
DESIGN CONSIDERATIONS FOR IMPROVED JPCP PERFORMANCE

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ABSTRACT

A major FHWA-sponsored research study on the performance of concrete pavements has recently been completed in which over 300 concrete pavements across North America—of different design and subjected to different traffic and environmental forces—were tested and evaluated. An evaluation of the performance of these different concrete pavement sections has provided considerable insight into their long-term performance and behavior. Based on the field performance results and on the current state of the practice, this paper provides guidelines and recommendations for effective jointed plain concrete pavement (JPCP) designs that will lead to an improvement in overall pavement performance.

INTRODUCTION

A recent study on the performance of concrete pavements has produced significant insight into their long-term performance and behavior (1-4). A wide range of concrete pavement designs—incorporating a variety of design features and under a variety of traffic and environmental loadings—was included in the evaluation, allowing for an assessment of those factors that contribute to overall concrete pavement performance. Based on the performance of more than 300 pavement sections included in the study and information from other studies, recommendations for the improved design and construction of concrete pavements have been developed and are presented in this paper. Key design considerations are provided for subsurface drainage, base type, shoulder type, edge support, transverse joint design (including joint spacing, joint orientation, joint load transfer, and joint sealant), longitudinal joint design, and concrete strength. However, it should be noted that the range of variables was limited in some cases. For example, only four sections had been exposed to more than 20 million ESAL applications.

In considering these recommendations, it must be realized that a pavement structure is a complex system with many interacting components. Design changes made to improve one aspect of pavement performance can adversely affect others. Therefore, the designer must first consider the impact of any design changes on all aspects of pavement performance before proceeding with any changes. Site conditions such as traffic level, subgrade type, and climate also affect pavement performance and require due consideration. In short, the total pavement system (i.e., support, drainage, thickness, jointing, materials, reinforcement, and so on) must be considered together, along with the specific site conditions, in developing a reliable concrete pavement design.

SUBSURFACE DRAINAGE

The importance of subsurface drainage to pavement performance has long been recognized, but only recently has it received much emphasis in design. An effective subsurface drainage system removes excess water from the pavement structure, thereby preventing or reducing the development of key moisture-related distresses. However, the addition of a drainage system can lead to increased costs. For example, a permeable base and edge drain system increases initial construction costs by about 20 percent, which must be offset by a corresponding increase in pavement life (5).

Identifying the Need for Drainage

A simple procedure for characterizing the drainage condition that considers the external and internal factors was developed. This approach employs a simple matrix for selecting the overall drainage coefficient, C_d (table 1). This factor, which is based on the AASHTO drainage coefficient, indicates the pavement's ability to drain excess water from within the structure and the exposure condition. It depends on the base type, the presence of edge drains, and moisture exposure condition. A flow chart of drainage design recommendations based on C_d is given in figure 1. In general, pavements with C_d greater than 1 do not require any drainage provisions, whereas pavements with C_d less than 1 will require the addition of subsurface drainage (except possibly in dry climates or pavements with low traffic volumes).

Effectiveness of Different Drainage Designs

The performance data collected under this study showed that sections constructed on permeable bases are performing better than sections containing other drainage designs and sections with dense-graded bases. This enhanced performance is generally manifested in lower faulting and fewer transverse cracks. In some cases, joint spalling and D-cracking are also less for permeable base sections, probably due to the joints being less saturated. However, most permeable base sections included in this study are relatively young and have not been exposed to substantial traffic loadings.

The pavement sections containing only longitudinal edge drains (and no permeable base) showed only a small advantage in pavement performance when compared to nondrained systems. This could be due to free moisture being unable to migrate to the longitudinal drain because of the relative impermeability of the base course. Thus, the water remains within the pavement, essentially creating a nondrained structure.

Daylighted cross sections, in which the dense graded aggregate base course extends to the ditch, is another means of providing drainage to a pavement structure. In this design, excess water can flow through the aggregate base and directly to the ditches. However, these designs are generally not recommended because they are not maintainable. The "outlet" portion of the daylighted base frequently clogs with dirt, grass, and other debris, serving to keep free moisture within the pavement system and accelerating the development of distress.

The overall drainability of the pavement sections included in this study was assessed using the drainage coefficient. An evaluation of the performance data generally shows that pavements with a higher C_d (better draining pavement) exhibit better performance, particularly in terms of reduced faulting.

Design Recommendations for Permeable Bases

For new pavements that have been identified as having a strong need for drainage, the most effective system for pavement subsurface drainage consists of the following three elements: a permeable base, a separator layer, and a longitudinal edge drain collector system. Proper design, construction, and maintenance of each component are extremely important. The provision of positive drainage will not overcome the effects of poor practices in other design areas.

Permeable Base

The permeable base should be placed directly below the PCC slab to intercept water infiltrating the pavement structure. A minimum thickness of 100 mm (4 in) is recommended for permeable bases, and the base should extend 0.3 to 0.9 m (1 to 3 ft) beyond each edge of the pavement (6). The minimum recommended permeability is 300 m/day (1,000 ft/day), although many permeable base materials have permeabilities in excess of 900 m/day (3,000 ft/day). The use of 100 percent crushed stone in permeable bases is also recommended to ensure stability during construction (6).

Permeable bases may be treated with either asphalt or portland cement to improve stability. The type of asphalt cement most commonly used is AC-20, but AC-40 can also be used to provide additional stability. Permeable asphalt-stabilized bases should be treated with 2 to 3 percent asphalt by weight. When using an asphalt-stabilized permeable base, potential stripping of the AC should be considered. It is unlikely that much AC will remain after 30 to 40 years of service, so the use of 100 percent crushed material is recommended for long-term stability.

Permeable cement-stabilized base should be treated with between 110 to 170 kg/m³ (190 to 280 lb/yd³) of portland cement). For higher strength bases, notching of the base to match the planned joints in the slabs is recommended for jointed concrete pavements. Under CRCP, the use of a permeable base may not be appropriate because of the potential problems with obtaining adequate stability.

The use of a stabilized permeable base is recommended if construction traffic will be allowed on the base. Ontario also requires that the surface layer be placed within 30 days to prevent contamination of the drainage layer from prolonged exposure (7). Specifying a level of consolidation that results in no appreciable displacement of the base following compaction is recommended for permeable bases. Most States specify one to three passes of a 4.5- to 9-Mg (5- to 10-ton) steel-wheeled roller (6). Anchoring dowel baskets on permeable bases can also be difficult, although this problem can be avoided by using a dowel bar inserter.

Separator Layer

Permeable bases must be placed over a separator layer to prevent contamination of fines migrating up from the underlying layers. Either geotextiles or a dense-graded aggregate layer can be used, but the use of dense-graded aggregate is preferred, especially over a weak subgrade. If an aggregate separator layer is used a minimum layer thickness of 100 mm (4 in) is recommended; this thickness may need to be increased when constructed on weak subgrades. On a very weak subgrade, a minimum separator-layer thickness of 300 mm (12 in) is recommended for heavily trafficked roads.

The gradation of an aggregate separator layer must be carefully selected to prevent pumping of the fines from the subgrade into the permeable base. The following filtration criteria should be satisfied (6):

$$D_{15}(\text{Separator Layer}) \leq 5D_{85}(\text{Subgrade}) \quad (1)$$

$$D_{50}(\text{Separator Layer}) \leq 25D_{50}(\text{Subgrade}) \quad (2)$$

$$D_{15}(\text{Permeable Base}) \leq 5D_{85}(\text{Separator Layer}) \quad (3)$$

$$D_{50}(\text{Permeable Base}) \leq 25D_{50}(\text{Separator Layer}) \quad (4)$$

In addition, the separator layer should contain no more than 12 percent fines and have a coefficient of uniformity (C_u) greater than 20 (6). The material for the separator layer should consist of durable, crushed aggregates. Detailed information on the selection of an appropriate geotextile material to serve as a separator layer is provided elsewhere (6).

Edge Drain Collector System

The edge drain must have the necessary hydraulic capacity to handle water being discharged from the permeable base. A geocomposite drain or an aggregate trench drain without a pipe is not recommended to drain permeable bases because neither provides adequate hydraulic capacity, nor can they be maintained (6).

The trench should be deep enough to place the top of the drainage pipe at least 50 mm (2 in) below the bottom of the permeable base. In deep freeze areas, a deeper placement may be necessary to avoid freezing problems. The drains should not be placed in the paver trackline or in the wheelpath to prevent damage to the drains. The backfill material for the trench should be at least as permeable as the permeable base material. Nonstabilized pea-gravels are not recommended as the backfill material because they cannot be compacted satisfactorily (8). Proper compaction of the backfill material is important to avoid settlement over the edge drain. Where settlement has been a problem, stabilized backfill material should be considered.

For maintenance considerations, minimum 100-mm (4-in) diameter perforated pipes and maximum outlet spacings of 75 m (250 ft) are recommended (6). However, in areas where the grade is very flat, outlet spacings may need to be decreased in order to facilitate removal of water from the edge drain. Solid-walled rigid pipes are recommended for the lateral outlet pipes. Smooth, long-radius bends and dual outlet systems are also recommended to allow flushing and video inspection equipment to enter the drain from either end. Outlet pipes should have at least 3 percent slope toward the drainage ditch, and the discharge end of the pipe should be placed at least 150 mm (6 in) above the 10-year design flow in the ditch (6). If adequate ditch depths are not provided, permeable bases should not be used.

Headwalls are recommended at drainage outlets to protect outlet pipes from damage, to prevent slope erosion, and to help locate the outlets. Headwalls should be placed flush with the slope so that they do not impair mowing operations or become a hazard (6). Removable rodent screens are recommended to discourage rodents from building nests in the pipe drains.

Longitudinal Edge Drains

Longitudinal edge drains (placed without a permeable base) have been used as a means of providing subsurface drainage on new and existing pavements. However, opinions differ on the effectiveness of edge drains by themselves in improving pavement performance. This study found that edge drains placed without a permeable base are generally not effective because infiltrated water cannot readily flow through a dense-graded base to reach the drain.

There are two basic types of edge drains: pipe drains and geocomposite drains. A partially wrapped trench is recommended with pipe drains to prevent subgrade fines from clogging the drains. When properly installed, geocomposite drains can perform as well as other types. However, flow capacity may not be adequate in some cases, and they cannot be maintained. Geocomposite drains should be placed on the shoulder side of the trench and backfilled with wet sand (9, 10).

BASE TYPE

Base courses are placed beneath concrete pavements to provide increased structural capacity, to prevent pumping of materials, and to provide a working platform for subsequent paving operations. JPCP performance is greatly affected by base type, most notably in the development of joint faulting and slab cracking. The use of a base course is strongly recommended, as slab-on-grade designs have not performed well even under moderate traffic loadings.

Selection of Base Type

The relative advantages and disadvantages of the different base types, along with key design considerations, are summarized in table 2. The use of a granular subbase beneath the base course is also recommended for most medium- and high-trafficked roadways. The subbase provides a strong construction platform and frost protection and prevents pumping of the subgrade.

Permeable Bases

Sections constructed on permeable bases showed good performance under low to medium traffic levels, provided that an effective separator layer and edge drains were present. On direct comparisons between adjacent permeable and nonpermeable sections, the permeable base sections consistently showed lower levels of faulting (see *Subsurface Drainage*). However, many of the permeable base sections were relatively young.

Lean Concrete Bases

A lean concrete base (LCB) provides uniform support to the pavement and provides a strong construction platform for paving operations, although not without additional costs. According to a recent survey, the use of an LCB in lieu of a conventional dense-graded aggregate base increases the construction cost by an average of 22 percent (5).

The results of this study showed that these designs performed well when shorter joint spacings were employed to counteract the increase in curling stresses created by the stiffer foundation support. A granular subbase and dowel bars are also recommended to prevent pumping of the subgrade and to provide effective joint load transfer.

Typically, LCB contain between 120 and 210 kg/m³ (200 and 350 lb/yd³) of cement, resulting in 28-day compressive strengths between 5.2 and 10.4 MPa (750 and 1,500 lb/in²). Due to erodibility concerns, cement contents and strengths in the upper portion of those ranges are preferred, especially for heavy traffic. Production and placement are essentially the same as for conventional concrete pavements, with thicknesses ranging from 100 to 150 mm (4 to 6 in).

Currently, many States treat the LCB surface with a double coating of a wax-based curing compound to break the bond between the base and the overlying jointed concrete pavement, thus minimizing the potential for random reflection cracking. However, several European countries take active steps to *promote* the bond between the slab and the base (11).

Germany bonds the two layers and cuts notches in the LCB to coincide with longitudinal and transverse joints (12). The bonding of these layers provides a thick monolithic slab, which decreases edge stresses, deflections, thermal curling, moisture warping, and interlayer erosion. It also promotes early cracking of joints and more uniform transverse joint openings, which improves sealant performance.

Stabilized Bases

Stabilized base courses may be placed under JPCP to increase support, reduce susceptibility to moisture and erosion, and to provide a strong working platform for paving operations. Both asphalt-treated bases (ATB) and cement-treated bases (CTB) have been used successfully. The performance of sections constructed on ATB and CTB varied considerably, possibly because of varying stabilizer content and construction practices. Stabilized bases, in comparison to dense-graded aggregate bases, were found to be more effective in reducing faulting. However, stabilized bases can cause increased thermal curling stresses, so it is imperative that shorter transverse joint spacings be employed.

ATB and CTB may consist of either plant-mixed or road mixed materials, although plant-mixed materials are recommended. Agency-approved aggregates and gradations should be used in the mixture, with granular materials preferred. To increase the erodibility resistance of these materials, a minimum of 8 percent cement and 6 percent asphalt is recommended (13). Thicknesses of 100 to 150 mm (4 to 6 in) generally have worked well for both base types.

Dense-Graded Aggregate Base

Dense-graded aggregate bases have been the traditional base course placed beneath concrete pavements. They are believed to be most appropriate for low- to medium-trafficked roadways. Dense-graded bases, consisting of high-quality crushed stone or gravel and a minimum thickness of 150 mm (6 in), are commonly used to provide a stable construction platform. Recommendations for dense-graded bases include limiting the fraction passing the No. 200 sieve to two-thirds of the fraction passing the No. 40 sieve, limiting the liquid limit to 25, limiting the plasticity index to 6, and providing compaction to 95 percent relative density (14).

The results of this study indicated that sections constructed on aggregate bases exhibited fair to good performance. While these sections were somewhat susceptible to pumping and faulting, they did exhibit less cracking than sections with other base types due to reduced stiffness and frictional qualities.

SHOULDER TYPE/EDGE SUPPORT

Edge stresses and corner deflections are critical pavement responses that affect cracking and faulting. Several design alternatives, including tied concrete shoulders and widened slabs, have been used to reduce the magnitude of these critical stresses and deflections in efforts to improve pavement performance. Widened lanes are generally recommended with or without the use of tied concrete shoulders.

Tied Concrete Shoulders

The use of tied concrete shoulders has grown considerably in the last few years, but their field performance has shown mixed results. In this study, low load transfer across the lane-shoulder joint was observed on several sections, suggesting an ineffective tie bar system and marginal benefit. In general, concrete shoulders constructed monolithically with the mainline pavement provide more consistent performance and better edge support than those added later because of the load transfer provided through aggregate interlock.

The tie bar system is a critical component that determines the effectiveness of this design. Of particular importance are the tie bar diameter and spacing. 16-mm (No. 5) bars are recommended as the minimum tie bar size; 13-mm (No. 4) bars were shown to be inadequate in many cases. Larger diameter bars may be required on heavy truck routes or merging areas where trucks frequently cross the lane-shoulder joint. Deformed, epoxy-coated bars should be used. The recommended tie bar length is 760 mm (30 in), and the tie bar spacing should not exceed 760 mm (30 in).

Widened Slabs

Widened slab sections showed outstanding performance, exhibiting low faulting and very few transverse cracks. Widened slabs were found to have a strong influence on preventing the development of joint faulting and slab cracking. Figure 2 illustrates the effect of widened slabs on the development of faulting in a 250-mm (10-in) doweled pavement. The faulting of the widened slab section is about two-thirds of the conventional slab. Widened slabs offer similar benefits to transverse slab cracking, as discussed in the *Slab Thickness* section.

The benefits of widened slabs are derived by keeping traffic away from the pavement edge, where they cause critical loading conditions. To obtain the full benefit, sufficient width slabs are required; however, excessively wide slabs are susceptible to longitudinal cracking. Analytical results also indicate a diminishing benefit of constructing slabs more than 4.3 m (14 ft) wide. Based on these considerations, slab widths between 4.0 and 4.3 m (13.5 to 14 ft) are recommended for widened slab sections.

TRANSVERSE JOINT DESIGN

Transverse joints relieve internal slab stresses caused by shrinkage, temperature and moisture gradients, and frictional restraint from the underlying base course, all of which lead to the development of random, uncontrolled cracking in the slab. Although transverse joints are a necessary and integral part of concrete pavement design and construction, many problems are associated with their design, construction, and performance. Indeed, the performance of many JPCP has historically not been driven by its structural capacity, but rather by its joint design.

JPCP Transverse Joint Spacing

To obtain optimum performance, transverse joints must be provided at appropriate intervals to limit the critical stresses to an acceptable level. Along with slab thickness, load transfer, concrete strength, and lateral edge support, transverse joint spacing is a key design factor affecting performance.

Guidelines for joint spacing are often given in terms of the ratio of slab length to radius of relative stiffness, L/l . The field data collected under this project indicate that an approximate correlation between L/l and slab cracking exists (see figure 3), with satisfactory cracking performance achieved by keeping L/l less than about 4.5 (3). However, this relationship is approximate and is better determined based on fatigue analysis results. Such an analysis has been conducted using the cracking model and analysis procedure developed under this study. The recommended maximum joint spacings are given in table 3 (3).

The joint spacings given in table 3 range from 3.7 to 6.1 m (12 to 20 ft). For cracking considerations, the desirable performance can be achieved using any joint spacing by varying the slab thickness; however, excessive joint movements resulting from longer joint spacing can adversely affect performance. The additional slab thickness required to accommodate the longer joint spacing may also prove uneconomical.

The limiting values given in table 3 were established as a practical guide. If acceptable performance can be demonstrated through current performance or analyses, longer joint spacings may be possible; however, joint spacing less than 3.7 m (12 ft) is not recommended because it will adversely affect rideability.

Uniformity of JPCP Transverse Joint Spacing

Traditionally, joints in concrete pavements have been placed at constant, uniform intervals. However, in the late 1950s, research was conducted on the effect of uniformly spaced joints on rideability (15). The study determined that faulting of uniformly spaced joints produced a rhythmic response in certain full-sized automobiles, significantly affecting rideability. This response was reduced the most by employing a random joint spacing. It was further indicated that slab spacing patterns in multiples of 2.3 m (7.5 ft) should be avoided.

Based on those findings, many agencies adopted random joint spacings in the 1960s and 1970s. Initially, the 3.7-4.0-5.8-5.5-m (12-13-19-18-ft) pattern was commonly used, but transverse cracking often occurred on the longer slabs. Consequently, shorter joint spacings (such as 3.7-4.6-4.0-4.3-m [12-15-13-14-ft]) are more commonly used today.

The results of this investigation did not reveal any strong advantages or disadvantages to the use of random joint spacings. If used, it is recommended that random joint spacings be kept relatively short without large differences in the length of the slabs that make up the joint spacing pattern (3).

Although many States currently employ random joint spacing, it is not known if their use is warranted for the wheelbase and suspension systems found on today's vehicles. It is also not known if random joint spacings are needed when dowel bars are specified in the design, since the dowel bars are expected to provide load transfer and reduce joint faulting.

Joint Orientation

Joint orientation refers to the angle of the transverse joint with respect to the centerline of the pavement. Perpendicular joints are constructed perpendicular to the centerline, whereas skewed joints are placed at an angle to the centerline, usually offset about 0.6 m (2 ft) per traffic lane in the counterclockwise direction. The purpose is to prevent the wheels of an axle from crossing the joint at the same time, thereby reducing the deflection at the joint.

Based on the results of this study, the use of skewed joints is recommended for nondoweled slabs (less than 5 million ESAL applications) (3). In such designs, skewed joints have been observed to show less faulting than perpendicular joints. However, because sections with skewed joints are also more susceptible to corner breaks, this suggests the need to limit the amount of skewing. Maximum skews of 0.6 m (2 ft) per traffic lane are recommended, with some suggesting a maximum skew of 0.3 m (1 ft) per 3 m (10 ft) of pavement width (16, 17).

If transverse joints are to be doweled, skewed joints are not recommended due to their reduced effectiveness (18). In addition, dowel alignment problems may be more apt to occur in skewed joint construction (17).

Transverse Joint Load Transfer

Transverse joint load transfer is the mechanism through which wheel loads are conveyed from one slab to the next. Effective load transfer reduces the magnitude of stresses and deflections at the joint. This, in turn, will help minimize such joint distresses as pumping, faulting, loss of support, corner breaks, and transverse cracking.

Load transfer across a transverse joint is achieved either through aggregate interlock between the abutting joint faces or through the use of mechanical load transfer devices (e.g., dowel bars). The use of dowel bars is recommended for nearly all jointed concrete pavement designs, with the possible exception of those pavements designed for extremely light truck traffic volumes. Even in those cases, the use of dowel bars should be considered carefully in light of the historical inability to accurately forecast truck loadings.

The selection of an adequate dowel bar diameter is critical in the design of the load transfer system. Guidelines were developed based on the faulting prediction models developed under this study and assuming a faulting limit of 2.5 mm (0.10 in) (3). The use of dowels is recommended for pavements designed for more than 5 million ESAL applications. The minimum recommended dowel diameter is 25 mm (1 in), with 38-mm (1.5-in) dowels recommended for pavements with high heavy truck volumes.

Dowel bars are generally 460 mm (18 in) long and spaced at 300-mm (12-in) intervals across the joint (19, 20). However, nonuniform dowel spacings may also be used to concentrate the dowels directly under the wheelpaths, where they are most needed. For example, the German design calls for 4 to 5 dowels at 250-mm (10-in) spacings in the wheelpaths, whereas between the wheelpaths dowels are placed at 500-mm (20-in) spacings (12).

Dowel alignment and coating are also very important to their effective performance. The FHWA recommends the alignment tolerance (vertical and horizontal) of 21 mm/m (0.25 in/ft) (19, 20). The use of corrosion-resistant material or coating is recommended to prevent corrosion of the dowel, which could result in lock-up of the joint. Materials that have been successfully used as a rust inhibitor include epoxy coatings, plastic coatings, and stainless steel sleeves. A bondbreaker between the dowel and the concrete is also recommended.

Joint Sealant and Reservoir Design

Joint sealing is an issue of current debate among many highway engineers. Many believe that a well-designed and maintained joint reservoir is critical in preventing the entry of incompressibles and moisture into the pavement structure, whereas others believe that, under some conditions, the benefits derived from joint sealing may not be enough to offset the costs associated with its placement.

The results of this study showed that, in direct project comparisons, sections with sealed joints had slightly less joint spalling than sections with nonsealed joints, although the differences were not that significant (2). However, many of these sections were not that old, so the long-term effects of joint sealing are still not known.

The decision to seal or not seal joints in concrete pavements should be based on many factors, including (but not limited to) items such as climate, expected heavy truck traffic, joint design, base type, and local experience. Of these, local experience is probably the most important, as agencies should have an indication of what works and does not work for their local conditions.

If determined necessary, the joint reservoir is designed in conjunction with both the type of sealant to be used in the pavement and the anticipated movements expected at the joint. The following three items must be considered:

1. *Type of sealant.* Among the pavement sections evaluated under this study, those containing preformed sealants exhibited the least amount of joint spalling. Where D-cracking is not a problem, preformed compression seals were highly effective in maintaining the joints clean and free of spalling, even in older sections (up to 21 years in one case) (2). Proper installation is important to obtain good performance using preformed compression sealants. Preformed compression sealants are used to seal both longitudinal and transverse joints in Germany (11).
2. *Anticipated joint movement.* The amount of opening experienced by a joint is a function of the joint spacing, the friction between the slab and the base, the concrete coefficients of thermal expansion and of drying shrinkage, and the temperature drop.
3. *Recommended shape factor.* The shape factor is the ratio of the sealant width to the sealant depth and is based on research conducted in the late 1950s (21). This research showed that, for the same width, sealants placed deeper were subjected to greater strains when subjected to thermal movement than those placed shallower (21). Recognition of this fact led to the consideration of sealant strains in the design of the joint reservoir and in the selection of the joint sealant.

Different requirements exist for preformed compression seals. These seals are placed in the joint under compression and are required to be compressed 20 to 50 percent of their normal width throughout its life. The determination of the required joint reservoir width and the selection of a proper preformed compression seal are an iterative procedure that should include input from the manufacturer.

LONGITUDINAL CONTRACTION JOINT DESIGN

Longitudinal contraction joints (also referred to as longitudinal weakened plane joints or longitudinal warping joints) are placed between adjacent lanes to prevent the development of longitudinal cracking. On conventional 7.3-m (24-ft) wide concrete pavement, longitudinal contraction joints are placed at the midpoint of the width of the paving, typically 3.7 m (12 ft) from the edge of the slab. On multi-lane facilities, the maximum longitudinal contraction joint spacing is 4.3 m (14 ft), which corresponds with the maximum width for PCC slab widening.

It is recommended that longitudinal contraction joints be established through sawcutting of the pavement to a depth of one-third of the slab thickness. As with the sawing of transverse joints, the timing of the longitudinal sawing operations is critical to preventing the development of random cracking; this is perhaps most crucial when paving in cold weather and over stabilized base courses (17).

Another way of forming longitudinal contraction joints is through the use of a plastic insert that is mechanically installed by the paver. While once very popular, this method is not recommended and has been dropped by most agencies, mainly because there are questions regarding the effectiveness of the plastic insert in forming the longitudinal contraction joint (17). It was observed in this study that significant longitudinal cracking occurred on many concrete pavements in which the longitudinal contraction joint was formed using a plastic insert, particularly for those pavements constructed on stabilized bases.

Tie bars are typically placed at the mid-depth of the PCC slab at the longitudinal contraction joint location through mechanical implantation. The primary purpose of tie bars is not to provide load transfer but rather to hold the lanes together so that lane separation and differential vertical movements are prevented.

An adequately designed tie bar system is critical to ensuring the effectiveness of the longitudinal construction joints. In cases where tie bars were omitted from the longitudinal contraction joint design, significant horizontal separation and vertical elevation differences have occurred between lanes (15). Such observations were also noted in this study where tie bars were not present between lanes and on several pavements with small tie bars (13 mm [No. 4] or smaller) or large tie bar spacings.

For most medium- and high-trafficked roadways, it is recommended that 16-mm (No. 5) bars be employed at 760-mm (30-in) intervals. However, larger diameter bars at closer spacings are suggested in areas frequently crossed by truck traffic (e.g., acceleration/deceleration lanes, truck climbing lanes, and high-volume merge areas) (17). For example, Germany uses between three and five 20-mm (0.8 in) bars for every 5-m (16-ft) slab on its high-type pavements (12).

CONCRETE STRENGTH

Concrete strength directly affects slab cracking and also influences other aspects of concrete pavement performance, including wear resistance, durability, spalling, and permeability. In terms of cracking performance, the consideration for the use of high-strength concrete is primarily a cost issue because slab thickness can be selected for any strength material to obtain the same performance. Other benefits of using higher strength concrete are more difficult to assess. In Europe, special attention is given to the quality of concrete, especially the material placed near the pavement surface, to ensure adequate wear resistance and durability (11).

Many countries in Europe use much higher strength concrete than in the United States. The minimum 28-day flexural strength is 5.5 MPa (800 lbf/in²) in Germany and 6.5 MPa (940 lbf/in²) in Austria (12). The mean values are considerably higher: 7.6 MPa (1,100 lbf/in²) in Austria and 8.3 MPa (1,200 lbf/in²) in Italy. No durability problems were found in any of the European sections inspected during the 1992 tour of European highways even though some of the sections had been exposed to severe freeze-thaw conditions and heavy use of deicing materials (11).

Other than the effects on slab cracking, the pavement sections did not show any strength-dependent performance trends. The average 28-day flexural strength was about 4.5 MPa (650 lbf/in²). This value was estimated from the long-term flexural strengths determined for the pavement sections, assuming that the long-term strength is about 10 percent higher than 28-day strength. The 28-day flexural strength of 4.5 MPa (650 lbf/in²) is representative of the typical design strength for concrete pavements in the United States.

For the design conditions, a minimum 28-day flexural strength of 4.5 MPa (650 lbf/in²) appears to be adequate to avoid any strength-related problems (3). Based on the excellent performance of European designs, however, the use of higher strength concrete seems to merit further evaluation in the United States.

SLAB THICKNESS

Slab thickness is a key design feature that has a major effect on performance of PCC pavements. Slab thickness most directly affects fatigue cracking. However, numerous design factors affect cracking the behavior of PCC pavements, and the consideration of the effects of those factors is an essential part of thickness design. Some of the more sensitive factors affecting fatigue performance of PCC pavements include joint design and spacing, shoulder type, slab width (widened slab), and PCC modulus of rupture. Other factors that affect slab thickness include subgrade stiffness (k-value), PCC elastic modulus (E_{PCC}), base type, slab/base friction, and climate.

The effects of joint spacing on slab thickness design are illustrated in figure 4. The 20 percent slab cracking used in this figure as the basis of comparison is arbitrary, but this is a reasonable failure criteria for design purposes because 20 percent cracking is representative of the onset of rapid cracking of slabs. Figure 4 clearly illustrates the importance of considering the effects of joint spacing in slab thickness design. The recommended minimum and maximum joint spacings for highway pavements are 3.7 m (12 ft) and 6.1 m (20 ft), respectively. The selection of joint spacing within this range is largely a matter of economics and designer preference.

The effects of various types of edge support on slab thickness are shown in figure 5. This figure shows the significance of load transfer efficiency (LTE) on cracking performance of tied PCC shoulder designs. For design purposes, a conservative value should be used because the LTE tends to degrade with pavement age. The recommended values of stress LTE are 20 percent for the shoulders that are constructed monolithically with the mainline and 10 percent for separately constructed shoulders.

The required slab thicknesses shown in figure 5 are based on considerations of midpanel fatigue cracking only. To avoid problems with excessive deflection, design features such as tied PCC shoulder and widened slab should not be used to reduce slab thickness below the minimum of the typical pavement thicknesses for the class of pavement being designed.

SUMMARY

This paper has described recommendations for various aspects of concrete pavement design based on the results of a comprehensive field study of concrete pavement and the current state of the practice. As mentioned earlier, it is critical that the entire pavement be designed as a system, and not as a collection of design features and elements derived independently. The relative effects of each individual design feature on the performance of the pavement must be directly considered and evaluated prior to its inclusion. A summary of design recommendations for these various aspects of jointed plain concrete pavement design is provided in tables 4 and 5.

For very heavily-trafficked roadways (design ESALs greater than 20 million), consideration should be given to adopting several positive design features in order to maximize the performance of the pavement and increase its reliability. For example, European researchers have defined four classes of “modernity elements,” factors that are expected to contribute to the overall performance of the pavement (22). The four classes are:

- Nonerodible base course (specifically, lean concrete base).
- Positive pavement drainage.
- Strengthened structure (thickened slab, doweled joints, or continuously reinforced concrete pavement [CRCP]).
- Optimization of the use of materials with respect to loading (widened PCC slabs or trapezoidal cross sections).

Many European concrete pavement designs incorporating three or four modernity elements exhibit outstanding performance in the face of very heavy traffic loadings (4). In this vein, heavily-trafficked concrete pavement designs in the United States should give consideration to the inclusion of three or four modernity elements in order to increase both the reliability of the design and the overall level of performance.

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TABLE 1 Simplified Design Matrix for Selecting the Drainage Coefficient

Edge Drain	Precipitation	Fine Grained Subgrade (A-4 through A-7)		Coarse Grained Subgrade (A-1 through A-3)	
		Nonpermeable Base	Permeable Base	Nonpermeable Base	Permeable Base
No	Wet	0.70–0.80	0.70–0.80	0.80–0.90	0.90–1.00
	Dry	0.80–0.90	0.80–0.90	0.90–1.00	1.00–1.10
Yes	Wet	0.85–0.95	1.00–1.10	0.95–1.05	1.05–1.15
	Dry	0.95–1.05	1.10–1.20	1.05–1.15	1.15–1.20

- Notes:
1. Permeable Base = Permeability ≥ 1000 ft/day or $C_u \leq 6$.
 2. Wet climate = Precipitation > 15 in/year;
Dry climate = Precipitation ≤ 15 in/year.
 3. The available data provided no information on the effectiveness of permeable bases without edge drains, and the data ranges provided in the table are estimates. This design is generally not recommended, although on a coarse-grained subgrade some vertical drainage may occur.
 4. Generally select mid-point of range and use other drainage features (adequacy of cross slopes, depth of ditches, etc.) to adjust upward or downward.

TABLE 2 Summary of PCC Pavement Base Types

Base Type	Advantages	Disadvantages	Key Design Considerations	Recommended Traffic Levels
Permeable Base (<i>stabilized and nonstabilized</i>)	Removes water from pavement Low susceptibility to erosion Decrease in moisture-related distresses (faulting, D-cracking, etc.)	Difficult to construct (<i>particularly nonstabilized</i>) Granular separator layer required May have to limit construction traffic High cost (from 14 to 24 percent greater than conventional aggregate base)	Design of separator layer Collector/outlet pipe design Adequate stabilizer contents (<i>generally 200–250 lb/yd³ of cement or 2–3% of asphalt</i>) Compaction/curing	Medium to High <i>Smith, Yu, Wade, and Darter</i>
Lean Concrete	Easy to construct Strong stable platform Strong resistance to erosion Improves pavement rideability Reduces slab stresses (<i>if bonded</i>)	High cost (about 22 percent greater than conventional aggregate base) Increased friction with slab Increased slab curling/warping Granular subbase required to prevent pumping	Shorter JPCP joint spacing Curing of base Bonding of base Notching of joints in base if bonded Match longitudinal joints	Medium to High (<i>with granular subbase</i>)
Asphalt Stabilized	Easy to construct Strong stable platform Some resistance to erosion Improves pavement rideability Reduces slab stresses (<i>if bonded</i>)	High cost (about 8–15 percent greater than conventional aggregate base) May be susceptible to stripping Increased friction with slab Increased slab curling/warping Granular subbase required to prevent pumping	Shorter JPCP joint spacing Asphalt content (<i>5–6% recommended</i>) Proper compaction Whitewashing of base prior to paving Bonding of base Match longitudinal joints	Medium to High (<i>with granular subbase</i>)
Cement Stabilized	Easy to construct Strong stable platform Some resistance to erosion Improves pavement rideability Reduces slab stresses (<i>if bonded</i>)	High cost (about 8–15 percent greater than conventional aggregate base) May be susceptible to erosion Increased friction with slab Increased slab curling/warping Granular subbase required to prevent pumping	Shorter JPCP joint spacing Cement content (<i>6–8% recommended</i>) Compaction Bonding of base Match longitudinal joints	Medium to High (<i>with granular subbase</i>)
Dense-Graded Aggregate	Easy to construct Low cost Low friction with slab	Susceptible to erosion May retain moisture for long periods	Compaction (<i>to 95% of AASHTO T180</i>) Controls on liquid limit, plastic limit, and percentage of fines	Low to Medium

TABLE 3 Recommended Maximum Joint Spacings for JPCP Designs (3)

Design ESALs	E_{PCC} lb/in ² /in	Thick, in	Dry-Freeze			Dry-Nonfreeze			Wet-Freeze			Wet-Nonfreeze		
			Subgrade k, lb/in ² /in			Subgrade k, lb/in ² /in			Subgrade k, lb/in ² /in			Subgrade k, lb/in ² /in		
			100	200	400	100	200	400	100	200	400	100	200	400
2 million	3 million	6 in	12	12	12	12	12	12	12	12	12	12	12	12
		7 in	12	14	14	12	14	14	12	14	14	12	12	14
		8 in	16	16	16	16	16	16	16	16	16	16	16	16
	5 million	6 in	12	12	12	12	12	12	12	12	12	12	12	12
		7 in	12	12	14	12	12	12	12	12	12	12	12	12
		8 in	16	16	16	14	15	16	15	15	16	13	13	13
5 million	3 million	7 in	12	14	14	12	12	14	12	12	14	12	12	12
		8 in	16	16	16	15	16	16	16	16	16	14	16	16
		9 in	18	18	18	18	18	18	18	18	18	18	18	18
	5 million	7 in	12	12	12	12	12	12	12	12	12	12	12	12
		8 in	14	15	16	12	12	12	12	13	13	12	12	12
		9 in	18	18	18	16	16	15	18	17	18	16	15	14
10 million	3 million	8 in	16	16	16	13	16	16	14	16	16	12	13	16
		9 in	18	18	18	18	18	18	18	18	18	18	18	18
		10 in	20	20	20	20	20	20	20	20	20	20	20	20
	5 million	8 in	12	13	14	12	12	12	12	12	12	12	12	12
		9 in	18	18	18	15	14	13	16	15	15	14	14	13
		10 in	20	20	20	19	18	17	20	19	19	18	17	15
20 million	3 million	9 in	18	18	18	18	18	18	18	18	18	16	18	18
		10 in	20	20	20	20	20	20	20	20	20	20	20	20
		11 in	20	20	20	20	20	20	20	20	20	20	20	20
	5 million	9 in	16	15	16	14	13	12	14	14	13	13	12	12
		10 in	20	20	20	18	16	15	19	17	16	17	16	14
		11 in	20	20	20	20	19	17	20	20	19	20	18	17
50 million	3 million	10 in	20	20	20	20	20	20	20	20	20	20	20	20
		11 in	20	20	20	20	20	20	20	20	20	20	20	20
		12 in	20	20	20	20	20	20	20	20	20	20	20	20
	5 million	10 in	18	17	16	16	15	13	17	15	14	16	14	13
		11 in	20	20	19	19	17	15	20	18	17	19	17	15
		12 in	20	20	20	20	19	17	20	20	19	20	19	17
100 million	3 million	11 in	20	20	20	20	20	20	20	20	20	20	20	20
		12 in	20	20	20	20	20	20	20	20	20	20	20	20
		13 in	20	20	20	20	20	20	20	20	20	20	20	20
	5 million	11 in	20	18	17	18	16	14	19	17	15	18	16	14
		12 in	20	20	19	20	18	16	20	20	17	20	18	16
		13 in	20	20	20	20	20	18	20	20	20	20	20	18

Note: k-values are dynamic values obtained directly from backcalculation (dynamic = 2* static).

TABLE 4 Summary of Structural Design Recommendations for Medium- and Heavy-Trafficked Roadways (3).

Design Aspect	Design/Construction/Performance Impacts	Recommended Use	Design Recommendation
Subgrade Preparation	- Stronger subgrade facilitates construction activities. - Stronger support decreases slab stresses. - Important to preventing volumetric changes.	Should be considered on every paving project depending on in situ soils.	- Minimum CBR of 6 obtained through stabilization (using appropriate stabilizing agent) - Replacement of existing soil with high quality material. - Increase uniformity by subcutting, remixing, and compacting. - Thick granular layer considered in frost areas.
Drainage	Reduced faulting, pumping, and erosion potential by removing excess moisture from pavement structure.	- On all projects in which: - need for drainage exists (according to procedure described in text), and - design traffic > 5 million ESALs. - Must be able to offset additional costs with corresponding increase in life.	- Permeable base drainage system consisting of: - Permeable base (stabilized or nonstabilized) - Separator layer - Pipe collector system - Nonerodible base constructed with permeable base beneath the shoulders and edge drains placed within the shoulder.
Base Type (and subbase)	- Stable base facilitates construction and aids in obtaining smooth surface. - Stabilized bases reduce load stresses, but also increase curling/warping stresses. - Drainage and frost protection provided by base.	- Permeable base or LCB for most medium- and high-trafficked roadways. - Stabilized bases and aggregate bases for low to medium-trafficked roadways. - Granular subbase beneath all base types for medium and high traffic.	- Permeable base: minimum 4 in thick; stabilized or nonstabilized; designed and constructed in accordance with guidelines. - LCB: minimum 4 in thick; minimum 8% cement; perhaps notched and bonded to slab. - ATB/CTB: minimum 4 in thick; minimum 6% AC or 8% cement; plant-mixed for high quality. - Aggregate: minimum 6 in thick; compacted to 95% density (AASHTO T-180). - Granular subbase: minimum 6 in thick.
Shoulder Type/Edge Support	Widened PCC slabs and tied PCC shoulders reduce critical edge stresses and corner deflections.	- Widened lanes with tied PCC shoulders on most high-type roadways, especially in urban areas. - Widened lanes on most medium- and high-type roadways.	- Tied PCC shoulders: - Tied with minimum No. 5 bar, 30-in long, at 30 in spacings - Monolithic paving preferred, with same thickness as mainline - Joints match mainline pavement - Widened PCC slabs: - Maximum 14 ft total slab width.
PCC Strength	Greater strength increases fatigue life and increases durability and wear resistance.		Minimum 28-day flexural strength of 650 lb/in ² .
PCC Thickness	Greater slab thickness increases fatigue life.		Designed in accordance with approved procedure, but checked with design tables included in chapter.

1 in = 25.4 mm; 1 ft = 0.305 m; 100 lb/in² = 0.69 MPa

TABLE 5 Summary of Transverse Joint Design Recommendations for Medium- and Heavy-Trafficked Roadways (3)

Design Aspect	Design/Construction/Performance Impacts	Recommended Use	Design Recommendation
Sawcut Timing	- Late transverse joint sawing results in uncontrolled random transverse cracking. - Late longitudinal joint sawing results in uncontrolled random longitudinal cracking, particularly on stabilized bases.		- Saw as early as possible without causing significant raveling, generally within 4 to 12 hours. - Sawcut timing can be related to concrete compressive strength (see guidelines).
Sawcut Depth	Inadequate sawcut depths of transverse or longitudinal joints result in uncontrolled random cracking.		Minimum sawcut depth of 25 percent of the slab thickness, but this might need to be increased to a depth of 33 percent of the slab thickness for slabs placed on permeable or stabilized bases.
JPCP Joint Spacing	- Shorter joint spacings reduce curling stresses and joint movements. - Increased maintenance requirements associated with greater number of joints.		- Joint spacing a function of slab thickness, climate, traffic, and subgrade support (see guidelines). - Generally between 15 and 18 ft, with 20 ft the absolute maximum. - Minimum recommended joint spacing is 12 ft.
JRCP Joint Spacing	Shorter joint spacings reduce curling stresses and joint movements.		Mixed performance results, but current trends are to shorter spacings (e.g., 30 ft).
Nonuniform Joint Spacing	Reduction in rhythmic response of vehicles due to joint faulting.	- Unknown if nonuniform joints are warranted for the wheelbases and suspension systems of today's vehicles. - Unknown if nonuniform joints are necessary on doweled pavements. - Not recommended for JRCP designs.	- If used, shorter joint spacing combinations with smaller deviations between slab sizes (e.g., 12-15-13-14 ft) have performed better. - Don't use on adequately designed doweled pavements.
Joint Orientation	Theoretical reduction in joint stresses and deflections due to axle wheels not crossing joint at the same time.	Recommended for use on nondoweled pavements only.	Maximum skew of 2 ft in 12 ft, with some suggesting no more than 1 ft in 10 ft.
Joint Load Transfer	Reduction in key joint distress (pumping, faulting, loss of support, corner breaks).	Dowel bars recommended on all pavements designed for 5 million or more ESAL applications.	- Dowel diameter primarily a function of slab thickness. - Minimum diameter of 1.25 in for most medium-trafficked roadways; 1.50 for high-trafficked roadways. - Dowel bars 18 in long, epoxy-coated for corrosion protection, and spaced uniformly across the joint at 12-in intervals.
Joint Sealant/Reservoir Design	Prevention of water and incompressibles from infiltrating in joint and pavement structure.	Recommended on most jointed pavements (unless local experience and conditions dictate otherwise).	- Joint sealant reservoirs should be designed with consideration given to the type of sealant, the anticipated movements, and the recommended shape factor (see guidelines). - Preformed joint sealants provide the best performance of all joint sealants.

1 in = 25.4 mm; 1 ft = 0.305 m

TABLE 5 Summary of Longitudinal Contraction Joint Design Recommendations for
Medium- and Heavy-Trafficked Roadways (3)

Design Aspect	Design/Construction/Performance Impacts	Recommended Use	Design Recommendation
Forming Method	Inadequate longitudinal joint forming leads to development of uncontrolled longitudinal cracking.		Sawcutting of longitudinal joints is more effective for creating the weakened plane than plastic ribbon inserts.
Sawcut Timing	Late longitudinal joint sawing results in uncontrolled random longitudinal cracking.		- Saw as early as possible without causing significant raveling, generally within 4 to 12 hours. - Sawcut timing can be related to concrete compressive strength (see guidelines).
Sawcut Depth	Inadequate sawcut depths of longitudinal joints result in uncontrolled random longitudinal cracking.		Minimum sawcut depth of 33 percent of the slab thickness.
Joint Spacing	Excessive spacing between longitudinal joints causes uncontrolled random longitudinal cracking.		Minimum 12 ft and maximum 14 ft spacings between longitudinal joints.
Tie Bars	Hold lanes together to prevent separation and excessive vertical movements.	All longitudinal joints (up to a maximum of 3 lanes tied together).	- Minimum No. 5 bar placed at 30-in intervals. - Larger diameter bars at closer spacings should be considered for areas frequently crossed by trucks (e.g., ramps). - Tie bars placed at mid-depth of the slab.

1 in = 25.4 mm; 1 ft = 0.305 m

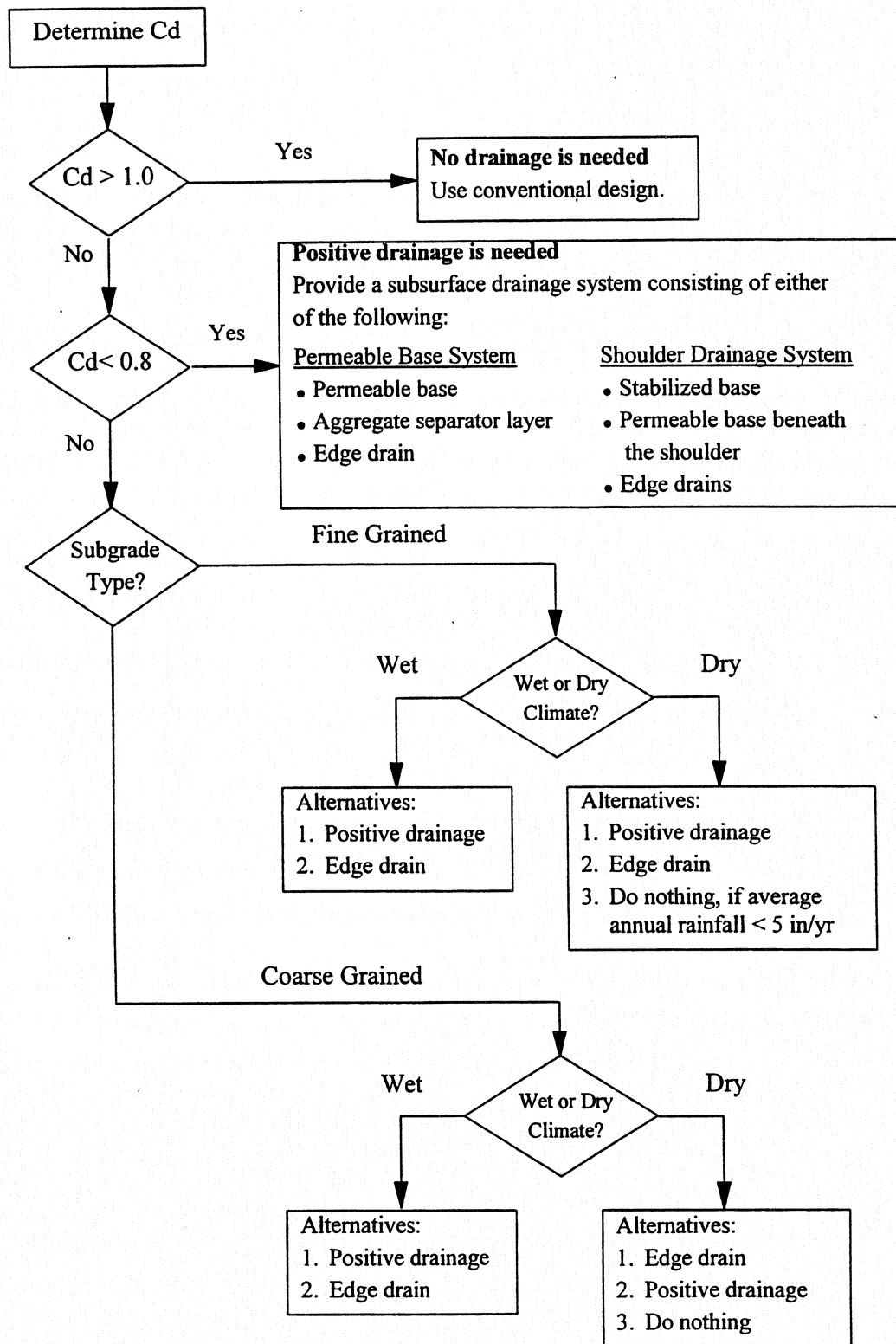


FIGURE 1 Flow Chart of Drainage Design Recommendations Based on Cd (3)

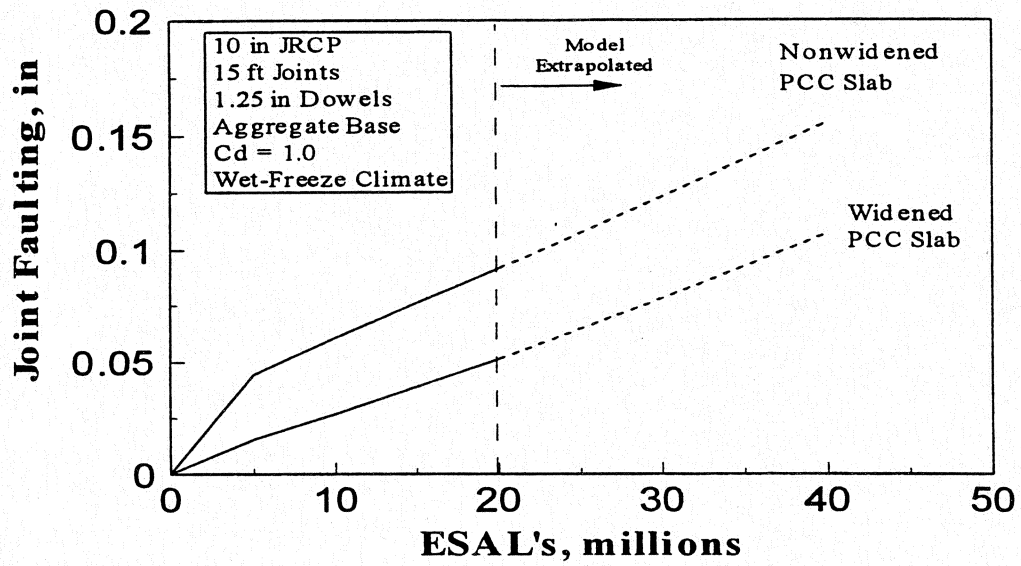
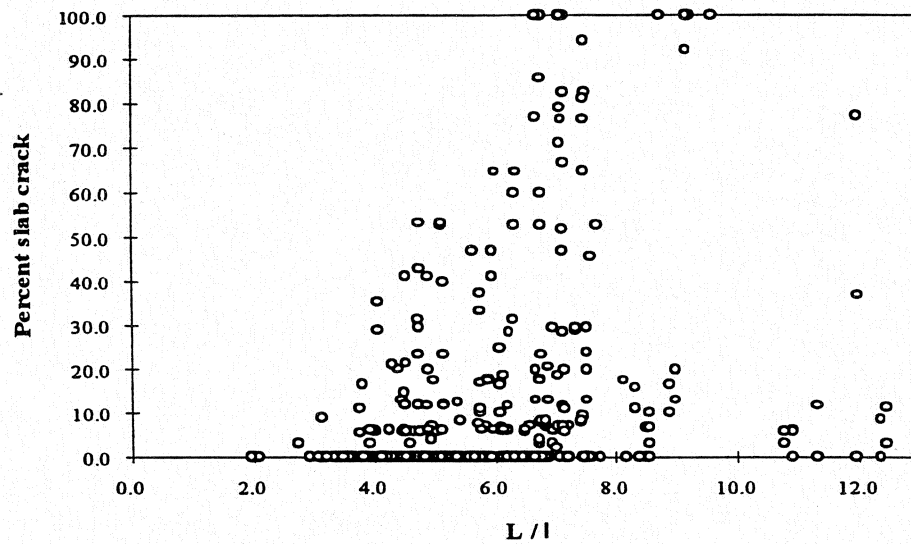


FIGURE 2. Effect of Widened Slab on Doweled Joint Faulting (3)

FIGURE 3. Cracking Performance as a Function of L/l (3)

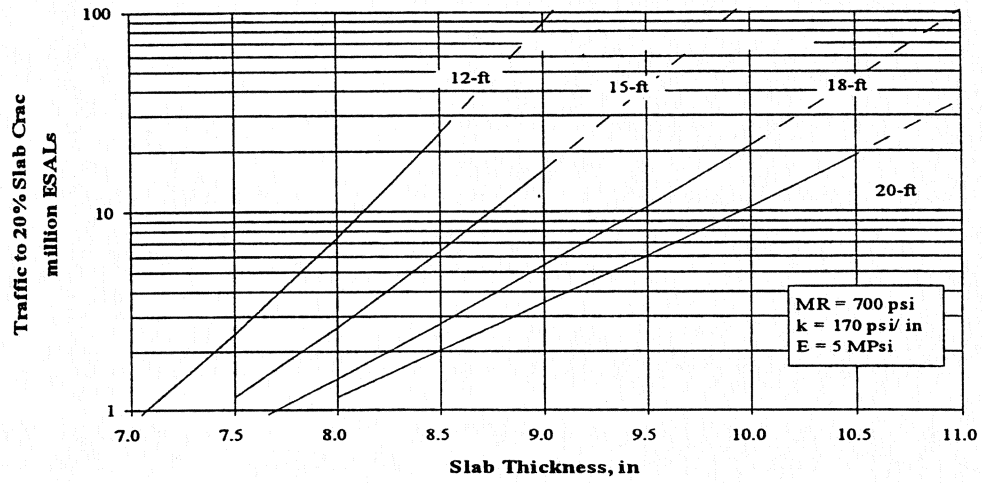


FIGURE 4. Sensitivity of Mid-Panel Fatigue Cracking (3)

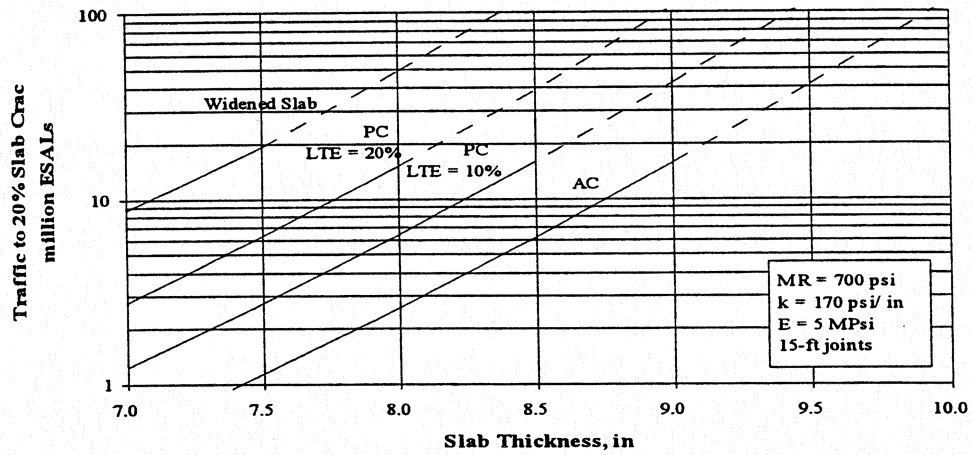


FIGURE 5. Effects of Widened Slab and Tied PCC Shoulders on Cracking (3)

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