Long Term Performance of Rapid Strength Concrete (RSC) Slabs on California Highways

Michael I. Darter, PE PhD
Emeritus Professor of Civil & Environmental Engineering,
University of Illinois

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Abstract

The California Department of Transportation (Caltrans) has used Rapid Strength Concrete (RSC) for pavement repair since the 1990s. Since RSC reaches opening strength in a matter of hours, this pavement rehabilitation strategy allows overnight pavement replacement; lanes are closed to traffic at 11:00 PM the latest, existing cracked slabs are removed, base course is repaired, dowel bars and interlayer placed, RSC is placed and cured, and lanes are opened to traffic typically by 5:00 AM the following morning. This study investigates the longevity and durability of this overnight pavement replacement with RSC. Twelve projects were surveyed using recent traffic lane video, all of them were original Jointed Plain Concrete Pavement (JPCP) and located on major California highways. In addition, five of the projects were field visited to allow on-site confirmation of real-time pavement condition.

Six of the twelve projects were "Individual Slab Replacement-Rapid Strength" (ISR-RSC) that were previously surveyed in 2008 (3 years RSC age) and recently in 2018 (13 years RSC age). These included both inner lanes (low trucks) and outer lanes (high trucks). The other six projects were "Lane replacement-RSC" projects (JPCP-RSC) with 9-17 years age RSC for only outer lanes (high trucks). A total of 3,562 RSC slabs were surveyed and the percentage exhibiting key distress types calculated.

- <u>RSC slabs exhibited very few durability or material distress types</u> (joint spalls, shrinkage cracking and surface defects) after up to 17 years of service (e.g., <2% slabs).
- <u>RSC slabs exhibited very few longitudinal cracks or corner cracks</u> (e.g., <2% slabs).
- <u>"Individual RSC" replaced slabs</u> (thinner and longer joint spacing) exhibited far more transverse fatigue transverse cracking in the heavy truck outside lanes (21%) than in the lighter trafficked inner lanes (3%).
- <u>"Lane Replacement RSC"</u> slabs (thicker and shorter joint spacing) exhibited far less transverse fatigue cracking in the heavy truck outside lanes than the "Individual RSC" replaced thinner slabs exhibited (e.g. 0.3% "Lane Replacement RSC" versus 21% "Individual RSC" slabs) under approximately the same truck loadings.
- <u>Two RSC concrete products</u> were included: CTS and 4X4 concrete. Both RSC concrete products produced excellent performance over the service lives.

The overall performance of the RSC slabs (both CTS and 4x4 RSC concrete materials) were considered to be outstanding over the service lives thus far (9 to 17 years) and are expected to survive many more years. Caltrans specifications and guidelines are considered excellent sources for rapid strength concrete slab materials and designs. <u>Recommendations to limit transverse fatigue cracking and durability of "Individual JPCP-RSC" slabs in the heavy truck lanes are provided.</u> The JPCP-RSC "Lane Replacement" slabs have proven that they can serve as a long-term strategy without fatigue cracking. Substantial evidence of the successful long-term performance of these rapid strength concrete (RSC) replacement slabs in California are provided.

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Introduction

Rapid Strength Concrete (RSC) provides a critical capability to rapidly place, cure, and open to traffic, concrete slabs over a few hours to restore structural and functional capability to a distressed pavement. The process of providing rapid construction and early opening of concrete pavements to traffic, has also been called "Fast Tracking" over the years. (ACPA, 1994) California carries out overnight repairs by limiting lane closures between 11 pm and 5 am.

In essence, the distressed concrete slab is removed, the base is repaired or replaced, dowels are anchored in wheel paths, a thin polyethylene flexible foam expansion joint filler is placed across the original transverse and longitudinal joint faces, a bond breaker is placed on the base-whether a new or old base, the slab is replaced with RSC, and the traffic lane is opened to traffic within the above time frame. Only cement mixes that fulfill high early strength requirements are used. RSC pavement must develop a minimum modulus of rupture of 400 psi at opening age according to Caltrans specifications. In addition, RSC pavement must develop a minimum modulus of rupture of 600 psi at 7 days after placement.

The requirement of 400 psi minimum at opening to traffic is set to minimize any significant concrete fatigue damage, dowel bar socketing, or any other potential damage from truck traffic. This agrees with an Illinois study yu conducted on field slabs showing a minimum flexural strength of over 300 psi was required to avoid significant early fatigue cracking within a year. For this study total truck traffic using each lane over the 9 to 17-year service lives was estimated using Caltrans traffic data.

An Ohio study showed strong correlation between slab cracking and air/pavement temperature difference between day and nighttime (with a built-in temperature gradient through the slab). The greater the difference between day and night temperature, the greater the amount of cracking. (Yu, Mallela, and Darter, 2006) Fortunately, the RSC in California are all placed at night, eliminating built-in temperature gradient as a problem.

However, the long-term concrete durability of these RSC slabs has always been of concern to State Highway Agencies (SHAs). A recent study investigated the design, construction, and performance of six repair methods, including slab replacement in seven State Highway Agencies (SHA). The study concluded that while there were many successful RSC operations around the country, there was a concern expressed by SHAs over long term durability of the rapid setting concrete used. (Darter, 2017)

Caltrans has a rigorous specification for preparation for and placement of RSC. The specification used for the 2005-06 RSC construction is included in full in the Appendix D of the 2008 research report "Evaluation of Rapid Strength Concrete Slab Repairs." (Bhattacharya, Zola, and Rawool, 2008) The current Caltrans RSC documents include a specification for "Individual RSC" slab replacement and "Lane Replacement RSC" plus the Concrete Pavement Guide (2015) provides detailed information on the specifics of design, materials, and construction.

- Section 40-5: Jointed Plain Concrete Pavement With Rapid Strength Concrete
- Section 41-9: Individual Slab Replacement, ISR (2015)
- Concrete Pavement Guide (2015)

This performance evaluation focuses on the survey of two California strategies of JPCP slab replacement.

1. **"Individual RSC" or Individual Slab Replacement with Rapid Strength Concrete (ISR-RSC).** Cracked or badly damaged JPCP slabs are removed and replaced with RSC slabs along a traffic lane. Of course, many original slabs not yet cracked are left in place along the lane. Slab thickness (typically 8-9 in) and joint spacing (typically 12-19 ft) remained the same and existing base courses were largely left in place. Dowels may or may not be included in transverse joints. Starting in 2010, dowels were only included at transverse construction joints, as Section 41-9 was created. Neither shrinkage or ASR requirements were specified. (California DOT, Standard Specification Section 41-9: Individual Slab Replacement)
2. **"Lane Replacement RSC" or JPCP-RSC.** All of the slabs and base course along one or more traffic lanes are removed and replaced with RSC. Slab thickness is typically increased (10 to 14 in), perpendicular joint spacing is uniform at 14 ft, the base course is replaced and dowels are placed at all transverse joints. Both RSC shrinkage and ASR requirements are included in these specifications. (California DOT, Non-Standard Special Provision Section 40-5: Jointed Plain Concrete Pavement With Rapid Strength Concrete or JPCP-RSC).

The long-term performance of these two approaches to the restoration of a highway traffic lane ("Individual RSC" slab and "Lane Replacement RSC" slab replacement) is documented in this report. Twelve RSC highway projects (6 "Individual RSC" and 6 "Lane Replacement RSC") ranging in age from 9 to 17 years were surveyed. Summaries of the types of distresses identified and their related designs, materials, and traffic are provided. Finally, estimates of longevity are made and recommendations are provided on how to improve performance of RSC replacement slabs.

Previous Caltrans Study of RSC Slab Performance

Caltrans conducted a study in 2008 titled "Evaluation of Rapid Strength Concrete Slab Repairs" that documented the short-term (3-year) performance of RSC. (Bhattacharya, Zola, and Rawool, 2008) Fifteen projects located in six Regions/Districts and 10 counties on major freeways containing 5,430 slabs were surveyed and any distress recorded. These “Individual RSC” projects averaged about 3 years in age at the time of the survey. The results are summarized as follows:

- “RSC material composition/design is not the cause of the panel distress or failures.
- <u>“Only 1.4 percent of the slabs surveyed showed premature distress.</u>
- “Difference in performance based on type of cement used, traffic level, level of subbase preparation, and the contractor performing the work could not be established due to a lack of representative data.
- “Mid-panel and surface cracking was the most prevalent distress type, followed by corner breaks and spalling, respectively.
- “Spalling was caused primarily by improper placement of the bond breaker foam/expansion joint material (or lack thereof).
- “In a few instances, mid-panel cracking resulted from excessive slab lengths or crack migration from adjacent slabs.
- “Corner breaks may be attributed to lack of re-compaction of the existing supporting material prior to RSC placement.
- “Of those sites where proper construction techniques were followed, there were very few minor observed distresses, if any.
- “Early age panel distress and failures observed on all the sites can be attributed to construction errors.” (Bhattacharya, Zola, and Rawool, 2008)

Follow Up Study of Long Term Performance

These 3-year results are impressive with only 1.4 percent RSC slabs showing any significant distress under heavy truck and auto traffic. But of course, the big question is what will be the long-term service life of these RSC slabs? Given the importance of the long-term performance and survival of these critical RSC slab replacements, it is of great interest to conduct a follow-up to this original study. Thus, a further study was planned and conducted that utilized Caltrans pavement management videos of a portion of these pavements taken over time. These video surveys were conducted by lane so that the impact of truck traffic level on RSC slabs could be evaluated.

This study examines the long-term performance in California of six projects from the same study published in 2008 where the “Individual RSC” placed RSC specification and design was used and the RSC manufacturer was known. These projects included several miles of traffic lanes and included 12 inner and outer traffic lanes. The “Individual RSC” slab replacements were in service for 12 to 13 years by 2018. The projects all had high auto and truck volumes, but the truck volume on individual traffic lanes on these projects varied widely. A majority of the projects had 4 traffic lanes in one direction.

In addition, six additional "Lane Replacement RSC" slab projects were located and surveyed and included in the overall analysis. These RSC projects ranged in age from 9 to 17-years by 2020. This provided a very interesting comparison of the performance of these two very different RSC slab designs over time.

Objectives of this Study

The objectives of this study are as follows:

- Provide measured performance data that documents the long-term performance of Rapid Strength Concrete (RSC) slab replacements in California.
- Include both "Individual RSC" placed slabs and "Lane Replacement RSC" placed slabs as defined by Caltrans specifications and guidelines.
- Identify distress types that develop long term in RSC slabs in the field so that they can be addressed in improved procedures, specifications and guidelines to minimize their occurrence in the future and extend their service life.
- Estimate the longevity of both the "Individual RSC" and the "Lane Replacement RSC" placed slabs so that their selection can be optimized on future projects.
- Provide recommendations on how to improve RSC project performance.

Field Surveys and Database

Six **"Individual RSC"** replaced slab projects and six **"Lane Replacement RSC"** projects were included in this survey. "Individual RSC" and "Lane Replacement RSC" slab concrete generally must meet the same requirements (such as strength) but the "Individual RSC" slabs do not have to meet shrinkage or ASR requirements.

<u>Caltrans "Individual RSC" slab replacements</u> surveyed in this study maintained the same slab original thickness, joint spacings, base course (unless damaged) of the existing pavement. Most of the "Individual RSC" slabs included the anchoring of dowels in transverse joints at each end. These are specified as California DOT, Section 41-9: Individual Slab Replacement.

<u>Caltrans "Lane Replacement RSC" slab replacements</u> surveyed in this study allowed an increase in slab thickness (to match the heavy outside lane truck loadings), replacement of the base course, use of dowels in all transverse joints, and shorter joint spacing (e.g., 14-ft standard). As the word "Lane Replacement RSC" implies, all of the existing slabs along one or more traffic lanes are replaced with RSC. These RSC lane replacements can continue for miles along a given project. This RSC alternative is specified as California DOT Section 40-5 Jointed Plain Concrete Pavement With Rapid Strength Concrete, JPCP-RSC. Both of these applications of RSC are subsequently described in more detail.

"Individual RSC" Placed Slab Projects

An overview of the six JPCP projects that contain hundreds of "Individual RSC" replaced slabs is shown in Table 1. There are six overall separate projects and the survey was done by lane, thus, the results are presented by project and lane. This makes it possible to include an evaluation of the level of truck traffic on performance since the truck lane distribution varies dramatically across multiple traffic lanes. A brief summary of the "Individual RSC" projects follows:

- Projects are located on major heavily trafficked freeways in Caltrans Districts 3, 7 and 8.
- Projects are located in Los Angeles, Ventura, Sacramento, and San Bernardino Counties.
- RSC slabs age ranges from 12 to 13 years, with an average of 13 years.
- RSC thickness ranges from 8 to 9 inches, average mostly 8 inches.
- RSC material includes both the CTS and 4X4 cement types.

Table 1. Summary of Six "Individual RSC" Projects Route, County, Design, RSC Construction Year, and RSC material.

Route	District, County, ID	Design	RSC Construction Year	Type RSC Material
I-10	8, San Bernardino 08-0A180	8-9 in JPCP 6-in LCB 4-in AB	2005	CTS
I-10	8, San Bernardino 08-49370	8-9 in JPCP 6-in LCB 4-in AB	2005	CTS
I-10	8, San Bernardino 08-4192U	8-9 in JPCP 4-in CTB 4-in AB	2005	CTS
I-5	7, LA 07-45050	8-9 in JPCP 4-in CTB 3-in AB	2005	4X4
US-50	3, Sacramento 03-0A840	8-9 in JPCP 6-in LCB 4-in AB	2005	CTS
SR-126	7, Ventura 07-24490	8-9 in JPCP 4-in CTB 4-in AB	2006	CTS

Table 2 provides a more detailed summary of these projects and the 12 traffic lanes that were included in the survey.

Table 2. Summary of "Individual RSC" 2018 Projects and Traffic Lanes Surveyed.

Route	District	County	MP to MP	RSC Material	Survey Lane*	AADTT 2016 Truck Traffic**	Total Trucks In Lane***
I-10	8	SBD	0 - 14 EBL	CTS	1 Inner	17000	2,016,625
I-10	8	SBD	14.5 - 20 WBL	CTS	4 Outer	20000	28,470,000
I-10	8	SBD	15.5 - 19.9 WBL	CTS	3 Inner	20000	11,862,500
I-10	8	SBD	15.5 - 20 EBL	CTS	3 Inner	20000	11,862,500
I-10	8	SBD	24.5 - 30 EBL	CTS	3 Inner	24000	14,235,000
I-10	8	SBD	24.5 - 30 EBL	CTS	4 Outer	24000	34,164,000
I-5	7	LA	76 - 88.6 NBL	4x4	1 Inner	17000	2,016,625
I-5	7	LA	76 - 88.6 NBL	4x4	2 Inner	17000	4,033,250
US-50	3	SAC	1.1 - 4.8 EBL	CTS	3 Outer	8500	10,083,125
US-50	3	SAC	0.84 - 2.9 EBL	CTS	1 Inner	8500	2,016,625
SR-126	7	VEN	0 - 13 EBL	CTS	1 Inner	2800	664,300
SR-126	7	VEN	0 - 4 EBL	CTS	2 Outer	2800	5,978,700
Averages							

*1 Inner Lanes, 4 Outer Lane. **Two direction AADTT. ***Total Trucks over 13 year service life.

- A total of 1,493 "Individual RSC" slabs located on six projects were surveyed using the latest 2018 Caltrans video monitoring films. All observable distresses were identified. The projects in Tables 1 and 2 were randomly chosen from a list of 15 projects surveyed in 2008 where the RSC material type was known and their condition was evaluated approximately 3 years after construction. (Bhattacharya, Zola, and Rawool, 2008)
- These 1,493 slab replacements were placed mostly in 2005 which makes them on average about 13 years of age (as of 2018) on major truck carrying freeways in California.
- The RSC material used was CTS on five projects (864 Slabs) and 4x4 (629 slabs) on one large project (Bhattacharya, Zola, and Rawool, 2008). Both CTS and 4x4 are described in the section "Description of RSC Slab Materials".
- These RSC slab replacements were completed in the inner lane (with the lowest truck volume, designated Lane 1) across to the outer heavy truck lane (designated Lane 4 if there are 4 lanes in one direction).
- The numbers of trucks that have passed over these slab replacements in 13 years were estimated from Caltrans traffic data and ranged widely from about 1 million to 34 million. There was a total of 12 traffic lanes surveyed from all projects that included the 1493 RSC slab replacements.
- In addition to the video surveys, on-site visits were made in July 2019 to five of the six projects. This was to confirm or validate that no additional distresses that could not be observed in the videos existed. The field observations confirmed

that there were no additional distress types that had occurred, particularly durability types of distress or joint faulting. Photos of these projects are provided later in this document.

"Lane Replacement RSC" Placed Slab Projects

Six projects of "Lane Replacement RSC" were identified in the same geographical area as was done in the "Individual RSC" slab replacement survey. This included freeways in the Los Angeles, Ventura, Riverside, and San Bernardino counties.

Table 3 shows the highways, counties, designs, RSC construction year, and type of RSC cement manufacturer for the six "Lane Replacement RSC" projects surveyed. These sections are located in similar areas and subject to similar truck traffic as the six projects in the "Individual RSC" surveys. A brief description of these "Lane Replacement RSC" sections is as follows:

- Projects are located on major heavily trafficked freeways in Caltrans Districts 7 and 8.
- Projects are located in Los Angeles, Ventura, Riverside, and San Bernardino Counties.
- Surveyed sections were all located on the outer heavy truck lanes.
- RSC slabs age ranges from 9 to 17 years.
- RSC slab thickness ranges from 9 to 12 inches.
- RSC material includes both the CTS and 4X4 cement types similar to the "Individual RSC" slabs. The manufacturer of cement for one of the RSC projects is still unknown but it was included since it was the oldest in the database (2003).

Note that these sections match the "Individual RSC" sections very well in terms of age (both averaged about 12 to 13-years), truck traffic (both averaged about 16 to 18 million trucks), and southern California location. However, the designs are significantly different.

- The "Lane Replacement RSC" slab thickness ranges from 9 to 12-inches as compared to mostly 8-inches for the "Individual RSC" slabs.
- Transverse joint spacing for "Lane Replacement RSC" was 14-ft but for "Individual RSC" was 12 to 19-ft matching the existing random joint spacing.
- Base course is replaced in the "Lane Replacement RSC" projects whereas fewer than 25% is replaced in the "Individual RSC" projects.

The software used to locate and select the "Lane Replacement RSC" sections was the Caltrans version of Google Maps that includes the County Post Miles (PM). The photo clarity is good and cracking, spalling, and surface defect distresses can be observed along the selected traffic lane quite easily.

Table 3. Summary of Six "Lane Replacement RSC" Projects Route, County, Design, RSC Construction Year, and RSC Material.

Route	District, County, ID	Design	RSC Construction Year	Type RSC
I-15 SBL Ontario Fwy	District 8, San Bernardino Co. 08-0A4224	11.4-in JPCP	2004	4X4
I-10	District 8 Riverside Co. 08-472304	12.0-in JPCP	2008	4X4
I-5	District 7 LA County 07-1219U4	10.7-in JPCP	2010	CTS
CA-60 Pomona Fwy	District 7 LA County 07-253304	9.0-in JPCP	2010	CTS
US-101 Ventura Fwy	District 7 Ventura Co. 07-251804	9.0-in JPCP	2011	CTS
I-10	District 8 Riverside Co 08-472104	11.4-in JPCP	2003	NA

*County line = 0.0 PM. See Caltrans PM on Google Maps.
**Software used to obtain PM is Caltrans version of Google Maps:
https://postmile.dot.ca.gov/PMQT/PostmileQueryTool.html?#
NA: Type of RSC cement was unknown.

Procedures used to collect the "Lane Replacement RSC" replacement slabs distress data collection sections shown in Table 4 are as follows:

1. Caltrans Google Maps with Post Miles (PM) was used to conduct the visual survey along specifically identified traffic lanes.
2. The design section information, location, traffic, design, construction year, and RSC material type are provided for each RSC project.
3. Significant lengths of traffic lanes were surveyed and all distress types recorded. The same distress types recorded for the "Individual RSC" slab study was collected for the "Lane Replacement RSC" slabs. A total of 2,069 "Lane Replacement RSC" slabs were surveyed on all 6 projects outer traffic lanes.
4. The type of RSC material used for these 6 projects were obtained from Caltrans. The two types were CTS and 4X4 with one project still unknown.

Table 4. Summary of "Lane Replacement RSC" Projects, Traffic Lanes Surveyed, Post Miles Surveyed, and Total Trucks in Surveyed Lane.

Route	District	MP to MP Direction	RSC Material	Survey Lane*	AADTT 2018 In Lane**	Total Trucks In Lane**
I-15	8	15.0-13.5 SBL	4X4	3 Outer	19,000	20 Million
I-10	8	4.9-5.7 SBL	4X4	3 Outer	17000	20 Million
I-5	7	59.0-59.6 NBL	CTS	4 Outer NBL	19500	12 Million
		58.0/59.8 SBL		4 Outer NBL		
CA-60	7	24.9-25.4 EBL	CTS	5 Outer	26500	15 Million
US-101	7	R30.2-29.4 SBL	CTS	3 Outer	6000	5 Million
I-10	8	19.7-16.7 WBL	NA	4 Outer	21500	23 million
*1 Inner lane, 3 or 4 Outer Lane. **Total Trucks over service life.						

Description of RSC Slabs Survey

The Caltrans Pathways Software was used to locate and rate each of the "Individual RSC" slab replacements. The software showed a "horizon" perspective of the highway ahead, and at the same time an "overhead" view of the RSC slab surface as shown to the right in Figure 1 (a skewed transverse joint is shown). An "overhead 3D" view of the slab surface was also provided to the far right in Figure 1 that helped to identify the severity of cracks and spalls. Each project was reviewed slab by slab, inner and outer lanes, and any observable distress types were recorded. The survey included 1,493 slabs from six projects, located on 12 lanes. All of these slabs were included in the 2008 study where the RSC material type was also known. The lanes were numbered from the inside out, so the innermost lane was 1, the next to the right was 2, next right 3, and the outside right was 4. Four projects had 4 lanes, one had 3 lanes, and one had 2 lanes in one direction.

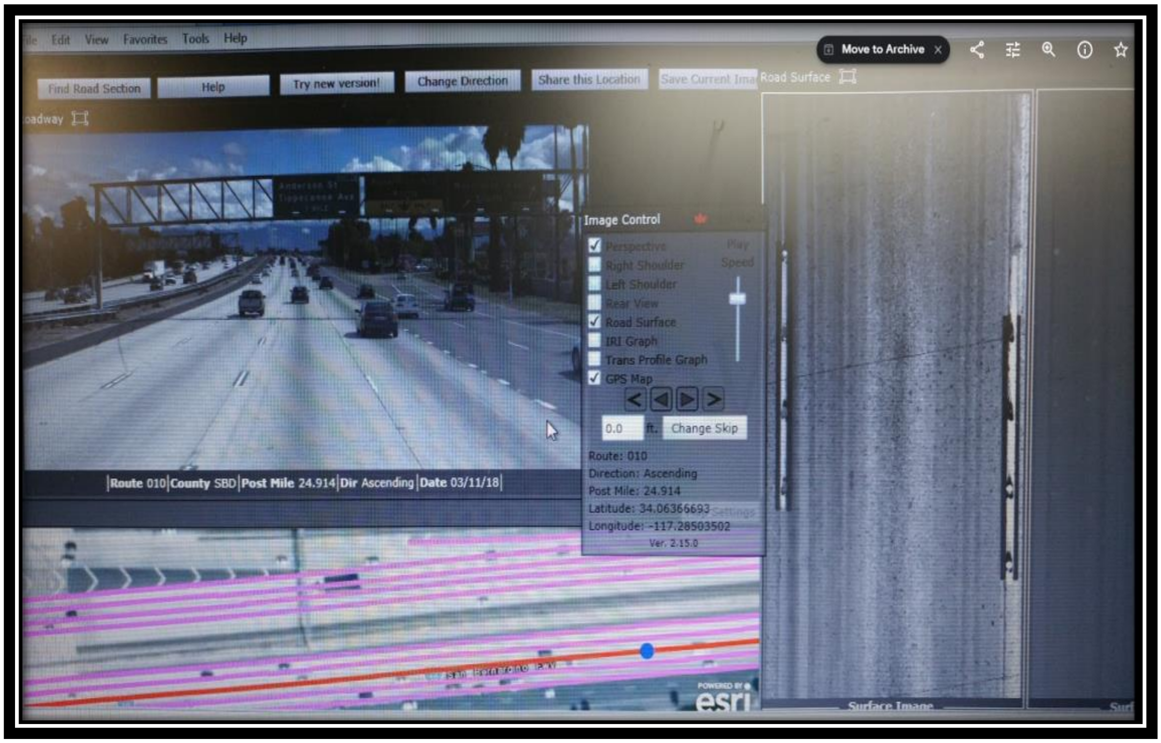

Figure 1. Section I-10, MP 24.5 to 39.1 East Bound.
(Pathways software used by Caltrans)

Figure 2 shows a transverse fatigue crack on a longer 18 to 19 ft slab. A large majority of the transverse cracks appeared to occur on the 18 to 19 ft RSC slab replacements, as would be expected. The original longer slabs were the ones that cracked much earlier than the original 12 or 13 ft slabs. Figure 3 illustrates this point with a plot of a California JPCP project with random joint spaced slabs and the development of transverse fatigue cracks over time. The longer slabs (18-19 ft) develop 5 to 6 times the percentage of transverse fatigue cracks than the shorter slabs (12-13 ft).

The Caltrans Google Maps/PM program was used to locate and rate each of the “Lane Replacement RSC” slab replacements. The exact location in PM (county PMs) was available in the video. The survey included 2,069 slabs from six projects located on six outer heavy truck lanes. The software shows a “horizon” perspective of the highway ahead as well as an overhead lateral view of the adjacent lane RSC slab surface. The program also provides a zoom capability to examine specific areas such as spalling and shrinkage cracking. All observable distress types were recorded. One limitation was some photo blockage of the surveyed lane by another vehicle. When this occurred, the video was simply advanced further down the highway until the adjacent surveyed lane was clear of vehicles. None of the slabs in these visually blocked areas were included in the survey.

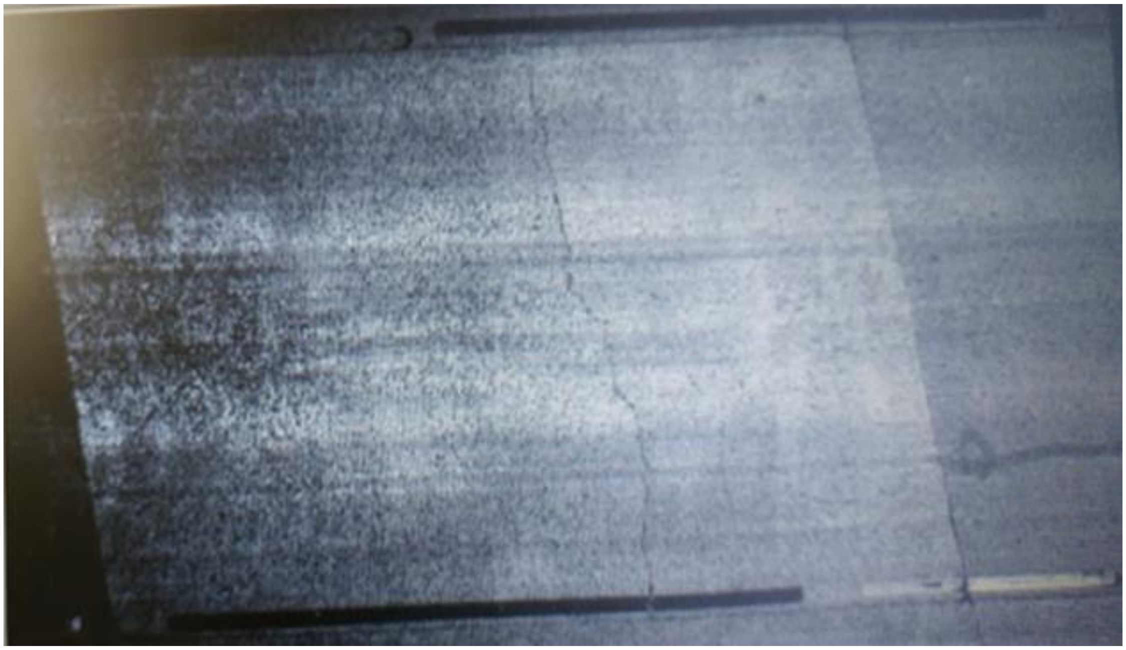

Figure 2. Photo of a transverse crack of a RSC slab with skewed joints.

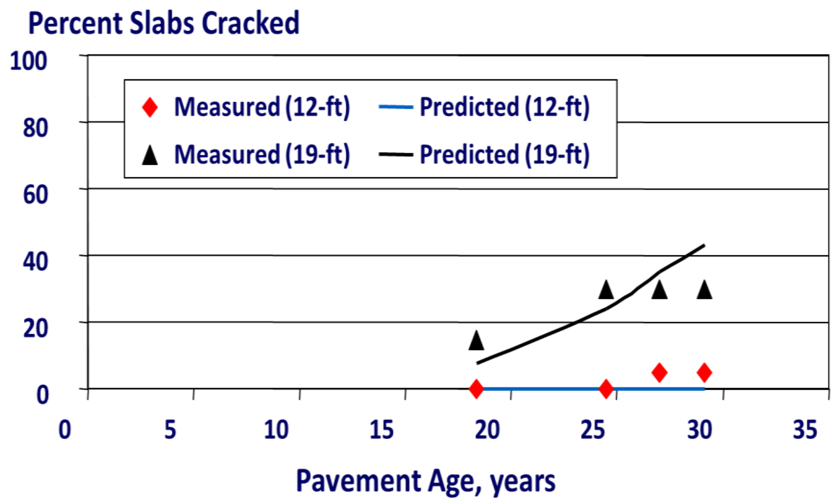

Figure 3. Slab transverse fatigue cracking for shorter slabs and longer slabs over time for a project in California (Note: Predicted by AASHTO PMED). (Darter, 2004)

California DOT Specification for "Individual RSC" Replacement"

The specification used for the 2005-06 RSC construction is included in full in the Appendix D of the 2008 research report "Evaluation of Rapid Strength Concrete Slab Repairs." (Bhattacharya, Zola, and Rawool, 2008) This specification was used until 2010 when a switch was made to plain language and published in the Standard Specifications. The most recent (2015) RSC specification is 41-9 INDIVIDUAL SLAB REPLACEMENT WITH RAPID STRENGTH CONCRETE. This "Individual RSC" slab replacement (also referred to as "random") is typically thought of as a shorter-term strategy because of the lack of certain critical specifications such shrinkage and aggregate quality. It is more of "plug and play" approach to slab replacement with no design considerations taken into account such as adequate pavement thickness or shorter transverse joint spacing.

A brief summary of the key items used to construct the "Individual RSC" slab replacement projects and included in the Caltrans specification referenced are provided here. The actual specification referenced above is very detailed and comprehensive and includes many more aspects than mentioned below.

- **Description:** The replacement of short segments of single or multiple sequential slabs and possibly the underlying base in the same lane to match the existing concrete thickness. Note that thickness of RSC slabs is the same as the existing JPCP regardless of traffic lane.
- **Removing Existing Pavement:** The existing concrete slab is removed and as needed the base course is replaced with a specified base material (typically lean concrete) and RSC slab. Concrete is removed by non-impacting methods. Each slab is removed without disturbing or damaging the underlying base.
- **Base Replacement**: The replacement base is finished to the grade of the original base layer. If concrete, it is not textured but finished as a smooth surface.
- **Bond Breaker:** A bond breaker is placed between the existing base (typically cement treated base or lean concrete base) or new replacement base and the new RSC slab that consists of one of the following:
  - 1. White curing paper specified in ASTM C 171.
  - 2. White opaque polyethylene film specified in ASTM C 171, except the minimum thickness must be 6 mils.
  - 3. Paving asphalt, Grade PG 64-10, under section 92, "Asphalts," of the Standard Specifications.
  - 4. Curing compound No. 5. Apply in two separate applications.

  Note that every effort is made here to separate the two layers. This has major implications on future performance.
- **Transverse & Longitudinal Joints:** A 1/4-inch thick commercial quality polyethylene flexible foam expansion joint filler is placed across the original

transverse and longitudinal joint faces prior to placement of the RSC slab. It is extended the excavation's full depth. The top of the joint filler must be flush with the top of the pavement. The joint filler is secured to the existing JPCP joint face to prevent the joint filler from moving during the placement of RSC. Holes are cut in the foam expansion joint filler for dowel bars anchored into the existing joint face.

- **Transverse Joint Spacing.** Transverse contraction joints are constructed in pavement widenings to match the spacing and skew of the contraction joints in the adjacent existing JPCP. Where the existing adjacent transverse contraction joint is longer than 15-ft, a transverse joint is cut midway between the existing joints. The sawing of contraction joints must be completed within 2 hours of completion of final finishing. Contraction joints are cut a minimum 3-9/16 inch deep. (Note: most RSC slabs on the six surveyed "Individual RSC" projects did not have this intermediate joint for the 18 and 19 ft slabs and many of them had developed transverse fatigue cracks).
- **Dowels in Transverse Joints.** It is believed (but could not be verified) that most or all of the projects included in the survey had dowels anchored in the transverse joints. No joint faulting or corner cracks were noted which indicates dowels were included. District 7 RSC projects in particular are likely to all have dowels, especially in isolated slabs. More recent standards indicate 4 dowels per wheel path in the truck lanes and perhaps 3 dowels per wheel path in other lanes. Dowels are spaced at 12-inches in the wheel paths with a diameter of 1.25-inches based on slab thickness of 9-inches or less.
- **Rapid Strength Concrete (RSC).** To reduce the disruption to traffic, Caltrans carries out overnight repairs, limiting lane closures to the hours between 11 pm and 5 am. Severely distressed concrete panels are removed and replaced with RSC during this limited time period. Only cement mixes that meet the early opening strength requirements within 2 to 4 hours after placement are used. RSC is a concrete made with hydraulic cement that develops opening age and 7-day specified modulus of rupture strengths.
    - RSC pavement must develop a minimum modulus of rupture of 400 psi before opening to traffic.
    - RSC pavement must develop a minimum modulus of rupture of 600 psi at 7 days after placement. (Note: If these strengths are not achieved there is a disincentive applied to the bid price.)
    - Two RSC materials were used on the projects in this survey: CTS and 4x4 and are described in the next section.
- **Spreading, Compacting, and Shaping.** Metal or wood side forms may be used. Side forms must remain in place until the pavement edge no longer requires the protection of forms. After RSC is placed on the top of the bond

breaker it is consolidated with high-frequency internal vibrators across the full paving width. The RSC is spread and shaped with powered finishing machines supplemented by hand finishing. After mixing and placement of RSC, no additional water must be added to facilitate finishing.

- **Final Finishing.** The Engineer can determine if the final texturing meets the specifications for coefficient of friction through observation or by testing. If the pavement does not comply, the pavement will be diamond ground as per Caltrans specifications. Note, all RSC slab replacements surveyed were diamond ground but most likely to achieve a smooth profile.
- **Durability Tests.** The "Individual RSC" slab specification does not place a maximum level of drying shrinkage or quality assessment for ASR. This specification was conceived as a "short-term" slab replacement (e.g., <5 years).
- **Comment on RSC Slab Curling:** All of the RSC slabs were placed at night and thus there was almost no negative built-in temperature gradient that would cause the slabs to curl upward like a saucer. This should minimize the amount to top down fatigue cracking. Note however that a significant moisture gradient (dry on top and wet bottom of slab) still exists and can cause significant upward curling of the slabs that contributes to top down fatigue cracking. Some RSC products (such as CTS) have much less drying shrinkage than conventional early opening concrete, thus less upward curling or shrinkage cracking may exist in the CTS RSC slabs. (Bescher and Kim, 2019)

California Specification & Guidelines "Lane Replacement RSC"

"Lane Replacement RSC" represents a total reconstruction of one or more traffic lanes. The California **"Concrete Pavement Guide Part 4: Rehabilitation Strategies, Chapter 400, Lane Replacement" (2015)** provides detailed guidance on the replacement of traffic lanes. This alternative is considered when more than 20% of slabs exhibit 3rd stage cracking. It is also recommended to replace two lanes at the same time due to overall better cost effectiveness.

The California Standard Specifications **Section 40-5 JOINTED PLAIN CONCRETE PAVEMENT WITH RAPID STRENGTH CONCRETE** is a comprehensive specification that describes many aspects to construct a long-term continuous "Lane Replacement RSC" designated JPCP-RSC. The typical usage of "Lane Replacement RSC" lane replacement is a seriously deteriorated and cracked JPCP that can no longer be maintained. Most often, these "Lane Replacement RSC" JPCP-RSC are outer heavy truck lanes. The pavement is basically removed and reconstructed with the following characteristics:

- New base course (typically lean concrete base but could be HMA also)
- New thicker JPCP slabs (e.g. 10-14-in) with 14-ft perpendicular joint spacings.

- RSC in the slab meets the same requirements as for "Individual RSC" slab RSC slab replacement.
- Dowels are placed at all transverse joints with an appropriate diameter to prevent joint faulting.
- Both RSC shrinkage and ASR requirements are included in these specifications.

Thus, the Caltrans **"Concrete Pavement Guide, Chapter 400 Lane Replacement," and "Section 40 Concrete Pavement"** specifies a JPCP-RSC structure and construction that represents a long-life strategy. https://dot.ca.gov/programs/maintenance/pavement/concrete-pavement-and-pavement-foundations

Description of RSC Slab Materials

Two different RSC materials were identified on the selected projects: CTS and 4X4. A brief summary of each is provided.

CTS Rapid Set Cement. A summary of information about CTS Rapid Set Concrete Mix used in the 2005 construction is provided below from the web site (https://www.ctscement.com/product/rapid-set-cement?c=PAVEMENT%20&%20OVERLAYS&t=Professionals)

- "Rapid Set® Cement, Rapid Hardening Hydraulic Cement
- Use to create fast-setting concrete, mortar and grout.
  Inherent sulfate resistance and low shrinkage.
  Ready for service in 1 hour.
- "Rapid Set® Cement is a fast setting, high performance cement that provides faster return to service, high strength, and increased durability. Rapid Set Cement qualifies as very rapid hardening (VRH) per ASTM C1600 (Standard Specification for Hydraulic Cement). Use for highway pavements, bridges, runways, tunnels, tilt-up, precast, sidewalks, floors, and other applications. For larger jobs, batch Rapid Set Cement mixtures using conventional ready mix or volumetric mixer equipment. Conforms to: ASTM C1600."

Further information is provided by Bescher and Kim, 2019:

- "CTS" is Rapid Set® cement, a belitic calcium sulfoaluminate (CSA) cement made by CTS Cement Mfg. Corp.
  - Non-proprietary technology
  - Rapid strength gain; opening strength (400 psi flex) in 1.5 hours
  - Very low shrinkage (note: the low shrinkage is a major benefit given that high early strength concrete typically exhibits high shrinkage)
  - High sulfate resistance
  - ASR resistant

- Can be used in volumetric mixer (mobile mix) or transit mixer (ready mix)

4X4 Concrete Mix. A summary of information about 4x4 Concrete Mix used in the 2005 construction is provided below from the web site (https://assets.master-builders-solutions.basf.com/en-us/4x4-concrete-comparison_ctif.pdf).

- "The 4x4 Concrete System in Practice To help agencies overcome these issues and meet the demands for fast-track pavement replacement and repairs, BASF has developed the 4x4 Concrete system, a patented, and economical method for achieving high-early strength. The 4x4 Concrete system is versatile, easy-to-place, achieves exceptional early strength, and is approved for use by a growing number of DOT agencies. Because the 4x4 Concrete system is made with locally available cements and aggregates, it can be developed by local concrete producers to meet the specific needs of transportation agencies and contractors. The secret to the development of very high early strength lies in the unique combination of BASF's Master Builders Solutions brand MasterGlenium® , MasterSet® DELVO and MasterSet® specialty admixtures."
- In summary, 4×4 is a concrete system that uses portland cement, retarder, accelerator, and super-plasticizer.
    - Patented technology; offered by multiple admixture suppliers
    - Rapid strength gain; opening strength (400 psi flex) in 4 hours "4x4"
    - Can be higher shrinkage if SRA isn't used (Type-III cement)
    - Cannot be used in volumetric mixer (transit mix only)

Summary of 2008 Condition Survey of "Individual RSC" Slabs

This early survey was conducted in the field on 15 projects located from San Bernardino to Sacramento. All of these projects were multilane (most projects had 4 lanes in one direction) and had high AADT and AADTT volumes.

Distress types identified and percent distressed RSC slabs are as follows (out of a total of 5,430 RSC slabs):

- Spalls and corner Breaks: 0.44% RSC slabs
- Mid-Panel and Surface Cracking: 0.81% RSC slabs
- Shrinkage cracking: 0.06% RSC slabs
- Other distress (Aggregate Pockets, Moving Slabs): 0.06% RSC slabs

These values are very low even for 3 years of service. Figure 4 shows that the average percentage of distressed slabs with 4×4 cement was 1.61% and with CTS cement was 0.58 %. These RSC projects were in service for about 3 years on average with a very low rate of distress.

Prevailing thought was that RSC slabs have more durability problems than conventional concrete. This was not the case after 3 years for these 15 RSC projects in California. Note that these projects are mostly located in non-freeze thaw climates but one was at about 4,000-ft elevation with some freeze-thaw cycles each year. But what about longer term such as 10 to 20 years or more traffic and climatic loading cycles? Will these RSC slabs maintain this high level of durability? This is an important question that Caltrans and many other State Highway Agencies (SHAs) would like to see addressed.

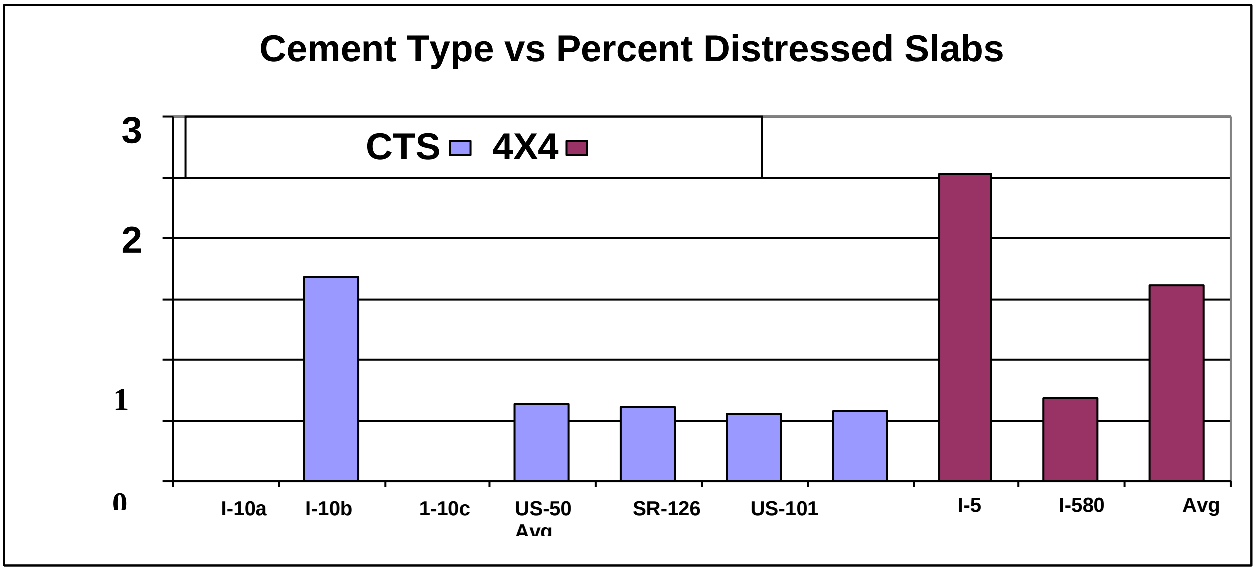

Figure 4. Results from 2008 Condition survey of 15 "Individual RSC" placed projects and 5430 RSC slabs after 3 years' service in California. (Bhattacharya, Zola, and Rawool, 2008)

Summary of the Condition Survey of "Individual RSC" Slabs

This follow up survey was conducted on 6 of the original 15 projects using the latest (2018) video data available plus some actual field validation. Table 5 summarizes the distress types identified and obtained for each of the 12 traffic lanes from 6 projects that included "Individual RSC" slabs. Note that there were some longer stretches of RSC slabs in a row but they all were placed at the same slab thickness and most at the same joint spacing as the existing JPCP. These sections have all been in service for approximately 13 years and have carried from 0.7 to 34 million trucks in their respective lanes.

A large majority of RSC slabs have not exhibited significant distress over 13 years as is shown in Table 5. Descriptions of the findings follows.

- **1,493 "Individual RSC" replaced slabs were surveyed** using Caltrans video images from six projects collected in the year 2018. All of these projects were originally surveyed in 2008. These RSC slabs were located in inner lanes (#1, #2, or #3) which are lower truck traffic; to the outermost lane (typically #2 or #4) which are the heaviest truck trafficked lanes.

- **Distress types identified on the 2018 RSC slabs.** Figure 5 shows the overall extent of occurrence of these four types of distresses.
    - Transverse mid-panel (fatigue) cracking: 8.8 percent RSC slabs
    - Longitudinal cracking: 0.3 percent RSC slabs
    - Corner cracking: 0.3 percent RSC slabs
    - Spalling along the transverse RSC/existing slab joint: 0.8 percent RSC slabs

Table 5. Summary of "Individual RSC" Survey Results for Six Projects including 12 Traffic Lanes at 13-Years.

Route	District	MP to MP	RSC Material	Survey Lane*	Total Trucks In Lane***	Total RSC Slabs	Trans Crk % Slabs	Long Crk % Slabs	Corner Crk %Slabs	Spall % Slabs
I-10	8	0 - 14 NBL	CTS	1 Inner	2 Million	3	**0.0**	**0**	**0.0**	**0.0**
I-10	8	14.5 - 20 SBL	CTS	4 Outer	28 Million	70	**2.9**	**0**	**0.0**	**0.0**
I-10	8	15.5 - 20 SBL	CTS	3 Inner	12 Million	183	**0.5**	**0**	**0.0**	**1.1**
I-10	8	15.5 - 20 NBL	CTS	3 Inner	12 Million	245	**0.4**	**0.4**	**0.0**	**2.0**
I-10	8	24.5 - 30 NBL	CTS	3 Inner	14 Million	6	**0.0**	**0**	**0.0**	**0.0**
I-10	8	24.5 - 30 NBL	CTS	4 Outer	34 Million	45	**4.4**	**0**	**0.0**	**2.2**
I-5	7	76 - 88.6 NBL	4x4	1 Inner	2 Million	68	**0.0**	**0**	**0.0**	**0.0**
I-5	7	76 - 88.6 NBL	4x4	2 Inner	4 Million	561	**0.2**	**0**	**0.0**	**2.1**
US-50	3	1.1 - 4.8 NBL	CTS	3 Outer	5 Million	51	**29.4**	**0**	**2.0**	**2.0**
US-50	3	0.84 - 2.9 NBL	CTS	1 Inner	1 Million	8	**12.5**	**0**	**0.0**	**0.0**
SR-126	7	0 - 13 NBL	CTS	1 Inner	0.7 Million	30	**10.0**	**0**	**0.0**	**0.0**
SR-126	7	0 - 4 NBL	CTS	2 Outer	6 Million	223	**45.7**	**3.6**	**1.3**	**0.0**
Averages						Total RSC = 1493	**8.8**	**0.3**	**0.3**	**0.8**
*1 Inner Most lane. **Two direction AADTT. ***Total Trucks over 13 year service life.										

- **The most prevalent distress type in 2018 in the RSC slabs was transverse cracking as shown in Figure 5.** Based on past studies including observations in the field and finite element stress analysis, these cracks are nearly always caused by top down fatigue damage from heavy repeated truck loadings. They are increased by the upward curling of slabs based on negative temperature gradients, moisture gradients, and built-in temperature gradients. An illustration of the critical fatigue loading and stresses is provided in Figure 6. Thin slabs such as these are mostly 8-inches thick and are by far the most likely to develop transverse fatigue cracking. (Darter, 2017)

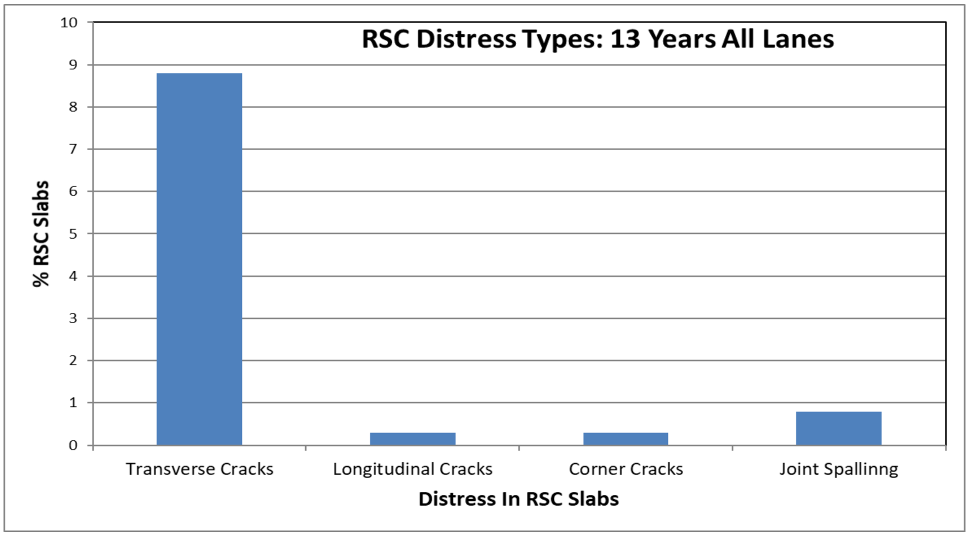

Figure 5. Summary of distress types identified in the "Individual RSC" slab replacements after 13 years of service (2018).

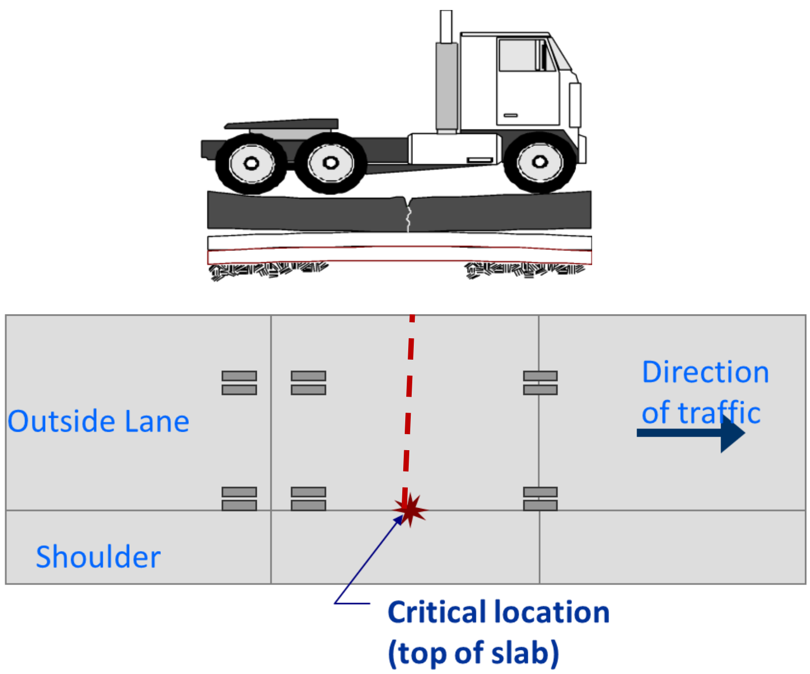

Figure 6. Illustration of the development of transverse top down fatigue cracking when slab is curled upward like a saucer (thicker slab and shorter joint spacing would reduce critical tensile stress and decrease transverse cracking.)

- **The overall average percent of "Individual RSC" slabs with transverse cracking was 8.8 percent slabs including all 12 traffic lanes surveyed**. The 2008 survey indicated 0.81 percent (but included other cracking also). So clearly, the number of transverse fatigue related mid-panel cracks has grown significantly over the 10-year period.

- **The transversely cracked "Individual RSC" slabs occurred at a far higher rate in the heavier outer truck lane.** The most informative results were obtained by summarizing the percent slabs transversely cracked in the outer truck lane (typically lane #4) with those in all inner lanes (e.g., 1, 2, and 3 for a 4-lane facility). Figure 7 shows a plot of the results. A photo of a typical top down transverse fatigue cracked slab from the SR-126 freeway near Ventura is shown in Figure 8.
    - Outer truck lane percent transversely cracked RSC slabs: 21 percent. (20 million trucks)
    - Inner lanes percent transversely cracked RSC slabs: 3 percent. (6 million trucks)

- **There was over 3 times the number of trucks in the outer lane than in the inner lanes.** This resulted in far more transverse fatigue cracking (e.g., 21% versus 3%) in the outer truck lanes than in the inner truck lanes.

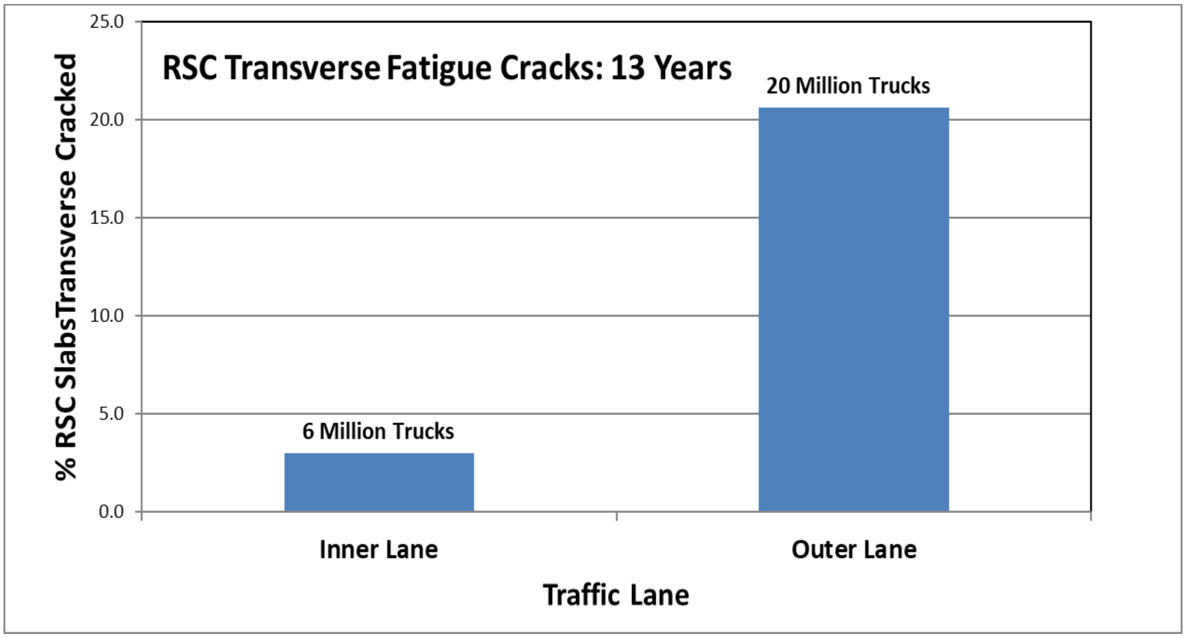

Figure 7. "Individual RSC" Slabs Transverse (Fatigue) Cracking over 13 years of Performance for Inner and Outer Traffic Lanes.

Figure 8. Highway SR-126 near Ventura, CA showing an original 18-19 ft thin slab (conventional concrete) placed in 1972 that developed a transverse fatigue top down crack (this result is common as these thin slabs cannot carry this many heavy truck axle loads).

- **Another interesting observation is that a large proportion of RSC slabs that were replaced with the RSC were the original longer 18 and 19 ft joint random spaced slabs.** Although the Caltrans specification called for a maximum joint spacing of 15-ft, most of the RSC slabs matched the existing random joint spacing of 12, 13, 18 and 19 ft. Figure 3 showed that the shorter 12 and 13 ft slabs do not often crack due to the reduced joint spacing and thus much lower fatigue damage in the original slabs. The longer original 18 and 19-ft slabs cracked transversely far more often and were replaced with the (mostly the same length) RSC slabs (US-50 had some shorter sawed intermediate 14-ft joint spacings that did not crack). These 18-19 ft RSC slabs, in turn, cracked far more quickly than the 12 and 13 ft long RSC slabs.

- **There were only very limited amounts of longitudinal cracking in the "Individual RSC" slabs.** A total percentage of RSC slabs with longitudinal cracking was only 0.3 percent after 13 years. The percent in 2008 was close to zero. The cause of these few longitudinal cracks could range from slight settlement of a portion of the foundation to improper forming of the longitudinal joints.

- **There were only very limited amounts of transverse or longitudinal joint spalling that occurred within the "Individual RSC" slabs.** There was much more spalling in the original old surrounding concrete slabs as would be expected for 40+ year old JPCP. The percent of joint spalling in the RSC slabs was only 0.8 percent. The 2008 survey combined corner cracking and spalls together and found the same 0.8 percent.

- **There were only very limited amounts of the corner cracking that occurred within the RSC slabs.** A total percentage of RSC slabs with corner cracking was only 0.3 percent. The percent in 2008 was 0.44 percent (for both spalling and corner cracking). The cause of the few corner cracks could be related to settlement of the foundation or missing dowel bars in the outside of the traffic lane. Placement and anchoring of dowel bars in wheel paths along transverse joints greatly helps to minimize corner cracking due to the dowel bar shear support when the corner is loaded by a heavy truck wheel. It is believed that most of these RSC slabs included dowels across the transverse joints.

- **Performance of the two RSC slab concrete materials CTS and 4x4** could not be directly compared as they exist on different projects and with widely varying truck traffic volumes. Having stated this, Table 6 was compiled to illustrate the performance considering the inner lanes only, which included both materials. Outer lanes did not include both materials, so they could not be compared. Note that the six CTS RSC inner lanes have received 7 million trucks and the 4x4 RSC inner lanes have received 3 million trucks over the 13 years. So, they still cannot be directly compared due to this large difference in truck traffic loadings. In summary, both the 4x4 and CTS RSC replacement slabs provided excellent performance over 13 years for these projects and there is no reason to expect they should not perform well for at least another 10+ years.

Table 6. Summary of the performance of Inner Lane "Individual RSC" slab material types over 13 years.

RSC Material	Inner Lane Trucks	Inner Lane Trans. Cracks	Inner Lane Long. Cracks	Inner Lane Corner Cracks	Inner Lane Spalls
4x4 (1 Project: 629 slabs)	3.0 million	0.10%	0.00%	0.00%	1.05%
CTS (5 Projects: 475 slabs)	7.1 million	3.90%	0.07%	0.00%	0.50%

- **"Individual RSC" slabs exhibited no observable durability distress** (e.g., "D" cracking, freeze-thaw damage, shrinkage cracking, ASR) over the 13 years of service (Note: none observed in 2019 field survey either). Most of these six projects were located in lower elevations and only one at about 4,000 ft had some freeze-thaw cycles. The rest are located in a hot and dry climate. This finding of no durability issues is important in that the general impression is that RSC materials often develop durability problems over time. In 2008, there was only 0.06 percent slabs with shrinkage cracks. None were observed during the 2018 video survey or during the 2019 field visual observations of the RSC projects.

Distress Not Included and Field Survey of "Individual RSC" Slabs

It was not possible to fully evaluate a few distresses in the RSC slabs using the Caltrans video survey: transverse joint faulting magnitude, underlying joint deterioration, erosion or loss of support beneath slab corners, and surface texture. Thus, a brief visual field survey was conducted of many of the RSC slabs to verify their condition.

A field survey was conducted and photos taken from along the shoulder of 5 RSC projects in July 2019. The survey did not find any significant joint faulting, pumping of materials onto the shoulder, surface map cracking or surface scaling. The surface texture of the either diamond ground or longitudinal tined RSC slabs was observed to be excellent after 14 years. Several photos and descriptions are provided in Figures 9 to 17 for illustration of the RSC slabs performance.

Photos of "Individual RSC" Projects

Figures 9 to 17 show several examples and descriptions of the six "Individual RSC" projects with replaced slabs.

Figure 9. Highway I-5 NB direction (PM 76-88), northwest of Los Angeles showing original inner #1 lane (left) and inner #2 lane with several "Individual RSC" slabs placed in 2005.

Figure 10. Highway I-5 NB direction (PM 76-88), northwest of Los Angeles showing a transverse joint between two 13-year old RSC slabs (Note that variation in mix color did not create any cracking or disintegration).

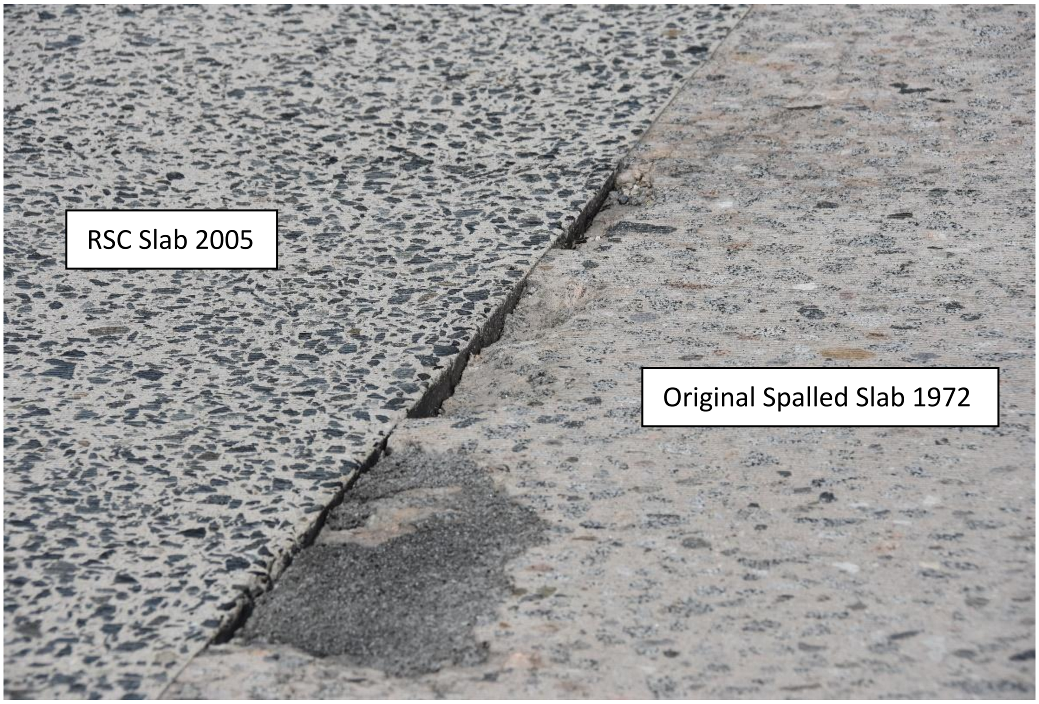

Figure 11. Highway I-5 NB direction (PM 76-88), northwest of Los Angeles showing a transverse joint between a 13-year old RSC slab on left and spalled original JPCP on right.

Figure 12. Highway I-10 EB direction (PM 0-39), near San Bernardino showing two 14-year old "Individual RSC" slabs in Lane #4 (outer lane).

Figure 13. Highway I-10 EB direction (PM 76-88), near San Bernardino showing a closeup of a 14-year old diamond ground transverse joint "Individual RSC" slab in Lane #4 (outer lane). Very good RSC durability shown here existed at all sites.

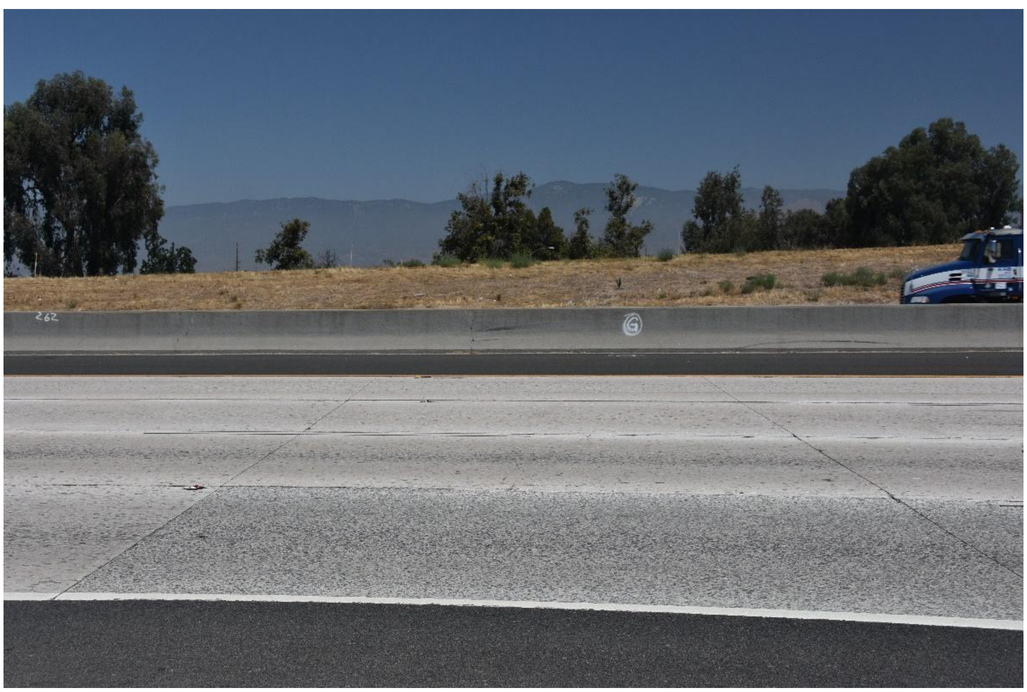

Figure 14. Highway I-10 EB direction (PM 76-88), near San Bernardino showing another 14-year old "Individual RSC" slab in Lane #4 (outer lane) with long joint spacing.

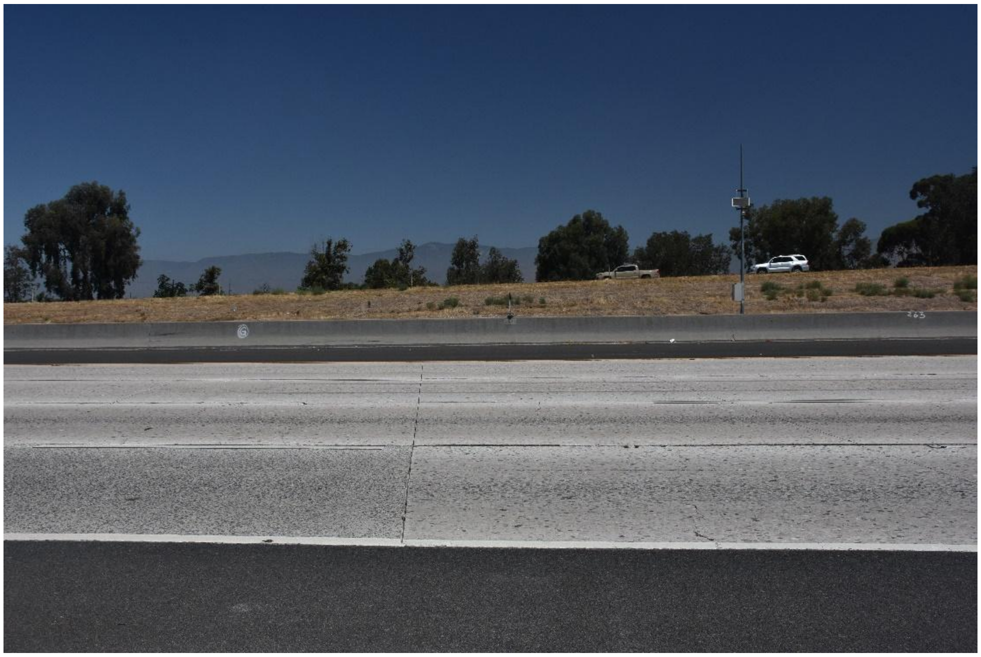

Figure 15. Highway I-10 EB direction (PM 76-88), near San Bernardino showing on the left side a 14-year “Individual RSC” slab surface Lane #4 (outer lane) and on the right an original (1970s) JPCP slab with a transverse fatigue cracking.

Figure 16. Highway SR 126 (PM 0-13) near Ventura showing some 14-year “Individual RSC” slabs in lanes #1 (left) and #2 (right) that was placed because the original RSC slabs placed in 2005 had transversely fatigued cracked.

Figure 17. Highway SR 126 (PM 0-13) near Ventura showing a RSC slab placed in outer truck lane in 2006 that has developed a top down transverse fatigue crack.

Summary 2020 Condition Survey “Lane Replacement RSC” Slabs

The software used to locate and select the RSC “Lane Replacement RSC” sections was the Caltrans version of Google Maps that includes the County Post Miles (PM). The photo clarity is good and surface cracking, shrinkage cracking, and joint spalling distresses can be observed along the selected traffic lane quite easily.

Procedures used to collect the “Lane Replacement RSC” distress data are as follows:

1. Caltrans Google Maps with PM was used to conduct the visual survey along specifically identified traffic lanes shown in Table 4.
2. The design section information, location, traffic, design, construction year, and RSC type of cement are also provided in Table 4 for each RSC project.
3. Significant lengths of traffic lanes were visually surveyed and all distress types recorded. The same distress types recorded for the “Individual RSC” slab study was collected for the “Lane Replacement RSC” slabs. A total of 2,069 “Lane Replacement RSC” slabs were surveyed on all 6 projects outer traffic lanes.
4. The type of RSC material used for these 6 projects were obtained from Caltrans. The two types were CTS and 4X4 with one older project unknown.

These six “Lane Replacement RSC” projects have the following characteristics.

- The “Lane Replacement RSC” projects are located in Southern California, similar to the “Individual RSC” projects, on major heavily trafficked highways carrying AADTT in 2018 from 6,000 to 26,500 (2-Directions).
- The “Lane Replacement RSC” sections are all located in the outer heavy truck lanes (Lanes #3, #4, and #5).
- Total Number of Trucks over the RSC traffic lanes service life ranges from 5 to 23 million, average 16 million. This is a very heavy truck loading for time periods of 9 to 17 years.
- Slab thicknesses for these “Lane Replacement RSC” projects ranged from 9.0 to 12.0-inches with a mean of 10.6-inches. Much thicker than the 8-in “Individual RSC” slabs.
- All of these “Lane Replacement RSC” projects had perpendicular joints at 14-ft spacing.

Results of Survey of “Lane Replacement RSC” Pavements

Results from the survey of the six “Lane Replacement RSC” projects were summarized into Table 7 and simplified in Table 8. The results are shown by “percent RSC slabs” for all distresses. These results show the overall performance for “Lane Replacement RSC” slabs from six projects with a total of 2,069 slabs, all in the outer truck lane.

Table 7. Summary of “Lane Replacement RSC” Survey Results for Six Projects that include 6 Outer Traffic Lanes.

Route	District	MP to MP Direction	RSC Material	Survey Lane*	Total Trucks In Lane**	Total RSC Slabs	Trans Crk % RSC Slabs	Long Crk % RSC Slabs	Corner Crk % RSC Slabs	Spall % RSC Slabs	Shrink % RSC Slabs
I-15 / 8	8	15.0-13.5 SBL	4X4	3 Outer	20 Million	200	0.0	0.0	0.0	3.0	1.5
I-10 / 8	8	4.9-5.7 SBL	4X4	3 Outer	20 Million	300	0.0	0.0	0.0	0.7	0.3
I-5 / 7	7	59.0-59.6 NBL	CTS	4 Outer NBL	12 Million	897	0.0	0.4	0.0	0.6	0.7
		58.0/59.8 SBL		4 Outer NBL							
CA-60 / 7	7	24.9-25.4 EBL	CTS	5 Outer	15 Million	161	0.0	0.6	0.0	0.6	1.9
US-101 / 7	7	R30.2-29.4 SBL	CTS	3 Outer	5 Million	169	0.6	0.0	0.0	1.2	0.0
I-10 / 7	8	19.7-16.7 WBL	NA	4 Outer	23 million	342	1.5	0.3	0.0	0.3	0.6
Averages						2069 Total RSC	0.3	0.2	0.0	1.1	0.8
*1 Inner lane, 3 or 4 Outer Lane. **Total Trucks over service life.											

These results show the following:

- **Transverse Top-Down Fatigue Cracking** = 0.3 percent RSC slabs outer lane. This is a very low percentage of transverse fatigue cracking after carrying from 5 to 23 million heavy trucks in the outer lanes for six projects. Thus, virtually no fatigue related transverse cracks have developed to date on heavily truck trafficked outer lane “Lane Replacement RSC” slabs.

- **Longitudinal cracks = 0.2 percent RSC slabs.** This result indicates that the longitudinal joints were formed very well and that no fatigue damage or settlements that might cause longitudinal cracking has occurred.
- **Corner cracks = 0.0 percent RSC slabs.** This result indicates that the dowel bars installed in all transverse joints have prevented any corner cracks to developed even after so many millions of heavy truck axle loadings.
- **Joint spalls = 1.1 percent** (within the RSC slabs). This is very minimal after 9 to 17 years of service and very heavy truck loadings. The RSC concrete appears to be very sound.
- **Slab drying shrinkage = 0.8 percent** RSC slabs. This is very minimal percent for RSC slabs, again at a very low value that will not hurt the long life of the CTS and 4X4 RSC slabs. These “Lane Replacement RSC” slabs ranged in age from 9 to 17 years.
- **Transverse joint faulting** was not observed at any project (by observing upstream joint faulting) due to all of the transverse joints being doweled. This is a critically important aspect.

Table 8. Summary of distress survey for the six outer “Lane Replacement RSC” placed slab projects totaling 2,069 RSC slabs.

Distress Type in “Lane Replacement RSC” Slabs	2020 Survey Averages (2069 RSC Slabs)
Transverse (mid-panel) Top Down Fatigue Cracks	0.3% RSC Slabs
Longitudinal Cracks	0.2% RSC Slabs
Corner Cracks	0.0% RSC Slabs
Joint Spalls (within RSC slab)	1.1% RSC Slabs
Shrinkage Cracking	0.8% RSC Slabs
Joint Faulting	None Observed

Two different RSC materials, CTS and 4x4, were included in the 6 projects including CTS and 4X4. These materials were previously described. The results from the survey are shown in Table 9. The results show very low percentages of all distress types for both material types. The only defect that was identified on one 4X4 project (I-15 located in San Bernardino Co.) was a small amount of “pitting” of the concrete surface along the project. No maintenance was required on this project to date and a photo is shown in Figure 22. Thus, it is concluded that both RSC lane replacement products have performed very well for up to 17 years and 23 million heavy trucks.

Table 9. Summary of distress survey for the two different Outer "Lane Replacement RSC" slab cement products.

Distress Type for "Lane Replacement RSC" Slabs	CTS Manufacturer	4X4 Concrete Mixture
Transverse (mid-panel) Top Down Fatigue Cracks	0.2% RSC Slabs	0.0% RSC Slabs
Longitudinal Cracks	0.4% RSC Slabs	0.0% RSC Slabs
Corner Cracks	0.0% RSC Slabs	0.0% RSC Slabs
Joint Spalls (within RSC slab)	0.8% RSC Slabs	1.8% RSC Slabs (some of surface of one section was "pitted")
Shrinkage Cracking	0.8% RSC Slabs	0.9% RSC Slabs
Joint Faulting	None Observed	None Observed

Photos of "Lane Replacement RSC" Projects

Figures 18 to 23 show several photos of the 6 "Lane Replacement RSC" projects. These RSC projects represent a wide range of designs, traffic, and RSC material types.

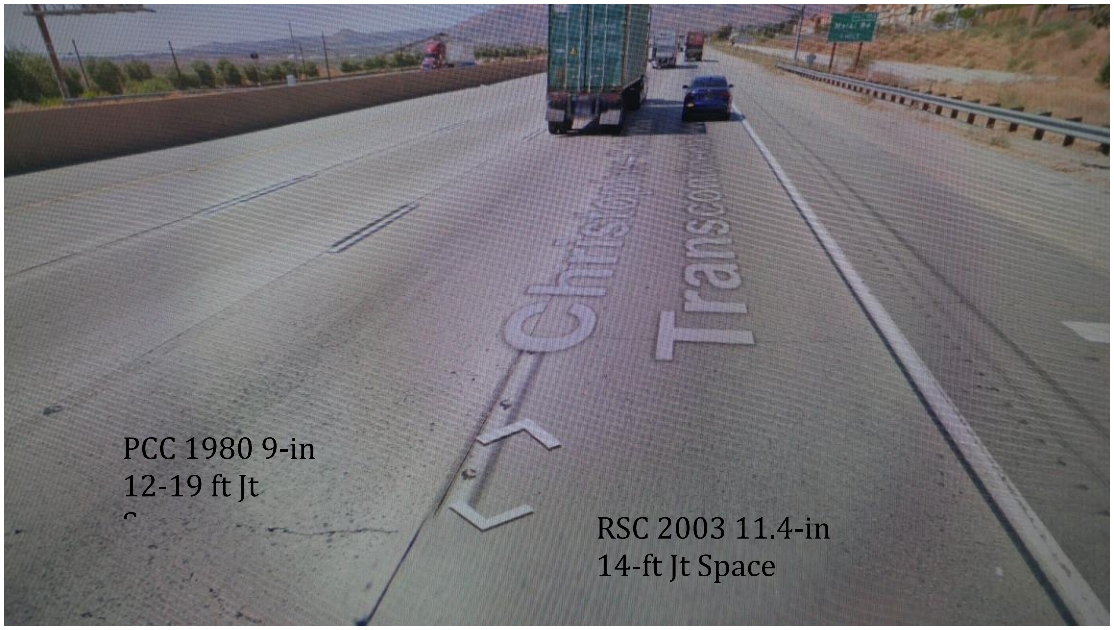

Figure 18. Photo (from Google Maps) of a "Lane Replacement RSC" project on I-10 located in Riverside Co., CA constructed in 2003.

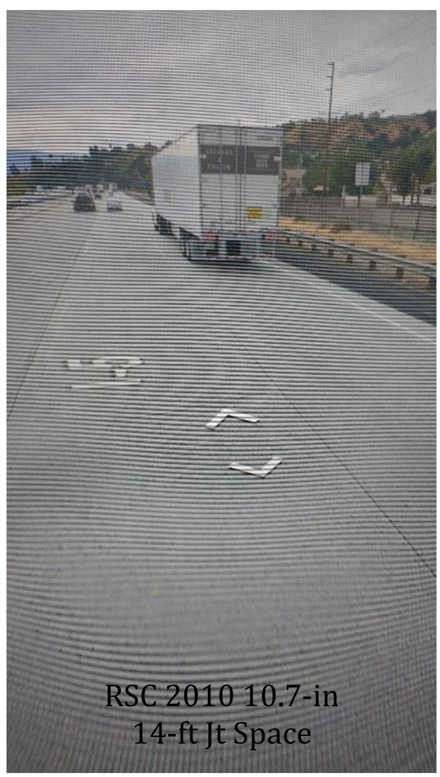

Figure 19. Photo (from Google Maps) of a "Lane Replacement RSC" section of I-5 located in Los Angles Co., CA constructed in 2010.

Figure 20. Photo (from Google Maps) of a "Lane Replacement RSC" section on CA-60 located in Los Angles Co., CA constructed in 2010.

Figure 21. Photo (from Google Maps) of a "Lane Replacement RSC" outer lane section of I-15 located in San Bernardino Co, CA constructed in 2004.

Figure 22. Photo (from Google Maps) of a “Lane Replacement RSC” outer lane section of I-15 located in San Bernardino Co, CA constructed in 2004 (note some “pitting” of the textured RSC surface of the 4x4 RSC slab).

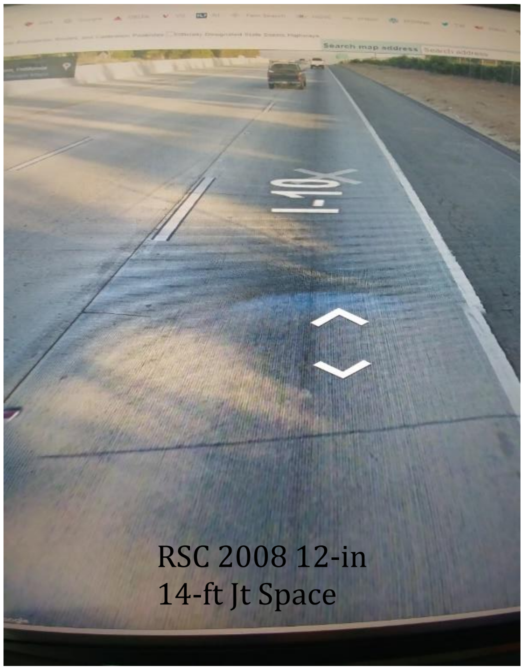

Figure 23. Photo (from Google Maps) of a “Lane Replacement RSC” outer lane section of I-10 located in Riverside Co, CA constructed in 2008.

Comparison of “Individual RSC” With “Lane Replacement RSC”

A direct comparison can be made between “Individual RSC” and “Lane Replacement RSC” projects regarding performance since they are both located in the same climate and subjected to the same aging and truck traffic. Table 10 provides an overall average summary of the results. The ages and total truck traffic were very similar for both sets of projects:

- **RSC Slabs Age at Survey**
  - “Individual RSC”: 12 to 13 years, Mean = 13 years
  - “Lane Replacement RSC”: 9 to 17 years, Mean = 12 years

- **RSC Slabs Total Trucks in Outer Traffic Lane**
  - “Individual RSC”: 1 to 34 million, Mean = 18 million
  - “Lane Replacement RSC”: 5 to 23 million, Mean =16 million

These results show that the “Individual RSC” and the “Lane Replacement RSC” projects carried about the same number of heavy trucks over about the same number of years on average.

Table 10. Summary of Average Distress for Six “Lane Replacement RSC” and Six “Individual RSC” Projects in the Outer Traffic Lanes.

Distress	Outer Lanes “Individual RSC” Slabs	Outer Lanes “Lane Replacement RSC” Slabs	Comments
Mean Age Total Trucks	13 Years 6 Million Inner 20 Million Outer	12 Years No Inner Lanes 16 Million Outer	Age and Total Trucks are very similar
Transverse Fatigue Cracking	21%	0.3	“Individual RSC” slabs show far more fatigue cracking
Longitudinal Cracking	0.9	0.2	Similar results showing excellent performance
Corner Cracking	0.8	0.0	“Individual RSC” had some dowels & “Lane Replacement RSC” had dowels at all transverse joints
Transverse Joint Faulting	Minor	Minor	Same as above
Spalling Transverse & Longitudinal Joints	1.1	1.1	Similar results showing excellent performance
Shrinkage Cracks	0.0	0.8	Slightly more shrinkage cracking in “Lane Replacement RSC”

Table 10 shows that with the exception of transverse fatigue cracking, there is no significant difference between the performance of the "Individual RSC" and "Lane Replacement RSC" slabs over an average of 12 to 13 years of their service life. The detailed results are summarized by distress type.

- **Transverse fatigue cracking (mid-panel) outer lanes.** "Individual RSC" slabs (21% cracked) showed far more fatigue cracking than the "Lane Replacement RSC" slabs (0.3% cracked) in Figure 24. The reasons for this dramatic difference are associated with the following design features.
    - **Thicker RSC slabs.** The mean slab thicknesses are as follows:
        - "Individual RSC" slab thickness = 8 to 9-inches
        - "Lane Replacement RSC" slab thickness = 9 to 12-inches
    - **Shorter RSC slab joint spacing**
        - "Individual RSC" slab joint spacing: 12-13-18-19 ft. (18-19 ft slabs develop large majority of transverse fatigue cracking, Figure 3).
        - "Lane Replacement RSC" slab joint spacing: 14-ft.
    - **Replacement of base course for all of the "Lane Replacement RSC" slabs**. Note that less than 25% of the "Individual RSC" projects required replacement of the base course, but that 100% of the "Lane Replacement RSC" required replacement.

Combined, the above changes in design dramatically affect the amount of transverse fatigue cracking due to heavy truck loadings which results in only 0.3 percent for "Lane Replacement RSC" versus 21 percent for "Individual RSC" slabs.

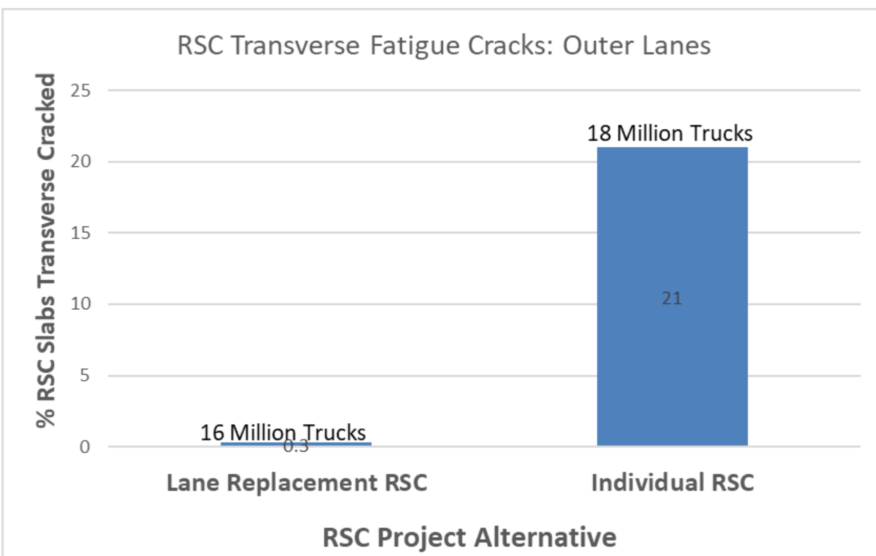

Figure 24. % RSC Slabs Transverse Cracked for "Lane Replacement RSC" and "Individual RSC" Outer Lanes.

- **Corner cracking.** Dowels were placed at some "Individual RSC" transverse joints (0.8% corner cracking) and at all "Lane Replacement RSC" transverse joints (0.0% corner cracking). Corner cracking is strongly related to corner edge support as fully provided by "Lane Replacement RSC" design.
- **Transverse joint faulting.** Dowels were placed at some "Individual RSC" transverse joints but at all "Lane Replacement RSC" transverse joints. Approximate joint faulting was assessed through either driving in the traffic lanes or from observing joints upstream from which significant faulting can be observed. No indication of significant transverse joint faulting was found for any of the RSC projects.
- **Longitudinal cracking** averaged 0.9% for "Individual RSC slabs" and only 0.2% for "Lane Replacement RSC" slabs. "Lane Replacement RSC" slabs had all base courses removed and replaced which may have resulted in more uniform support and lower longitudinal type cracking.
- **Spalling of transverse joints (in the RSC slab)** was 1.1% for both types of RSC replaced slabs which is also an insignificant amount. The concrete materials used in the RSC performed very good and construction must have been good quality to have such low joint spalling. There was one 4x4 cement project that exhibited some "pitting" of the surface that increased spalling.
- **Shrinkage cracking** of the surface varied from 0.8% for "Lane Replacement RSC" slabs to 0% for "Individual RSC slabs". These are both low after 9-17 years of service in a dry and hot climate.

Thus, the only real significant difference in performance of "Individual RSC" and "Lane Replacement RSC" is the transverse top down fatigue cracking. This result is explainable given the key design differences between "Individual RSC" slabs and the "Lane Replacement RSC" slabs: thicker slabs, shorter joint spacing, and base course replacement.

Longevity of RSC Slabs

A key question that is of great interest to Caltrans and all highway agencies is: "What is the longevity of the RSC slab replacements for these projects?" There has often been some skepticism of the durability of slabs placed with high early strength concrete and opened very quickly. There certainly have been some early opening high early strength concrete projects that developed distress such as shrinkage cracks, spalling, and surface pitting or disintegration. One well documented Caltrans RSC project deteriorated significantly over a few years period due reportedly to a high degree of mixture and production variability issues (Van Dam 2018).

This study surveyed 12 randomly selected RSC projects located in southern California with one in Sacramento that have been in service on major freeways ranging from 9 to

17 years with an average of 12 to 13 years. Two RSC materials were used in these projects: CTS and 4X4. The overall condition of these RSC replacement slabs was found to be excellent with the exception of transverse fatigue cracking on the thin slab "Independent RSC" slabs located in the heavy truck lanes. These projects include two to five lanes in each direction and have heavy truck traffic volume on the outer lanes (average = 17 million trucks/lane over 12-13 years) and much lower truck traffic volume on the inner lane (average = 6 million trucks).

Thus, the longevity of RSC replacement slabs must consider the amount of truck traffic and the time over which it will be applied as well as design (slab thickness, joint spacing, base support), and concrete durability. The following sections address longevity based on concrete durability issues and on structural capacity issues.

Durability of RSC Materials

From a durability standpoint, the performance of these RSC projects indicates no significant difference between the following conditions and materials considering shrinkage cracking, joint spalling, and surface deterioration:

- **Inner and outer traffic lanes.** Very low amounts of durability distresses for each with no significant difference between them.
- **CTS and 4X4 RSC materials.** Very low durability distresses for each with no significant difference between them.
- **"Individual RSC" and "Lane Replacement RSC" slab replacement applications.** There were no real significant differences from a durability standpoint between these applications. The CTS and 4X4 RSC materials used on these different RSC applications were likely very similar (inner lanes or outer lanes). Very low durability distresses for each material type indicates no significant difference between them.

The only noted durability issue was on I-15 located in San Bernardino Co. where a few portions of the concrete surface were "pitted" perhaps during surface tinning (see Figure 22. This project is 16 years old and no maintenance had been performed to date and it may be that it is due to the texturing process and has not changed since placement.

Thus, longevity for these 12 RSC projects seems to be related to truck traffic loadings (inner versus outer lanes) and design factors (slab thickness, joint spacing, base course).

Inner Traffic Lane Survivability

Eight of the total 12 traffic lanes of “Individual RSC” were considered “inner” lanes with lower truck traffic (mean total trucks/lane was 6 million over 13 years). The average percent transverse cracking for these inner lanes was 3.0% (ranged from 0 to 12.5%). Six of these inner lanes had <1% of any kind of distress but two lanes had 10% and 12.5% transverse cracking.

Based on these results, the data shows that 6 of 8 inner lane “Individual RSC” slab replacements survived 13-years with almost no transverse cracks. Thus, it is estimated that on average they will last 15 to 20 years total prior to developing significant fatigue transverse cracking.

There was no inner lane (lower truck volume) “Lane Replacement RSC” projects but any improvements to design would result in a higher longevity. These RSC slabs should easily survive more than 30 years prior to developing significant fatigue transverse cracking.

Outer Traffic Lane Survivability

Four of the 12 “Individual RSC” traffic lanes were considered “outer” lanes with higher truck traffic (average was 20 million trucks). The average percent transverse cracking for these outer lanes was 21% which is a considerable amount of fatigue cracking.

Based on these results, the data shows that 2 of the 4-outer lane “Individual RSC” slab replacements survived 13-years with low transverse cracking and two with higher transverse cracking. Thus, it is estimated that on average this group will last up to 13-years prior to developing significant fatigue transverse cracking.

By comparison, the transverse cracking results from the 6 outer lanes of the “Lane Replacement RSC” projects showed virtually no transverse fatigue cracking (mean of 0.3%). The reason: the outer lanes of the “Lane Replacement RSC” project had increased slab thickness (9 to 12-inches) and 14-ft doweled joint spacing and showed only 0.3% transverse fatigue cracking while carrying an average of 16 million heavy trucks. These JPCP-RSC should have a very long life of >20-years.

Table 11 provides a visual summary of the longevity results and expectations that are driven largely by fatigue transverse cracking of the RSC slab replacements surveyed in this study.

Table 11. Estimated Longevity of RSC slab replacements.

RSC Placement/Design	Outer Lane High Truck Volume	Inner Lane Low Truck Volume
"Individual Slab RSC" (Thin Slab, Longer Joint Spacing)	<13 Years	15-20 Years
"Lane Replacement RSC" (Thick Slab, Shorter Joint Spacing)	>20 Years	>30 Years

Other Distress Types Measured

The other distress types were so few in number that after 9 to 17-years of service it is highly unlikely that they will suddenly increase significantly in numbers and severity. Transverse joint faulting was not measured but there was no obvious joint faulting existing on any of the projects observed during the July 2019 field validation survey.

Dowels are critical to longevity of all RSC slab replacement under significant truck traffic to control joint faulting. Dowels must be of an appropriate diameter. If the dowels are too small for the level of truck loadings, then there is a chance that faulting could develop over time requiring diamond grinding. Reasonable recommendations are provided in the California DOT Concrete Paving Manual (2015) for doweling of slab replacements. Faulting must be controlled through doweling RSC replacement slabs at all transverse joints or faulting and corner cracking will likely develop.

RSC Material

The RSC material properties are key factors in longevity for any slab material. Both CTS and 4x4 materials were used on these projects and both produced excellent performance. The only significant distress that occurred for both of these materials was transverse fatigue cracking which is affected largely by truck traffic, slab thickness and joint spacing, as well as slab strength and modulus. As far as is known, the CTS and 4x4 met or exceeded the Caltrans strength specification of 400 psi at 2 hours. The RSC replacement slabs are relatively thin (about 8-9 inches) and were debonded from the LCB/CTB base course due to the bond-breaking material used, and thus the occurrence of top down transverse fatigue cracking is not surprising compared to regular concrete used in JPCP slabs given the level of truck traffic.

Given the longer service lives of both "Individual RSC" and "Lane Replacement RSC", it is even more important to pay strict attention to durability issues. The California specification should include all of the durability criteria used for regular JPCP construction to the RSC material including shrinkage and ASR protections (these are not in the California 41-9 specification currently).

Recommendations for Improvement of RSC Slab Replacement

The 12 RSC projects surveyed and analyzed in this study clearly demonstrate that the Caltrans specifications and design guidelines under which these were constructed have produced some excellent performance from both a materials durability and a structural capacity standpoint. These key documents on rapid closure and replacement of JPCP slabs are available to other agencies for their consideration.

There are only three key recommendations that are clearly in order based on the findings from this study.

- **"Individual RSC" slab replacement is recommended for (1) lower truck traffic inner lanes on multiple lane highways (unless there exists >15% cracked slabs); and (2) as a short-term strategy for replacement of cracked slabs in outer heavier truck lanes to extend pavement life.** While the slab thicknesses will still be that of the existing cracked slabs, the transverse joints should all be spaced at 14-ft which is now specified by Caltrans (note that most of the joint spacings of the RSC slabs replaced on the 6 projects retained the original random 12 to 19-ft skewed joints). This should be considered a shorter-term repair (<13 years) until a significant number of original slabs are cracked and "Lane Replacement RSC" replacement can be performed.
- **"Lane Replacement RSC" is recommended for higher truck traffic outer lanes.** The minimum design thickness can be determined by design using the Caltrans design procedure (AASHTOWare PMED Pavement Design procedure with proper joint spacing of 14-ft and base type selected). The "Lane Replacement RSC" approach solves the transverse fatigue cracking problem by increasing the slab thickness, shortening the slabs to the standard 14-ft spacing, using dowels for all transverse joints, and providing a new base course.
- **"JPCP-RSC Random"** is recommended when the life of the existing JPCP can be extended, certain cracked JPCP slabs that are randomly cracked can be replaced using the same specification as JPCP-RSC with a few exceptions regarding dowel payment and smoothness. In terms of plans, these new slabs will have the same thickness (typically 8-9 in) and joint spacing (typically 12-19 ft), as the existing JPCP. The base should be replaced whenever the slab is replaced, and dowels should be placed at all

transverse joints. Since it would follow the JPCP-RSC specifications, shrinkage or ASR requirements would be included. (California DOT, Non-Standard Special Provision Section 40-5: Jointed Plain Concrete Pavement With Rapid Strength Concrete or JPCP-RSC and JPCP-RSC Random).

It is believed that these recommendations for “Individual RSC” and “Lane Replacement RSC” slabs would be cost effective and minimize any significant transverse fatigue cracking of the RSC slabs over many years into the future and extend greatly the life of the JPCP-RSC project with minimal future lane closures. This study has shown that JPCP-RSC projects that follow these recommendations, along with good construction quality, have provided good durability and structural performance for many years.

Acknowledgements

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