter) may be a very cost-effective corrosion-resistant alternative to smaller diameter epoxy or plastic-coated solid black steel bars. It is also possible, but expensive, to use solid stainless steel dowel bars in highly corrosive environments or where a high degree of reliability is desired.(15) The use of extra strength hollow pipe (1-in inside diameter) filled with asphalt or portland cement concrete has been allowed for about 10 years as an alternate if 1 1/4-in solid black steel bars were required. The extent of use of this alternate and the resulting pavement performance is not known.(16)

DOWEL LENGTH

Dowel bar lengths are commonly 15 to 18-in, with the shorter bars being used for shorter slabs (for assumed high-strength concrete and precise dowel placement). Studies show that embedment lengths of six diameters are adequate for dowels 1-in and larger.(17) According to a 1987 summary of State highway practices for rigid pavement joints, 26 of the 30 States currently specifying dowel bars in their pavements use lengths of 18-in. The other four used 15-,22-, or 16-inch lengths. These longer lengths have been used to compensate for the uncertainties of placement during construction. If the joint can be formed or sawed accurately over the mid-point of the dowel, 6-in embedment would be adequate when short slabs are used, making the use of 12 to 14-in dowels feasible. However, an improved non-destructive method to verify that the dowels are located accurately relative to the joint is needed before this change can be effectively implemented. With short joint spacings, the opening is less and if the length of embedment is adequate, greater misalignment can be tolerated without causing distress at the pavement joint. There is a concern that if very large rigid dowels are used, it could increase pavement stresses. However, 1.625-in diameter dowels were used on the gravel subbase of the AASHO Road Test and extended AASHO Road Test with no problems reported.

DOWEL SPACING

Analysis was done for a pavement system with seven nonuniformly placed dowels using the nonuniform dowel bar spacing option of the computer program JSLAB. One example considered a 36,000-lb tandem axle placed at the joint and the other case considered a 36,000-lb tandem axle placed at the corner. The results were compared to the case of a joint with 12 uniformly spaced dowels. Stresses and deflections calculated for the 7-dowel joint were similiar to those obtained for the 12-dowel joint. Therefore, the use of fewer than 12 dowels for a 12-ft lane transverse joint may be satisfactory.(18) A more recent analysis has indicated that at least four dowels should be used in each wheel path.(10) According to the 1987 summary of State highway practices, 29 of the 30 States using dowel bars place them 12-in center-to-center. Arkansas uses a 15-in spacing. With larger diameter dowels (1.5-in or more) on short slab length jointed plain pavements, fewer dowels may be satisfactory by increasing the spacing or by nonuniform distribution of the dowels in the slab or both. Additional full-scale laboratory testing or field experimentation may be needed to determine the optimum combination of size and spacing. For pavements with short slabs, the use of fewer, shorter, larger diameter corrosion-resistant dowels will reduce joint or slab distress due to misalignment or corrosion and freezing of the dowels. The instrumented concrete pavements now being monitored on I-80 in Iowa and two different locations in Illinois will provide substantial information to validate or improve technical guidance on these important factors.(14,19)

BOND BREAKING AND CORROSION PROTECTION

Without proper bond breaking and corrosion protection, many dowels excessively restrain joint movements resulting in transverse cracking. Both bond breaking and corrosion protection considerations must be adequately addressed for satisfactory long-term joint performance. Without them, the resulting transverse cracks will allow the movements denied by the locked joints and may result in faulting of the undoweled crack and breakdown and spalling of the crack edges.

The bond breaker is used to prevent the concrete from bonding to the dowel bar, so the dowel will function as a load transfer device, not as a reinforcing bar. By allowing some movement, it also reduces stresses in the pavement caused by thermal curling or moisture warping, although this can best be minimized by keeping the slabs as short as practical.

Ramey, 1967, concluded "that single shop epoxy coatings are easiest to install. Bituminous coatings provide both corrosion resistance and bond breaking, but are hard to install if they do not dry. Oil and grease provide good bond breaking but little corrosion protection. Corrosion protection is essential in order to prevent 'freezing' of dowels. Eight percent colloidal graphite aided bond breaking. However, vaseline appeared the best of the grease type coatings because it is water-insoluble and has more 'body' than other greases. Painted metallic coatings did not perform well due to inadequate thickness. Thicker coatings (too expensive) would probably give good results."(20)

The corrosion protection prevents corrosion by-products from "freezing" the dowel so that it will not move and also prevents loss of cross-section in the critical joint area so the dowel remains effective. The problem of corrosion in load transfer devices varies in severity due to the variance of metal corrosion with temperature, moisture, and the chemical environment to which the metal is exposed. Local experience can be useful in evaluating dowel bar effectiveness and whether dowel bars need to be protected from corrosion. Where deicers are used or in marine environments where pavements are exposed to salt spray or air, a load transfer device should be selected according to its resistance to corrosion in the presence of chlorides. Due to the low cost of epoxy-coated dowels, it is recommended that epoxy-coated bars be used as a minimum to help assure long-term performance.

Research by Battelle Memorial Institute, 1966, concludes the best coating for corrosion protection from deicing salts are zinc, nickel, or an asphalt epoxy. NCHRP Synthesis 19 states: "Methods of reducing corrosion and extending dowel life include (a) pretreatment with a plastic coating, and (b) use of stainless steel or some other noncorrodible metal."(3)

Old stainless, monel surfaced, or nickel clad bars were removed from the I-96 pavement near Portland, Michigan after 21 years of service and were found to be in remarkable condition. The bars had been exposed to considerable salting due to Michigan's adverse environment. Uncoated bars from nearby contraction and expansion joints were highly deteriorated, demonstrating the benefits of protective coatings. However, the stainless steel clad or monel clad bars previously used are no longer produced. Dowels wrapped with corrosion-resistant metals have had mixed results.(21)

Plastic-coated bars provide good performance at a moderate cost, require no bond breaking coating (concrete does not bond to plastic), and maintains relatively low pull-out values in service. Epoxy-coated dowels can be produced at a lower cost than the plastic-coated dowels with the same advantages (except they require use of a bond breaker), so plastic-coated dowels bars are seldom used. Epoxy coatings have been used extensively since 1975 and, to date, seem to be working well. Short-term experiments have shown satisfactory results when compared with uncoated control samples. However, there is no long-term performance information available yet.(22) A recent report by the New York State DOT showed after 10 to 14 years, no corrosion or other deterioration of plastic-coated dowels or epoxy-coated I beams was apparent.(23)

There is no question that Type 316 stainless steel will provide corrosion protection under all climatic conditions as it is the highest quality stainless available. Due to its high cost, it is not very practical for use as solid dowel bars. Type 304 stainless steel has performed well in the past but is also expensive. The use of concrete-filled stainless steel pipe shows promise as a cost-effective alternate to large-diameter epoxy or plastic-coated solid dowels or smaller diameter solid stainless steel dowels.(15)

Research into other types of coatings and bars is being performed at the present time. Ohio has experimented with fiber-reinforced polyester dowel rods on four projects and 1 1/4-in solid stainless steel dowels on one project. The stainless steel is believed to be Nitronic 33, a low-nickel austenitic stainless steel produced by ARMCO. Research indicates it should provide better protection than Type 304 stainless steel. Hopefully, continued research will develop a suitable corrosion-resistant dowel bar material at a reasonable cost. For the present time, the only proven effective material for long-term performance has been the stainless steel bar or a stainless steel sleeve tightly wrapped over a black steel dowel bar. The Type 316 stainless steel concrete-filled pipe appears to provide significant potential as a cost-effective alternate, particularly in urban areas or highly corrosive environments.

CONTRACTION JOINT SPACING

Transverse contraction joints are designed and spaced to permit slab movements, thus reducing frictional drag stresses induced in the concrete to tolerable values. Under normal warm weather construction conditions, the pavement attains its greatest length soon after placement because of the high early heat of hydration. The resulting contraction due to a temperature reduction in the slab and drying shrinkage causes the slabs to shorten significantly at early ages. Therefore, expansion joints are seldom needed and only contraction joints are typically provided.(24) New Jersey is currently the only State that routinely uses expansion joints in its 78.5-ft jointed reinforced concrete pavements. Michigan uses an expansion joint every eighth joint (324 ft) in its JRCP if it is paved between September 15 and April 15.

Economics suggest that slabs be as long as possible to minimize the number of load transfer assemblies required but short enough to prevent transverse cracking in unreinforced slabs and to allow proper joint sealing. Longer joint spacing has several advantages: fewer joints generally mean fewer problems (most concrete pavement problems are joint-related), less joints to seal, and less dowels required. Their main disadvantage is that longer slabs mean wider joint openings and, for unreinforced slabs, may result in undesirable transverse cracking. NCHRP Synthesis 19 reports aggregate interlock is ineffective at openings of .035 to .04-in and the longer the unreinforced slab, the more susceptible it is to midslab transverse cracking. Shorter slabs have many advantages. Faulting is reduced. Less stress is placed on the joint sealant. Aggregate interlock is improved. Less maintenance is required because of less joint problems. Misalignment of the dowel bars does not become critical, because slabs are moving less which also means less frictional problems. Curling and warping stresses are reduced when compared to longer slabs; short slabs hinge at the joints and act more like flexible pavements. Smaller joint openings mean joints are less likely to fill with incompressibles. These factors are causing some States and a number of foreign countries to switch from JRCP to JPCP.(3,7,13,25)

Many agencies are using random joint spacings either with or without skewed joints. Skewed randomized joints are used primarily for unreinforced pavements with short joint spacings. The use of skewed joints with dowels is possibly an unnecessary refinement because adequate dowels effectively eliminate faulting.(3) New York, Florida, Illinois, and Wisconsin research show little benefit from skewed doweled joints.(23,26,27,43) However, the report on Instrumentation for the I-80 pavement in western Iowa states a preliminary analysis of the data shows less stress in skewed joints.(14) Randomized spacing patterns prevent rhythmic or resonant responses in vehicles moving at normal rural expressway speeds. Research in California indicated slab spacing patterns of 7.5-ft multiples should be avoided.(28) Whether this is still appropriate for today's traffic has not been determined.

One study in California (experimental sections constructed in 1971) determined that faulting could be reduced by approximately one half through a reduction in undowelled joint spacing from 12-13-18-19 to 8-11-7-5.(1) A 1985 performance survey indicated the condition was excellent. However, a new survey in the spring of 1987 shows a drastic change in condition of the test section on the southbound lanes. There was evidence of extensive pumping, and some 40 interior corner breaks were found in the 3150-ft section, all in the 11-ft slabs. This is approximately 40 percent of all slabs of that length. There also were a number of incipient cracks that will eventually break through. This pavement was repaired in 1988. The condition of the pavement in the northbound lanes remained good. It appears that poor drainage conditions are the probable cause of poor performance of this test section. California's standard random joint spacing is now 12-15-13-14 ft.(8)

However, CALTRANS experience applies only to slabs on lean concrete bases or cement-treated bases with a granular subbase. This design prevents pumping of the subgrade. To prevent cracking, joint spacing in feet should not exceed 1.75 times the slab thickness in inches with a maximum of 15 ft. In January 1987, California revised its preferred design to include an asphalt-treated permeable or cement-treated permeable base (with edgedrains) on top of their standard gravel subbases.(29) Due to relatively high deflections of PCC pavements over some asphalt-treated or crushed aggregate permeable bases, it is believed by the authors that dowels should be used particularly on medium and high traffic volume pavements to prevent settlement or unevenness between slabs if satisfactory long-term performance is expected. Caution is advised where the slab width exceeds the slab length. This can result in undesirable longitudinal cracking of the slabs. On airfield pavements, the length to width ratio of slabs is limited to be between 0.75 to 1.25. Additional research is underway to provide additional guidance in this area due to the increased interest in widened lanes with or without tied PCC shoulders to reduce edge loading conditions.

DOWEL ALIGNMENT TOLERANCES

The primary reason for placing limits on dowel placement tolerance is to minimize problems associated with locked joints. The most significant difference between ideal design conditions (of total contact with surrounding concrete and perfect alignment) and construction practices is the placement accuracy of the dowels. Under the ideal condition, there is no misalignment-- the dowel is free to move and no stresses are developed within the concrete when the joint opens and closes, except for restraint caused by friction between the slab and base. With short slabs, only small stresses would result from dowel restraint due to temperature curling and moisture warping. This ideal case rarely exists.(30)

If the dowel is longitudinally misaligned by less than one-half of the dowel embedment length (6-in embedment is necessary for a high joint load transfer efficiency), partial load transfer may be provided depending on the dowel diameter and the recommended embedment length. If it is misaligned greater than one-half the embedment length, it will function at a reduced rate and may cause spalling. With time, the load transfer ability of the dowel would progressively lessen. Load transfer efficiency is zero when the dowel embedment is less than 3-in.(17,31)

Vertical and/or horizontal misalignment can cause spalling of the surface as a result of insufficient depth of cover to resist tensile stresses caused by loading and/or expansive forces caused by corrosion of the dowel bar which exceeds the tensile strength of the concrete. Vertical skewing is when the dowel is misaligned in a plane parallel to the centerline. Misalignment beyond that permitted by a bond-breaker, corrosion coating, or sleeve may cause crushing of the concrete at the joint face. Horizontal skewing is when the dowel is misaligned in a plane parallel to the pavement surface. This causes stresses in the vertical plane and may cause longitudinal cracks. Figure 5 shows general categories of possible dowel bar misalignments.

In 1940, Friberg indicated that "the stresses in the concrete due to misalignment and extreme joint movement may be higher than those caused by traffic loads. The dowel misalignment affects both the dowel and the pavement edge. The largest edge stresses may occur when two or more dowels deviate in the same direction." A tolerance of 1 percent, or 1/8-in/ft of dowel was recommended.(10)

In 1973, Parameter reported that evidence indicated that the recommended tolerances for alignment of dowel bars was too severe, and misalignments of 3 to 4 percent would in fact be acceptable. Therefore, a relaxation of the tolerances previously specified by the British Cement and Concrete Association was made and are as follows: For basket assemblies before concreting, dowel bars should be placed approximately mid-depth of the slab parallel to finished surface and to the centerline of the roadway within a tolerance of 2 percent. Also, no bar should differ in alignment from an adjoining bar by more than 2 percent in either plane. For implanted dowels after concreting, dowel bars have to be placed at mid-depth of the slab parallel to finished surface and to the centerline of the roadway within a tolerance of 4 percent. Also, no bar should differ in alignment from an adjoining bar by more than 4 percent in either plane.(32)

A recent survey of the performance of unreinforced concrete roads constructed between 1970 and 1979 in Great Britain indicated that structural performance was unaffected by the method of dowel bar placing. There was more deep spalling at transverse joints when the insertion techniques were used, implying that the alignment and position of the dowel bars were often unsatisfactory.(33) The performance of 29 unreinforced and 42 reinforced concrete pavements from seven experimental concrete road sites was used to revise the thickness design procedure for both unreinforced and reinforced concrete pavements. This information generally verified the AASHTO design equations, and the design procedure has been extended to 300 million equivalent standard axle loads.(34)

In the USA, in the past, maximum allowable alignment error of 1/4-in per 18 in length of the dowel was specified. Some States have recently revised their allowable tolerance levels. For example, Georgia DOT specifies an allowable tolerance of 3/8-in/ft in both the horizontal and vertical directions. Several other agencies specify an allowable tolerance of 1/4-in/ft in both the horizontal and vertical directions.(35)

In 1980, a Florida DOT report concluded that the effect of misalignment is reduced by dowel looseness, and that the thicker the bond breaker coating, the greater misalignment can be tolerated. However, this may result in undesirable looseness and socketing of the concrete around the dowel. With a film thickness of .01-in around the dowel, the misalignment which can be tolerated is 1.44, .70, and .36-in for joint openings of 1/4, 1/2, and 1-in respectively.(36) Shorter slabs also allow for greater misalignment tolerances because there is less slab movement to cause stress from the dowel misalignment on the concrete, and an adjacent joint may take the small additional movement without intermediate slab cracking.

Proper alignment is important. Many studies have shown stringent tolerances are important for proper functioning of the slab and long-term performance. Presently, no clear consensus exists as to what the practical limits should be on dowel placement tolerances. A reasonable tolerance must be permitted to reduce construction costs. On many contracts, very little inspection has been carried out for dowels during or after concreting. It is only during rehabilitation that the deterioration of the joint due to improperly aligned dowels is likely to be noticed. Periodic checks must be performed, using ground-penetrating radar, metal detectors, or other means of verifying the dowel location, to evaluate the adequacy of construction placement. It would be interesting to know how many joint failures are the direct product of improper construction rather than improper joint design.

DOWEL PLACEMENT

Dowels may be placed in concrete by using wire basket assemblies or by using an automatic dowel bar inserter (implanter). Use of the inserter is not that widespread to date because of concern for proper alignment. As of 1987 only 7 of the 23 States using dowel bars allowed the use of inserters, and 5 of the 7 specified either baskets or inserters. In the past few years, new dowel bar inserters have been introduced and are being promoted by manufacturers as being capable of accurate dowel placement and finishing of the concrete after insertion without disturbing the concrete quality.

In 1987, a field investigation on a section of I-45 in Texas was conducted to determine the accuracy of placement by inserters and wire baskets using a radar technique to locate the position of the dowels in the concrete. The results of this investigation show the following: The average dowel depths were the same for both types of joints with the average within joint variation being .8 and .6 in for the basket and inserter joints, respectively. The maximum vertical misalignment (based on 103 joints analyzed) was found to be 1.1 in for baskets and .6 in for inserters. The range at each joint averaged .5 and .3 in for the basket and inserter joints, respectively. Of the 1367 dowels evaluated at basket joints, 53 had vertical misalignments greater than .5-in. Of the 53, 16 had misalignments greater than .7-in. None of the 1329 inserted dowels had greater misalignment than .7-in, and only 4 inserted dowels had misalignments greater than .5-in. The percentage of dowels with less than 1/4-in vertical misalignment over 12-in was 85 and 96 for basket and inserter joints respectively.(35)

Due to variability of the radar output, only the presence of longitudinal displacement rather than the degree or magnitude could be estimated. Displacement of the dowels during construction or sawing at an improper location could be the cause of the improper placement. Assuming other sources of variability for both construction methods were constant, it appears that more longitudinal displacement was detected where dowel inserters were used rather than the basket assemblies. However, the number of occurrences was very small relative to the number of dowels evaluated. The basket and inserter type joints exhibited similiar distributions of horizontal misalignment levels both in magnitude and dowel position. Maximum horizontal misalignment estimated was 2 and 2 1/4-in for basket and inserter joints, respectively. Overall, individual dowel horizontal misalignment averaged approximately 1/3-in. The precision of the estimate regarding the degree of horizontal misalignment was approximately 1/2-in.(35) A similar study was also conducted in Wisconsin in 1987, but the results are not yet available. A study of dowel placement accuracy with a dowel inserter was also conducted in Idaho in 1986. Based on the field evaluation, it was concluded that the radar device had potential to effectively evaluate dowel bar misalignment. The dowel inserter used appeared generally to be meeting the specified dowel bar placement tolerances during the second day of the inserter's use.(37)

Other research studies on the use of dowel bars versus inserters have not shown a statistically significant difference. Some researchers, though, have indicated that inserted dowels seem to be better. Contractor experience also plays a major part when considering variations in performance.(31) Dowel alignment must be checked very carefully at the beginning and during paving operations to ensure that proper alignment is being maintained. If the use of inserters continues and care is taken to properly calibrate the equipment, then the potential for development and improvement of dowel placement is greater for the inserter than the dowel basket. Use of inserters can save significant amounts of money and time. This will make the use of dowels altogether more attractive to States not currently using dowels on medium and high truck traffic volume roads. Beeson et al. noted a savings of $30,000 per Interstate mile for a project using inserted dowels instead of basket assemblies.(38) An improved nondestructive testing method is needed to verify the accuracy of the dowel placement (including the location of the sawed joint relative to the dowel bar) during or shortly after (1 day or less) the pavement is constructed. This will help to eliminate or minimize problems due to incorrect dowel placement. Similar procedures should also be developed to verify tie bar placement and temperature steel placement if used.

SLAB THICKNESS AND RELATED CONSIDERATIONS

Using repeated loading tests in the laboratory, it has been established that slab thickness has an influence on load transfer durability. This is due to the increase in aggregate interlock from the larger contact area of a thicker slab. Also, the increase in the inertia of the slab tends to reduce deflections and the rate at which effective load transfer decreases, especially in the case of non-treated subbases. Today, studies have determined that an increase in thickness could only reduce the faulting rate, not the amount. For example, if slab thickness is increased by 10 percent, the resulting faulting would only be reduced by 25 percent with a treated subbase.(39)

The structural design of JPCP has traditionally been performed to determine the required slab thickness to avoid fatigue cracking. The joint spacing was independently selected and maximized in order to minimize joint costs, and not with a view to optimize load transfer at the joints. This practice has led to a substantial amount of intermediate slab cracking over time due to environmental and traffic loadings for the longer slabs.(6,8,13,40) In some cases, it is also believed that longitudinal cracking has resulted in the wheel path due to the combined effect of traffic loading and curling and warping stresses.

In 1977, a structural design procedure for plain jointed concrete pavement was developed to take into direct consideration major design factors such as slab thickness, slab length, slab strength, traffic volume and distribution, foundation support, and climatic conditions throughout the pavement design life.

It should be noted that this procedure has not been verified by long-term pavement performance, but is the result of theoretical analyses.(40) This procedure showed the following results:

- If a thicker slab is used, a longer joint spacing could be allowed for the same level of cracking. Decreasing the traffic level from a very heavy axle load distribution to a moderate level would decrease the slab thickness by approximately 1-in or would increase slab length by approximately 3-ft.
- If a stabilized base with a high cracking index (C.I.) is allowed, a decrease of up to 1.5-in is allowed in the slab thickness.
- A C.I. of 0 ft/1000-ft^2 with a slab thickness of 12-in corresponds to a joint spacing, under typical conditions, of about 10-ft, while using a C.I. of up to 10 ft/1000-ft^2 will correspond to a 25-ft slab length.

Theoretical analysis show that bending stresses in slabs are greatest when loads are applied near an edge, if no load transfer is provided. Therefore, a non-reinforced slab with a free edge condition would have to be designed thicker since no load transfer is provided should a crack occur or the designer must accept a reduced service life. The cost of increasing the thickness of the concrete is such that the use of dowels and less erodible or permeable bases are much more effective in modifying joint behavior. Reports show that the proper use of dowels is equivalent to up to 5 additional inches of concrete in an undoweled pavement. A theoretical analysis indicates that a 9-in doweled slab with 100 percent load transfer will have the same deflection as a 14-in undoweled slab with no aggregate interlock.(15) The additional joint surface area for the thicker undoweled pavement does not increase the load transfer provided by aggregate interlock so it is equal to the load transfer provided by the dowels in the thinner concrete pavement.(3,13) Based on Westergaard's corner formula, a 9-in pavement would have to be increased in thickness to 15-in to reduce deflection by 50 percent. This goal can be realized less expensively by a better load-transfer system.(2)

A 1985 Wisconsin Interstate Pavement Rehabilitation Study concludes, "...building nonreinforced concrete pavements with additional thickness (2"-3") in lieu of positive load transfer devices (dowel bars) at transverse contraction joints is not successful in preventing or reducing joint faulting to an acceptable level during a pavement's life. The average PSI of these pavements is ranging from 1.9 to 2.9 at 10 years of age." Both the 1984 PCA Design Guide and the 1986 AASHTO Guide for the Design of Pavement Structures incorrectly imply that additional thickness (2 to 3-in) will replace the need for dowel bars, which has been shown in Wisconsin to be incorrect. Wisconsin is continuing to monitor these and other recently constructed jointed plain concrete pavements. They have research underway to determine the effectiveness of joint sealing, of various base drainage alternatives, and of doweled and undoweled transverse joints. These studies will help to define under what conditions undoweled pavement will perform satisfactorily.(41,42,43,44)

As part of a comprehensive study to evaluate the significance of pavement design and materials on D-cracking, one hundred four 200-ft long test sections were constructed on State Route 2 (four-lane divided highway) near Vermilion, Ohio, in 1974. One of the 13 different design typical sections constructed was a 15-in thick plain pavement slab with 20-ft skewed joints and bituminous shoulders which placed directly on the clay subgrade. Pumping was evident along the pavement edge in 1977 less than 3 years after construction. Faulting developed several years later, and by 1984 had reached as much as 3/8-in at isolated joints. About half the transverse joints were not faulted. A similar section, which included a 15-in thick plain pavement slab with tied portland cement shoulders and skewed joints, developed pumping along the outside edge in 1981, 6 to 7 years after construction. In 1984, no faulting of the pavement was evident. However, a survey in 1987 revealed faulting averaging .11 inches in both sections. A 9-in doweled pavement section with asphalt shoulders constructed directly on the clay- shale subgrade also faulted up to 3/8-in at most joints, which also emphasizes the need for good drainage or gravel subbases even under doweled PCC pavements.(45) Similar results were also obtained at the AASHO Road Test. The performance of these sections emphasize that the whole structural system, not individual design features, must be considered if satisfactory long-term performance is to be achieved.

Starting in 1976, Texas State Highway District 19 constructed five projects with 13-in thick jointed concrete pavements placed directly on moderately well drained clay sand to sandy clay sand subgrade without subgrade treatment, subbase, or the use of load transfer devices at contraction joints. These methods were used at high-volume intersections in urban areas and at diamond interchanges in the district. Maximum slab side dimensions are 13 to 18-ft. Slab widths exceeding 30-ft are not tied. Performance through 1984 was considered satisfactory with no observed subgrade pumping or significant amount of joint faulting or spalling. These pavements should be monitored to see if these thick undoweled pavements will provide satisfactory long-term performance under these conditions.(46) Available research indicates these pavements will fault significantly unless the subgrade is well drained and the joint sealing is well maintained.

INFLUENCE OF TRAFFIC ON LOAD TRANSFER

The weight of axles and their number are two factors which directly affect the durability of load transfer for a given structural pavement design. The transverse distribution of heavy vehicle traffic, the frequency of overloads, the geometry of heavy axles, and vehicle speeds are also an influence on the load transfer characteristics of a joint.(13)

The PIARC report "Concrete Pavements--Load Transfer at Transverse Contraction Joints and Design of Concrete Pavements" contains a guide for the recommended traffic limits on doweled and undoweled pavements. The tables include excellent comments that emphasize the extent to which performance is affected by construction quality, maintenance of sealing, and the effectiveness of the drainage system. From the detailed studies of old pavements, general recommendations intended to provide quantitative information on traffic limits were developed.(13) Two of these tables are also included in a recent PIARC publication, "1987 CONCRETE ROADS Practical Guide for Technology Transfer."(47)

The Portland Cement Association has developed design guidelines mainly used as a simplified method for determining pavement thickness. Tables are provided to determine the allowable average daily truck traffic (ADTT) on undoweled and doweled pavements. However, these thickness design guides do not reflect the 1975 PCA recommendation that all PCC pavements with an ADTT of over 300 heavy trucks be doweled.(22,48,49) Even this recommendation appears high based on the performance of undoweled pavements in many States.

The 1984 PCA design limits are controlled by a fatigue analysis or an erodibility analysis, whereas the PIARC Report traffic limits are based on empirical data collected from a series of observations made in many countries on old, long, nonexperimental pavement sections. Although the PIARC approach seems to be fairly reasonable, the traffic limits are still considered too high for undoweled pavements.(48) It is believed by the authors that dowels should be used for any daily commercial vehicle traffic above 100 for treated or untreated subbases except in extremely dry areas or areas with very small annual temperature changes. The quality of the coarse aggregate is also a significant factor. As dowels cannot be economically retrofitted on short slab pavements, they should be installed initially to prevent undesirable pavement faulting or differential slab elevations due to foundation settlements, consolidation of base or subbase under traffic, frost heave, or swelling soils.(7,41,43)

INFLUENCE OF SUBBASE

Adequate foundations are essential to concrete pavements. Inadequate foundations require costly maintenance resulting in delays and user inconveniences. The major characteristics of good subbases are the rapid removal of water by good drainage and the confinement and protection of poor soils to minimize their adverse effects. Subbases must be built of durable materials in order to remain stable under all climatic and traffic conditions. (50,51) The types of base most frequently used in the past for Interstates and some primary and secondary roads are econocrete, cement treated, bituminous stabilized, untreated granular bases and relatively low strength (lean) concrete. However, there is increasing information that many stabilized bases have not performed better than granular bases (particularly those with 7 percent or fewer passing the No. 200 sieve with nonplastic fines). Recently, at least four States (California, Michigan, New Jersey, and Pennsylvania) have adopted open-graded base courses (open-graded crushed stone, asphalt-treated permeable material, or cement-treated permeable material) as the standard or preferred base for rigid pavements. (See references 8,29,52,53,54,55,56,57)

Cement-treated bases are relatively rigid and if the cement content is high, are subject to relief cracking. "Clipping" or trimming the cement-treated base may disturb the surface and provide an erodible plane between the concrete and the base. Pumping often results in faulted slabs with medium to high traffic levels.

In bituminous stabilized bases, the bituminous material can be leached out. The material immediately below the pavement has been found to contain almost no trace of asphalt for a few inches. In other cases, where positive drainage was not provided (or a bathtub section was created) on undoweled pavements and where longitudinal joints were not tied, significant pumping and faulting have developed within 5 years. "Whitetopping" with tied PCC shoulders or full-depth asphaltic concrete shoulders and constructing a PCC slab where the AC is milled out of the main traveled lanes (PCC inlay) are designs particularly susceptible to problems due to the poor drainage conditions.(54)

Untreated granular bases are prone to greater pavement growth and fractures in the joint areas are common due to compressive stress. Granular subbases can be open-graded with high permeability to remove water quickly so that pumping will not occur and the subgrade surface will not be affected, provided a suitable filter material is used. They can also be dense-graded with low permeability to divert the water from the subgrade to drains or ditches (this has generally resulted in poor performance). They are normally used to minimize the accumulation of water beneath pavements over moisture-sensitive subgrades. Under heavy traffic, however, densely graded granular subbases tend to pump significantly.(47) Minnesota and Iowa have reported breaking of the slabs under the dowels on pavements with granular bases. This may be due to a combination of thin pavement slabs, small diameter dowels, heavily overloaded trucks, and poor subbase support.

Econocrete bases are basically concrete pavements of increased depth which are constructed of locally available materials. The base and the pavement are sometimes constructed monolithically. Lean concrete or econocrete bases have some advantages in terms of joint design. They tend to reduce deflections and increase joint efficiency by the increase in subgrade support. The deterioration due to pumping action is reduced. Pavement growth caused by base particles infiltrating joints is reduced so there are fewer compressive restraint problems. Friction in conjunction with stronger bases reduces joint openings. Their major disadvantage is with curled or warped slabs. Curled or warped slabs placed on extremely rigid bases act like an unsupported beam and will tend to crack near the joint. If placed on a less rigid base, the base will deflect with the slab and cracking is less likely to occur. If econocrete bases are used, short joint spacing must also be used. Also, cracks in the rigid base may reflect upward through the PCC slab. Another disadvantage is the relatively high cost. In many cases, doweled pavements with permeable bases and positive drainage can be constructed for about the same cost or less and offer the potential for significantly improved service lives. For heavy truck traffic stabilized open-graded bases should be considered.

A research project consisting of duplicate 8- and 9-in thick pavement sections (27-ft long reinforced slabs with skewed joints), with and without dowels, constructed on bituminous-treated, cement-treated and conventional dense-graded gravel base, was built on I-94 near Rothsay, Minnesota in 1970. After 13 years of service, the doweled pavements outperformed the undoweled pavements in terms of reducing the amount of joint faulting. The performance of the two roadways was more consistent with the thicker slabs. Due to the degree of faulting, all undoweled pavements needed to be planed. The undoweled test sections on asphalt-treated bases performed the poorest due to extensive cracking. The performance of undoweled pavements on gravel base and cement-treated bases was similar, and 6-in thick, 2 1/2-ft wide tied and doweled concrete shoulders were also added in 1984, in addition to the planing, in an attempt to reduce future faulting and extend the pavement life. The performance of the doweled JRCP on the gravel base and the cement-treated base was similar after 5.5 million equivalent standard axle load applications. One section of pavement over the cement-treated base experienced some construction-related random cracking. It is likely that the extensive random cracking on many of the stabilized test sections was due to the following: The plastic ribbon used in the longitudinal joint was not effective; there was evidence that some of the joints were sawed late; and the PCC slab bonded to the stabilized bases, which resulted in high friction factors and may have contributed to cracking of the concrete at an early age.(58)

STATE PRACTICES REGARDING USE OF DOWELS

Current practices regarding the use of dowels vary across the country. The differences between the States is mainly related to environmental and climatic variations. A summary of pavement types and contraction joint spacing used by State highway agencies can be found in table 1. Most of the western States with dry arid climates have previously used plain concrete pavements without dowels. They believe that a JPCP with nonerodible support provided by a treated base and an aggregate subbase is capable of supporting the slabs under the heaviest loads using only aggregate interlock at the contraction joints. Many of the western States have had faulting problems. In some instances, particularly on heavy trafficked roads, the use of aggregate interlock for load transfer has not been satisfactory. With the increasing volume of truck traffic and heavier axle loads, even States with good previous performance cannot reasonably expect these designs to perform satisfactorily for the next 30 to 40 years without significant rehabilitation. The use of doweled plain jointed concrete pavements on permeable bases in new or reconstructed pavements should increase significantly, to reduce pavement damage from the increasing numbers and weights of truck traffic. However, until permeable bases have demonstrated satisfactory long-term performance they should be used with caution.

A study conducted by the Florida DOT measured faulting at seven test sites over a 12-year period. Both doweled and nondoweled plain jointed concrete pavements were tested so that a direct comparison could be made. Stelzenmuller, Smith, and Larsen concluded, "It was found that doweled joints show less faulting than nondoweled joints and that dowels increase the effective load transfer when properly designed and installed. Aggregate interlock provides 40 percent or more load transfer during warm weather, but frequently less than 40 percent during cold weather. Dowels retard joint faulting better than aggregate interlock."(7) A comprehensive study of faulting on I-10 in Florida is nearly completed and is expected to be published soon. This will provide additional information on the performance of doweled and undoweled joints, skewed and unskewed joints, and other related design features under Florida conditions.

Results from the Michigan, Minnesota, and Missouri test roads and studies done in Georgia indicate that doweled joints definitely fault less than nondoweled joints. New Jersey found that load transfer devices are needed for heavily trafficked pavements to avoid the faulting of those joints that open excessive amounts. New Jersey's stainless steel or monel-wrapped dowels in 78-ft expansion jointed PCC pavements have performed satisfactorily for over 40 years. The disadvantage is that the currently used construction procedures result in a relatively rough-riding concrete pavement and higher construction costs.

In the past, there have been several projects that have shown serious faulting with doweled pavements. An example is the AASHO Road Test section of plain jointed concrete left in service on I-80 for 12 years. Serious faulting was observed. Using the Friberg analysis method, it was found there is a high correlation between the dowel concrete bearing stress and faulting. The faulting that occurred was on the 8-in slab sections with 1-in diameter dowels. Faulting was found to decrease with increasing thickness and dowel diameter as seen in figure 6.(5,10) It should also be noted that during the AASHO Road Test, all pavement sections were doweled. Although considerable pumping occurred, faulting was notably absent throughout the project.(59) It appears that a minimum dowel diameter of 1-1/4 in. should be used.

Recommendations for the prevention of faulting on heavily trafficked pavements were made by Spellman, Woodstrom, and Neal from a California study which included use of the following: (1) dowel bars of adequate size, spacing, and corrosion resistance, (2) shorter joint spacing (6-8 ft) to reduce seasonal and daily joint openings, (3) increased thickness of the slab to reduce joint deflections under loads, (4) minimized water infiltration, (5) subsurface drainage, (6) erosion-resistant subbase and shoulder material to minimize the availability of pumpable material. As noted earlier, significant transverse cracking occurred on one roadway in California (with 8-11-7-5 randomly spaced joints) where 40 percent of the 11-ft panels cracked within 16 years of construction, probably due to a poor drainage condition. Performance of a similar test section in the other roadway was still satisfactory.(7,8)

While some plain undoweled pavements have had satisfactory results, the majority of the doweled pavements have had outstanding performance where dowel bar corrosion or misalignment have not caused the joints to "freeze" or lock up. In order to obtain satisfactory long-term performance (without the need for major rehabilitation), the use of corrosion-resistant dowel bars as load transfer devices should be seriously considered during pavement design procedures. Even if some spalling of the joints develops, the rideability of the pavements over their useful life is expected to be much better than on short-slab plain pavements with faulted joints.

CONCLUSION

A review of current design practices has shown that past designs are not adequate for the medium and heavy truck volumes being applied to many pavements these days. Adequate guidance must be provided to designers to assure that harmful pumping and faulting will not occur prematurely on future pavements. Today, for a proper design, both the mechanistic and empirical approaches should be employed to design a pavement that can be expected to perform adequately under the increasing truck traffic volumes and heavier axle loads forecasted for a 30- to 40-year performance period without major pavement rehabilitation.

Proper transverse joint design usually requires the provisions of positive load transfer using corrosion-resistant dowels, well-compacted drainable bases, and longitudinal edge-drains or under-drains, and selection of appropriate slab lengths so joint sealants can be maintained and intermediate slab cracking prevented. Keeping the slabs as short as practical will reduce the curling and warping stresses in the pavement and reduce intermediate slab cracking. Short joint spacing will also reduce stresses due to poor dowel bar alignment and due to the results of base or subbase friction.

Considerable evidence is also available to show that pumping and faulting can be prevented using corrosion-resistant dowels of an adequate diameter over 6- to 12-in of subbase with good drainage characteristics. Although some States believe that by using stabilized subbases (including lean concrete or asphaltic concrete bases) they can reduce the rate of faulting, stabilized subbases cannot completely eliminate the pumping and faulting problem. Corrosion-resistant dowels of an adequate diameter can prevent faulting or at least reduce it to a tolerable level during the useful life of the pavement. In addition, by limiting differential slab elevations, the dowels will help reduce reflective cracking if the pavement is subsequently overlaid. Although the past performance of some plain undoweled pavements may have been satisfactory, it is very unlikely that the same designs today would give similar results due to the increasing numbers of trucks and heavy axle loads. Increasing the thickness of the concrete slabs is generally not the answer to the faulting/pumping slab problem. Increased slab thickness has not been proven to be a cost-effective alternative to using treated or untreated permeable subbases and edgedrains, and dowels for other than extremely light truck traffic. The use of dowels will usually prevent pumping and faulting at a very small additional cost. Typically, corrosion-resistant dowels can be installed for approximately \$1.50 per yd^2 of pavement. In most cases, this is less than the cost of the additional 2-in of concrete pavement which has been proven to be structurally inadequate compared to a thinner pavement with dowels. With the development of improved construction techniques, such as dowel inserters and nondestructive testing to verify dowel placement, the cost of doweled pavements can be reduced or a significantly improved design can be used for about the same cost. The improved construction techniques and lower costs should also make the use of dowel bars more attractive to the States presently not using them.

Although there is some research in this area, there is a need for additional research. Research to determine the optimum combination of dowel bar lengths, spacing (uniform vs. nonuniform), materials, and diameters in combination with various bases and subbases and drainage conditions would provide improved design guidelines. Improved construction inspection would also help to ensure the proper performance of load transfer devices within pavements. The improvement of nondestructive testing techniques to quickly verify accurate placement of dowels and tie bars is also desperately needed.

Designers need to consider all options in making a design best serve the public, both functionally and economically. While some plain undoweled pavements have had outstanding performance, current guidance is not adequate to determine under what conditions this can be safely done. Without such guidance and without accurate predictions for truck traffic loadings, the increased use of corrosion-resistant dowels of an adequate diameter, tie bars, widened lanes and tied shoulders, well-drained bases, and short slab lengths appear to be in the long-term interest of the traveling public. The consequences of not providing positive load transfer on heavily trafficked roadways must be seriously reconsidered by both highway administrators and pavement designers. The traveling public, who are the taxpayers, deserve to have the very best roads possible for their money.

REFERENCES

(1) Pavement Design Principles and Practices, A Training Course, Participant Notebook NHI Course 13111 (Washington, D.C: Federal Highway Administration, September 1987), 844 pp.

(2) "Joint-Related Distress in PCC Pavement Cause, Prevention and Rehabilitation," NCHRP Synthesis 56 (1979), 42 pp.

(3) "Design, Construction and Maintenance of PCC Pavement Joints," NCHRP Synthesis 19 (1973), 46 pp.

(4) R.E. Smith, M.I. Darter and S.M. Herrin, Highway Pavement Distress Identification Manual, FHWA-RD-79-66 (Washington, D.C: Federal Highway Administration, March 1979), 198 pp.

(5) L.J. McKenzie, R.J. Little and P.G. Dierstein, Behavior of Contraction Joints in the Rehabilitated AASHO Test Road, FHWA-IL-PR-75 (Illinois Department of Transportation, March 1977), 79 pp.

(6) M.I. Darter, Design of Zero-Maintenance Plain Jointed Concrete Pavement, Vol. I - Development of Design Procedures, FHWA-RD-77-111 (Washington, D.C: Federal Highway Administration, June 1977), 261 pp.

(7) J.L. Arellano and R. Staudt, Plain Cement Concrete Pavement on Cement-Treated Base, Research Project 70-03, Final Report, Pennsylvania Department of Transportation, March 1988, 31 pp.

(8) B.F. Neal, Evaluation of Design Changes and Experimental PCC Construction Features, FHWA/CA/TL-85/07, Final Report, California Department of Transportation, July 1987, 112 pp.

(9) B.E. Colley and H.A. Humphrey, "Aggregate Interlock at Joints in Concrete Pavements," HRR No. 189, 1967, pp 1-18.

(10) K.W. Henrichs, M.J. Liu, M.I. Darter, S.H. Carpenter and A.M. Ioannides, Rigid Pavement Analysis and Design, FHWA - RD-88-068 (Washington, D.C: Federal Highway Administration, February 1989), 374 pp. (In publication).

(11) Construction and Maintenance of Rigid Pavements General Report, XVIII Brussels World Road Congress, PIARC, September 1987, 42 pp.

(12) Concrete Design Task Force, Review of Minnesota's Concrete Pavement Design, Minnesota Department of Transportation, March 4, 1985.

(13) Concrete Pavements - Load Transfer at Transverse Contraction Joints and Design of Concrete Pavements, Bulletin de Liaison des Ponts et Chaussees, Numero Special IX, Paris 1979.

(14) J.K. Cable, W.F. Klaiber, D.Y. Lee, Pavement Instrumentation, FHWA-EP-88-621-001 (Washington, D.C: Federal Highway Administration, March 1988), 119 pp.

(15) K.N. Black, R.M. Larson and L.R. Staunton, "Evaluation of Stainless - Steel Pipes for Use as Dowel Bars," Public Roads Vol. 52 No. 2 (Washington, D.C: Federal Highway Administration, September 1988.)

(16) "Engineering and Design - Rigid Pavements for Roads, Streets, Walks and Open Storage Areas, Technical Manual 5-822-6 and AFM 88-7, Chapter 1, Headquarters, Department of the Army, April 1977.

(17) L.W. Teller and H.D. Cashell, "Performance of Doweled Joints Under Repetitive Loadings," Bulletin No. 217, Highway Research Board, (Washington D.C., 1955).

(18) D.A. Anderson, W.P. Kilareski and D.R. Luhr, Fourth Cycle of Pavement Research at the Pennsylvania Transportation Research Facility, Vol. 7, Fourth Cycle of Pavement Research Summary Report, FHWA-PA 84-029, Pennsylvania Department of Transportation, December 1984, 58 pp.

(19) Mechanistic Pavement Design Procedures Evaluation, Testing Program and Instrumentation Report, Interim Reports, Research Project IHR-518, Illinois Department of Transportation, 1987.

(20) G.E. Ramey, Investigation of Dowel Bar Coatings, Alabama HPR Report No. 35, 1967, 95 pp.

(21) C.J. Arnold, Performance of Several Types of Corrosion Resistant Load Transfer Bars, for as Much as 21 Years of Service in Concrete Pavements, Research Report No. R-1151, Michigan Department of Transportation, August 1980, 23 pp.

(22) "Joint Design for Concrete Highway and Street Pavements," ISO59.03P, Portland Cement Association, Skokie, IL, 1975 (Revised 1980).

(23) J.M. Vyce, Performance of Load-Transfer Devices, Report FHWA/NY/RR-87/140, New York State Department of Transportation, July 1987, 35 pp.

(24) Joint Spacing in Concrete Pavements: 10-Year Reports on Six Experimental Projects, Research Report 17-B, Highway Research Board, 1956.

(25) Concrete Roads, Technical Committee Report No. 7, XVIII Brussels World Road Congress, PIARC, September 1987, 96 pp.

(26) L.L. Smith, "Load Transfer at Contraction Joints in Plain Portland Cement Concrete Pavements," Research Bulletin No. 90, Division of Materials, Research and Training, Florida State Road Department, 1965, 43 pp.

(27) Behavior of Plain PCC Pavement with Skewed Joints Randomly Spaced, FHWA-IL-PR-78, Final Report No. 78, Illinois Department of Transportation, June 1978, 28 pp.

(28) R.H. Cooley, "The Case for Skewed Joints," HRB Bulletin No. 274, 1960.

(29) Chapter 600, Design of Pavement Structural Section, Highway Design Manual, California Department of Transportation, January 1987, 75 pp.

(30) S.D. Tayabji and B.E. Colley, Improved Rigid Pavement Joints, FHWA/RD-86/040 (Washington, D.C: Federal Highway Administration, February 1986), 148 pp.

(31) E.P. Segor, Jr. and J.R. Cobb, "A Study of Misaligned Dowels in Concrete Pavements," Alabama HPR Report No. 32, 1967, 62 pp.

(32) B.S. Parameter, "The Design and Construction of Joints in Concrete Pavements," TRRL Report 512, 1973, 55 pp.

(33) J.M. Gregory, The Performance of Unreinforced Concrete Roads Constructed Between 1970 and 1979, Research Report 79, Transport and Road Research Laboratory, Crowthorne, England, 1987, 19pp.

(34) H.C. Mayhew and H.M. Harding, Thickness Design of Concrete Roads, Research Report 87, Transport and Road Research Laboratory, Crowthorne, England, 1987, 13 pp.

(35) P.A. Okamoto, Field Evaluation of Dowel Placement Along a Section of I-45 in Texas, (Washington, D.C: Federal Highway Administration, May 1987), 49 pp.

(36) "Misaligned Dowels in Concrete Pavement," Report FL/DOT/OMR-80/225, Florida Department of Transportation, 1980, 46 pp.

(37) S.D. Tayabji and P.A. Okamoto, Evaluation of Automatic Dowel Bar Inserter and Radar Method for Checking Dowel Bar Placement, (Washington, D.C: Federal Highway Administration, October 1986).

(38) M.G. Beeson, J.L. Burati, Jr., and H.S. Hill, Jr., Comparative Analysis of Dowel Placement in Portland Cement Concrete, Clemson University, December 1981, 93 pp.

(39) R.G. Packard, "Design Considerations for Control of Joint Faulting of Undoweled Pavements," International Conference on Concrete Pavement Design, Purdue University, February 1977, 15 pp.

(40) J.S. Sawan and M.I. Darter, "Structural Design of PCC Shoulders," Transportation Research Record No. 725, Transportation Research Board, 1979, pp. 80 - 88.

(41) "1985 Wisconsin Interstate Rehabilitation Study," Wisconsin Department of Transportation, Division of Highways and Transportation Services, 1985.

(42) S.F. Shober, Evaluation of Plain Concrete Pavement, Progress Report No. 1, Research Project 0624-50-56, Wisconsin Department of Transportation, September 1975, 72 pp.

(43) J.M. Parry, Evaluation of Plain Concrete Pavement Progress Report No. 2, Research Project 0624-32-18, Wisconsin Department of Transportation, June 1988, 50 pp.

(44) T.S. Rutkowski, "Performance Evaluation of Drained Pavement Structures," letter to Mr. Frank Mayer, FHWA dated June 24, 1988 (and attachments), Wisconsin Department of Transportation.

(45) D. Stark, The Significance of Pavement Design and Materials on D-Cracking, Interim Report, FHWA/OH-86/008, Ohio Department of Transportation, December 1986.

(46) S.R. Wimberly, Thick Concrete Pavement Evaluation Report, Experimental Project 633-1, Final Report, Texas State Department of Highways and Public Transportation, Austin, TX, March 1985, 47 pp.

(47) Concrete Roads, Practical Guide for Technology Transfer, PIARC Technical Committee on Concrete Roads, Paris, France, 1987, 109 pp.

(48) "Thickness Design for Concrete Highway Streets and Pavements," Portland Cement Association, Skokie, IL, 1984.

(49) "Subgrades and Subbases for Concrete Pavements,"Publication No. ISO29.02P, Portland Cement Association, Skokie, IL, 1971, 21 pp.

(50) Guide for Design of Foundations and Shoulders for Concrete Pavements, ACI 325 3R-85 (Revised 1987), ACI Committee 325, American Concrete Institute, 1987, 8 pp.

(51) Guide for the Design and Construction of Concrete Parking Lots, ACI Committee 330 Report, ACI Materials Journal, November - December 1987, pp. 532-558.

(52) M.A. Chiunti, Experimental Short Slab Pavements, Construction Report, Research Report No. R-1016, Michigan Department of Transportation, August 1976, 22 pp.

(53) T.M. Green and E.C. Novak, Jr., Drainage and Foundation Studies for an Experimental Short Slab Pavement, Research Report No. R-1041, Michigan Department of Transportation, February 1977, 32 pp.

(54) C.J. Arnold, M.A. Chiunti and K.S. Bancroft, "Jointed Concrete Pavements in Michigan Design Performance and Repair," 2nd International Conference on Concrete Pavement Design, Purdue University, 1981, pp. 67-73.

(55) G.J. McCarthy and W.J. MacCreery, "Michigan Department of Transportation Recycles Concrete Freeways," Third International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, 1985, pp 643-647.

(56) G.S. Kozlov, "Implementation of Internal Road Drainage Design and Application," TRR 993, Transportation Research Board, 1984, pp 35-46.

(57) G.J. Malasheskie, "Open-Graded Subbase to Provide All-Season Pavement Subdrainage," Pennsylvania Department of Transportation, 1986, 14 pp.

(58) A.D. Halverson, Concrete Pavements on Treated Bases, Investigation No. 193, Long-term Performance Report - 1986, Minnesota Department of Transportation, 1986, 61 pp.

(59) The AASHO Road Test Report 5 Pavement Research, Highway Research Board Special Report 61E, 1962, pp 139-242.

Table 1.
Summary of State practices:
Spacing of transverse contraction joints.(10)

STATE	Spacing, ft.		
	Plain	Plain Doweled	Reinf. Doweled
ALABAMA		20	39
ARIZONA	15-13-15-17	15-13-15-17	
ARKANSAS		15	45
CALIFORNIA	12-15-13-14		
COLORADO	12-15-13-14		
CONNECTICUT			40
DELAWARE			40
DIST. OF COLUMBIA			
FLORIDA		<20	
GEORGIA		20	
HAWAII	13-12-18-19		
IDAHO	13-18-17-12	13-15-16-14	
ILLINOIS			40
INDIANA	12-13-19-18	12-13-19-18	40
IOWA	15	20	
KANSAS	15	15	30
KENTUCKY		12-13-17-18	
LOUISIANA		20	58.5
MARYLAND			40
MICHIGAN			41
MINNESOTA	13-16-14-17	13-16-14-17	27
MISSISSIPPI		20	21.25
MISSOURI		30	42.5
MONTANA	12-15-14-13		
NEBRASKA	16.5		
NEW MEXICO		14-14-12-15	
NEW YORK		20	63
NORTH DAKOTA	13		
OHIO	20	17	40
OKLAHOMA	15		
OREGON		14	
PENNSYLVANIA		20	40
PUERTO RICO	20		
SOUTH CAROLINA		20	
SOUTH DAKOTA	15		
TENNESSEE		19-25-24-18	
TEXAS	15	15	60
UTAH	11-10-14-15		
VIRGINIA	20		40
WASHINGTON	9-10-14-13		
WISCONSIN	12-13-19-18	12-13-19-18	40
WYOMING	12-13-16-14		

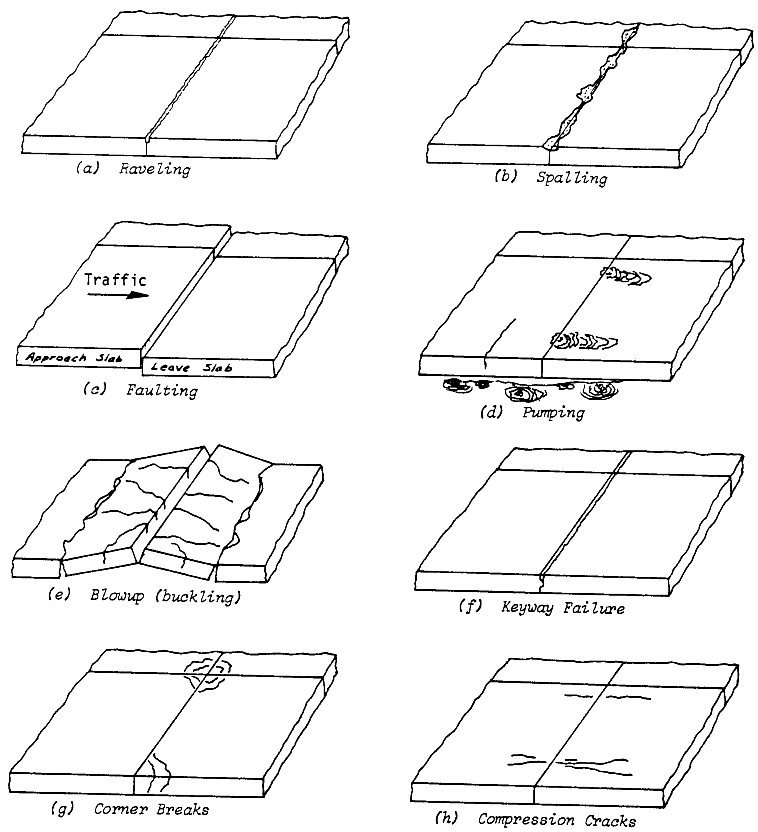


Figure 1. Distress at joints. (3)

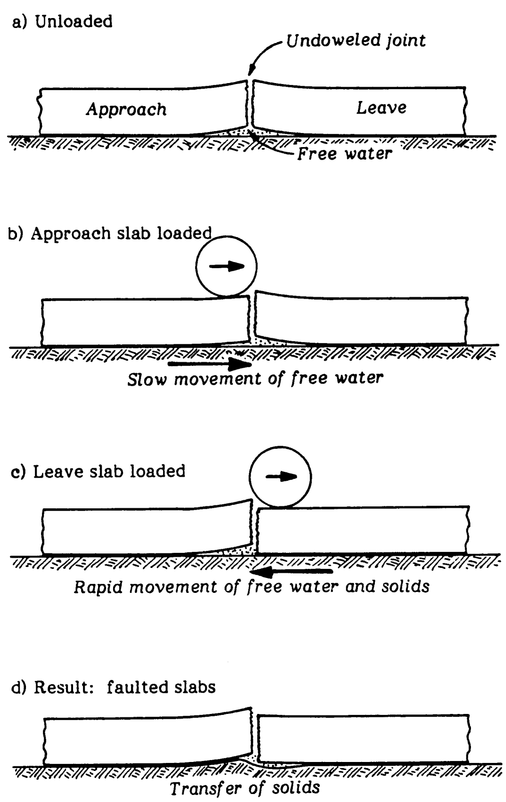
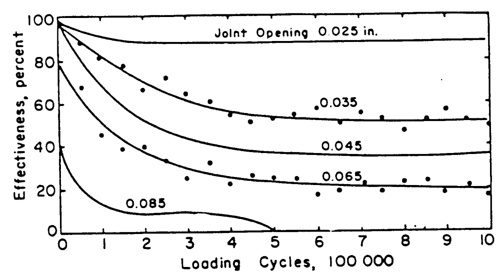
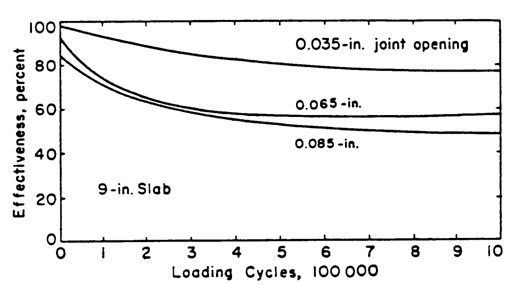


Figure 2. Faulting process for undoweled joints. (2)



(a) Influence of joint opening on effectiveness (9 in. slab, 6 in. gravel subbase, k = 145 psi)



(b) Influence of joint opening on effectiveness (9 in. slab., cement stabilized subbase, k = 542 pci)

Figure 3. Joint load transfer effectiveness for gravel and cement treated subbase for various joint openings. (10)

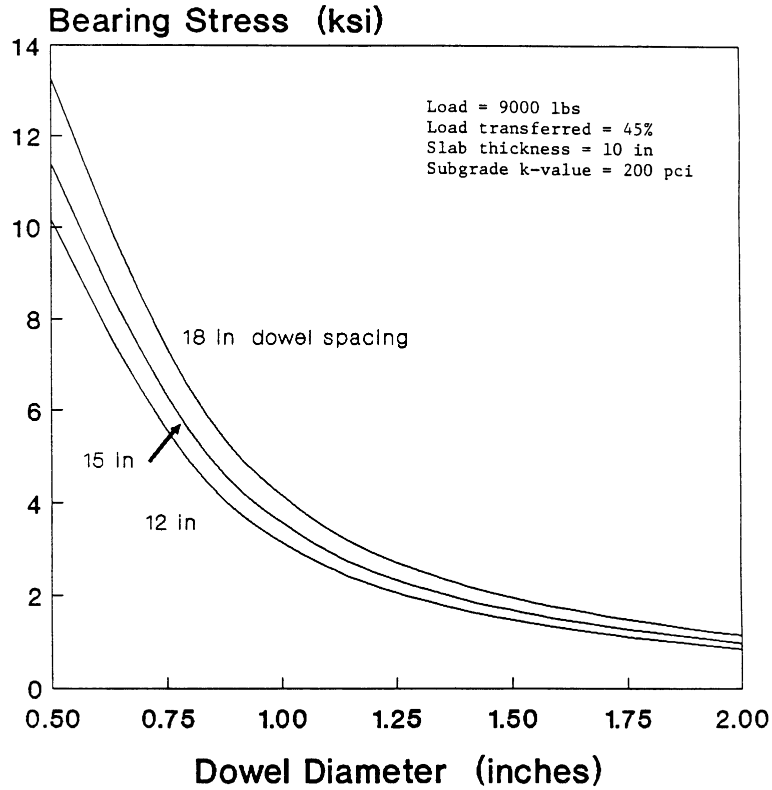


Figure 4. Sensitivity of bearing stress vs. dowel diameter with varying dowel spacing. (10)

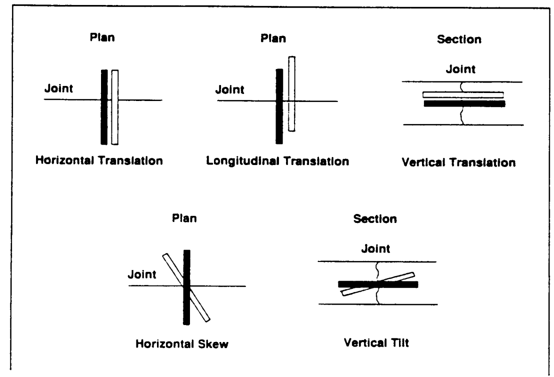


Figure 5. Dowel misalignment categories. (30)

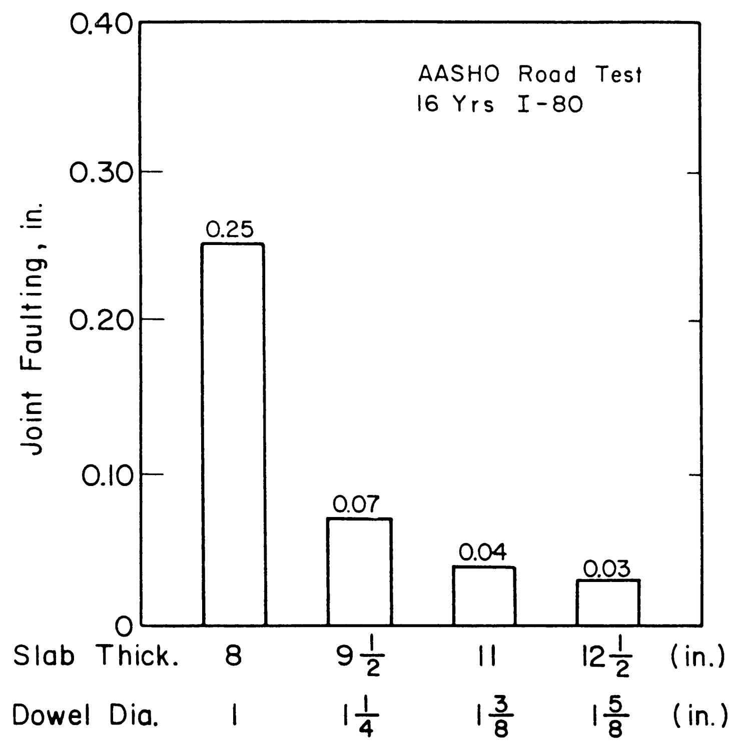


Figure 6. Joint faulting on plain jointed concrete AASHO Road Test sections left in-service on I-80. (1)