Of these steps, Number 8 could be considered as step number 1 in planning for future projects. Performance should be the ultimate guide.

Of the many possible methods that could have been used to correct the poor pavement in Butte, two were selected. The MDOH has recently reviewed the needs on all of its PCCP and decided to proceed with three more projects. Consideration is being given to crack, seat and overlay, partial CPR, and other techniques. Figure 7 is a flow chart illustrating steps to follow in undertaking pavement rehabilitation.

RECOMMENDATIONS

The following is a list of guidelines for future undertakings:

1. Review concrete rehabilitation projects on a yearly basis for about 5 years after construction to determine if the method used was successful; problem areas should be remedied immediately.
2. Perform some degree of rehabilitation on all concrete pavement approximately every 3 to 5 years. CPR is a valid approach, but it is most effective if used early. For example, if the 8- to 12-yr life of joints cannot be realized, even through proper maintenance, smaller, less expensive rehabilitation projects would go a long way in stopping joint failure and consequent pumping, subgrade failure, broken slabs, and other expensive distresses before they start.
3. Do not "cookbook" CPR projects. Each project should be viewed separately, with careful attention given to the parameters unique to each. The poor performance of some CPR projects observed in other states appears to stem not so much from the techniques used as from the misapplication of a repair strategy.
4. Resist the tendency, however tempting, to leave out parts of the whole of CPR. The effectiveness of each component of repair often relies on others being accomplished first.
5. Approach projects through a team effort. Input from planners, designers, and construction personnel is necessary to provide a balanced project that satisfactorily meets the needs.
6. Provide up-to-date training for inspection personnel. CPR work is extremely sensitive to the quality of construction. Consider having one crew do the inspection for all rehabilitation projects.
7. Accept the fact that traffic control is a major factor to be addressed in any project. A well-thought-out plan is essential.
8. Be prepared to do some public relations work. It is not enough to be secure in the knowledge that what is being done is correct from an engineering standpoint. The public perception of what is being done must also be dealt with and explanations of the work should be available to the public, legislators, and others.
9. Continue to maintain contact with the FHWA, other states, research personnel, and the industry. This will result in an exchange of information vital to keeping up with the art of CPR.

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Field Performance of Bonded Concrete Overlays

GERALD F. VOIGT, MICHAEL I. DARTER, AND SAMUEL H. CARPENTER

Bonded concrete overlays provide two improvements to an existing pavement: increased structural capacity and a new riding surface. The importance of these benefits and improved construction technology have encouraged several states to construct bonded concrete overlays over the past several years to evaluate this type of rehabilitation. A fair amount of performance data have accumulated so that an initial evaluation of this rehabilitation technique can be conducted. The University of Illinois is currently conducting a study for the Federal Highway Administration (FHWA) entitled *Determination of Rehabilitation Methods for Rigid Pavements.* One objective of this study is to improve design and construction procedures for selected rigid pavement rehabilitation techniques. Field performance data has been collected on more than 150 projects in 24 states for the following rehabilitation techniques: *(a)* full-depth repair, *(b)* partial-depth repair, *(c)* diamond grinding, *(d)* crack and seat and overlay, *(e)* tied concrete shoulders, *(f)* joint load transfer, and *(g)* bonded and unbonded concrete overlays.

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Data from bonded overlays of jointed pavements were collected from 11 projects located in Iowa, Louisiana, New York, South Dakota, and Wyoming. Described in this paper are the design, construction procedures, and performance of several bonded overlay projects in the data base. Based on this information, and results from analysis of the data base, some conclusions on the design, construction, and performance of bonded concrete overlays have been developed.

Bonding a thin layer of portland cement concrete to an existing rigid pavement can produce an excellent riding surface and greatly increase the structural capacity of the pavement. Bonded concrete overlays are unique among rehabilitation techniques in that, when constructed properly, improved ridability and structural capacity are obtained through the creation of an effective monolithic slab of increased thickness. The effective monolithic slab thickness is equivalent to the thickness of the existing slab plus the added thickness of the overlay *(1–3)*. However, the existing pavement must be in relatively good structural condition for this procedure to be effective. This is not only because the existing slab will still receive the critical tensile stresses under load, but also because existing pavement condition is crucial to overlay performance *(2, 3)*.

The addition of a few inches of portland cement concrete to the existing slab results in reduced critical stresses and deflections in the slab system *(1, 3)*. A 1-in. bonded concrete overlay has approximately the same structural benefit in reducing stresses as 2.5 in. of asphalt concrete *(4)*. The effectiveness of bonded concrete overlays versus equivalent thicknesses of asphalt concrete is shown in Figure 1. Typically, the critical tensile stress is located along the outside edge at the bottom of the existing slab under an edge wheel load. When the existing slab and the concrete overlay act together under load, tensile stress is reduced. Under load, reduced tensile stress means reduced fatigue damage per load application and extended pavement life.

Figure 2 shows a load-stress diagram for a typical 9-in. pavement with varying thicknesses of bonded concrete overlay. This diagram was developed using an ILLISLAB finite-element analysis of an 18-kip single axle free edge load on a 12-ft by 20-ft slab. A 3-in. bonded concrete overlay results in a 37 percent reduction in critical edge stress. This will result in a substantial increase in allowable load applications before slab cracking occurs.

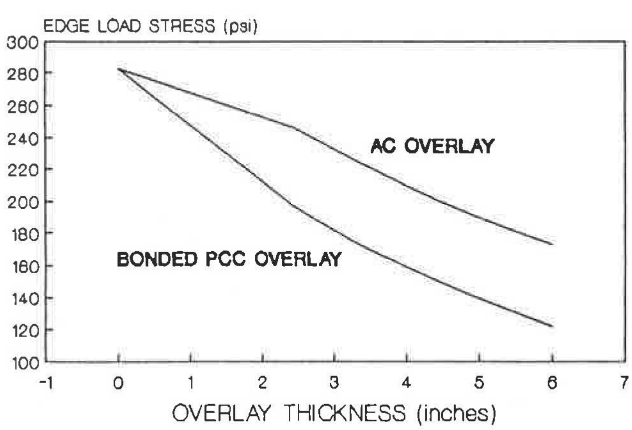

FIGURE 1 Comparison of free edge stress for bonded concrete overlay and equivalent thickness of asphalt concrete overlay.

Vertical deflection and subgrade stresses are much greater under the corner loading position *(1)*. Consequently, pumping and loss of support are most critical at the outer slab corners under corner loads. When the effective slab thickness is increased by a bonded overlay, vertical deflection and subgrade stress are decreased significantly. Figure 2 also shows a load deflection diagram with varying thicknesses of bonded concrete overlay. When a 3-in. bonded overlay is applied to a 9-in. concrete pavement, the deflection under a 9-kip corner wheel load decreases by 31 percent (assuming 90 percent load transfer efficiency at the transverse joint). This reduction in deflection will likely result in reduced pumping, faulting, and loss of support.

BONDED OVERLAY DESIGN AND PERFORMANCE: REPRESENTATIVE PROJECTS

Thirty-one bonded overlay performance sections in five states are contained in the data base. A description of the location, original pavement, design, overlay construction techniques, traffic, environmental conditions, and performance is given in the following pages for four representative projects. Several of the projects contain more than one uniform section (defined as an original pavement and overlay containing uniform design factors such as surface preparation, thickness, and reinforcement). Projects are also divided into separate uniform sections by direction, because differences in traffic may influence performance.

NEW YORK, I-81

Original Pavement Design

The project begins at the north end of the I-481 interchange at North Syracuse and extends 3 mi north to 1 mi north of the Cicero interchange with NY-31. The original six-lane pavement built in 1957 was a 9-in. jointed reinforced concrete pavement (JRCP) *(5)*. The slabs were placed directly on the subgrade. Transverse contraction joints were spaced at 43 ft and dowelled.

Bonded Overlay Rehabilitation Design

The thin-lift, nonreinforced bonded concrete overlay was constructed in 1981. The design consisted of a 3-in. overlay placed directly on the prepared pavement surface. On some deteriorated joints, partial-depth removal of the concrete was performed before the application of the overlay. At these joints, the overlay thickness may have been increased to as much as 6 in. The following design and construction procedures were employed *(5)*.

1. Initial surface preparation consisted of cold-milling followed by sandblasting and airblasting to ensure that the con-

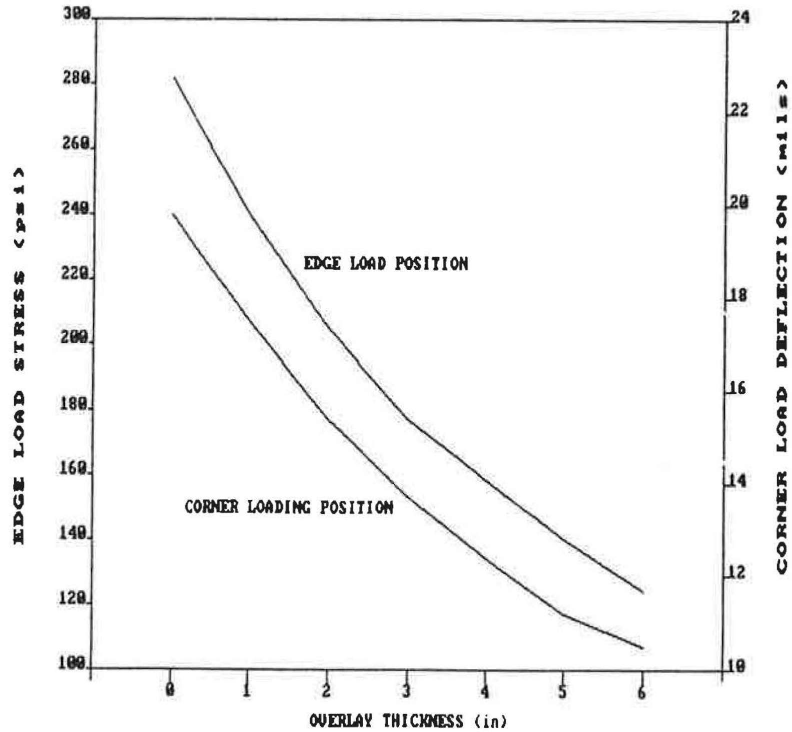

FIGURE 2 Edge load stress and corner deflection versus overlay thickness on a standard 9-in. concrete pavement.

crete was free of oil and debris. Once cleaned, the pavement was covered with polyethylene sheeting to protect the surface until overlay placement began.

2. Just ahead of the paving train, a mixture of water, sand, and portland cement was spread as a bonding agent.

3. A 3-in. lift of low-slump PCC was placed. Joints in the overlay were sawed directly above the existing pavement joints and were sealed before the pavement was opened to traffic.

Traffic and Environment

The pavement's current average daily traffic (ADT) is 2,300, with approximately 8 percent trucks *(5)*. The overlay has received 1.207 million 18-kip equivalent single load axles (ESALs) in the outer lane since construction. The project is located in a wet-freeze environment and receives 39 in. of precipitation annually *(6)*. The Freezing Index is approximately 750 *(6)*.

Observed Distress

The pavement was surveyed in August 1985. After 4 years of service the overlay was performing well. Surveys were performed in both the northbound and southbound lanes and the distress level appeared equivalent in both directions. A considerable amount of shrinkage cracking was noted over entire slab areas in both lanes in both directions. For the most part these cracks were tight and showed no signs of deterioration. Several transverse cracks were also observed. These cracks were generally of low severity, but within two 1,000-ft survey sections, one full-lane-width medium-severity working crack in the southbound lanes and four in the northbound lanes had developed. These cracks are suspected to be reflective cracks from the underlying pavement. No longitudinal cracking was found and the overlay showed no signs of joint-related distress such as corner breaks or spalling. The mean faulting of the overlay joints was 0.04 in. in the outer northbound lane and 0.05 in. in the outer southbound lane.

LOUISIANA, US-61

Original Pavement Design

This project begins north of Baton Rouge and extends approximately 0.8 mi in the southbound lanes. The original two-lane pavement built in 1959 was a 9-in. jointed plain concrete pavement (JPCP) on a 6-in. sand subbase. Transverse joints were spaced at 20 ft and dowelled. The entire section was built on a heavy clay embankment *(7)*.

Bonded Overlay Rehabilitation Design

The overlay was constructed in April 1981. Slab settlement problems and dowel bar misalignment in the contraction joints of the original pavement led to minor slab cracking and pavement damage *(7)*. Deflection testing showed the pavement to be structurally sound *(7)*. To design against the existing problems in the Louisiana project, several other improvements concurrent with the overlay were performed *(7)*.

1. Longitudinal subdrains were installed along the lane-shoulder joint before the overlay was placed.

2. Partial-depth repair was performed at spalled joints.
3. Louisiana highway authorities elected to isolate the overlay section by placing 3 pressure relief joints, one at each end of the project and the other at the center of the project. The joints were sawed full depth, 4 in. wide, and were filled with a Styrofoam insert.
4. Transverse joints were cleaned with a saw blade and compressed air. The reservoirs were sealed with a preformed compression seal. This was done to protect the joints from incompressibles [shot] during surface preparation.
5. Initial surface preparation consisted of shotblasting to remove approximately 1/8 in. of concrete, followed by airblasting just before application of the bonding agent.
6. A water-cement grout was sprayed onto the pavement surface just ahead of the paving operation. When paving operations lagged behind the bonding agent application, wet burlap was used to cover the applied grout to prevent it from hardening.
7. A thin lift of PCC followed immediately. A minimum thickness of 3 in. was specified for the overlay; however, an average thickness of 4 in. resulted because of design changes. Overlay joints were sawed directly above the existing pavement joints. The transverse contraction joints were sealed with hot pour sealant, while the pressure relief joints were sawed and sealed with neoprene compression seals.

Traffic and Environment

The pavement's current ADT is 11,860, with approximately 15 percent trucks *(8)*. The overlay has received 1.2 million 18-kip ESALs in the outer lane since construction. The project is located in a wet-nonfreeze environment and receives 56 in. of precipitation annually *(9)*. The area is not regularly subjected to frost penetration to depths below the subgrade surface *(9)*.

Observed Distress

Distress data from two 1,000-ft survey sections were collected in June 1986. Reflective cracking was not a significant problem. No longitudinal cracking in the paving lanes was observed, but a longitudinal crack had reflected through along the centerline of the entire project because no centerline joint was sawed. Transverse cracks had formed close to sawed transverse joints at approximately 12 percent of the joints in the survey sections. A previous inspection by Louisiana Department of Transportation (LaDOT) personnel had revealed that these cracks were located in areas of delamination *(7)*. The outside edge of approximately 16 percent of the overlay joints had experienced some delamination *(7)*. To alleviate the problem, Louisiana used an epoxy resin to rebond the overlay to the existing pavement just 4 months after construction of the overlay. After 4 yr of service, 12 percent of the corners had cracked *(7)*. The surveys in June 1986 after 5 yr of service indicate no significant increase in the percentage of cracking in the disbonded areas. No other significant distress was observed, although some small areas of surface scaling were noted. The serviceability of the overlay was rated at 3.7 and the mean faulting of outer lane transverse joints was 0.02 in.

IOWA, I-80 (Grinnel)

Original Pavement Design

The project is located near the city of Grinnel. It begins at Milepost 182.00 and extends in an easterly direction 9.17 mi to just beyond Milepost 191.17. The original four-lane pavement built in 1964 was a 10-in. JRCP on 4 in. of gravel subbase. Transverse joints were spaced at 76.5 ft and dowelled with 1.25-in. bars *(10)*. Longitudinal subdrains were placed along the lane-shoulder joint *(10)*.

Bonded Overlay Rehabilitation Design

The thin-lift, nonreinforced bonded-concrete overlay was constructed in 1984. The following design and construction procedures were employed *(10)*:

1. Initial surface preparation consisted of cold-milling followed by sandblasting.
2. A thin spray of cement-water grout was applied to the cleaned surface.
3. A 4-in. lift of PCC was placed on the prepared surface. The joints were matched with the existing pavement contraction joints and were sealed before the pavement was opened to traffic.

Traffic and Environment

The pavement's current ADT is 14,100 with approximately 33 percent trucks *(10)*. The overlay has received 1.27 million 18-kip ESALs in the outer lane since construction. The pavement is located in a wet-freeze environment and receives 35 in. of precipitation annually *(11)*. The Freezing Index is approximately 750 *(11)*.

Observed Distress

The project was surveyed in July 1985, at which time the overlay had served traffic for approximately one year. The condition of the overlay was very good. Some reflective cracking had developed, but mostly consisted of low-severity hairline cracks. An average of 500 ft of low-severity transverse cracking and 24 ft of medium-severity transverse cracking had developed per 1,000 ft of pavement. No significant longitudinal cracking was evident. Several full-depth repairs were encountered in each survey section. These patches were likely placed to repair deterioration caused by the severely D-cracked underlying pavement. In several instances where patches were applied in only one lane, a crack propagated through the overlay in the opposite lane at the location of the patch joints. At other locations, inner and outer lane joint sawing was also mismatched by up to several feet. In almost every instance a crack developed in the opposite lane at the mismatched location. The survey sections contained no corner breaks, no shrinkage cracking, and only one slightly spalled joint. The mean faulting of the outer lane transverse joints was 0.05 in.

TABLE 1 SUMMARY OF PERFORMANCE DATA FOR EACH PROJECT

Project	Age (yr)	ADT	Percent Trucks	Accumulated 18 k ESAL (millions)	Mean Faulting (in.)	Low-Severity Transverse Crack (ft/1,000 ft)	Deteriorated Transverse Crack (ft/1,000 ft)	Low-Severity Longitudinal Crack (ft/1,000 ft)	Deteriorated Longitudinal Crack (ft/1,000 ft)
A(1)[a]	7	651	43	0.1/0.04	0.07/0.06	127/43	468/350	5/0	51/10
A(2)[a]	7	651	43	0.1/0.04	0.09/0.02	24/124	625/525	0/0	100/48
A(3)[a]	7	651	43	0.1/0.04	0.07/0.03	0/0	720/360	0/0	8/0
A(4)[a]	7	651	43	0.1/0.04	0.05/0.10	300/520	840/160	45/0	0/95
A(5)[a]	7	651	43	0.1/0.04	0.09/0.07	0/0	300/180	55/17	40/0
A(6)[a]	7	651	43	0.1/0.04	0.01/0.04	137/149	54/54	5/0	0/10
A(7)[a]	7	651	43	0.1/0.04	0.10/0.02	560/240	180/70	40/53	20/20
B	1	14,100	33	1.27	0.05	504	24	4	0
C	6	10,800	38	5.4	0.06	372	60	10	0
D	9	7,500	11	0.58	0.07	90	490	41	0
E	2	4,300	17	0.11	0.02	215	12	5	0
F	7	21,100	8	0.51	0.04	9	30	7	16
G(1)[a]	12	1,100	4	0.96/0.96	0.06/0.07	47/62	277/565	4/18	70/75
G(2)[a]	12	1,100	4	0.96/0.96	0.06/0.04	120/23	524/518	25/10	85/22
H	5	11,860	15	1.2	0.02	35	0	0	0
I	5	23,000	8	1.21	0.05	526	12	0	0
J	4	4,412	3	0.033	0.02	0	0	0	0
K(1)	1	4,390	27	0.08	0.01	48	0	8	0
K(2)	1	4,390	27	0.08	0.01	168	0	240	0

[a]For two-lane roads, data for both drive lanes are shown (i.e., northbound/southbound).

Although this project has had only one year of service, it is performing similarly to a project on Iowa I-80 constructed in 1979 (see Project *C*, Table 1).

IOWA, COUNTY ROUTE (C17)

Original Pavement Design

This well-documented project is located in the eastern portion of Clayton County, Iowa. It begins at the town of Clayton and extends in a westerly direction for 1.3 miles. The original pavement was constructed in 1968. The nonreinforced slabs were 6 in thick and placed directly on the subgrade. Transverse contraction joints were sawed every 40 ft and dowelled with 0.75-in. bars. Expansion joints were placed at 120-ft intervals *(10, 12)*.

Bonded Overlay Rehabilitation Design

The bonded concrete overlay sections placed on County Route 17 in 1977 were part of a research project to evaluate the effectiveness and constructability of this technique *(12)*. As part of the research, 2-, 3-, 4-, and 5-in. overlay thicknesses were constructed with varying surface preparation and reinforcement methods. Patching of the original pavement was not performed in the reinforced sections because the reinforcement was being tested as an alternative to pre-overlay patching *(12)*. Pre-overlay repair for each of the non-reinforced sections consisted of full-depth and partial-depth repairs of badly distressed areas.

The Clayton County project was divided on the basis of design variables, so that in the data base it is represented by seven sections of alternate design. Construction procedures used on the surveyed sections are described as follows:

Sections 1 and 2

1. Initial surface preparation consisted of sandblasting to remove paint markings and adequately clean the pavement *(10, 12)*.
2. Just ahead of the paving operation a mixture of sand, cement, and water was spread as a bonding agent. The mixture was spread with brooms and squeegees. This created some problems with uniformity of application *(12)*. The squeegee was reported to leave too thin a film of grout, which dried very rapidly. Brooming proved to be better, but still did not provide uniform grout application *(12)*.
3. Following the application of the bonding agent, a 3-in. lift of PCC was laid on the prepared surface.
4. In Section 2 a small amount of reinforcement was placed in the overlay. Number 4 bars, 12 ft in length, were placed in the transverse direction, staggered at 30-in. centers *(10, 12)*. The purpose of the reinforcement was to test the adequacy of steel as a substitute for full-depth repair before overlay.
5. Transverse joints were sawed full depth over the existing pavement joints. The longitudinal joint was not sawed in either section *(12)*.

Sections 3 and 4

1. Initial surface preparation consisted of cold milling to a depth of 0.25 in., except at transverse joints of more than 0.25 in. At these joints, the higher slab was planed to the level of the lower slab *(12)*.
2. Just ahead of the paving operation, a mixture of sand, cement, and water was spread as a bonding agent.
3. Following the application of the bonding agent, a 5-in. lift of PCC was placed on the prepared surface.
4. The same amount of reinforcement was placed in Section 4 as in Section 2.

Section 5

1. Surface preparation consisted of sandblasting followed by the application of a sand-cement-water bonding agent to the surface. The same specifications and procedures were used on this section as were used in Sections 1 and 2 *(12)*.
2. Following the application of the bonding agent, a 4-in. lift of PCC was laid on the prepared surface.

Section 6

1. Surface preparation consisted of cold milling followed by application of a bonding agent to the surface *(12)*. A 4-in. lift of PCC was laid on the prepared surface.
2. This section contained transverse reinforcement.

Section 7

1. Initial surface preparation consisted of sandblasting followed by application of a sand-cement-water bonding agent to the surface.
2. Following the application of bonding agent, a 2-in. lift of PCC was laid on the prepared surface.
3. Transverse joints were sawed full depth over the existing joints after sufficient curing had taken place.

Traffic and Environment

The pavement is a truck-haul route with an ADT of 651 (approximately 43 percent trucks) *(10, 12)*. The overlay has received 0.10 million 18-kip ESALs in the eastbound lane since construction and 0.04 million in the westbound lane. The project is located in a set-freeze environment and receives 33 in. of precipitation annually *(11)*. The Freezing Index is approximately 750 *(11)*.

Observed Distress

The overlay sections at Clayton County were surveyed in July 1985, approximately 7 yr after construction. Because of the long joint spacing (40 ft) and heavily loaded trucks using the pavement, the original pavement was extensively cracked before the overlay was placed. Each section showed a considerable amount of low- and medium-severity transverse cracking and several sections exhibited high-severity cracks. A significant amount of longitudinal cracking had also developed in each section. A definite difference in the level of distress between the eastbound and westbound lanes was noted. This is attributed to trucks traveling fully loaded in the eastbound lane and traveling empty in the westbound lane.

Table 2 gives a summary of cracking for each section at the Clayton County project. It is interesting to note that the thinnest overlay section (2 in. nonreinforced) contains the lowest amount of total cracking. This result is, of course, contrary to what would be expected. However, it may be attributable to the condition of the underlying pavement. Surveys conducted by Darter and Barenberg in 1979 *(2)* showed that at that time practically all the cracks in the original slab had reflected through the overlay. Thus, it is apparent that Section 7 (2 in. nonreinforced) was placed over a portion of the underlying pavement containing relatively fewer broken slabs than the other sections.

It is also interesting to compare the performance of the reinforced sections with that of the nonreinforced sections. Reinforced sections, which received no initial pavement patching, were sandwiched between sections of similar thickness containing no reinforcement. Therefore it is likely that in these sections the underlying pavement was in the same condition. The reinforcement was not effective in reducing reflective cracking through the overlay, as the level of cracking (normalized to 1,000 ft of roadway in the drive lane) was greater for each reinforced section. Also, much of the cracking in the reinforced sections had deteriorated to medium- and high-severity levels.

TABLE 2 SUMMARY OF PERFORMANCE DATA FOR EACH UNIFORM SECTION AT CLAYTON COUNTY, IOWA

Clayton County Section	Drive Lane Direction	Design Type	Transverse Cracking			Longitudinal Cracking			Average Joint Faulting
			Low	Medium	High	Low	Medium	High	
Section 1	East	3 in. plain	127	428	35	5	51	0	0.07
	West		43	325	25	0	10	0	0.06
Section 2	East	3 in. reinforced	0	720	0	0	8	0	0.07
	West		0	360	0	0	0	0	0.03
Section 3	East	5 in. plain	0	300	0	55	40	0	0.09
	West		0	180	0	17	0	0	0.07
Section 4	East	5 in. reinforced	560	180	0	40	20	0	0.1
	West		240	70	0	53	20	0	0.02
Section 5	East	4 in. plain	24	625	0	0	100	0	0.09
	West		124	525	0	0	48	0	0.02
Section 6	East	4 in. reinforced	300	720	120	45	0	0	0.05
	West		520	160	0	0	95	0	0.1
Section 7	East	2 in. plain	137	54	0	5	0	0	0.01
	West		149	54	0	0	10	0	0.04

NOTE: East = loaded trucks, West = unloaded trucks. Cracking normalized to 1,000 ft of drive lane.

3 in. Reinforced	*4 in. Reinforced*	*5 in. Reinforced*
0 percent low	26 percent low	76 percent low
100 percent medium	63 percent medium	24 percent medium
0 percent high	11 percent high	0 percent high

None of the sections appeared to be delaminated, although some small areas of patching were found on Sections 1, 4, and 5. These patches replaced small broken-out pieces of the overlay. The joints on the overlay sections were performing well. Some secondary cracking near saw cuts was found on 25 percent of the sawed transverse joints. This type of distress was most prevalent in the 2- and 3-in. overlay sections. Faulting of the overlay sections is shown in Table 2. No shrinkage cracking problems were observed.

OVERALL BONDED OVERLAY PERFORMANCE

Before distresses are quantified on a general basis, an overall description of the bonded overlay sections should be given to keep the results in perspective. The age of the overlays, at the time they were surveyed, ranged from just over 1 yr to 12 yr. A histogram of the age distribution of the overlays is presented in Figure 3. A considerable number of sections have been in service for 7 years, including the seven sections in Clayton County, Iowa. The thicknesses of the overlay sections may significantly influence the level of distress. Figure 4 shows the distribution of the overlay thicknesses over the bonded overlay sections. A description of the general design features for each overlay design section is given in Table 3.

Distresses that may directly affect the structural capacity of the overlaid pavement are *(a)* transverse and longitudinal cracking, *(b)* joint faulting and pumping, *(c)* corner breaks, *(d)* shrinkage cracking, and *(e)* D-cracking. Rideability of the overlay may be directly affected by most of these distresses. A description of these distresses for the 31 performance sections is described below and quantified in Table 1. The amount of distress is standardized to 1,000 ft of traffic lane for comparison. The severity levels employed in describing cracking are those defined in the NCHRP Project 1-19 (COPES) distress manual *(13)*.

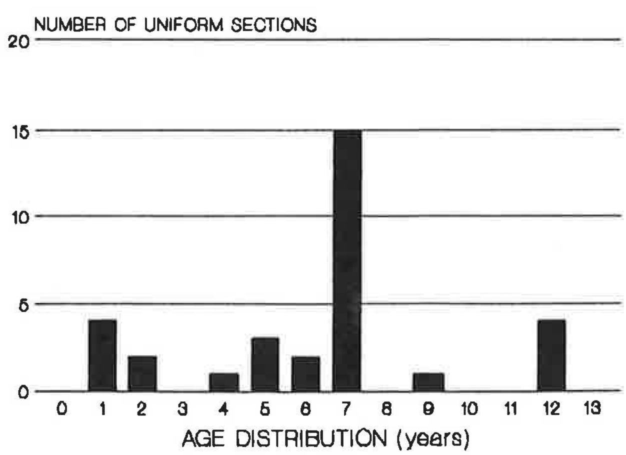

FIGURE 3 Histogram of the age distribution of bonded concrete overlays in the data base.

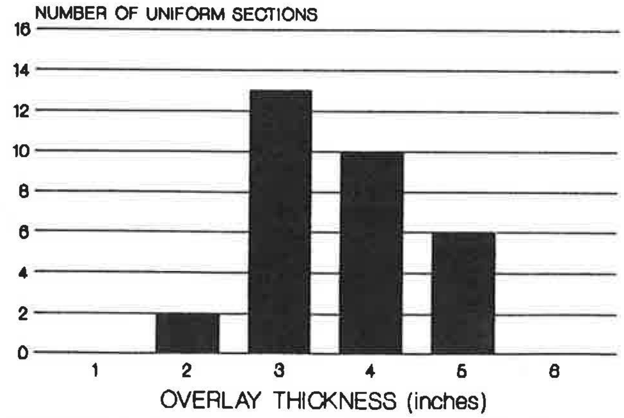

FIGURE 4 Histogram of the thickness distribution of bonded concrete overlays in the data base.

Transverse Cracking

Transverse cracking observed at the surface of bonded overlays is largely caused by reflection of cracks that existed in the pavement before overlay *(1–3)*. Some cracks also develop in the overlay because of shrinkage or debonding. The existence of reflective cracks is inevitable in any bonded overlay that is built over a pavement exhibiting transverse cracking *(2)*. To achieve good performance from the overlay, the existing working cracks should be patched before overlay. If an overlay is placed on a pavement exhibiting a large amount of medium- to high-severity cracking, the overlay will deteriorate rapidly from reflection cracking.

The distribution of the severity of transverse cracking in the traffic lane for bonded overlays is shown in Figure 5. Practically all sections contained some low- and medium-severity transverse cracking; only three of the sections contained high-severity cracking. Only one section did not contain any transverse cracking. Of the sections that exhibited some medium-severity cracking, 50 percent contained less than 200 ft/1,000 ft of outer lane pavement. This is an average of 1 medium-severity transverse crack every 60 ft.

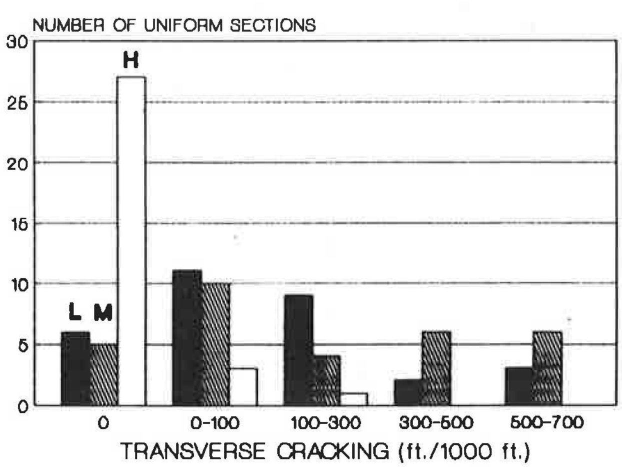

FIGURE 5 Distribution of transverse cracking severity in the outer lane on bonded concrete overlays.

TABLE 3 GENERAL OVERLAY DESIGN AND CONSTRUCTION VARIABLES FOR EACH PROJECT

Project	Location	Surface Preparation	Overlay Thickness (in.)	Overlay Type	Year of Overlay Construction
A(1)[a]	Iowa, Clayton County	Sand blast	3	Plain	1978
A(2)[a]	Iowa, Clayton County	Sand blast	3	Reinforced	1978
A(3)[a]	Iowa, Clayton County	Cold mill	5	Plain	1978
A(4)[a]	Iowa, Clayton County	Cold mill	5	Reinforced	1978
A(5)[a]	Iowa, Clayton County	Sand blast	4	Plain	1978
A(6)[a]	Iowa, Clayton County	Cold mill	4	Reinforced	1978
A(7)[a]	Iowa, Clayton County	Sand blast	2	Plain	1978
B	Iowa, I-80 Grinnel	Cold mill Sand blast	4	Plain	1984
C	Iowa, I-80 Auoca	Cold mill Sand blast	4	Plain	1979
D	Iowa, US-20 Waterloo	Cold mill Sand blast	3	Plain	1976
E	Iowa, US-141 Perry	Cold mill Sand blast	3	Plain	1983
F	Iowa, SR-12 Souix City	Cold mill Sand blast	3	Plain	1978
G(1)[a]	Iowa, Greene County	Sweeping	5	Reinforced	1973
G(2)[a]	Iowa, Greene County	Sweeping	4	Reinforced	1973
H	Louisiana, US-61 Baton Rouge	Shot blast Air blast	4	Plain	1981
I	New York, I-81 Syracuse	Cold mill Sand blast Air blast	3	Plain	1981
J	S. Dakota, SR-38A Souix Falls	Cold mill	3	Plain	1985
K(1)	Wyoming, I-25 Douglas	Cold mill Air blast	3	Plain	1985
K(2)	Wyoming, I-25 Douglas	Cold mill Air blast	3	Plain	1985

[a]For two-lane roads, data for both drive lanes are shown.

A model developed for reflective cracking in bonded concrete overlays is as follows:

$$\text{CRACK} = 11.328\ \text{ESAL}^{.07546}\ \{21.426\ [\text{AGE}(\text{FI} + 1)/1000]^{.668761}\} + \text{ESAL}^{.002}\ (378.5\ \text{INDEXM} + 1257.1\ \text{INDEXH})$$

where

CRACK = Total length of medium- and high-severity deteriorated reflective cracks, feet/mile

ESAL = 18-kip equivalent single axle loads accumulated on the overlay, millions

AGE = Time since construction of the overlay, years (an indicator of the number of temperature cycles affecting shrinkage and expansion of concrete layers)

FI = Freezing Index, Fahrenheit degree-days below freezing

INDEXM = 0, if total linear feet of medium- and high-severity cracking on existing pavement before overlay placement ranged between 0–100 ft/mile (if original pavement was JPCP) 0–200 ft/mile (if original pavement was JRCP)

= 1, if total linear feet of medium- and high-severity cracking on existing pavement before overlay placement ranged between 100–500 ft/mile (if original pavement was JPCP) 200–1,000 ft/mile (if original pavement was JRCP)

INDEXH = 0, if total linear feet of medium- and high-severity cracking on existing pavement before overlay placement ranged between 0–100 ft/mile (if original pavement was JPCP) 0–200 ft/mile (if original pavement was JRCP)

= 1, if total linear feet of medium- and high-severity cracking on existing pavement before overlay placement was greater than 500 ft/mile (if original pavement was JPCP) 1,000 ft/mile (if original pavement was JRCP)

Statistics: $R^2 = 0.75$

SEE = 326 ft/mile (standard error of estimate)

n = 13 (Clayton County sections not included)

Equation Range of Applicability:

ESAL: Ranged from 0.03 million to 5.4 million

AGE: Ranged between 0.5 to 12 yr

FI: Ranged from 0 in Louisiana to 1250 in South

Dakota, but fell between 700 and 1000 for the majority of the projects.

INDEX(x): The data base included pavements within all three cracking index levels:

	Jointed Plain	*Jointed Reinforced*
Low	= 0–100 ft/mile	0–200 ft/mile
Medium	= 100–500 ft/mile	200–1,000 ft/mile
High	= >500 ft/mile	>1,000 ft/mile

Sensitivity of the cracking equation is shown in Figure 6. It is interesting to note the influence of the cracking index on the amount and occurrence of reflective cracking. As would be expected, the existing cracking reflects through the overlay very rapidly after placement, within the first 2 years as predicted by the model. The amount of cracking exhibited on the overlay is almost entirely governed by the index (amount) of existing cracking.

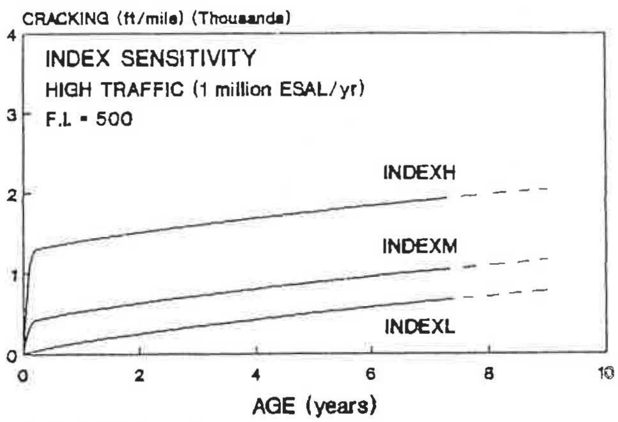

FIGURE 6 Sensitivity of the bonded overlay cracking model to cracking index.

Longitudinal Cracking

Longitudinal cracking, like transverse cracking, is generally caused by the reflection of cracks that had developed in the existing pavement before overlay construction. It appears to be inevitable that existing longitudinal cracks will propagate through the overlay *(2)*. The question of severity becomes the critical factor. Figure 7 shows the histogram of the severity of longitudinal cracking on the 31 bonded overlay uniform sections. Ten sections did not contain low-severity longitudinal cracking and thirteen sections did not contain medium-severity longitudinal cracking; none of the 31 sections contained any high-severity longitudinal cracking. Of those sections that exhibited low-severity longitudinal cracking, 83 percent contained less than 50 ft per 1,000 ft of roadway. Similarly, of the 13 projects in which cracks had deteriorated to medium severity, 77 percent contained less than 50 ft of cracking per 1,000 ft of roadway. The maximum amount of longitudinal cracking on any section was 240 ft.

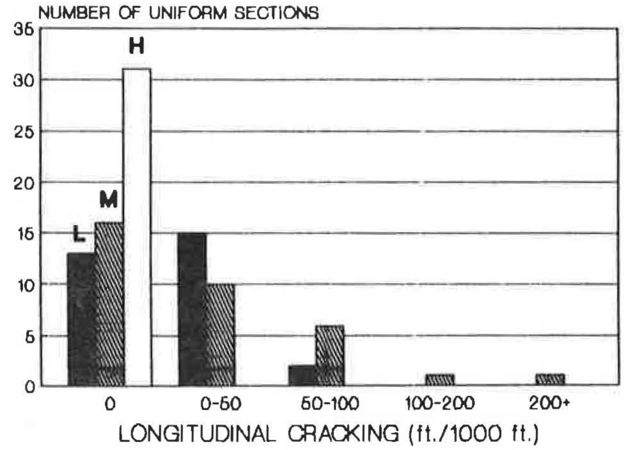

FIGURE 7 Distribution of longitudinal cracking severity in the outer lane on bonded concrete overlays.

Transverse Joint Faulting and Pumping

None of the 31 performance sections had a significant faulting problem. The average faulting in the drive lane ranged from 0.01 to 0.10 in. Faulting significantly affects ride quality when it exceeds 0.20 in. *(14)*. The following equation was developed using non-linear regression to predict faulting as a function of equivalent single axle loads and dowel bar diameter in the existing pavement joints:

$$FAULT = 0.0015897\ ESAL^{.233} [-10.942 - 30.657\ BASE + 0.0005652\ (FI + 1)^{2.299} + 33.322\ (DIA + 1)^{-.8477}]$$

where

FAULT = Mean faulting of the transverse overlay joints, inches

ESAL = 18-kip equivalent single axle loads accumulated on the overlay, millions

BASE = 0, if base is granular
1, if base is stabilized (asphalt, concrete, etc.)

FI = Freezing Index, Fahrenheit degree-days below freezing

DIA = Diameter of dowel bars in original pavement, inches (0 if no dowel bars exist in the original pavement)
Note: all dowel bar spacing was 12 in. on centers.

Statistics:

R^2 = 0.54
SEE = 0.02 in. (standard error of estimate)
n = 27

Equation Range of Applicability:

ESAL: Range from 0.03 million to 5.4 million

FI: Range from 0 to Louisiana to 1250 in South Dakota, but fell between 700 and 1000 for the majority of the projects.

DIA: Ranged between 0 (no dowels) and 1.25 in.

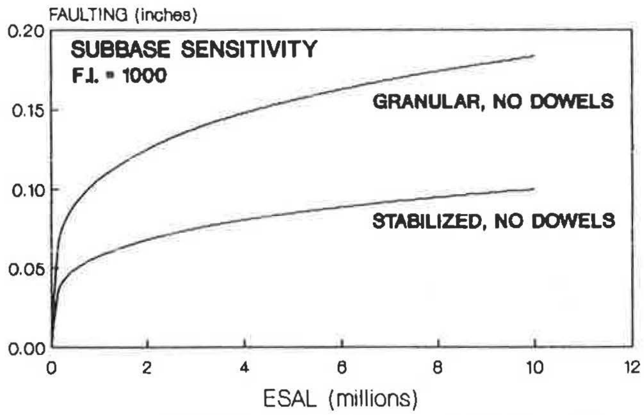

FIGURE 8 Sensitivity of the faulting model to the subbase type.

Sensitivity of the faulting model is illustrated in Figure 8. The functional form of the model is very similar to that obtained from a much larger data base of original jointed plain and jointed reinforced pavements in NCHRP Project 1-19 (COPES) *(13)*. Faulting starts out rapidly and then levels off. Comparison of predicted bonded overlay faulting and new pavement faulting is shown in Figure 9.

When significant pumping occurs, the potential for faulting of the slab increases. No overlay section exhibited significant pumping.

Secondary Joint Cracking

Secondary joint cracking was found on approximately 50 percent of the sections. This distress can cause significant problems when the broken pieces debond, loosen, and break out, as was found on two projects. The cause of secondary joint cracking has not been proven, although it is hypothesized that either the cracking initiates before saw cuts are made *(2)* or that the joint in the overlay is missawed. Cracks start at the approximate location of the joint during the earliest stages of overlay curing, and propagate to the surface at random angles as time passes *(2)*. This is a likely occurrence in thinner overlays, because the distance the crack must propagate is less than in thicker overlays. If the crack has not propagated far at the time the joints in the overlay are sawed, the crack can reroute itself to meet the saw cut *(2)*. If the sawing operation is performed too late, the crack cannot adjust itself to meet the saw cut and a secondary crack along the joint will result *(2)*.

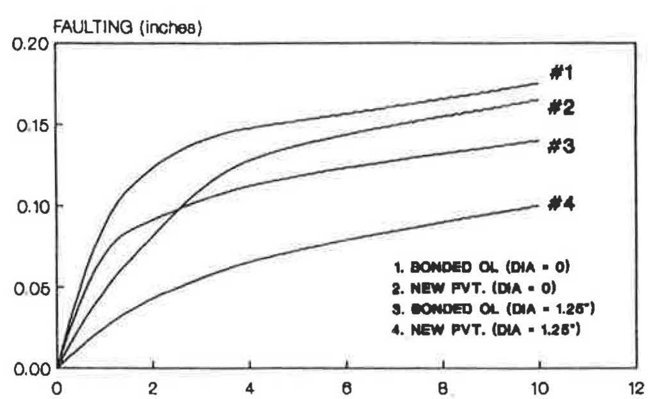

FIGURE 9 Comparison of predicted bonded overlay faulting to new pavement faulting.

Shrinkage Cracking

This distress was observed on 25 percent of the sections. Typical shrinkage cracking appears as tight transverse cracks spaced at intervals of 1 to 3 ft. This distress can be attributed to excessive heat and moisture loss during initial curing, such as that possibly caused by high air temperatures, high wind velocity, or insufficient insulation.

D-Cracking

Although it is likely that some of the original sections on which the overlays were built contained some D-cracking at joints and cracks, only one section experienced this problem in the overlay. This project was the 9-yr-old section on US-20 near Waterloo, Iowa. Approximately 90 percent of the overlay joints in the surveyed sections of this project exhibited D-cracking. The joints in the original pavement are known to have been badly D-cracked before placement of the overlay *(2)*. Since similar materials were probably used in the new overlay concrete, it is not surprising that this distress has appeared in the overlay. Some of the cracking in the overlay is probably also reflected from the D-cracking in the underlying pavement concrete. However, the D-cracking observed on the overlay is not yet severe and the rehabilitation has extended the life of the pavement by many years.

Delamination

Delamination along the joints was observed on two projects. On one of these projects (Clayton County, Iowa) delamination was linked to secondary joint cracking on those sections in which waterblasting was used as the surface preparation technique *(2, 12)*. The other project was US-61 in Louisiana. The delamination occurred near the transverse joints. An LaDOT survey indicated that 36 percent of the joints experienced some form of delamination *(7)*. Debonding of the overlay may be partly attributed to shear failure of the bond from a large temperature differential through the overlay and existing slab. According to Paul Kuhn of Caltrans, another bonded concrete overlay project constructed in California on I-80 near Donner's Summit debonded extensively within a few days after construction. This was attributed to extreme temperature changes in September in a high-altitude location. This project was not surveyed.

Delamination of a bonded concrete overlay will lead to rapid failure. Delamination is most critical and most likely to occur at the slab corners *(15, 16)*. Laboratory and field tests conducted under previous studies have identified 200 psi as the minimum acceptable bond strength at the overlay interface *(1, 15, 16)*. According to Domenichini, satisfactory field results have been obtained in Europe with bond strengths of 400 psi *(15)*.

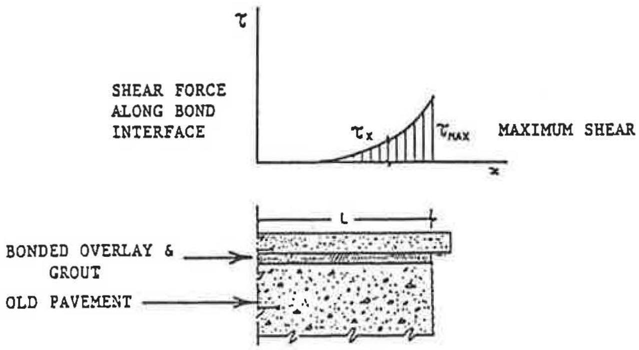

FIGURE 10 Shear stress distribution at the slab edge as modeled by Domenichini *(15)*.

Domenichini studied the shear stresses developed at the interface of a thin bonded overlay and existing slab, as shown in Figure 10 *(15)*. Domenichini computed shear stresses acting along the bond interface as a function of drying shrinkage, taking into account relative air humidity, overlay concrete water-cement ratio, overlay thicknesses, and the exposed surface area *(15)*.

The effect of relative air humidity is shown in Figure 11. The shear stress can only be kept below the maximum bond strength values (about 450 psi from field tests) if the curing procedure can produce a condition similar to that at 90 percent ambient relative humidity *(15)*. If the curing compound or other technique cannot produce these conditions, the shear stresses may exceed tolerable levels. Curing is absolutely critical to proper bonding and the overall effectiveness of the overlay; thus, careful control of the curing methods should always be performed, especially in less than perfect weather conditions. It should be noted that Domenichini's results are based on a 1-in. overlay. The effect of inadequate curing on thicker bonded concrete overlays is somewhat lower in magnitude, but equally important.

CONCLUSIONS

Important design and construction considerations for bonded concrete overlays are: *(a)* existing slab cracking, *(b)* pre-overlay repair, *(c)* surface preparation, *(d)* overlay thickness, *(e)*

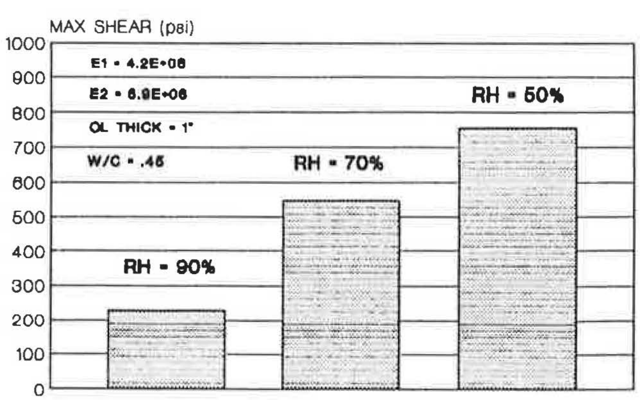

FIGURE 11 Effects of relative humidity on the shear stress induced by drying shrinkage at or near the slab edges *(15)*.

sawing of the joints, and *(f)* curing of the overlay concrete.

Cracking in the existing pavement should be expected to reflect through the overlay during the earliest stages of the life of the overlay. Working cracks will reflect through to about the same severity as that of the crack in the existing pavement. However, the thicker the overlay, the less severe the reflected crack will tend to be in comparison to that of the existing crack. Bonded overlays should not be placed on pavements with a significant amount of unrepaired working cracks (greater than 100 ft/mile in JPCP, or greater than 200 ft/mile in JRCP), unless the cracks are repaired full depth and joints are placed in the overlay to match the repair joints.

Increased slab cracking from structural fatigue was not identified on any of the projects, except Clayton County, Iowa, where thin original pavement slabs existed (6 in.) and traffic levels varied by direction. Bonded overlays will normally increase slab thickness beyond the point where normal traffic loads can cause appreciable fatigue damage.

Only one bonded overlay exhibited D-cracking. The existing pavement had severe D-cracking and it appears that either this cracking reflected through the overlay after 9 years, or the overlay concrete contained a D-cracking aggregate.

Secondary joint cracking is a prevalent distress on bonded concrete overlays. Because there were many projects that had no secondary joint cracking, it is obvious that good construction techniques are available to eliminate this problem. It is critical that the joints in the overlay are sawed as soon as possible before a crack forms from contraction of the base slab. It is recommended that joints be sawed completely through the overlay as soon as possible after placement (within 3 to 4 hr).

Faulting of transverse joints in the overlays has not been a significant problem. The maximum average faulting has been measured as 0.10 in. Faulting increase with traffic was modeled like new pavement faulting. The development of faulting in bonded concrete overlays will not be appreciably different from that of faulting in new PCC pavements. This is because, other than a reduction in deflections, the overlay provides no preventive measures against faulting. Thus, subdrainage or joint resealing should be considered if the existing pavement has faulted excessively.

Pumping was not observed and does not appear to be a problem on bonded overlays for the traffic levels applied. However, the fact that faulting is present indicates that pumping is occurring beneath the slabs. The decreased deflections from thick monolithic slabs have some effect on reducing pumping effects.

Some shrinkage cracking was identified. A substantial amount of shrinkage cracking indicates that either curing of the overlay concrete was not adequate, or the mix design was inadequate. However, less than ideal weather conditions (e.g., higher temperatures and wind velocity) at the time of construction of the overlay may require upgraded curing techniques to prevent shrinkage cracking and debonding. Prevention of the problem may warrant the application of wet burlap and curing compound at twice the normal rate for most projects.

Some occurrences of debonding of the overlay at corners indicate the need for improved techniques to achieve bond. Analytical results show that horizontal shear stresses are highest at the edges and can become high enough to cause debonding if adequate curing and water-cement ratio are not used. This requires the use of a low water-cement ratio and highly efficient curing, which may be the most economical way of ensuring that adequate bond is achieved. The use of liquid (low viscosity) epoxy resin material has shown great promise of providing improved bonding.

Transverse steel reinforcement as a means to limit or prevent reflective cracking in a thin bonded overlay was not very effective on one project where it was used. Better results are obtained when the existing pavement is repaired full-depth before overlay.

Applying the bonding grout with a pressure spraying device just ahead of the paving operation provided a uniform application of material.

Predictive models for joint faulting and cracking were developed using the data base. These models can be used as design checks for bonded concrete overlay designs.

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