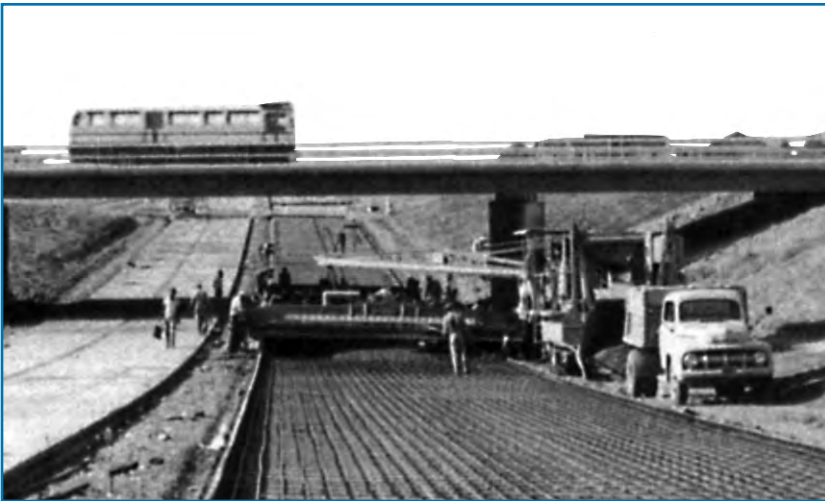


# CRCP in Texas

## Five Decades of Experience



photos courtesy Texas DOT

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## INTRODUCTION

The first continuously reinforced concrete pavements (CRCP) were constructed in Indiana and Illinois in the 1930s and 1940s. Based on pavement performance results, the state of Texas first used CRCP in 1951 on two contiguous projects in Fort Worth, Texas.

Because of these pavements' outstanding performance, the Texas Highway Department (now the Texas Department of Transportation—TxDOT) continued to construct many roads using CRCP. Texas is now the leading state in lane miles of CRCP. In recent years, the TxDOT has constructed all of its high-volume heavy-traffic roads with CRCP.

### **On the cover:**

**North-South Freeway (now I-35) in Fort Worth during construction and at completion in 1951.**

The excellent performance of CRCP in Texas can be attributed to TxDOT's consistent leadership in the development of CRCP technology. This CRSI Research Series provides a historical overview of the research and continuous improvement that the TxDOT has made over the past 50 years.

## CRCP Crack Behavior

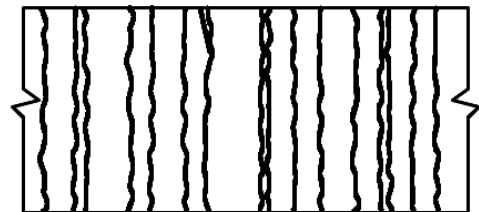
CRCP is, simply, concrete pavement that is reinforced with steel bars. The reinforcing bars control the width of the transverse cracks that form and hold them closed to control the amount of movement at the cracks, and maintain load transfer.

CRCP is a unique concrete pavement in that there are no intermediate transverse contraction or expansion joints built in for crack control, as is the case with jointed concrete pavements. Instead, over time, a series of transverse cracks appear across the pavement width (Figure 1). The transverse cracks do not impair the structural integrity of the pavement.

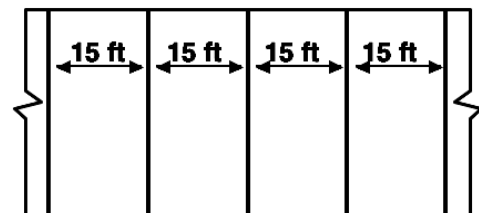
The cracks occur naturally in the concrete and are somewhat randomly spaced. A crack spacing of 3 to 8 feet apart is desirable.

Without joints and their associated spalling, curling, and faulting

**Figure 1**



**CONTINUOUSLY REINFORCED CONCRETE PAVEMENT WITH TYPICAL TRANSVERSE CRACK PATTERN**



**UNREINFORCED CONCRETE PAVEMENT WITH TRANSVERSE CONTRACTION JOINTS AT 15 FT. SPACING**

problems, CRCP typically provides a much smoother ride. The absence of joints also reduces maintenance costs by eliminating the need for joint sealing operations. CRCP therefore provides excellent long-term performance with considerable reduction in both annual and life-cycle costs compared to other pavement types.

## TxDOT'S Major Findings

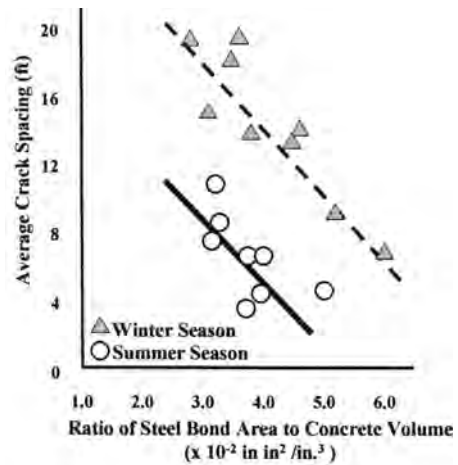
Over the years, the TxDOT has made great advances in understanding the behavior of CRCP. In the 1950s, the TxDOT first recognized the importance and interrelation of properties such as crack width, steel stress, and crack spacing. Based on findings at various project sites, several relationships between crack spacing and other CRCP properties were developed.

Much of the subsequent research has focused on factors that influence crack spacing, because in Texas, maintaining desirable crack spacing has a direct bearing on how well the pavement performs. Described below is an overview of TxDOT's major findings.

### Steel Bond Area

Using data collected in Texas, Illinois, and Indiana, the TxDOT found that a linear relationship exists between crack spacing and the longitudinal steel bond area (Figure 2). For smaller reinforcing bars, the bond area is larger and the resulting crack spacing is smaller. For larger reinforcing bars, the total bond area decreases and crack spacing increases, assuming the same steel percent. From this analysis, the TxDOT limited bar size to 5/8 inch diameter (#5 bar) to prevent the formation of wide crack spacing.

**Figure 2**  
RELATIONSHIP BETWEEN CRACK SPACING, STEEL BOND AREA, AND PLACEMENT SEASON



### Placement Season

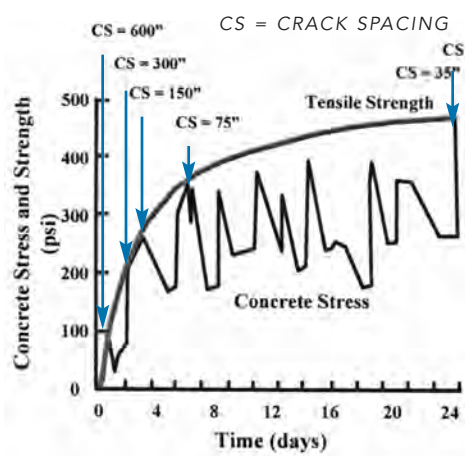
The TxDOT also found that placement season influences crack spacing. The crack spacing is wider in cold-weather placement than it is for warm-weather placement, i.e., higher temperatures increase the crack frequency. The influence of temperature on cracking was investigated in greater detail in the 1980s and 1990s.

### Pavement Age and Concrete Stress/Strength

Whenever the concrete stress exceeds the concrete tensile strength, a crack forms. The TxDOT found that crack spacing decreases rapidly during the first 30 days after concrete placement (Figure 3). It is during this period that the concrete has not yet reached a large percentage of its strength.

As shown in Figure 3, the crack spacing is slightly less than 35 inches at 24 days. This relationship also demonstrates the need for uniform concrete strength throughout the section if evenly spaced cracks are to form. Likewise, crack spacing is directly related to concrete strength. Lower concrete strength will translate to reduced crack spacing.

**Figure 3**  
RELATIONSHIP BETWEEN CRACK SPACING AND PAVEMENT AGE



### Percent Longitudinal Steel

An inverse relationship between crack spacing and percent longitudinal reinforcing steel was seen in the Texas sections. For pavement with 0.6 percent steel, the crack spacing was slightly less than that measured in pavement with 0.5 percent steel.

The higher the amount of reinforcing steel placed in the pavement, the better the pavement performance —until the point is reached where the trend starts to level off or the crack spacing is too small for bond to develop.

### Crack Width

Crack width is directly related to crack spacing. The closer the cracks are spaced, the smaller the crack widths. Larger crack widths translate to reduced load transfer by aggregate interlock, increased shear stress in the reinforcing steel from wheel loading, and increased infiltration by water and foreign matter.

Aggregate interlock is the projection of aggregate particles from one side of a crack in the concrete slab into the recesses in the other side of the crack so as to affect load transfer in compression and shear and maintain mutual alignment.

## Case Studies of CRCP Performance

### 1950s and 1960s

In the 1950s and through the 1960s, CRCP was a new, untried technology in Texas. Therefore, many different pavement designs were investigated. Several of these early

projects are listed in [Table 1](#). This section describes the key issues the TxDOT encountered in CRCP construction and performance and how the TxDOT addressed them.

**Table 1**

#### SELECT CRCP SECTIONS IN TEXAS DURING THE 1950s AND 1960s.

Date	Case Study	Location	Subbase Type	Pavement thickness	Longitudinal bar size & spacing	% Long. Steel	Lessons Learned
1951-53	1	Tarrant Co., I-35 E, Dallas	8 in. crushed stone with two-course surface treatment	8 in.	#6 @ 8 in.	0.7	CRCP can provide excellent performance.
1959	2	Falls/McLennan Co's., I-35 Bruceville-Eddy	Crushed stone/gravel; JCP with HMA overlay	8 in.	#6 @ 11.5 in. #6 @ 11.5 in.	0.5	Stagger the longitudinal laps.  Improve the transverse construction joints.  Thin CRCP overlays can provide excellent performance.
1958	3	Potter Co., I-40, Amarillo	6 in. CTB	8 in.	#5 @ 7.5 in.	0.5	CRCP shoulder tied into CRCP mainline improves performance and lengthens pavement service life.
1960	4	Walker Co., I-45, Huntsville	6 in. crushed sandstone	8 in.	#5 @ 7.5 in. #5 @ 6.5 in.	0.5 0.6	Set limitations on the maximum grind of the cement.  Require the use of vibratory equipment during construction.  Use subbases stabilized by cement or asphalt.  Limit construction during hot ambient temperature.  The influence of coarse aggregate on CRCP performance needs more research.
1962-64	5	Harris Co., Loop 610 S., Houston	8 in. cement stabilized 6 in. lime stabilized clay	6 in.	#5 @ 17 in.* #5 @ 13 in.* #5 @ 10.5 in.*	0.3 0.4 0.5	Important interactions between coarse aggregate type and percentage of longitudinal reinforcing steel.
1963	6	Jefferson Co., I-10, Beaumont	6 in. CTB on 6 in. lime stabilized clay	8 in.	#5 @ 7.5 in.	0.5	Slipform paver, used for first time, performs adequately.

\* Calculated assuming #5 diameter bar  
CTB = cement-treated base  
JCP = jointed concrete pavement  
HMA = hot-mix asphalt

## Case Study No. 1: Tarrant County

Two different CRCP sections opened in Tarrant County between 1951 and 1953. Staged construction was used on these sections. The highway agency completed the subbase and surface treatments in the late 1940s, and operated traffic on that surface for 2 to 4 years. All soil movements that occurred (i.e., differential swelling and settlement) were corrected prior to placement of the CRCP. A two-course surface treatment eliminated subgrade pumping, providing a uniform and stable support for the pavement.

The two sections of CRCP provided excellent performance for 40 years without any pavement maintenance, except for surface texture corrections for safety purposes. The pavement was in excellent condition when, due to gradeline corrections and additional capacity requirements, reconstruction was required. [CRCP's outstanding performance in Tarrant County sparked interest in its use throughout Texas.](#)

## Case Study No. 2: Falls and McLennan Counties

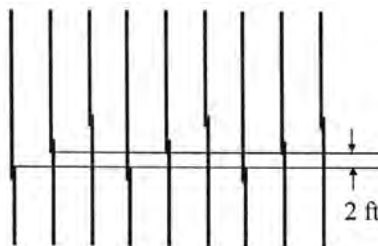
In 1959, the highway agency constructed approximately seven miles of CRCP in Falls and McLennan Counties near the town of Bruceville–Eddy. In this pavement, the longitudinal reinforcing bar was 40-foot-long Grade 50 steel (yield stress of 50,000 psi).

Most of this CRCP was placed on top of an unstabilized crushed stone and gravel subbase with a high percentage of fines. Approximately one mile of pavement in the northbound lanes was placed on top of an existing jointed concrete pavement (JCP) that had been overlaid with 4 to 6 inches of hot-mix asphalt (HMA).

Since initial construction, several issues surfaced that required unique solutions. These solutions have subsequently become part of current industry design and construction practices. These issues are described below.

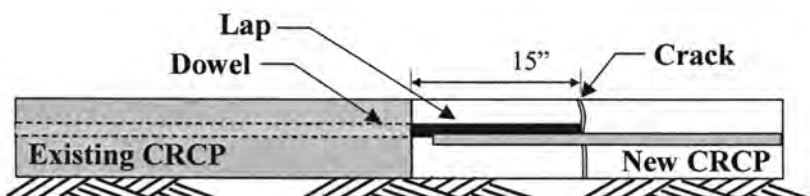
**Figure 4**

### STAGGERED LONGITUDINAL LAPS IN CRCP



**Figure 5**

### CONSTRUCTION JOINT FAILURE



### LONGITUDINAL LAPS

Condition surveys taken on the first mile of construction revealed that widened cracks occurred every 40 feet along the pavement. These cracks corresponded to the locations at which reinforcing bars were lapped together.

After these initial observations, the TxDOT chose to stagger each lap relative to the adjacent laps (Figure 4). For subsequent projects, the pavement design details were revised so that [only one-third of the laps could be placed within any two longitudinal feet across the pavement.](#)

On most current projects where the reinforcing bars are placed on chairs, industry practice is to stagger each lap because it allows for easier inspection.

### TRANSVERSE CONSTRUCTION JOINTS

Construction specifications at the time called for longitudinal reinforcing bars to protrude from the end of the concrete pavement a length of 20 times their diameter—or 15 inches (Figure 5)—at the end of a day's construction. These protruding reinforcing bars would provide a lap for splicing with bars in subsequent construction..

In all cases where construction was not resumed for three or more days, the transverse construction joints failed, with wide cracks seen consistently near

the construction joints. During this three-day break, shrinkage and hydration stresses built up in the curing concrete that caused the free pavement ends to move back and forth longitudinally. Subbase restraint was small, so the longitudinal movement was large.

When construction started up again, the bond between the reinforcing bars and the new, weaker concrete could not sustain the stress from the longitudinal movement of the existing pavement. This resulted in bond slip-page failure, forming wide transverse cracks 15 inches into the new construction (matching up with the end of the protruding bars).

The cracks were wide enough that all load transfer was lost. Failures then developed that required full-width repairs at all those locations as soon as the facility was opened to traffic.

To prevent failures at construction joints on subsequent projects, the TxDOT changed the longitudinal reinforcing bar details at these locations, calling for the [longitudinal reinforcing steel to extend a minimum of four feet into the new pavement with laps being staggered](#).

The amount of longitudinal reinforcing steel was doubled at the transverse construction joint. As later design models improved, this requirement was found to be overly conservative and was revised.

#### CONSTRUCTION OF UNBONDED CRCP

The one mile of pavement that included original jointed concrete pavement overlaid with hot-mix asphalt, and topped with the new

CRCP, represented the first known use of an “unbonded” CRCP overlay in this country.

Designers reduced the thickness of the CRCP by one inch to reflect the increased support from the existing pavement. This section provided excellent performance, with pavement distress limited to the transverse construction joints noted above. Indications were that [a thinner overlay could provide performance equal to that of a new pavement](#).

### Case Study No. 3: Potter County

In the City of Amarillo on a highway with old jointed concrete pavement, failures were identified on the outside asphalt shoulders at regular longitudinal intervals of approximately 50 feet, about 5 to 6 feet from the pavement edge. The failures appeared to coincide exactly with irrigation sprinklers along the side of the highway. The highway agency concluded that water being kicked back from the sprinkler heads was causing the failures.

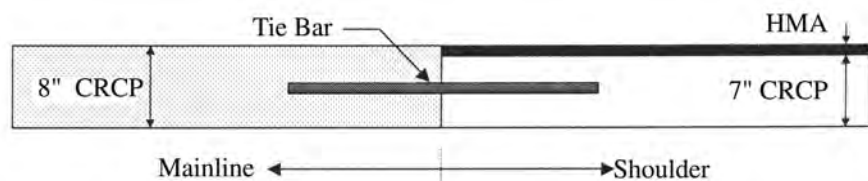
To remedy this problem, when the road was rebuilt with CRCP in 1958, a

7-inch-thick CRCP shoulder (with a one-inch-thick asphalt surface for color contrast) was tied into the new 8-inch-thick mainline CRCP ([Figure 6](#)). This solution prevented the formation of failures in the shoulder.

In a 1974 condition survey, another benefit was noted. The stronger CRCP shoulder meant that the CRCP on the mainline was experiencing interior loading instead of edge loading. Pavement stresses were reduced. [The CRCP shoulders substantially increased the pavement life and performance](#).

**Figure 6**

#### NEW SHOULDER DESIGN



## Case Study No. 4: Walker County, Interstate 45

Two experimental CRCP test sections were constructed on Interstate 45 south of the City of Huntsville. The variables studied included the influence of longitudinal reinforcing steel and concrete strength on CRCP performance.

One-half of the CRCP in each direction (to allow for an accurate comparison of performance, assuming that the amount of traffic on all sections would be identical) was constructed with 0.5 percent longitudinal steel and the other half with 0.6 percent.

Because the roadway sections were built over an entire construction season, observations of performance resulting from a variety of climatic conditions were made.

TxDOT's design equations at the time related percent longitudinal reinforcing steel ( $\rho_s$ ) to the concrete tensile strength ( $f_t$ ) and the reinforcing steel yield strength ( $\sigma_y$ ), as follows:

$$\rho_s \propto \frac{f_t}{\sigma_y}$$

For a constant  $\sigma_y$ , the stronger the concrete, the more reinforcing steel was required.

Grade 60 reinforcing bars were used for the longitudinal reinforcing. To study the effects of reducing the amount of steel, the strength of the concrete was reduced from a 5-sack cement mix to a 4.5-sack mix. Strain gages were placed on the longitudinal reinforcing bars and within the concrete. The TxDOT made the following conclusions from these test sections.



Interstate 45 south of the City of Huntsville

Hal Stegman, Texas DOT

### CEMENT TYPE

Higher strains were measured in the concrete in the southbound pavement with 0.6 percent longitudinal steel than in the northbound pavement with 0.5 percent. This was counter to TxDOT's expectations, because a higher percentage of reinforcing steel percentage should have carried more stress and reduced the strain in the concrete.

This discrepancy was explained when it was found that the contractor had switched cement types between the northbound and southbound pavements. Type I cement was used in the northbound direction, but Type III was used to pave the southbound. Because Type III cement is more finely ground than Type I, it generates more heat of hydration, which caused the increased stress in the concrete and reinforcing steel.

As a result of these observations, a special provision was made in the concrete specification to **limit the maximum grind of the cement**.

### CONCRETE VIBRATION

No vibration equipment was used when placing the CRCP. The TxDOT later found that the top four inches of the concrete in the slab were fully consolidated, while the bottom four inches were low-strength and honeycombed. This situation was exacerbated when the ambient temperature at placement was greater than 90°F.

Honeycombing of the concrete is an obvious result of inadequate vibration. The CRCP specification was rewritten to **require the use of vibratory equipment during construction**.

### SUBBASE PUMPING

As traffic commenced, the sandstone subbase began to pump through the edge of the CRCP at the shoulder joint. A similar observation was made on the CRCP at the Falls/McLennan Counties Project (Case Study No. 2).

Subsequently, it was mandated that **subbases be stabilized by cement or asphalt throughout Texas**. This would help prevent pumping under the

concrete pavement and mitigate high concrete stress due to loss of support at pavement edges.

#### MAXIMUM PLACEMENT TEMPERATURE

The influence of concrete placement during hot weather on the long-term behavior of CRCP—including the number and spacing of cracks—was established on this test section. For the CRCP constructed in hot weather, numerous closely spaced cracks formed due to the ambient heat added to the heat of hydration of the concrete.

The TxDOT subsequently wrote a specification to [limit the concrete temperature during construction](#). The influence of temperature on CRCP would be investigated in greater detail during the 1980s and 1990s.

#### COARSE AGGREGATE TYPE

The aggregate in the concrete mix used in this experimental section of I-45 contained siliceous river gravel, while a later section placed north of Huntsville contained limestone aggregate. Different crack patterns and distributions were observed between these two CRCP sections.

The TxDOT initiated a research project through the Texas Transportation Institute at Texas A&M University to investigate how aggregate properties can influence crack patterns. The study found that siliceous river gravel and limestone aggregate have different coefficients of thermal expansion, moduli of elasticity, and strengths. The TxDOT concluded that [certain aggregate properties had significant effects on pavement behavior](#). This led to additional research in the 1980s.

## Case Study No. 5: Harris County

Six-inch-thick test sections were constructed on two frontage roads in Houston to investigate the effects of aggregate type and reduced longitudinal reinforcing steel percentages on CRCP performance. One set of test sections contained siliceous river gravel; the other used lightweight aggregate, a manufactured expanded shale product.

The section with siliceous river gravel contained longitudinal reinforcing steel percentages of 0.3, 0.4, and 0.5. The lightweight aggregate section used reinforcing steel percentages of 0.3 and 0.4. Strain gages were attached to the reinforcing bars and the concrete was monitored for crack formation and crack width.

The findings of the Harris County study, summarized below, demonstrated that there are [important interactions between the longitudinal reinforcing steel and the coarse aggregate](#). This emphasized the need to consider the steel percentage in conjunction with coarse aggregate properties such as modulus of elasticity and thermal coefficient of expansion.

#### LIGHTWEIGHT AGGREGATE

From concrete cores taken from the test sections, the TxDOT learned that concrete made with lightweight aggregate has a modulus of elasticity less than half that of concrete made with

traditional rock aggregate. Therefore, for the same strain, the stress in the concrete is less than half.

Furthermore, the coefficient of thermal expansion (the change in volume caused by a change in temperature) of lightweight aggregate is significantly lower than that of siliceous river gravel so that concrete made with lightweight aggregate does not crack as readily as that made with traditional rock aggregate.

#### STEEL PERCENTAGE

After 35 years of service, the performance of the CRCP sections using 0.3, 0.4, and 0.5 percent longitudinal reinforcing steel was assessed and compared. The TxDOT found that the [minimum adequate steel percentage was 0.5 for the test sections with siliceous river gravel aggregate](#).

Lower steel percentages were not adequate. Cracks were so wide in the 0.3 percent sections that, after 35 years, grass was growing through them. Cracks, however, were still tight in the CRCP sections reinforced with 0.5 percent longitudinal reinforcing steel.

In contrast, the lightweight aggregate test sections looked about the same as when new, thus showing that a [lower steel percentage \(0.3 percent\) was adequate when combined with lightweight aggregate](#).

## Case Study No. 6: Jefferson County, Interstate 10



Herman Kelly, Texas DOT

The 8-inch-thick CRCP on I-10 south of Beaumont was placed over 6 inches of stabilized sand shell and 6 inches of sand/clay subgrade stabilized with lime. [A slipform paver \(left\) was first used in Texas to construct the pavement on I-10 and was found to adapt well to CRCP construction.](#)

## Further Advances in CRCP Design and Construction

### 1970s

In the 1970s, the TxDOT initiated research to investigate ways to further improve the performance of CRCP. The first step was to survey every mile of concrete pavement in the state in order to prioritize rehabilitation requirements. The TxDOT also decided to periodically survey CRCP sections and establish a database—the Texas Rigid Pavement Database (TxRPD)—to provide performance data for further development of design methods and construction specifications, and to analyze the results of maintenance.

Using the database, researchers looked for 20-year performance differences in similar pavements. When these differences were found, the agency hired the University of Texas at Austin to investigate the causes of these differences.

This section summarizes the major findings from the analysis of the TxRPD in the 1970s. One of the most significant factors identified was the influence of concrete coarse aggregate type, leading to extensive research in the 1980s.

#### CRCP PERFORMANCE INDICATORS

One of the first observations from the TxRPD was that serviceability alone was not an adequate indicator of CRCP performance. Serviceability of CRCP did not show a steady decrease throughout the service life, as is typically seen with other pavement types. **Better indicators of pavement performance were provided by pavement failures such as punchouts and spalls.**

#### CONCRETE CURING

Cores taken from Loop 610 in Houston showed that the concrete in the top portion of the slab was noticeably weaker than the concrete in the bottom. This was opposite to TxDOT's expectations. In the past, the bottom of the slab had been weaker because of insufficient vibration.

The TxDOT realized that this weak surface layer might be linked to concrete placement and curing conditions which led to the occurrence of delamination spalling. **Concrete curing needed to be carefully monitored to ensure that the concrete surface properties would be adequate.** Also, a better overall understanding of the curing process was needed.

#### THEORETICAL MODELING OF CRCP

Theoretical models to predict the behavior of CRCP were first developed in 1974. CRCP-1 software was developed as part of National Cooperative Highway Research Program Project 1-15, and it combined all the known variables to date that influenced CRCP performance.

The design input of pavement thickness, concrete properties, percent longitudinal reinforcing steel, and environmental factors was used to predict crack spacing, crack width, and reinforcing steel stress. The number of punchout failures could also be predicted as a function of traffic and other input.

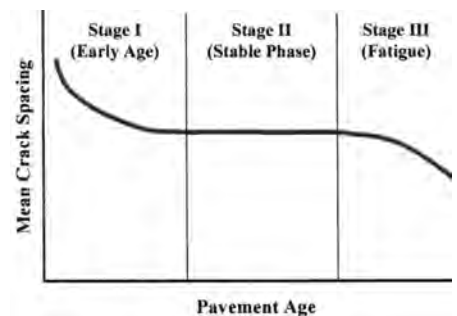
As a better understanding of CRCP has evolved over the years, the program has been modified to the current version of CRCP-10.

#### INFLUENCES OF FATIGUE ON CRACK SPACING

The effect of pavement age, traffic loading, and fatigue on crack spacing in CRCP was first recognized in the 1970s. This relationship is shown in [Figure 7](#). During Stage I (about the first three months after placement) concrete cracks due to environmental and internal stresses. During Stage II (20 to 30 years), the pavement stabilizes and the longitudinal reinforcing steel keeps the cracks tight. During Stage III, the pavement begins to fail as more cracks develop due to fatigue and repetitive traffic-induced stresses.

**Figure 7**

#### STAGES OF CRCP CRACK SPACING



#### CONCLUSIONS

Several conclusions drawn in the 1960s were reinforced in the 1970s. From a reexamination of the CRCP test sections in Case Study No. 4 after 16 years, the TxDOT concluded that:

- stabilized bases resulted in better CRCP performance,
- more failures were found in sections with a lower percentage of reinforcing steel, and
- more failures were found in sections that were cured at higher temperatures.

## 1980s

In the 1980s, pavement thickness design criteria were revised. Additionally, an extensive evaluation of CRCP in Texas with different coarse aggregates was undertaken. This led to revisions of both AASHTO and Texas Pavement Designs by 1985.

### PAVED SHOULDERS AND CRCP THICKNESS DESIGN

During the initial years of CRCP implementation, slab thickness was based on the assumption that wheel loads were 3 feet or greater from the pavement edge, creating an interior loading condition. These dimensions resulted from a Bureau of Public Roads (now, the Federal Highway Administration) study conducted in the 1950s. This interior loading condition allowed for thinner CRCP (8 inches) in contrast to the 10 inches required for jointed concrete pavement.

However, the TxDOT observed that pavement failures first developed at the outside pavement edge along super-elevated right hand curves. With older, unpaved shoulders, drivers stayed away from the edge, but with the advent of the Interstate Highway Program, paved shoulders were used. Observations of vehicle operations revealed that the back axles were off-tracking onto the shoulder.

This loading situation shifted the critical stress state from the pavement interior to the pavement edge. Studies by the Georgia Department of Transportation revealed a substantial percentage of edge loads even on tangent sections.

Adding to this problem was the fact that the Bureau of Public Roads had mandated that the maximum thickness for CRCP was 8 inches. This was later increased to 10 inches in the early 1980s.

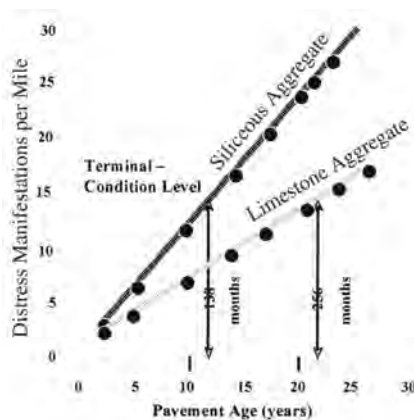
To mitigate the increased failures due to edge loading, the use of CRCP shoulders was increased substantially as a result of the success in Potter County (Case Study No. 3) and other projects. A review of performance from sections in the TxDOT revealed that **concrete shoulders provided superior performance, because the pavements were operating under the design assumptions of interior loading.** On a number of older projects, concrete shoulders were added to prolong pavement life.

### COARSE AGGREGATE TYPE

From Case Study No. 5 and subsequent review of the TxDOT, the differences in performance of CRCP constructed with siliceous river gravel versus limestone became apparent (Figure 8). Pavements with limestone lasted on average 10 years longer than ones constructed with siliceous river gravel.

**Figure 8**

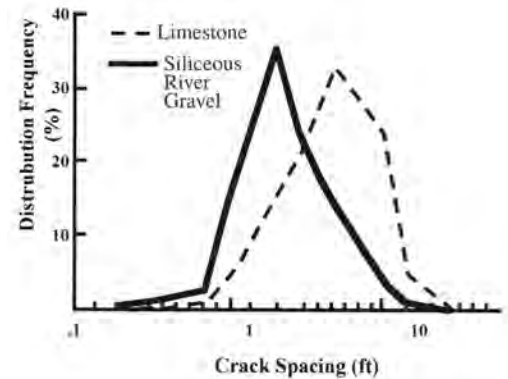
### INFLUENCE OF AGGREGATE TYPE ON CRCP PERFORMANCE



These differences are due to the influence of coarse aggregate type on crack spacing (Figure 9). CRCP constructed with siliceous river gravel had crack spacing that stabilized at 2 to 3 feet, while CRCP constructed with limestone had crack spacing that averaged 6 feet. Shorter crack spacing tends to lead to increased punchout failures and reduced pavement life in Texas.

**Figure 9**

### INFLUENCE OF AGGREGATE TYPE ON CRACK SPACING



To better understand the material properties that caused these differences, the TxDOT commissioned a series of laboratory and field studies. Laboratory tests revealed that the concrete shrinkage, coefficient of thermal expansion, and modulus of elasticity were significantly different between the two aggregate types. Using these results, concrete mix designs were developed for 85 field tests in Houston.

Additional findings noted that placement season, placement time and temperature, and reinforcing steel percentage were all strong factors contributing to crack spacing. **High ambient temperatures during placement were the single most influential factor after aggregate type.** Correlation between the early-age and long-term condition surveys of these sections proved instrumental in identifying these new factors.

## 1990s to Present

### MODELING AGGREGATE PERFORMANCE

Theoretical models were developed to account for the differences in performance of CRCP constructed with concrete containing siliceous river gravel versus limestone. The theoretical mechanistic-empirical software model (CRCP-8 by then) was calibrated and validated using collected data.

In addition, these studies led to a variety of techniques for improving pavement performance, including night placement, aggregate blends, various curing techniques, and even saw-cutting the fresh concrete to control crack locations.

The CRCP-8 Steel Standard was also developed, which allows the percentage of reinforcing steel to be varied based on coarse aggregate type. This was an attempt to achieve equal performance regardless of aggregate type, but this standard is no longer in use.

As verified in the 1970s and 1980s, one significant factor influencing CRCP performance is aggregate type. However, it is not always possible to use the optimum aggregate. If the aggregate type cannot be changed, then the designer can specify optimal paving conditions for the best possible CRCP performance.

Changing paving season can have as much impact on CRCP performance as does changing the aggregate type. Yet it is often impractical to specify or change the season in which the CRCP is constructed. Other environmental conditions that can be modified include changing the placement time of day, and restricting placement when high evaporation rates and temperatures are expected.

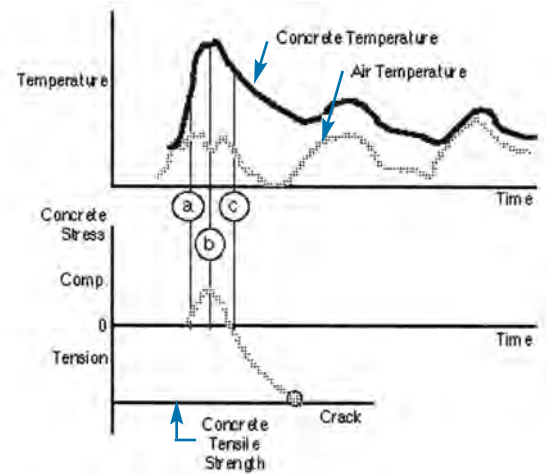
From the 1990s to the present, development continues toward a better understanding of the ambient temperature during construction and the effects of concrete moisture levels on CRCP performance. Monitoring these two factors during construction can provide major improvements to CRCP performance.

### CONCRETE TEMPERATURE

Hot weather placement has been known to cause the formation of erratic crack spacing, including y-cracking, narrow crack spacing, and crack intersections. Given these conditions, punchouts can develop rapidly and result in a significant increase in pavement repairs and maintenance.

**Figure 10**

#### RELATIONSHIP BETWEEN TEMPERATURE AND CONCRETE CRACKING



The relationship between temperature and concrete cracking is shown in Figure 10. After the concrete sets (point "a" in Figure 10), the concrete goes into compression as the temperature continues to increase. When the concrete temperature starts to decrease, the stresses (point "c") transition from compression to tension. At the point when the tensile stresses exceed the tensile strength, the concrete will crack.

For CRCP placed when the air temperature was greater than 90°F, the failure rate was 3 to 4 times what it was at cooler temperatures.

It was determined that both the ambient temperature at the time of paving and the concrete temperature need to be monitored throughout the entire construction operation. If the ambient temperatures are too high, nighttime paving is one possibility to reduce the rate of crack formation.

#### EVAPORATION

In one of the Houston CRCP field sites, the TxDOT found that as the evaporation rate of moisture from the concrete increases, the amount of cracks that spall increases. Severe spalling resulted from very high evaporation rates. In one case, the TxDOT had to place a bonded concrete overlay on top of relatively new CRCP to rehabilitate the spalled surface.

Because [the evaporation rate is a key factor affecting long-term performance of CRCP](#), it should be closely monitored during construction. If negative conditions occur, it is possible to use curing methods, concrete temperature controls, and time of placement restrictions to minimize the detrimental effects.

**"In Texas, CRCP rides smoother and lasts longer. CRCP has no joints, so we don't have to worry about load transfer from one slab to the other, dowels getting misaligned, rusted, or needing replacement, slab blowups due to improper joint maintenance, or leaking joints."**

— Kenneth W. Fults, P.E.  
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