Productivity Aspects of Urban Freeway Rehabilitation with Accelerated Construction

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Abstract: Over the last 5 years the California Department of Transportation (Caltrans) has completed three experimental long-life urban freeway rehabilitation projects by utilizing a fast-track (accelerated) construction approach of around-the-clock operations under extended closure. This paper presents the fast-track rehabilitation approaches and the as-built production rates of major rehabilitation operations monitored at the three experimental projects. The monitoring results show that the contractor's production rates varied considerably depending upon the construction logistics, material delivery and hauling methods, lane-closure tactics, and/or pavement designs being implemented. A higher production rate and a noticeable "learning-curve effect" were observed when full-width rehabilitation was compared with partial-width rehabilitation, when continuous lane reconstruction was compared with random slab replacements, and when full roadbed closures were compared with partial lane closures. Findings in this study suggest that Caltrans should evaluate project-specific conditions and constraints, which might restrict use of a preferred rehabilitation scheme, by taking production rate variances into account when establishing schedule baselines of construction staging plans and incentive/disincentive contracts for urban freeway rehabilitation projects.

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Contribution and Benefits of Study

Caltrans and other state transportation agencies will find this case study beneficial for maximizing construction productivity and pavement life expectancy while minimizing traffic delay impacts during accelerated urban freeway rehabilitations. The study will also benefit pavement contractors in developing critical path method (CPM) schedules that take into account learning-curve productivity increases across repeated short, intense work periods.

Introduction

Californian Urban Pavement Rehabilitation Strategies

Rehabilitation of pavements in an urban highway network often causes severe traffic delays and disruptions to the traveling public. The challenge of how to economically rebuild rapidly deteriorating urban pavements under high traffic volume, while minimizing inconvenience to the traveling public, has been a challenging task for many state transportation agencies (TRB 1998).

In addressing the urgent need to rehabilitate vast sections of urban pavements, several states, including Georgia, New York, and Wisconsin, have adopted an approach that provides longer lasting pavements that require less maintenance (FHwA 1998). In order to provide long-life pavements, these states have used a combination of high-performance design components, (such as thicker pavement sections), and improved design details, including dowelled slabs, full-depth paved shoulders, positive subsurface drainage, and improved materials specifications. These states' departments of transportation concluded that the initial premium cost of long-life pavements are more than offset by the savings achieved through reductions in maintenance and rehabilitation requirements, traffic delays, and accident exposures to the traveling public.

In California, a similar long-life rehabilitation approach was undertaken by Caltrans to meet the growing rehabilitation needs of some of the state's most heavily traveled urban freeways. In 1998, Caltrans launched the 10-year long-life pavement rehabilitation strategies (LLPRS) program to rebuild approximately 2,800 lane km of severely distressed urban freeways among the state's 80,000 lane km highway system (Caltrans 1998). The goal of the LLPRS program was to employ an accelerated construction schedule, utilizing extended closures with around-the-clock operations, and to provide pavements with design lives of 30 plus years. This fast-track approach was aimed at lessening the overall impact of rehabilitation projects on road users and neighboring

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communities. By offering financial incentives to the contractor, Caltrans sought to increase the contractor's productivity and, consequently, to compress the project schedule.

Since launching the LLPRS program, Caltrans has completed three such experimental projects. The first project was on Interstate-10 (I-10) near the city of Pomona where, in the fall of 1999, a 2.8 lane km segment of deteriorated concrete truck lane was rebuilt with fast-setting hydraulic cement concrete in one 55 h weekend closure. The second was the Interstate-710 (I-710) Long Beach project, where in the spring of 2003 a 4.4 km stretch (total 23.3 lane km) of badly damaged concrete pavement was rehabilitated with long-life asphalt concrete (AC) pavements during eight 55 h weekend closures. Caltrans undertook the third project in the fall of 2004 on Interstate-15 (I-15) near the city of Devore I-15. In this project, two outer truck lanes on a 4.5 km roadway segment were reconstructed using rapid strength concrete. Caltrans completed the project using two 210 h (about 9 days for each direction) one-roadbed continuous closures with round-the-clock operations.

Studies on Rehabilitation Productivity

There have been several studies that addressed the productivity aspects of urban pavement maintenance and rehabilitation. Hinze and Carlisle (1990) evaluated factors related to the productivity of nighttime rehabilitation and maintenance activities on major urban highways. The researchers found that nighttime productivity is affected by traffic volume, type of work, material delivery, lighting, supervision, communication, and worker morale. However, Ellis and Kumar (1993), who examined typical highway rehabilitation operations in Florida, found no appreciable difference between hourly production rates for nighttime and daytime operations.

Dunston et al. (2000) compared production rates achieved during a project using full weekend closure with those documented for a similar project using nighttime closures. They observed that higher average shift production rates were achieved using a full weekend closure strategy that allowed a longer period of uninterrupted work. Lee et al. (2002) conducted a similar study, examining productivity differences between nighttime short-term (7 and 10 h) closures and 55 h weekend closures in urban freeway rehabilitation and found that the average slab replacement rate during the extended weekend closure was nearly 40% greater than the rate for nighttime closures.

Hancher and Taylor (2001) investigated the effect of night work on the schedule, cost, quality, and productivity of highway rehabilitations, and developed a decision-making tool that evaluates the potential of a project for nighttime construction. These researchers stated that properly implemented nighttime construction could greatly decrease the duration of highway rehabilitation projects, and provide a safe environment both for workers and for the traveling public.

These investigations have provided an understanding of the constraints that impact rehabilitation capacity, as well as a foundation for analyzing alternative rehabilitation strategies given project-specific conditions. Alternative processes for demolishing and reconstructing damaged pavements can be effectively analyzed in terms of productivity and cost effectiveness, as shown by Lee and Ibbs (2005) through the development of the construction analysis for pavement rehabilitation strategies (CA4PRS) computer simulation model. The program estimates the maximum highway pavement distance that can be rehabilitated under different closure time frames. Utilizing the linear scheduling technique and estimates of rehabilitation resource productivities, the CA4PRS model balances the competing project constraints of pavement design, construction logistics, and traffic operations to help highway planners determine the most effective method for rehabilitating deteriorated highways.

Scope and Objective of Study

The purpose of this case study was to monitor and to compare the production rates of five major rehabilitation operations (i.e., concrete slab demolition, roadway excavation, base placement, AC paving, and concrete paving) implemented at the three experimental LLPRS projects in California. A comparison of production rates was based on the as-built progress data (hourly production rates, hourly truckloads, truck loading/unloading cycle times, etc.) recorded during one 55 h weekend closure at I-10 Pomona, during three of the eight 55 h weekend closures at I-710 Long Beach, and during two 210 h, continuous (24/7) closures at I-15 Devore. Because of the relatively small sample size of the study, the comparison uses typical production rate data for similar rehabilitation activities rather than statistical analysis. This approach was taken to minimize potentially biased results from a statistical analysis.

By collecting benchmark production data under differing sets of construction logistics, material delivery and hauling methods, lane-closure tactics, and/or pavement designs, the study was aimed to help Caltrans develop a construction database that can be used to establish scheduling baselines for construction staging plans and incentive/disincentive schemes for future long-life urban freeway rehabilitation projects. The study was also intended to examine the contractor's "learning-curve effect" by tracking down production rate change over the repeated extended closures.

Experimental LLPRS Projects

This section describes the major features of the three experimental LLPRS projects in which Caltrans evaluated the effectiveness of its fast-track rehabilitation approach in reducing construction duration and minimizing traffic delay impacts.

Concrete LLPRS Demonstration on I-10 Pomona

Completed in February 2000 at a cost of $16 million dollars, I-10 Pomona was the first experimental project, serving as the testing platform for Caltrans' concrete LLPRS (Lee et al. 2002). The project was to rehabilitate the deteriorated two concrete truck lanes along a 5 km stretch (20 lane km) of I-10 near the city of Pomona. The project segment, having four lanes in each direction, was originally built in the early 1960s and had an anticipated design life of 20 years. Traffic volumes in this stretch of freeway were as high as 240,000 average daily traffic (ADT) with approximately 9% heavy trucks.

In October 1999, 2.8 lane km of inner truck lane were rebuilt during one 55 h weekend closure (10:00 p.m. Friday until 5:00 a.m. Monday) with around-the-clock operations. The remaining segment (17.2 lane km) was rebuilt during either 7 h (9:00 p.m.–4:00 a.m.) or 10 h (10:00 p.m.–8:00 a.m.) weekday nighttime closures depending on the traffic demand. To allow an expedient reopening of the freeway, the existing 230 mm concrete slabs were replaced with the same thickness of fast-setting hydraulic cement concrete (FSHCC) slabs, which achieved traffic-opening strength (i.e., 2.8 MPa of third-point flexural strengths) in 4 h.

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During the weekend closure, the main tasks were removal and replacement of old concrete slabs at the inner truck lane without disturbing the underlying cement-treated base (CTB). At several locations where the existing CTB was badly deteriorated, both slab and CTB were removed and replaced. While the rehabilitation work was underway, the inner two lanes remained open to traffic (half closure) and movable concrete barriers (MCBs) were installed between the traffic and construction lanes.

AC LLPRS Demonstration on I-710 Long Beach

The I-710 Long Beach Project rebuilt about 4.4 centerline km (26.3 lane km) of the six-lane segment at the southern end of I-710 near the Port of Long Beach (Lee et al. 2005). First opened to the public in the early 1950s, the project segment carries an ADT of more than 164,000 vehicles during weekdays, 13% of which are heavy trucks.

Two long-life AC rehabilitation strategies were employed for the existing pavement, which consisted of a 203-mm concrete slab on top of 102 mm of CTB and 305-mm aggregate base (AB) layers. For most of the 17 lane km segment, the existing concrete slabs were cracked, seated, and overlaid (CSOL) with four AC layers, containing either conventional AR-8000 or polymer-modified PBA-6a binders, of varying thickness (230 mm total thickness with asphalt-saturated geo-textile fabric between the first AC two layers). Under the four freeway overpass structures (9.3 lane km), where minimum clearance requirements did not allow an AC overlay, full-depth asphalt concrete (FDAC) reconstruction was implemented, replacing the old slabs and the underlying CTB and subgrade with four AC layers of varying thickness (325 mm total thickness) on top of a new 150 mm AB layer. The FDAC pavement design incorporated the same AC materials as specified in the CSOL AC overlay design except for the first AR-8000 rich bottom layer, which was added to provide additional stiffness and fatigue resistance.

The contractor started the first weekend closure in March 2003 and completed all the designated rehabilitation work by the eighth weekend closure in June 2003, two weekends ahead of the initial Caltrans plan, at a cost of about $20 million incentive. During the weekend closures, the contractor applied "counterflow traffic," in which one side of the freeway was completely closed for the construction roadbed. Traffic was diverted to a temporary traffic roadbed on the other side of construction through traffic crossovers in the median. The AC-rehabilitated outside shoulder on the traffic roadbed was temporarily converted to a main traffic lane to provide two traffic lanes in each direction, and the MCB was installed as a safety divider between the two directions of traffic.

Concrete LLPRS Implementation on I-15 Devore

The I-15 Devore project was to rebuild the deteriorated two truck lanes along a 4.5 km stretch (11 lane km) of I-15 near the city of Devore in a fast-track approach utilizing continuous one-roadbed closures (hereinafter called "continuous closures") with around-the-clock (24 h/7 days week) construction (Lee et al. 2005). This project was the larger-scale implementation of the Caltrans' LLPRS program based on the experience and lessons-learned from the previous I-10 Pomona and I-710 Long Beach projects.

Built between 1969 and 1975, the project segment has three to four lanes in each direction and it carries an ADT volume of approximately 110,000 vehicles; about 10% of these are heavy trucks. The decision to use a continuous closure option was based upon the unique traffic patterns of the I-15 corridor, which has consistently high weekday commuter traffic and even higher traffic on weekends, during which leisure travelers in the Los Angeles area go to and from Las Vegas and resort locations along the Colorado River.

The existing 230-mm concrete slabs in the outer truck lanes in both directions were rebuilt with new 290-mm doweled concrete slabs (i.e., continuous lane reconstruction including widening of the lane to 4.3 m) using rapid strength concrete (RSC) with Type III cement, which provided traffic opening strength in 12 h after mixing, on top of new 150 mm AC base. The contract called for replacement of only the badly damaged portion of the inner truck lane (about 16%) with 230 mm undoweled concrete slabs placed directly on top of the existing CTB (i.e., individual random slab-only replacement).

Reconstruction of the truck lanes was completed in two 210 h continuous closures (about 9 working days for each direction) in October 2005 at a cost of $16 million. During each continuous closure, counterflow traffic was applied, shifting both directions of traffic to the other side of construction on the traffic roadbed with one additional lane converted temporarily from the AC-rehabilitated shoulder. The MCB was moved twice a day in 1/2 h for each operation with minimal disruption to the live traffic for a dynamic lane configuration, which provided three northbound lanes and two southbound lanes in the morning and vice versa in the afternoon.

Rehabilitation Productivity Comparison

This section describes the major rehabilitation operations undertaken at the three experimental LLPRS projects and presents the as-built production rates collected during the following monitoring periods: (1) one-time 55 h weekend closure at I-10 Pomona; (2) three of the eight 55 h weekend closures at I-710 Long Beach (first, second, and seventh); and (3) two continuous closures at I-15 Devore.

Concrete Slab Demolition Operation

Two types of slab demolition methods, both of which are commonly used in California, were employed at the three projects utilizing similar equipment: (1) "nonimpact demolition" (at the I-10 Pomona and I-15 Devore Projects), in which the existing slabs are saw cut and lifted out by excavators, then hauled away by long-bed end-dump trucks (about 11 m^3 capacity); and (2) "impact demolition" (at the I-710 Long Beach project), in which the existing slabs are rubblized into pieces, bucketed out by excavators, and hauled away by short-bed end-dump trucks (about 7 m^3 capacity).

Nonimpact Demolition on I-10

During the weekend closure for I-10 Pomona, the majority of the 2.8 lane km segment required use of the nonimpact demolition method (slab lift-out) for removal of slabs. At about 10% of the locations, where the underlying CTB was badly damaged, both the slabs and CTB were removed using the impact demolition method, in which the pavement structure was rubblized using mechanical breakers (also known as "stompers"). For the nonimpact demolition operation, each 3.6×4.5 m slab panel was saw cut transversely into three pieces before being dug out by excavators.

During the weekend closure, workers from two crews, working concurrently about 50 m apart, were rotated to perform 30

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continuous hours of slab demolition. The total volume of concrete slabs hauled away during that period was 2,080 m^3. The hourly slab demolition rate ranged between 17.9 and 205.4 m^3/h with an average rate of 68.3 m^3/h. There was no significant difference in the hourly rate between the daytime and nighttime demolitions. Each crew was able to load concrete slabs onto approximately nine end-dump trucks per hour, achieving an average loading cycle time of 5.5 min per truck.

Nonimpact Demolition on I-15

At the I-15 Devore Project, the nonimpact demolition method was again used for removal of the concrete slabs, in a way similar to what was done at I-10 Pomona. The existing slabs at the outer truck lane were saw cut longitudinally along the inner truck lane, and excavators loaded the slab pieces into end-dump trucks. Random slabs to be replaced at the inner truck lane were saw cut around their perimeters. Eye anchors were installed in the cut slabs, and steel chains were connected to the anchors so the slabs could be lifted out as whole pieces.

Two crews working simultaneously in parallel carried out slab demolition mostly during the daytime hours. The nighttime hours were reserved for the AC base paving at the outer lane segments. At each continuous closure, an average of 4,061 m^3 (about 4.5 lane km) of concrete slab was removed every 5 days. The daily demolition quantity varied between 323 and 1,184 m^3 with an average amount of 836 m^3. The hourly rate fluctuated between 49.4 and 101.6 m^3/h with an average rate of 76.7 m^3/h. Each crew hauled away an average of 8.3 truckloads of concrete slab each hour, at an average per truck loading cycle time of about 7 min.

Impact Demolition on I-710

At the I-710 Long Beach project, the contractor utilized the impact demolition method for the concrete slab removal at the FDAC sections. The existing deteriorated slabs were rubblized with stompers or, occasionally, with a guillotine breaker. The crumbled slabs were then loaded to end-dump trucks by excavators. The contractor employed two crews working simultaneously, lane-by-lane, either in the same or in the opposite direction.

During the weekend closures, slab demolition was performed mostly during the nighttime hours due to the tight time constraints required by the round-the-clock operation sequence. The two concurrently working crews removed an average of 1,355 m^3 (0.4 km segment, three traffic lanes plus shoulders) of concrete slabs in about 7.5 h at each closure. The hourly slab demolition rate ranged between 17.9 and 315.7 m^3/h, with an average rate of 183.3 m^3/h. On average, 12.1 truckloads were hauled away per hour per crew, for a loading cycle time per truck of about 5 min.

Productivity Comparison of Slab Demolition

Fig. 1 summarizes the as-built slab demolition progress recorded at the three projects. It shows that the average hourly rate of impact slab demolition at I-710 Long Beach was about 250% higher than the comparable rates at I-15 Devore and I-10 Pomona, where the nonimpact demolition method was predominantly used. Between the I-10 Pomona and I-15 Devore projects, a slightly higher rate was observed at I-15 Devore, probably because two construction access lanes were available for on-site construction traffic there, whereas just one construction access lane was available at I-10 Pomona. At the I-15 Devore Project, the use of chain liftup demolition for random slabs at the inner truck lane, a practice Caltrans typically uses for individual slab repair or replacement during nighttime closures, was about 60% slower than the continuous lane demolition in the outer truck lane.

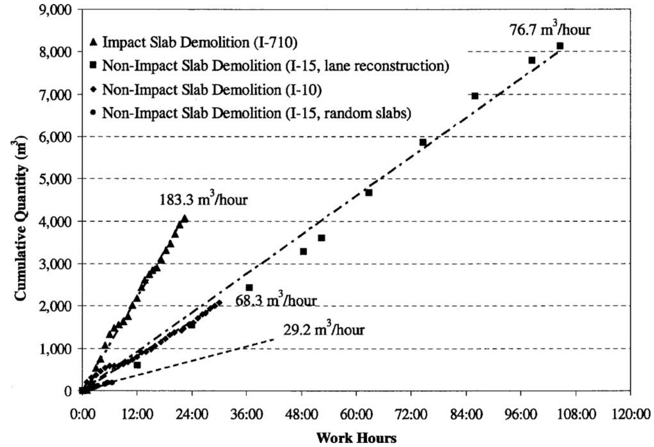

Fig. 1. As-built progress of concrete slab demolition (I-10, I-710, and I-15). (Note: Bottommost dashed line is extrapolation of progress of nonimpact demolition of random slabs at I-15.)

Roadway Excavation Operation

Bucket-Out Excavation on I-710

For the I-710 Long Beach project, the contractor utilized conventional earth-moving equipment—including excavators, motor graders, and front loaders—for excavating the road base and subgrade materials crumbled from impact slab demolition. Excavators and motor graders were used to cut the road base and the subgrade beneath to a depth 625 mm below that of the final surface. The subgrade was then compacted with vibratory steel rollers. Roadway excavation was carried out lane by lane by two crews working concurrently. At each weekend closure the two crews excavated an average of 2,472 m^3 (0.4 km segment, three traffic lanes plus shoulders) of road base and subgrade materials in about 2 h, mostly during daytime hours. The hourly excavation rate fluctuated between 12.9 and 525.4 m^3, with an average rate of 195.9 m^3/h. Each crew hauled away an average of 9.9 truckloads/h, with about 3 min loading cycle time per truck.

Base Milling on I-15

At the I-15 Devore Project, milling machines were utilized to remove the underlying road base, which remained relatively intact under the nonimpact slab demolition. The contractor milled away 210 mm of the road base under the outer truck lane in two paths, one-half lane at each path. During the daytime, one crew performed base milling operations, working unidirectionally in segments.

At each continuous closure, an average of 3,736 m^3 (4.2 lane km) of road base materials was milled away over a period of 5–6 working days. The daily milling quantity varied between 137 and 907 m^3 with an average amount of 679 m^3. The hourly rate ranged between 70.3 and 218.7 m^3/h with an average rate of 133.7 m^3/h. On average, 13.1 truckloads of road base materials were hauled away per hour, and the average loading cycle time of hauling trucks was about 2 min.

Productivity Comparison of Roadway Excavation

Fig. 2 compares the as-built progress of roadway excavation at I-710 Long Beach and I-15 Devore. The base milling at I-15

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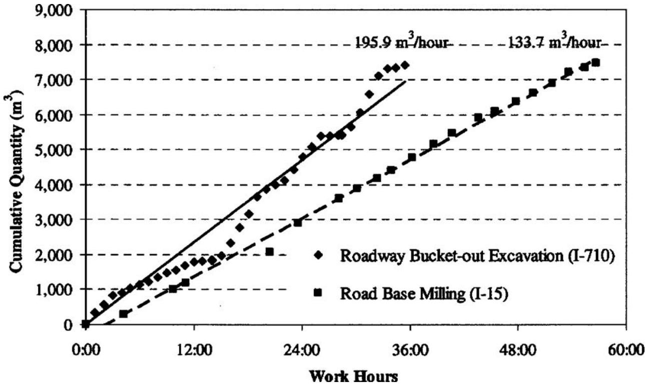

Fig. 2. As-built progress of roadway excavation (I-710 versus I-15)

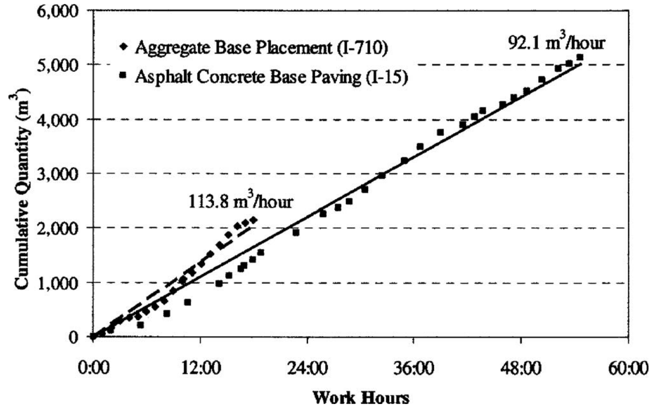

Fig. 3. As-built progress of base placement (I-710 versus I-15)

Devore was about 30% slower than the bucket-out excavation at I-710 Long Beach. However, the base milling made consistent progress with less fluctuation in the hourly rate.

During the first weekend closure at I-710 Long Beach, the equipment workability deteriorated as the subgrade contained an excessive amount of salt, making it difficult to compact to the required density. However, as the weekend closures went on, the excavation crews' performance improved gradually, indicating a "learning-curve effect," as explained later.

Base Placement Operation

Aggregate Base Placement on I-710

For the I-710 Long Beach project, the contractor utilized motor graders and vibratory steel rollers to place and compact new aggregates (recycled from the previously demolished concrete slabs). Two crews performed subgrade cutting and placement of new 150 mm AB (for stabilization of the poor subgrade), with only a slight lag time between the two operations.

During the second and seventh weekend closures, the two concurrently working crews placed an average of 1,080 m^3 (0.4 km segment, three traffic lanes plus shoulders) of aggregates in about 9 h. The hourly placement rate ranged between 21.6 and 186.4 m^3/h, with an average rate of 113.8 m^3/h. Each crew placed 7.4 truckloads of aggregates with an average unloading cycle time of 1 min per truck.

AC Base Paving on I-15

Hopper paving was used at the I-15 Devore Project. An AC transfer vehicle (called a "shuttle buggy") fed hot mix asphalt (HMA) into a self-propelled paver to place 150 mm of AC base at the outer truck lane. One paving crew, working in a single direction, then laid two 75 mm layers of AC base paving.

At each continuous closure, the crew paved an average of 2,577 m^3 (4.2 lane km) of AC base materials over a period of 3–5 working days. The daily paving quantity varied between 205 and 1,453 m^3 with an average amount of 498.5 m^3. During the first continuous closure, the AC base paving was performed at nighttime. However, during the second continuous closure nighttime temperatures too low for compaction purposes forced the contractor to switch operations to daytime hours. The hourly paving rate ranged between 38.2 and 113.3 m^3/h with an average rate of 92.1 m^3/h. On average, 12.3 truck loads of AC base materials were placed per hour, and the average unloading cycle time of delivery trucks was about 2 min.

Productivity Comparison of Base Placement

Fig. 3 shows the as-built progress of base placement recorded at I-710 Long Beach and I-10 Devore. As shown in the figure, the AC base paving at I-15 Devore was about 35% slower than the direct aggregate dumping at I-710 Long Beach because of the smaller hourly truck discharge that could be conveyed to the paver hopper with the shuttle buggy. On both projects, the average hourly rate of base placement increased about 30% at the later closures.

AC Paving Operation

As stated earlier, two AC pavement designs were implemented at the I-710 Long Beach project: (1) "230 mm AC overlay paving" at the CSOL sections, where the required vertical clearance was provided; and (2) "325 mm full-depth AC paving" at the FDAC sections under the freeway overpass structures, where the minimum clearance requirements did not allow an AC overlay.

AC Overlay Paving on I-710

For the AC overlay paving, the contractor employed the "windrow paving method," utilizing a self-propelled paver equipped with a windrow pickup machine (called an "ant-eater") and double-dump semitractor trailers, also known as "semibottom dump trucks" (SBTs). Once cracked and seated with a guillotine breaker and pneumatic-tired rollers, the existing concrete slabs (including shoulders) were overlaid layer by layer by one paving crew in four strips (pulls), each approximately 4.3 m in width. An alternating paving sequence between each pull was used to avoid potential paving stoppages due to the AC cooling time required.

During each weekend closure, the paving crew placed an average of 6,523 t of HMA (about 1.1 km segment, three traffic lanes plus shoulders, three AC lifts) in about 18 h. The hourly paving rate ranged between 112.9 and 542 t/h with an average rate of 357 t/h. On average, 16 trucks (SBT) discharged HMA windrows per hour, and the average discharge cycle time of HMA delivery trucks was about 4 min.

Full-Depth AC Paving on I-710

During the first and second weekend closures, the contractor employed the "hopper paving method" for the first AC layer (either a 50 mm AR-8000 working platform, or a 75 mm AR-8000 rich bottom) and the windrow paving method for the subsequent AC layers. The contractor thought that hopper paving was more appropriate for the first AC layer as it would be placed over a loosely bound and uneven subgrade surface. However, starting

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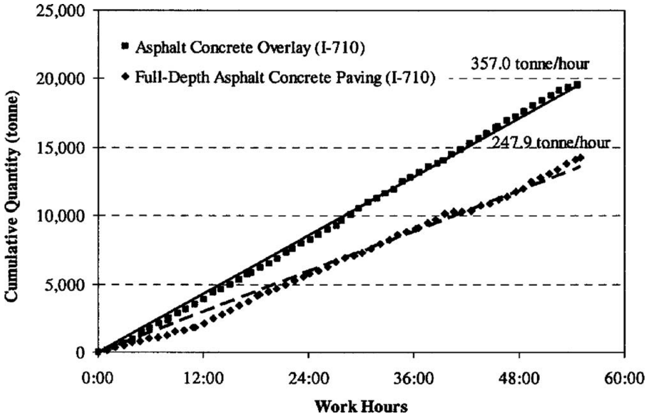

Fig. 4. As-built progress of asphalt concrete paving (I-710)

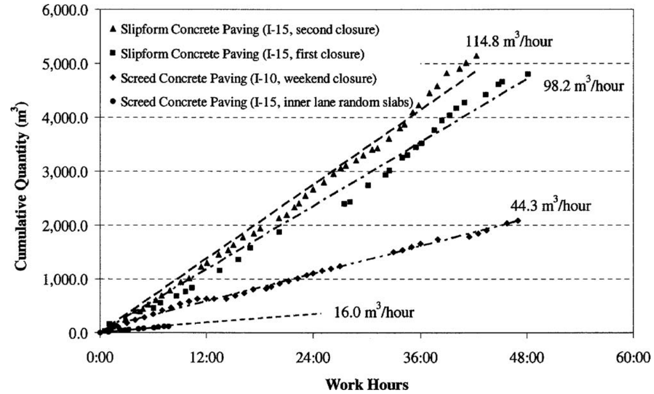

Fig. 5. As-built progress of concrete paving (I-15 versus I-10). (Note: Bottommost dashed line is extrapolation of progress of screed concrete paving of random slabs at I-15).

with the third weekend closure, all AC layers were placed using the windrow paving method, as the newly placed AB provided a solid surface for the HMA windrows.

During each weekend closure, the paving crew, which finished the CSOL AC overlay first, placed an average of 4,763 t of HMA (about a 0.4 km segment, three traffic lanes plus shoulders, three to four AC layers in four to five lifts) in about 18 h. The hourly paving rate varied between 33.3 and 472.9 t/h, with an average rate of 247.9 t/h. On average, 11.6 truckloads of HMA were placed per hour, and the average discharge cycle time of HMA delivery trucks was about 5 min.

Productivity Comparison of AC Paving

Fig. 4 compares the as-built progress of AC overlay and full-depth AC paving at I-710 Long Beach. The average hourly rate of full-depth AC paving was about 30% less than that observed during the CSOL AC paving. One of the main reasons for this sharp decrease in the paving crew's performance was the relatively short length of the FDAC sections (0.4 km on average) compared to the CSOL sections (1.1 km on average). The FDAC sections required more frequent paving stoppages to bring the paver back to the original starting point after each pull. The paving crew also experienced difficulty in accommodating changes in pavement alignment within the short distances of the FDAC sections.

Use of the hopper paving method (with double end-dump trucks for HMA delivery) for the first AC layer (during the first and second closures only) was another reason for the loss of productivity at the FDAC sections. Compared to the windrow paving method, where multiple SBTs simultaneously laid down the HMA windrows, the hopper paving was noticeably slow as each end-dump truck had to individually unload the HMA into the paver hopper. The unstable subgrade condition also contributed to the paving slowdown at the FDAC sections. For instance, during the first weekend closure, the paver repeatedly got stuck in the weak subgrade. At some locations, delay was caused by fine sands being pumped from the subgrade during compaction.

The average nighttime paving rate was slightly slower (about 10%) than the average daytime paving rate at both CSOL and FDAC sections. No noticeable difference in the paving rate was observed between the AR-8000 rich bottom (5.2% binder content with 3% air-void) and PBA-6a (4.7% binder content with 7% air-void) asphalt mixes being placed with the windrow paving method.

Concrete Paving Operation

Screed Paving on I-10

At the I-10 Pomona Project, the new 230 mm slabs were placed manually with a roller screed (hand-operated rotating tube) due to the high concrete slump of FSHCC, which did not allow use of a slip-form paver. To prevent a premature hardening of FSHCC during the delivery, ready mix trucks (rotating drum) were used instead of end-dump trucks.

During the weekend closure, the concrete paving operation for the 2.8 lane km segment continued for about 47 h and the total volume of FSHCC placed during that period was 2,089 m^3. The hourly paving rate ranged between 9.1 and 106.1 m^3/h with an average rate of 44.3 m^3/h. No significant difference in the hourly paving rate was observed between the daytime and nighttime hours. Approximately ten truckloads of FSHCC were placed per hour, and the average discharge cycle time of ready-mixer trucks was about 4 min.

Slip-Form Paving on I-15

For the I-15 Devore project, the contractor utilized a slip-form paver for double-lane paving of the continuous 290 mm slabs at the outer truck lane, and the majority of 230 mm slabs at the inner truck lane. Use of a concrete spreader (a conveyor belt placer similar to the shuttle buggy for HMA transfer) was abandoned after initial efforts, and the concrete was discharged directly by end-dump trucks in order to speed up the placement process.

At each continuous closure, an average of 5,654 m^3 (about 5.0 lane km) of RSC was placed over a period of 5–6 working days (4–13 h/day). The daily paving quantity varied between 395.5 and 1,612.9 m^3, with an average amount of 1,028.0 m^3. The hourly slip-form paving rate ranged between 84.8 and 176.4 m^3/h, with an average rate of 98.2 m^3/h during the first continuous closure (for the northbound lanes), and 114.8 m^3/h during the second continuous closure (for the southbound lanes). On average, 17.3 truckloads of concrete were placed per hour and the average discharge cycle time of concrete delivery trucks was about 1 min.

Productivity Comparison of Concrete Paving

Fig. 5 compares the as-built progress of concrete paving at I-10 Pomona and I-15 Devore. The screed paving rate at I-10 Pomona was about 60% less than the slip-form paving rates recorded at I-15 Devore. The benefit of using FSHCC at I-10 Pomona, which

J. Constr. Eng. Manage., 2007, 133(10): 798-806

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Table 1. Production Summary of Experimental LLPRS Projects (I-10, I-710, and I-15)

Project name	Major activities	Unit	Estimated quantity	Duration (h)	Number of observations	Average hourly trucks per crew	Average loading/unloading cycle time (min)	Average hourly production rate
I-10 Pomona	Nonimpact slab demolition	m^3	2,080	30:00	30	9.0	5.5	68.3
	Screed concrete paving (with fast-setting hydraulic cement concrete)	m^3	2,089	50:45	37	10.0	4.0	40.9
I-710 Long Beach	Impact slab demolition	m^3	4,065	22:28	24	12.1	5.0	183.3
	Roadway bucket-out excavation	m^3	7,416	45:04	37	7.7	3.0	195.9
	Aggregate base placement	m^3	2,159	18:01	19	7.4	1.0	113.8
	Asphalt concrete overlay (at crack, seat, and AC overlay sections)	t	19,570	54:40	59	16.0	4.0	357.0
	Asphalt concrete paving (at full depth AC replacement sections)	t	14,289	54:58	59	11.6	5.0	247.9
I-15 Devore	Nonimpact slab demolition	m^3	8,121	104:42	105	8.3	7.0	76.7
	Road base milling	m^3	7,216	61:48	62	131.1	2.0	112.7
	Asphalt concrete base paving	t	5,128	54:36	55	13.2	1.0	92.1
	Slip-form paving (with rapid strength concrete)	m^3	9,941	90:26	91	17.3	1.0	109.9

saved 8 h of concrete curing time compared to the 12 h RSC used at I-15 Devore, was offset by a loss of productivity due to the high slump, which restricted use of a slip-form paver. Also, the concrete delivery was less efficient because of the frequency (about 10%) of material buildups in the mixer drums despite the reduced loading volume for FSHCC delivery (6 out of 7.5 m^3 loading capacity).

At the end of the second continuous closure for the I-15 Devore project, some random slabs were paved manually with a roller screed due to schedule pressure to reopen the freeway on time. The screed paving for those slabs at the inner truck lane was about 80% slower than the slip-form paving for the rest of the slabs. When compared to the continuous screed paving of an entire lane at I-10 Pomona, the screed paving at I-15 Devore was about 65% slower as the randomly dispersed (located) slabs disrupted the continuation of screed paving progress.

Findings and Lessons Learned

The monitoring results showed that the contractors' production rates varied considerably depending upon the construction logistics, material delivery and hauling methods, lane-closure tactics, and pavement designs being implemented, even under similar equipment and resource configurations. Such variances in production rates pointed out the importance of constructability review during the project planning/design stage. Planners must examine the project-specific conditions and constraints that may favor or restrict rehabilitation alternatives, and they must analyze the time and cost impact of each alternative.

Table 1 summarizes the as-built production rates recorded during the monitoring periods at the three projects; the table includes the number of observations to indicate the data sample size. Overall, contractor production rates were higher for full-width rehabilitation than for partial-width rehabilitation. In addition, they were higher for continuous lane reconstruction than for random slab replacement, and higher for full roadbed closures than for partial lane closures.

Examination of the contractor as-built progress data revealed that the use of repeated extended closures for similar types of operations induced a noticeable improvement in production rates ("learning-curve effect"). Table 2 summarizes the average hourly production rates of demolition/excavation and AC paving operations monitored during three weekend closures for the I-710 Long Beach project. A comparison between the first and seventh weekend closures revealed an average demolition/excavation hourly rate improvement of about 43%, and a combined hourly rate for AC paving (CSOL AC overlay and FDAC AC paving) increase of about 17%. A significant learning-curve effect was also observed at the I-15 Devore project where during the second continuous closure the contractor's slab demolition and concrete paving rates increased by 27 and 17%, respectively, over the first continuous closure.

The monitoring results indicated that a strategy using extended closures (with around-the-clock operations) is preferable to one employing traditional nighttime closures because the longer closures can drastically shorten overall construction time. At the I-10 Pomona project, the average slab replacement rate during the weekend closure was about 40% greater than the average rate during the nighttime closures. The large difference in the production rates resulted from the longer period of uninterrupted work and less traffic interference afforded by the weekend closure. It was estimated that the amount of the rehabilitation work done

J. Constr. Eng. Manage., 2007, 133(10): 798-806

Table 2. Production Summary of Demolition/Excavation and Asphalt Concrete Paving at I-710

Period	Activities	Unit	Estimated quantity	Duration (h)	Number of observations	Average hourly production rate
First weekend closure	Slab demolition/roadway excavation	m^3	3,342	20.8	22	160.7
	Asphalt concrete paving*	t	11,799	40.7	44	289.7
Second weekend closure	Slab demolition/roadway excavation	m^3	4,939	24.0	24	205.8
	Asphalt concrete paving*	t	11,054	36.6	39	302.0
Seventh weekend closure	Slab demolition/roadway excavation	m^3	3,200	13.9	15	231.0
	Asphalt concrete paving*	t	10,966	32.3	35	339.5

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over one 55 h weekend closure would otherwise have taken approximately 27 days of nighttime closures to complete.

Reduction of total closure time from using extended closures was also reported at the I-15 Devore project. According to a preconstruction analysis with CA4PRS software, the amount of rehabilitation work done during the two continuous closures (9 days each) would have taken more than 10 months if performed only during nighttime closures (Lee et al. 2005).

The as-built progress data showed little evidence of "fatigue effect" (loss of productivity) from the scheduled overtime during the extended closures. Under the tight time constraints required of a fast-track approach, the effect of fatigue might have been less evident. The slight decreases in production rate at the end of some operations were more related to intentional slowdowns (worker pacing) for extra work hours and/or final adjustments.

The importance of having a comprehensive, agreed-upon contingency plan for maintaining an accelerated pace for when adverse events occur was highlighted during these LLRPS projects. For example, during the I-710 Long Beach Project, the unstable subgrade encountered during the first weekend closure caused a temporary work suspension and a disruption of scheduling for the remaining rehabilitation operations at the FDAC section. Prior agreement on contingency procedures in the event of unstable subgrade could have prevented the loss of productivity at the FDAC section and helped the contractor to stay on schedule during the first weekend closure.

Summary and Conclusions

This paper presented the fast-track rehabilitation approaches and the as-built production rates of major rehabilitation operations undertaken at the three experimental long-life urban freeway rehabilitation projects in California. Comparison of as-built progress data reveals that contractor production efficiency was greatly affected by the construction logistics, material delivery and hauling methods, lane-closure tactics, and/or pavement designs being implemented. A higher production rate and a noticeable "learning-curve effect" were observed when full-width rehabilitation was compared with partial-width rehabilitation, when continuous lane reconstruction was compared with random slab replacements, and when full roadbed closures were compared with partial lane closures.

Examination of the as-built progress data indicated that extended closure with around-the-clock operations is a viable alternative to the traditional nighttime closures that allows a drastic reduction in total closure time. However, it is recommended that tradeoffs between schedule compression and traffic delay impact be assessed quantitatively and qualitatively when comparing it with the nighttime closures.

Among the many factors (such as construction logistics, pavement designs, and construction access) impacting the contractor's production rate, the one with the largest impact was material delivery and hauling constraints as a matter of loading/unloading cycle time and available hourly truck numbers. This agrees with earlier findings reported by the writers.

The findings suggest that Caltrans should investigate project-specific conditions and constraints (such as traffic volume, pavement condition, resource and budget availabilities, etc.) that might restrict use of a preferred rehabilitation method and/or approach. The findings also suggest that the apparent variances in production rates should be properly accounted for in establishing scheduling baselines for construction staging plans and incentive/disincentive schemes for future long-life pavement rehabilitation projects in urban areas. It is also suggested that Caltrans should consider applying incremental production targets and incentives that can accelerate the contractor's learning-curve effect across repeated extended work periods.

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J. Constr. Eng. Manage., 2007, 133(10): 798-806