Long-Term Performance of Jointed Plain Concrete Pavement with Rapid Strength Concrete On California Highways

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Rapid Strength Concrete (RSC) slabs on six California jointed plain concrete pavement (JPCP) highway projects were surveyed. These projects had been previously surveyed in 2008 at 3-years of age and by 2018 had reached a service life of 13-years. Of the initial 5430 slabs examined in 2008, a total of 1493 RSC slabs, located on 12 traffic lanes, were observed and distress types recorded again in 2018. These slabs included both CTS and 4x4 RSC located in both inner and outer lanes. Only a small percentage (1.4%) of the 5,430 RSC slabs exhibited any distress in 2008 after 3-years' service and the increases were small over the next 10 years of service with the exception of transverse fatigue cracks. The transverse (top down fatigue) type of cracking had the highest percentage and largest increase of any distress type. The heavy truck outside lanes exhibited 21% transversely cracked RSC slabs and the inner passing lanes 3%. The outer truck lanes carried over 3 times more trucks than inner lanes. The RSC slabs were mostly 200-223 mm thick and thus susceptible to fatigue damage. The overall performance of the RSC slabs (both CTS and 4x4 RSC materials) were similar and considered to be outstanding over 13 years with a large majority expected to survive many more years.

Rapid strength concrete | pavement performance

1. 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 to between 11 pm and 5 am.

Briefly, 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, 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 2.758 MPa (400 psi) at opening age according to Caltrans specifications. In addition, RSC pavement must develop a minimum modulus of rupture of 4.137 MPa (600 psi) at 7 days after placement.

The requirement of 2.758 MPa (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. However, the long-term concrete durability of these RSC slabs has always been of concern to State Highway Agencies (SHAs). (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 in "Evaluation of Rapid Strength Concrete Slab Repairs." (Bhattacharya, Zola, and Rawool, 2008) The current Caltrans RSC specification for individual or random slab replacement and the Concrete Pavement Guide (2015) provides detailed guidance on the specifics of design, materials, and construction of RSC.

- Section 41-9: Individual Slab Replacement, ISR (2015)
- Concrete Pavement Guide (2015)

Note that there is also another California specification (Section 40-5 Jointed Plain Concrete Pavement with Rapid Strength Concrete, JPCP-RSC) for the removal and replacement of longer continuous stretches of concrete traffic lanes.

2. RESEARCH SIGNIFICANCE

There are significant findings of this research to both researchers and practitioners. Prevailing thought is that rapid strength concrete (RSC) shows more distress than conventional concrete. The overall findings however show that the RSC slabs as defined and constructed in California provides outstanding performance over 13 years and a large majority are expected to perform for another 10 years on heavily trafficked highways (as long as adequate slab thickness and joint spacing, and good quality construction are provided). This means that in California deteriorated concrete slabs can be replaced rapidly over night with high confidence that they will perform for many years into the future. Of course, good quality construction is essential.

3. PREVIOUS CALTRANS STUDY OF RSC 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 projects averaged about 3 years in age at the time of the survey. Key results are summarized as follows:

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- “RSC material composition/design is not the cause of the panel distress or failures.
- “Only 1.4 percent of the slabs surveyed showed premature distress.
- “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)

A. Follow Up Study of Long Term Performance of RSC Replacement Slabs. These results are impressive with only 1.4 percent RSC slabs showing any significant distress after 3 years of service life 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 randomly selected projects from the same study published in 2008 where RSC was used and the RSC manufacturer was known. These projects included several miles of traffic lanes and used all 12 inner and outer traffic lanes. The RSC slab replacements were in service for approximately 13 years. The individual projects all had high auto and truck volumes, but the truck volume on individual traffic lanes on these projects varied widely.

B. Field Surveys and Database. An overview of the six JPCP projects that contain hundreds of 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 total of 1,493 RSC slabs located on six projects were surveyed using the latest 2018 Caltrans video monitoring films, all observable distresses were identified. The projects chosen in Table 1 were from a list of 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. Caltrans Regions covered by the projects include San Bernardino (3), Los Angeles (1), Ventura (1) and Sacramento (1).
- 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 all lanes including 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 range from less than 1 million to 34 million. There was a total of 12 traffic lanes surveyed from all projects that included the 1493 RSC slab replacements.

Table 2 provides a more detailed summary of these projects and 12 traffic lanes that were included in the 2018 survey.

- Distresses that were identified in these slabs include the following:
  - Transverse cracking
  - Longitudinal cracking
  - Corner cracking
  - Joint spalling (spalling that occurred within the RSC slab, not in the surrounding concrete)

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.

4. DESCRIPTION OF RSC SLAB SURVEY

The Caltrans Pathways Software was used to locate and rate each of the 1493 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. An “overhead 3D” view of the slab surface was also provided that

Table 1. Summary of RSC projects location, construction, traffic, age in 2018, and RSC.

Route	District, County, ID	Post Mile	2016 2-Way AADTT	Design	Constr. & RSC Constr. Year	Age of RSC, years	Type RSC Material
I-10	8, San Bernardino 08-0A180	0–14.8	17,000	8-9 in JPCP 6-in LCB 4-in AB	1970s, 2005	13	CTS
I-10	8, San Bernardino 08-49370	14.8–20.0	20,000	8-9 in JPCP 6-in LCB 4-in AB	1970s, 2005	13	CTS
I-10	8, San Bernardino 08-4192U	24.5–39.1	17,000	8-9 in JPCP 4-in CTB 4-in AB	1970s, 2005	13	CTS
I-5	7, LA 07-45050	76-88.6	17,000	8-9 in JPCP 4-in CTB 3-in AB	1970s, 2005	13	4X4
US-50	3, Sacramento 03-0A840	0.8–4.8	8,500	8-9 in JPCP 6-in LCB 4-in AB	1972, 2005	13	CTS
SR-126	7, Ventura 07-24490	0–13	2,800	8-9 in JPCP 4-in CTB 4-in AB	1972, 2006	12	CTS

Table 2. Summary of 2018 Projects and Traffic Lanes Surveyed.

Route	District	County	MP to MP+	RSC Material	Survey Lane*	ADTT 20 ck Traffi	Total Trucks In Lane***	Total RSC Slabs	Trans Crk % Slabs	Long Crk % Slabs	Corner Crk %Slabs	Spall % Slabs
I-10	8	SBD	0 - 14 EBL	CTS	1 Inner	17000	2,016,625	3	0.0	0	0.0	0.0
I-10	8	SBD	14.5 - 20 WBL	CTS	4 Outer	20000	28,470,000	70	2.9	0	0.0	0.0
I-10	8	SBD	15.5 - 19.9 WBL	CTS	3 Inner	20000	11,862,500	183	0.5	0	0.0	1.1
I-10	8	SBD	15.5 - 20 EBL	CTS	3 Inner	20000	11,862,500	245	0.4	0.4	0.0	2.0
I-10	8	SBD	24.5 - 30 EBL	CTS	3 Inner	24000	14,235,000	6	0.0	0	0.0	0.0
I-10	8	SBD	24.5 - 30 EBL	CTS	4 Outer	24000	34,164,000	45	4.4	0	0.0	2.2
I-5	7	LA	76 - 88.6 NBL	4x4	1 Inner	17000	2,016,625	68	0.0	0	0.0	0.0
I-5	7	LA	76 - 88.6 NBL	4x4	2 Inner	17000	4,033,250	561	0.2	0	0.0	2.1
US-50	3	SAC	1.1 - 4.8 EBL	CTS	3 Outer	8500	10,083,125	51	29.4	0	2.0	2.0
US-50	3	SAC	0.84 - 2.9 EBL	CTS	1 Inner	8500	2,016,625	8	12.5	0	0.0	0.0
SR-126	7	VEN	0 - 13 EBL	CTS	1 Inner	2800	664,300	30	10.0	0	0.0	0.0
SR-126	7	VEN	0 - 4 EBL	CTS	2 Outer	2800	5,978,700	223	45.7	3.6	1.3	0.0
Averages									8.8	0.3	0.3	0.8

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

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. A large majority of the transverse cracks appeared to occur on the 5.5-5.8 m (18-19 ft) RSC slab replacements as would be expected. The original longer slabs were the ones that cracked much earlier than the original 3.7-4.0 m (12-13 ft) slabs. Previous studies showed that the longer slabs develop about five times the percentage of transverse fatigue cracks than the shorter slabs. (Darter, 2004)

5. CALIFORNIA DOT SPECIFICATION "INDIVIDUAL SLAB REPLACEMENT" WITH 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) 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. A brief summary of only a few key items used to construct the 2005 individual slab RSC replacement projects and included in the Caltrans specification referenced are provided.

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 white curing paper, white opaque polyethylene film, HMA, and curing compound in 2 applications. Note that every effort is made here to separate the two layers.

- **Transverse & Longitudinal Joints:** A 6 mm (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.

- **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. (Note: most RSC slabs on the six surveyed projects did not have this intermediate joint for the 5.5-5.8 m (18-19 ft) slabs and many of them exhibited transverse cracks).

- **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 2.758 MPa (400 psi) before opening to traffic.
  - RSC pavement must develop a minimum modulus of rupture of 4.137 MPa (600 psi) at 7 days after placement. (Note: If these strengths are not achieved there is a disincentive applied to the bid price.)
  - Note: Two RSC products were used on the projects in this survey: CTS and 4x4 and are described in the next section.

6. DESCRIPTION OF RSC SLAB MATERIALS

A summary of information about CTS Rapid Set Concrete Mix used in the 2005 construction is provided below from the web site (website link)

- **"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
  - High sulfate resistance
  - ASR resistant
  - Can be used in volumetric mixer (mobile mix) or transit mixer (ready mix)

A summary of information about 4x4 Concrete Mix used in the 2005 construction is provided below from the web site (website link).

- "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 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)

7. BRIEF SUMMARY OF THE 2008 CONDITION SURVEY

The 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. 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.

8. SUMMARY OF THE 2018 CONDITION SURVEY

This follow up survey was conducted on 12 lanes of 6 of the original 15 projects using the latest (2018) video data available plus some actual field validation. Table 2 summarizes the distress types identified and obtained for each of the traffic lanes and projects that included independent RSC slabs. 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.

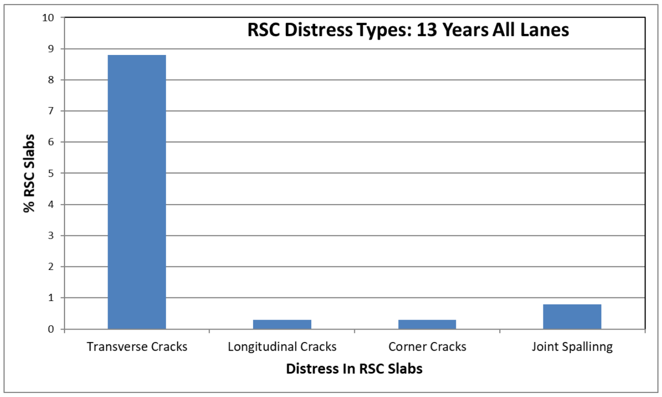

Fig. 1. Summary of distress types identified in the California DOT RSC slab replacements after 13 years of service (2018).

1,493 RSC Replaced Slabs Were Surveyed

Caltrans video images from six projects taken in the year 2018 were utilized. All of these projects were originally surveyed in 2008. These RSC slabs were located in all traffic lanes from the innermost lane (#1) to the outermost lane (typically #4 and the heaviest truck trafficked lane).

Distress Types Identified on the 2018 RSC Slabs

Figure 1 shows the overall extent of occurrence of these four types of distresses in the 2018 survey (see also Table 2 results).

- Transverse mid-panel (fatigue) cracking: 8.8 percent slabs
- Longitudinal cracking: 0.3 percent slabs
- Corner cracking: 0.3 percent slabs
- Spalling along the transverse RSC/existing slab joint: 0.8 percent slabs

The most prevalent distress type in 2018 in the RSC slabs was transverse cracking as shown in Figure 1. 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. Note that in addition, if the bond between the slab and concrete base course is reduced as typically caused by the "bond breaker" layer placed on the base, the slab will curl upward more causing higher top of slab stresses and more top down fatigue cracking. Thin slabs such as these that range from 200 to 230-mm (8-9 inch) are by far the most likely to develop transverse fatigue cracking. (Darter, 2017)

The overall average percent of 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.

Transverse Cracking of Inner and Outer Traffic 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 2 shows a plot of the results.

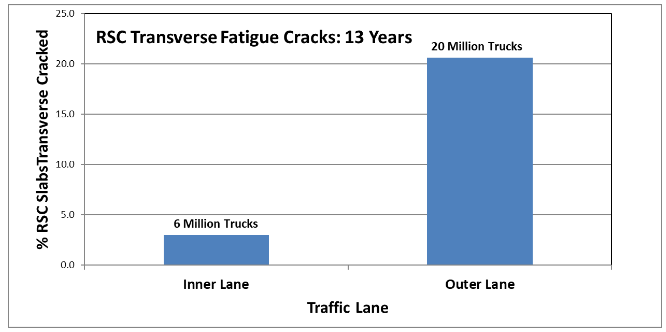

Fig. 2. RSC Transverse (Fatigue) cracking over 13 years of performance for inner and outer traffic lanes.

- Outer truck lane percent transversely cracked: 21 percent. (20 million trucks)
- Inner lanes percent transversely cracked: 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 top-down transverse fatigue cracking (e.g., 21% versus 3%) in the outer truck lanes than in the inner truck lanes.

Another interesting observation is that a large proportion of existing slabs that were replaced with the RSC slabs were the original longer 5.5 and 5.8 m (18-19 ft) joint random spaced slabs. The shorter 3.7 to 4.0 m (12-13 ft) slabs do not often crack transversely. All of the RSC slabs were placed on plastic sheeting bond breaker separating them from the CTB or LCB. Thus, the RSC slab and CTB/LCB could not form a monolithic bonded slab and this may result in higher upward curling (from moisture gradient and hourly temperature gradients) and higher top of slab bending stresses (from truck loads and slab weight). All this leads to creating a more rapid transverse top down fatigue crack development at least for these thin 200-223 mm (8-9 in) slabs.

Longitudinal Cracking

There were only very limited amounts of longitudinal cracking in the RSC slabs in 2018. A total percentage of RSC slabs with longitudinal cracking was only 0.3 percent. The percent in 2008 was not recorded separately due to its practically zero value. 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.

Joint Spalling

There were only very limited amounts of transverse or longitudinal joint spalling that occurred within the RSC slabs in 2018. 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.

Corner Cracking

There were only very limited amounts of the corner cracking that occurred within the RSC slabs in 2018. 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

Table 3. Summary of the performance of RSC 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: 864 slabs)	7.1 million	3.00%	0.07%	0.00%	0.50%

cracking). 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.

9. PERFORMANCE OF THE TWO RSC SLAB CONCRETE MATERIALS CTS AND 4X4

The performance could not be directly compared as they exist on different projects and with widely varying truck traffic volumes. Having stated this, Table 3 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 similarly compared. Note that the CTS RSC inner lanes have received 7 million trucks and the 4x4 RSC inner lanes have received 3 million trucks over the 13 years which explains the higher percent RSC CTS slabs transversely cracked. 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.

RSC slabs exhibited no observable durability distress. No "D" cracking, freeze-thaw damage, shrinkage cracking, or ASR was observed after 13 years of service. However, most of these six projects were located in lower elevations. Only one at about 3,000 ft had some freeze-thaw cycles. 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 field visual observations of the RSC projects.

10. DISTRESS NOT INCLUDED AND FIELD SURVEY

It was not possible to evaluate the following 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, surface map cracking, surface scaling, and surface texture. Thus, it was necessary to conduct a visual field survey of many of the slabs to verify firsthand the condition of the RSC slabs.

A field survey was conducted and photos taken from along the shoulder of 5 RSC projects in July 2019. The survey of 5 of the 6 RSC projects did not find any significant joint faulting, pumping of materials onto the shoulder, surface map cracking or surface scaling. The surface texture of the mostly diamond ground RSC slabs was observed to be excellent after 14 years. Photos of typical RSC slabs are shown in Figures 3 and 4.

11. SURVIVAL ANALYSIS

A key question to be addressed is "What is the mean longevity of the RSC slab repairs for these projects?" The latest 13-year performance survey provides the data but given the differences in truck loadings between the inner low truck lanes and outer high truck lanes (a factor of 3 times more), and the fact that

Fig. 3. Highway I-10 EB direction (PM 0-39), near San Bernardino showing two 14-year old RSC slabs in Lane #4 (outer lane).

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

the RSC slab thicknesses were the same, the survival analysis must be considered separately for these different lanes.

First of all, from a durability standpoint, there was no difference from a performance standpoint between the inner and outer lanes or RSC material type. All lanes and both materials showed excellent RSC concrete durability performance with no significant distress type or amount occurring in the 13-year old RSC slabs. The 2019 field validation, previously described, verified that there were no observable durability issues on any of the 5 projects included.

Inner Traffic Lane Survivability

Eight of the total 12 traffic lanes 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. These two lanes may have had higher than the estimated truck traffic over the past 13 years or some unusual design difference. Given their current 13-year excellent condition and lower truck traffic these inner lanes can be expected to exhibit more than 20 years of service before any significant amounts of distress develop.

Outer Traffic Lane Survivability

Four of the total 12 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% (3 to 46%). This is 7 times greater than the cracking in the inner lanes. The truck traffic was 20 million on the outer lanes compared to 6 million in the inner lanes.

In summary, from an RSC material durability standpoint, both the inner and outer traffic lanes show a similar survivability of 13+ years, likely more than 20-years. From a structural standpoint, the relatively thin RSC slabs in the outer heavy truck lanes show about a 13-year service life or until >20% RSC slabs show transverse fatigue cracking.

12. RSC MATERIAL PERFORMANCE

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 2.758 MPa (400 psi) at 2 hours. The RSC replacement slabs are relatively thin and were debonded from the LCB/CTB base course due to the debonding material and thus the occurrence of top-down transverse fatigue cracking is not surprising given the level of truck traffic.

13. RECOMMENDATIONS FOR IMPROVED RSC SLAB PERFORMANCE

The current California specification Section 41-9 INDIVIDUAL SLAB REPLACEMENT WITH RAPID STRENGTH CONCRETE is very comprehensive and effective. In addition, the California DOT Concrete Pavement Guide (2015) provides valuable design recommendations for individual slab replacement. These documents were recently selected as an effective national "Best Practice" for slab replacement for States to consider for full depth repair and slab replacement practice. (Darter, 2017).

The most significant distress to occur was transverse (top-down) fatigue cracking. Since the occurrence of transverse top down cracking that occurred appeared to mostly be on the longer random slabs (5.5-5.8 m versus 3.7-4 m), it is recommended to shorten this joint spacing with an intermediary joint. This criterion was implemented into the Caltrans specification in 2005, 2010 and the latest in 2015 in section 41-9 INDIVIDUAL SLAB REPLACEMENT WITH RAPID STRENGTH CONCRETE. As mentioned however, there was only a few intermediary joints provided on the RSC replaced slabs included in this study.

In addition, if the existing slabs are 200 to 223-mm (8-9 inch) on a given JPCP project, then consider the continuous replacement approach at 250-mm (10 inch) or thicker on lanes carrying most of the heavy truck traffic. The inner lanes RSC slab thickness may not need to be increased as they normally do not carry many trucks. This along with shortening joint spacing will minimize and control the only significant distress type that has developed on the RSC slabs.

14. OTHER RSC PROJECTS

There are many additional RSC projects in California. It would be of interest to survey those RSC projects located in heavy freeze regions of the state to see if large numbers of freeze-thaw cycles will impact the durability of the RSC material. There have been reports of surface durability problems of a few RSC projects such as the one described by Van Dam and Dufalla 2018 where variability of materials and construction was believed to be high. Certainly, quality construction in all aspects is key to good performing RSC slabs. If construction quality is deficient there may likely be additional distresses develop.

15. "RANDOM SLAB REPLACEMENT" VERSUS "CONTINUOUS REPLACEMENT"

The six RSC projects with 12 lanes surveyed in this study included what Caltrans defines as "random slab replacements". These RSC slabs all maintained the same base type, slab thickness and joint spacings of the existing pavement. These are specified as California DOT, Section 41-9: Individual Slab Replacement, ISR. There is also a Caltrans "continuous slab replacement" procedure with RSC. (California DOT Section 40-5 Jointed Plain Concrete Pavement With Rapid Strength Concrete, JPCP-RSC). "Continuous slab replacement" for RSC allows the increase in slab thickness, replacement of the base course, use of dowels, shorter joint spacing (e.g., 4.27 m (14 ft) standard), and the removal of all existing old fatigue damaged concrete in the traffic lane, because it has a much higher likelihood of cracking than new RSC slabs.

The results from this study shows that both the "random slab replacement" approach may work best on the inner (lower truck volume) lanes and the "continuous slab replacement" approach would work better on the outer (higher truck volume) lanes.

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