



THE USE OF RAPID SET® CEMENT IN CONCRETE ROADS AND BRIDGES — CHEMISTRY, APPLICATIONS, AND OPPORTUNITIES —

ABSTRACT

Rapid Set® cement concrete has a long history of use in concrete roads and bridges. In the United States, it has been primarily used for fast-track pavement rehabilitation of highways. In California alone, more than 1,000 lane-miles of Rapid Set® cement concrete pavement have been placed by the California Department of Transportation. It is also regularly used by other Departments of Transportation nationwide. Generally, this concrete is best suited when closure times are short. The cement has other advantages, however. The carbon footprint of Rapid Set® cement is about 30% lower than that of portland cement, making sustainable roads and bridges a real possibility. Rapid Set cement concrete exhibits very low shrinkage, which enhances durability and also allows opportunities in improving mix design. This article summarizes the chemistry, applications, and future opportunities that Rapid Set® cement offers pavement engineers, municipalities, DOTs, and asset management stakeholders.

1. INTRODUCTION

Rapid Set® cement has been successfully used in concrete roads and bridges in the United States since the mid 1970s. Recently, more attention has been placed on this cement since it can be placed quickly, exhibits excellent durability, and has a low carbon footprint. The reduced carbon footprint is primarily due to the lower limestone content of the clinker raw mix, ease of grind of the cement clinker, and the lower burning temperatures of the clinker. All things considered, the production of Rapid Set® cement emits about 30% less carbon emissions than the production of portland cement.

Rapid Set® cement is mineralogically different from traditional portland cement. Correspondingly, the concrete exhibits characteristics that deviate somewhat from those of portland cement concrete. Rapid Set® cement concrete develops strength more quickly and shrinks less than conventional portland cement concrete. As a result, the use of the concrete has focused primarily on fast track pavement rehabilitation. This article introduces the chemistry and various concrete road and bridge applications of this cement. It also introduces some of the innovative opportunities this material brings, mostly centered around rapid strength gain and low shrinkage.

2. CHEMISTRY OF RAPID SET® CEMENT

Rapid Set® cement is a belitic calcium sulfoaluminate (BCSA) cement. The discovery and development of this cement dates back to the mid 1970s. The original Ost patent (Ost et al., 1975) describes a rapid setting calcium sulfoaluminate (CSA) cement containing CSA as a minor phase and belite (dicalcium silicate) as the major phase. The development of the BCSA cement was in large part based on the work on CSA cements by Professor Alexander Klein at UC Berkeley (Klein, 1963) and the associated work by Mehta (Mehta & Monteiro, 1993) and other researchers. The Ost patent described this belitic cement as “Very High Early” (VHE) cement. The basic hydration mechanism of Rapid Set® cement differs from that of portland cement. Hydration of CSA cements involves rapid precipitation of ettringite crystals which is the cause of the rapid strength gain. Subsequently, the slowly hydrating belite contributes to the long-term strength gain. Rapid Set® cement meets the requirements of ASTM C1600 (Very Rapid Hardening) which is the standard specification for rapid hardening hydraulic cement. The most interesting features of Rapid Set® cement are:

- Speed - Setting times as short as 20 minutes.
- Strength - 1.5 hour strength as high as 5,000 psi.
- Shrinkage - As low as 200 microstrains at 28 days without shrinkage-reducing admixture.
- Sustainability - 0.67 tons of CO₂ emitted per ton of cement.

2.1. Drying Shrinkage

High drying shrinkage is a major drawback of portland cement concrete. Shrinkage causes tensile stresses to develop in the concrete, which increases its propensity to crack. From a cement chemistry perspective, there are three causes for the reduced shrinkage of Rapid Set® cement:

1. The hydration of the Rapid Set® cement causes the formation of ettringite crystals in a slightly expansive process. This early expansion partially compensates for the later drying shrinkage of the concrete.
2. The hydration reaction binds water into the ettringite crystals, eliminating most of the shrinkage-inducing free water in the concrete. Rapid Set® cement concrete exhibits little to no bleed water.
3. The Rapid Set® cement contains less total silicates. Table 1 shows that most portland cements contain about 70-80% by weight of silicates. The hydration of these compounds leads to the formation of calcium silicate hydrates (C-S-H gel) that are metastable, and therefore dimensionally unstable. Rapid Set® cement contains only 45% by weight of silicates, therefore the amount of shrinkage-inducing C-S-H gel is reduced.

Table 1 – Silicate Content in Portland Cement and Rapid Set® Cement

Cement Type	Alite	Belite	Sum of Silicates
Type I Portland	59	15	74
Type II Portland	46	29	75
Type III Portland	60	12	72
Type IV Portland	30	46	76
Type V Portland	43	36	79
Rapid Set® Cement	0	45	45

When Rapid Set® cement and Type II portland cement are tested in a standard drying shrinkage test such as ASTM C596, the Rapid Set® cement exhibits about a third of the drying shrinkage (Figure 1).

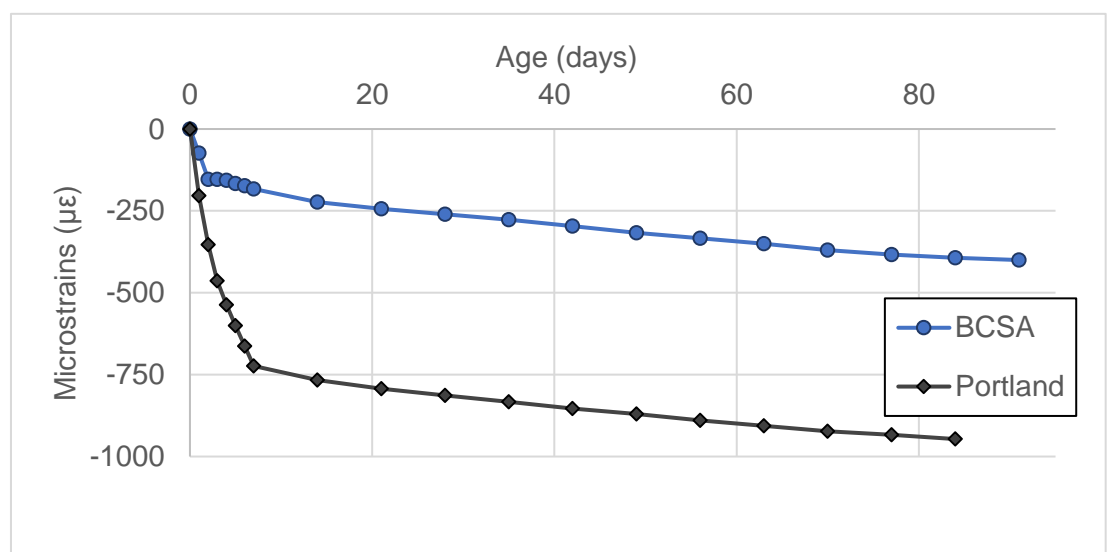


Figure 1 – ASTM C596. Rapid Set® Cement vs. Type II Portland Cement

2.2. Durability

In addition to the low shrinkage characteristics, Rapid Set® cement also displays long term strength gain which contributes to the durability of the material. As shown in Table 1 above, Rapid Set® contains significant amounts of belite, which is directly responsible for long term strength gain in both Rapid Set® and portland cement systems. A long-term study was completed on Rapid Set® cement mortar and the compressive strength was monitored over a period of two years. As expected, we see continuous strength gain even at two years (Figure 2).

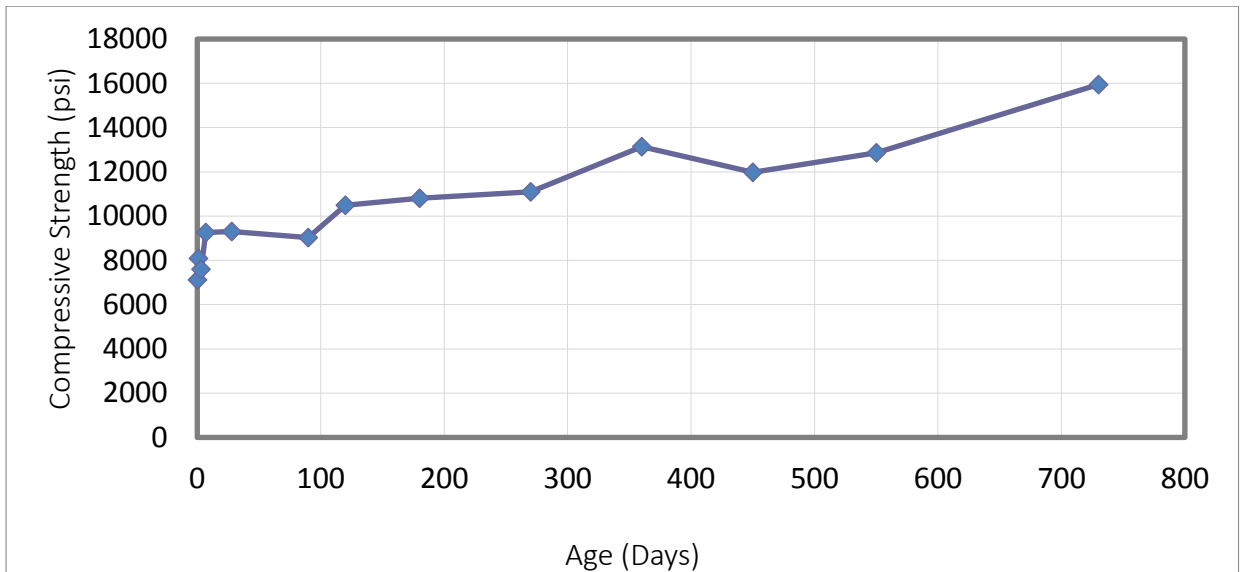


Figure 2, Long Term Compressive Strength Testing (ASTM C109 Modified)

Such durability has been observed in the field. In 1993, the Port of Seattle initiated the rehabilitation of its concrete runway 16R. Due to restrictions on closure time of the runway, Rapid Set® cement concrete was used for overnight panel replacement. In 1994, a thorough fatigue life analysis was conducted on the Rapid Set® cement concrete by CTL Labs. The results showed that the expected fatigue life of the Rapid Set® cement concrete was approximately 87 years from placement. In 2012, the Port of Seattle allowed for the removal of one Rapid Set® cement concrete slab constructed in 1995 from the runway for research purposes. After 17 years in the field under continuous aircraft loading, the fatigue life of the concrete was measured to be more than 100 years remaining. The compressive strength was 11,400 psi and the flexural strength was 1,160 psi. (Ramseyer & Bescher, 2016), which represents a near 100% increase from opening strengths.



Figure 3 – Removal of Pavement After 17 Years in the Field. Runway 16R.

2.3. Carbon Footprint

Rapid Set® cement and other CSA cements are widely known for their low carbon emissions associated with lower production temperatures and lower limestone requirements. During cement production, there are three main sources of CO₂ emissions. The first is calcination, in which limestone is converted into calcium oxide while releasing CO₂. The second source of CO₂ is the combustion of fuel for heating up the cement kiln. The third contributor to CO₂ emissions is associated with electricity needed for grinding and operating the kiln.

The Intergovernmental Panel on Climate Change (IPCC) has developed an equation based on the theoretical amount of CO₂ emitted per ton of clinker produced during the calcination process on the basis of the stoichiometric relationship between CO₂ emission and CaO production, and the percent CaO in the clinker (Equation 3) (Gibbs et al, 2001).

$$\text{Carbon Emissions} = \% \text{ CaO} * 0.785$$

The average production temperature for Rapid Set® cement is about 1250° C. The reason for the drastic reduction in production temperature is that BCSA cements do not require the formation of alite, which requires a minimum of 1450 °C. The reduction in temperature of the kiln drastically reduces the carbon emissions. There is some thought in the scientific community that CSA cement uses less energy to grind (Aranda, 2013), but the carbon emissions from the electrical use is significantly lower than the other two components.

Table 3 below shows the comparison of portland cement production and BCSA production assuming that both are made in a short-dry cement kiln. The values for portland cement were based on industry estimates provided in the literature (Worrell, 2001), and the values for BCSA cement were provided by CTS Cement Manufacturing Corp. In summary, BCSA cement is a promising low carbon footprint alternative to portland cement concrete.

Table 2 – CO₂ Emissions Calculations for Portland and Rapid Set®

	Portland Cement	Rapid Set® Cement	Units
Calcination Reaction	0.504	0.396	tons CO ₂ / ton clinker
Combustion Process	0.272	0.182	tons CO ₂ / ton clinker
Clinker Electricity	0.034	0.034	tons CO ₂ / ton clinker
Total CO₂ per Ton Clinker	0.810	0.612	tons CO ₂ / ton clinker
% Clinker in Cement	95	90	percent
Clinker CO₂ per Ton Cement	0.770	0.551	tons CO ₂ / ton cement
Cement Grinding	0.033	0.033	tons CO ₂ / ton cement
Total CO₂ Emissions	0.803	0.584	tons CO ₂ / ton cement

3. DEVELOPMENT AND USE OF RAPID SET® CEMENT

It is estimated that approximately 2 million tons of Rapid Set® cement have been manufactured to date in the United States. The relative geographic distribution of the use of Rapid Set® in the country is shown in Figure 3 below (darker are stronger markets). It can be seen that Rapid Set® is primarily used in densely populated areas where extended infrastructure closure times are not possible.

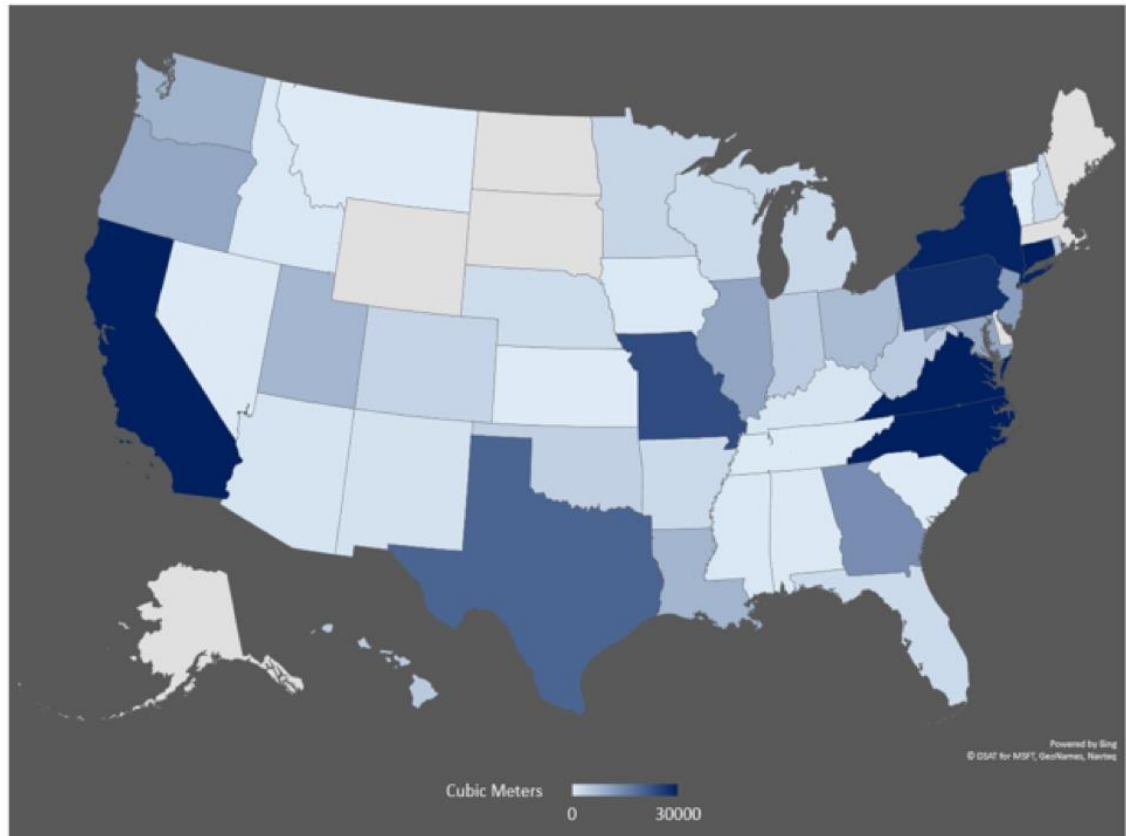


Figure 4 – Use of Rapid Set® Cement Concrete in the United States between 2009 and 2018. (Source: CTS Cement)

3.1. Rapid Set® Use in California

In 1994, the Northridge earthquake caused the collapse of two major overpasses in Los Angeles, California. The emergency repair situation required the use of a rapid strength concrete leading to the first use of Rapid Set® cement concrete by Caltrans. The overwhelming success of this single project became a catalyst for the continued and regular use of Rapid Set® in California.

Less than one year after the Northridge earthquake, Caltrans developed an individual slab replacement (ISR) program that would be conducted overnight using Rapid Set® cement concrete to minimize traffic disruptions and to extend the life of the aging pavement infrastructure. Typically, one or two lanes of the freeway are shut down at 10 p.m. and poorly performing individual slabs are removed and replaced. It is also worth noting that the use of volumetrically produced concrete with Rapid Set® cement concrete was developed to expedite the production process for ISR projects where panels are often far apart and

discontinuous. Once the concrete was placed, only two to three hours of curing is necessary before re-opening the pavement to traffic at 5 a.m. In California, there are steep consequences for late re-opening of a highway, typically \$1,000 per minute after the expected re-open time.

Specifications and best practices have subtly evolved over time, but the performance requirement has been kept at 400 psi flexural for opening and 600 psi flexural for ultimate strength. It is also worth noting that Caltrans is exploring a drying shrinkage limit in addition to the early strength requirements for Rapid Strength Concrete. This will undoubtedly improve good practice in the state. To date, it is estimated that more than 1,000 lane-miles of Rapid Set® cement concrete pavement has been placed in California alone.



Figure 5 – ISR Removal (Left), Panel Replacement with BCSA (Right)

Although Rapid Set® cement concrete is almost always used for individual slab replacement, there have been some occasions where Rapid Set® cement was used in new construction or extended lane reconstruction. In 1999, a 3.2-kilometer continuous stretch of jointed plain concrete pavement (JPCP) on the I-10 Freeway in Los Angeles was paved using Rapid Set® cement concrete. This section of freeway has high levels of vehicle traffic and the use of Rapid Set® cement concrete was necessary to minimize the closure time. In total, the project was completed on time over a single 55-hour closure.

The use of continuously reinforced concrete pavement (CRCP) in California is not as extensive as JPCP, but it has been used with Rapid Set® cement concrete when there are time critical sections. Figure 6 below is an example of a recent CRCP project on Highway 101 just north of Los Angeles.

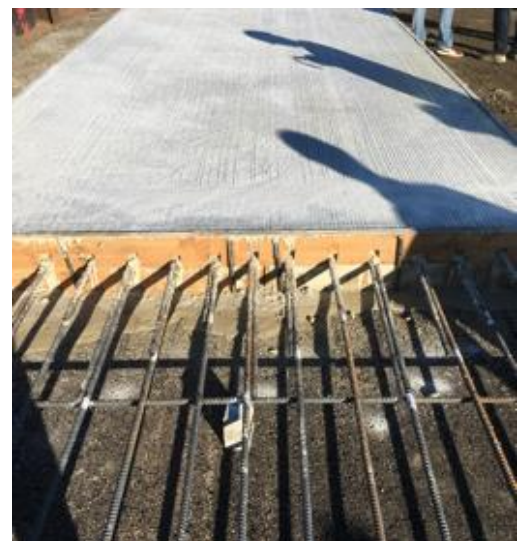


Figure 6 – JPCP Placement on I-10 (Left), CRCP Section on Highway 101 (Right)

3.4. Rapid Set® Latex Modified Concrete Bridge Overlay

One of the more innovative uses of Rapid Set® cement is in latex-modified concrete for thin bridge overlay project. The Rapid Set® Latex Modified Concrete (RSLMC), sometimes called Very Early Strength Latex Modified Concrete (VESLMC), exhibits all of the advantages of latex modified concrete, but structural strength (2,500 psi to 3,000 psi) is obtained in 3 hours. The ACI Specifications for latex modified concrete (ACI Group 548) contains a section (3.3) on VESLMC that was developed around Rapid Set® cement.



Figure 7 – Georgia DOT Rapid Set Latex Modified Concrete Bridge Overlay Project

3.4. Maintenance of Concrete Pavement in Mexico

Rapid Set® cement concrete has also been used extensively in Mexico. The scope of work is very similar to that of the United States, but the specifications and practices are a little different and were developed separately. One of the largest uses of Rapid Set® cement concrete is on the Mexico-Querétaro highway. This highway is the most important economic artery in Mexico, with a capacity of over 35,000 vehicles per day, of which 40% is truck traffic. Like California, the importance of this asset requires constant rehabilitation to maintain an adequate level of service. This strategic highway needs a system of maintenance and replacement of slabs that allows it to extend the life of the asset by gradually replacing the damaged slabs and minimizing inconvenience to the public.

In 2015, the Ministry of Communications and Transportation (SCT) selected a 300-meter section of continuously reinforced concrete pavement to be replaced with Rapid Set® cement concrete. This project was under the supervision of the Directorate General of Technical Services (DGST) of SCT and the Mexican Institute of Cement and Concrete (IMCYC) was chosen to develop a construction protocol and verification tests of the mix. For this project, the road closure began at 7:00 pm and needed to be re-opened by 7:00 am. The construction schedule is shown in Figure 8. (Source Grupo Cementos de Chihuahua).

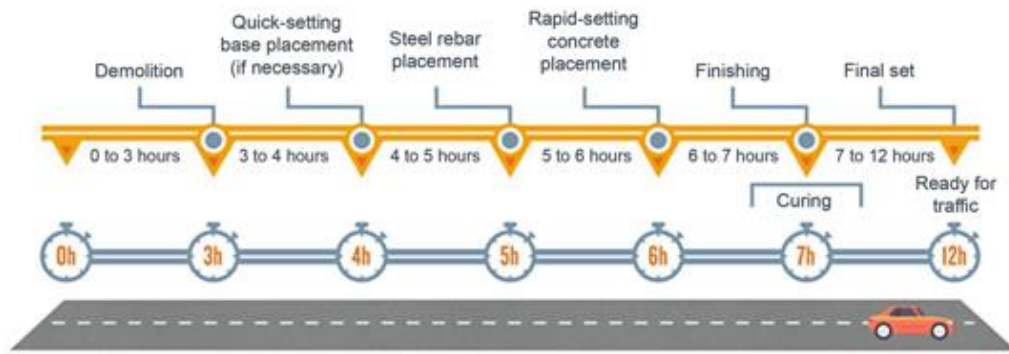


Figure 8 – Construction Schedule for CRCP Rehabilitation using BCSA.

3.5. Bridge Hinge Reconstruction

In 2014, Rapid Set® cement concrete was used for the first time on a major structural bridge project in San Francisco, California, USA. The bridge is a conventional reinforced box girder type which was originally constructed in 1964. Over the decades, the bridge hinges were gradually degrading and needed to be reconstructed. The bridge is a part of Interstate 280, which is a major thoroughfare into downtown San Francisco.

In the design phase, two rehabilitation approaches were considered. The first option was staging a partial construction setup where a portion of the bridge could still be available for traffic during construction. This option was estimated to take longer than six months to complete the reconstruction of four bridge hinges, assuming work was being done seven days a week. The second option was to redirect the viaduct for a continuous 100 hours, and complete the reconstruction using Rapid Set® cement concrete. This option was estimated to only take three 100 hour shifts to complete the reconstruction of four bridge hinges. Eventually, the second option was chosen in order to minimize traffic disruption and reduce safety concerns.

The concrete specifications were 1,200 psi compressive strength at 3 hours and 3,500 psi compressive strength at 4 hours. The concrete had to be self-consolidating and maintain workability for one hour. On-site testing was performed on the concrete 16 times throughout the duration of the project, and the coefficient of variance in compressive strength was less than 7% at all ages, and in unit weight was less than 0.4% (Maggenti, 2015). The consistency of the concrete was considered very good and all performance specifications were met.

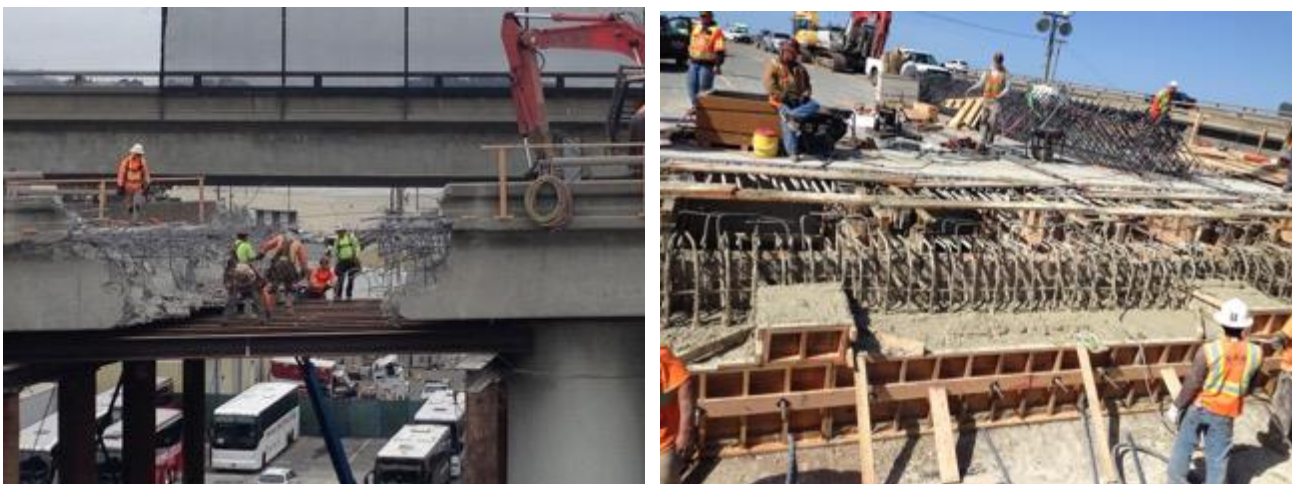


Figure 9 – Removal of Bridge Hinge (Left), Reconstruction of Bridge Hinge (Right)

4. OPPORTUNITIES IN PAVEMENT DESIGN

The properties of Rapid Set® cement concrete allow the development of innovative concepts in pavement design. Bonded concrete overlay over asphalt (BCOA), is not a new concept, but it is gaining further acceptance. Using Rapid Set® cement on BCOA project may provide unforeseen advantages and wider joint spacing. It is also possible to reduce the typical transverse cracking generally observed in continuously reinforced concrete pavement (CRCP) constructed with portland cement concrete. This section will review two promising opportunities for Rapid Set® cement.

4.1. Bonded Concrete Overlay Over Asphalt

Some US DOTs consider that concrete overlays over asphalt are a suitable, economical route to pavement rehabilitation. A recent study by the University of California Pavement Research Center compared the performance of several types of concrete overlays (4.5 inches thick) over asphalt, including Rapid Set® cement concrete. These overlays were subjected to accelerated cyclical loading under a Heavy Vehicle Simulator (HVS) and their shrinkage performance was extensively evaluated in outside conditions with precipitation. The Rapid Set cement concrete overlays performed very well.

4.2. Rapid Set® Cement Continuously Reinforced Concrete Pavement

CRCP is a type of jointless pavement increasingly adopted by several DOTs in the United States, such as in California and Texas. It is favored for its durability and ability to sustain heavy loads. Recently, Caltrans started the construction of more than 40 miles of CRCP on Highway 8 near the Mexico border. This artery is heavily trafficked by trucks. One drawback of portland cement CRCP is the transverse cracking every 3 ft to 8 ft, caused by the drying shrinkage of the portland cement.

It has been proposed that the use of Rapid Set® cement concrete would eliminate this cracking. At the University of Oklahoma, in collaboration with the University of California, Los Angeles, two experimental sections of Rapid Set® cement CRCP were constructed and compared with the standard portland cement concrete CRCP. The first experimental slab followed the ODOT CRCP specifications (0.73% steel reinforcement) using Rapid Set® cement concrete and the second experimental slab also used Rapid Set® cement concrete, but with a 25% reduction in the steel reinforcement to 0.55%. After more than one year of observation, the portland cement concrete slab exhibited multiple cracks while the Rapid Set® cement concrete slabs did not. Although the research is not yet complete, the preliminary results are very promising.

5. CONCLUSIONS

Rapid Set® cement was developed in the United States in the 1970s and has a growing history of acceptance by the infrastructure community and many DOTs. The main use thus far has been for individual, full depth concrete panel replacement. Opportunities for other pavement types such as CRCP, JPCP or white toppings have been demonstrated and specifications have been developed. The use of the material for paving machines is also possible. Although the path for acceptance of a “newer” cement is complex, it is clear the basic properties of the concrete (speed, strength, sustainability and shrinkage) can provide unique answers to some key challenges of modern concrete infrastructure, including quick return to service, durability, and low carbon footprint.

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