TEN-YEAR PERFORMANCE OF DOWEL BAR RETROFIT – APPLICATION, PERFORMANCE, AND LESSONS LEARNED

Linda M. Pierce
State Pavement Engineer
Washington State Department of Transportation
P.O. Box 47365
Olympia, Washington 98504-7365
360-709-5470 phone, 360-709-5588 fax
piercel@wsdot.wa.gov

Jeff Uhlmeyer
Pavement Design Engineer
Washington State Department of Transportation
P.O. Box 47365
Olympia, Washington 98504-7365
360-709-5485 phone, 360-709-5588 fax
uhlmeyj@wsdot.wa.gov

Jim Weston
Technology Implementation Technician
Washington State Department of Transportation
P.O. Box 47365
Olympia, Washington 98504-7365
360-709-5496 phone, 360-709-5588 fax
westonj@wsdot.wa.gov

Jim Lovejoy
Pavement Soils Testing Engineer
Washington State Department of Transportation
P.O. Box 47365
Olympia, Washington 98504-7365
360-709-5477 phone, 360-709-5588 fax
lovejoj@wsdot.wa.gov

Joe P. Mahoney
Professor
Civil and Environmental Engineering
University of Washington
Box 352700
Seattle, Washington 98195-2700
206-685-1760 phone, 206-543-1543 fax
jmahoney@u.washington.edu

For presentation at the
2003 TRB Annual Meeting
Prepared July 2002

Number of words = 4565
Tables and Figures at 250 words each = 2750
Total number of words = 7315

TEN-YEAR PERFORMANCE OF DOWEL BAR RETROFIT – APPLICATION, PERFORMANCE, AND LESSONS LEARNED

ABSTRACT

WSDOT has been rehabilitating its aged PCC pavements, over the last 10 years, using dowel bar retrofit, panel replacements, and diamond grinding. These pavements have been rehabilitated, using dowel bar retrofit, to extend the performance life beyond the original design life of 20 years. The first dowel bar retrofit application in Washington State was constructed as a test section in 1992. Since that time, WSDOT has dowel bar retrofitted over 350 lane kilometers (225 lane miles). This paper will describe dowel bar retrofit performance, application, and lessons learned over the last 10 years.

INTRODUCTION

In the late 1980's, the Washington State Department of Transportation (WSDOT) investigated various rehabilitation options for its aging Portland cement concrete (PCC) pavements. The PCC pavements in Washington state, like many states, were only designed to have a 20-year performance life. As of 1992, over 2,180 lane kilometers (1,355 lane miles) of PCC pavements have been in service for over 20 years and over 1,316 lane kilometers (818 lane miles) have been in service for 30 or more years. Since the majority of these pavements are on the Interstate system, they have also experienced anywhere from two to five times the original traffic design levels.

PCC pavements constructed prior to the 1970's were 230 mm (9 inches) thick, undoweled, with perpendicular transverse joints spaced 4.6 meters (15 feet) apart. In the 1970's, the joint spacing was changed to a skewed random joint spacing of 4.3, 2.7, 3.4, and 4.0 meters (14, 9, 11, 13 feet). For both joint designs, the transverse contraction joints are sawed to a depth of D/4 (where D is the slab thickness), and the longitudinal contraction joints are sawed to a depth of D/3. The longitudinal and transverse joint saw cut widths ranged from 5 to 8 mm (3/16 to 5/16 inches).

The majority of the PCC pavements have a crushed stone base, with a maximum aggregate size of 19 mm (3/4 inch). In some locations, the base material consists of asphalt treated or cement treated base. The majority of the shoulders have been constructed with asphalt concrete.

To date, the main form of distress has been joint faulting and longitudinal cracking in the wheel paths. Typically, in areas where the base and subgrade materials consist of good draining aggregate and soil (American Association of State Highway and Transportation Officials (AASHTO) A-4 (*1*) or coarser) the form of distress has been longitudinal cracking with minimal joint faulting. Where the base material consists of cement treated base or a slow draining base (10 percent or more passing the 0.075 mm (No. 200) sieve) and subgrade materials (finer than AASHTO A-4) the prevalent form of distress is joint faulting. In addition, WSDOT has also experienced joint faulting on roadway sections with asphalt treated bases. This faulting is caused by a reduction in support due to stripping of the asphalt treated base. Minimal cracking has occurred on sections with asphalt treated base.

Of the concrete pavements that have fatigued (longitudinal cracking), the cracks developed within 10 to 15 years of construction and have not required pavement rehabilitation. The faulted pavements have deteriorated at such a rate that rehabilitation of approximately 80 lane kilometers (50 lane miles) of dowel bar retrofit is necessary every year for the next twenty years. Prior to 1992, the common rehabilitation treatment for addressing distressed PCC pavements was to place a 100 mm (4 inch) thick asphalt concrete overlay. Since the major distress in the PCC pavement is joint faulting, reflective cracking of the asphalt concrete overlay was the main distress that caused future rehabilitation. The main concern for WSDOT was to better understand the mechanisms of faulting and the most appropriate and cost effective rehabilitation method.

In the early 1990's, WSDOT began to research the various rehabilitation alternatives that were being evaluated nationwide, as well as internationally. Work conducted in Puerto Rico and Georgia (*2*) by retrofitting the concrete panels with dowel bars showed exceptional potential. WSDOT determined that dowel bar retrofit would be a viable solution to its faulted concrete pavements. In order to verify construction and performance potential, WSDOT constructed its first dowel bar retrofit test section during the summer of 1992.

TEST SECTION OVERVIEW AND PERFORMANCE

The test section PCC pavement was originally constructed in 1964 and consists of 230 mm (9 inch) undoweled concrete on a crushed stone base (maximum aggregate size of 12.5 mm (1/2 inch and maximum of 10 percent passing the 0.075 mm (No. 200) sieve) with 4.6 meter (15 foot) joint spacing. The existing distress consisted of a few slabs with single transverse cracks, and joint faulting from 2 to 16 mm (3/32 to 5/8 inch).

A 600-meter (1,970 feet) test section, with each design feature measuring approximately 150 meters in length (490 feet), was constructed with the following four design features (*3*):

- Dowel bar retrofit and diamond grinding,
- Dowel bar retrofit, 1.2 meter (4 foot) wide tied and doweled concrete shoulder, and diamond grinding,
- 1.2 meter (4 foot) wide tied and doweled concrete shoulder and diamond grinding, and
- Control section, which received no treatment except diamond grinding.

The dowels used in the dowel bar retrofit process are epoxy coated, 457 mm (18 inch) in length, and 38 mm (1-1/2 inches) in diameter. A total of 8 dowel bars (4 per wheel path) were placed at each transverse joint. The dowel bar slots were cut to a width of 64 mm (2-1/2 inches), a depth of approximately 146 mm (5-3/4 inches) or as required to place the center of the dowel at mid depth, and an approximate length of 560 mm (22 inches) for bar placement. The dowel bars within each wheel path were spaced 305 mm (12 inches) apart. The first dowel bar in the right wheel path was placed 305 mm (12 inches) from the lane/shoulder edge. The first dowel bar in the left wheel path was placed 610 mm (24 inches) from the longitudinal joint of the adjacent lane. Figure 1 shows the details of the dowel bar retrofit placement.

The PCC shoulder was tied to the existing right lane with 16 mm (5/8 inch) reinforcing bars with a length of 762 mm (30 inch). Three epoxy coated dowel bars were placed at each transverse contraction joint (Figure 2).

Falling weight deflectometer (FWD) testing (for determining joint load transfer) and faulting measurements were conducted just prior to construction, two weeks after construction, and annually thereafter. Joint load transfer was calculated as the deflection of the unloaded slab divided by the deflection of the loaded slab times 100. FWD testing was conducted when the air temperature was less than 24°C (75ºF) so that the upward curling of the slab was minimized. The results of the joint load transfer efficiency and faulting summaries are shown in Figure 3 and 4, respectively.

In summary, the experimental features that contain retrofitted dowel bars, have maintained an average joint load transfer between 70 to 90 percent over the last 10 years, excluding anomalies. In addition, the dowel bar retrofit sections have the following joint faulting measurements:

- 25 joints have no faulting,
- 16 joints with 1.6 mm (1/16 inch) faulting, and
- 7 joints with 3.2 mm (1/8 inch) faulting

The concrete shoulder beam has not performed as well as expected. The average load transfer ranges from 30 to 70 and all joints currently having some measure of faulting. Joint faulting measurements for the concrete shoulder beam are as follows:

- 3 joints with 1.6 mm (1/16 inch) faulting,
- 14 joints with 3.2 mm (1/8 inch) faulting, and
- 5 joints with 4.8 mm (3/16 inch) faulting

One reason for the lower performance may be that this section had the lowest initial joint load transfer efficiency and there my be a point at which the load transfer efficiency is too low to expect dramatic improvement with only a tied concrete beam.

The control section is performing as expected with joint load transfers efficiency ranging from 30 to 70. Joint faulting measurements for the control section are as follows:

- 4 joints with no faulting,
- 1 joint with 1.6 mm (1/16 inch) faulting,
- 8 joints with 3.2 mm (1/8 inch) faulting,
- 8 joints with 4.8 mm (3/16 inch) faulting, and
- 2 joints with 6.4 mm (1/4 inch) faulting

As can be seen in Figure 3, there are several locations where the average load transfer changes dramatically from one year to the next (for instance in 1995 and 1999 for the control and tied shoulder sections, and in 2001 for both of the dowel bar retrofitted sections). These changes do not appear to correlate with the air temperature during the time of FWD testing, however, the test section is located in an area subjected to significant freeze/thaw effects. Since the FWD testing is conducted during the spring of each year, these changes are related to the effects of spring thaw rather than air temperature.

WSDOT began dowel bar retrofitting PCC pavements on a full scale in 1993, with only one change, all dowel bar retrofit projects would be constructed with three dowel bars per wheel path. This change occurred based on the results of the joint load transfer restoration study conducted in Florida (*4*). The Florida study indicated that three dowel bars per wheel path performed equally, in terms of faulting, as five dowel bars per wheel path. Therefore, based on economics alone, WSDOT choose to use three retrofitted dowel bars per wheel path as the standard. Table 1 shows a summary of the dowel bar retrofit projects constructed to date.

DOWEL BAR RETROFIT APPLICATION AND PERFORMANCE

WSDOT conducts an annual pavement condition survey on 100 percent of the state highway system. For PCC pavements, the following distresses are collected: International Roughness Index, cracking, patching, scaling, faulting, spalling and pumping. Of the above distress types, the most critical indicators of pavement performance are faulting and cracking. WSDOT has established the following pavement condition criteria for rehabilitating (or reconstructing) PCC pavements.

- Average faulting less than 3 mm (1/8 inch) and the number of panels with multiple cracks less than or equal to 10 percent – do nothing
- Average faulting between 3 mm (1/8 inch) and 13 mm (1/2 inch), and the number of panels with multiple cracks less than or equal to 10 percent – dowel bar retrofit
- Average faulting greater than or equal to 13 mm (1/2 inch), number of panels with multiple cracks less than or equal to 10 percent, and average daily traffic less than or equal to 50,000 – dowel bar retrofit
- Average faulting greater than or equal to 13 mm (1/2 inch), number of panels with multiple cracks less than or equal to 10 percent, and average daily traffic greater than 50,000 – reconstruction
- Number of panels with multiple cracks greater than 10 percent – reconstruction

The above criteria is based on American Concrete Pavement Association (ACPA) (*5*) and Federal Highway Administration (FHWA) (*6*) recommendations, as well as the technical expertise and pavement performance history in Washington state. In addition, ACPA, FHWA (*7*), and the experience obtained on a WSDOT project indicates that it is more cost effective to remove and replace an existing concrete pavement when more than 10 percent of the panels require replacement. This recommendation is based on the higher costs associated with panel removal, required handwork, and traffic control items. In addition, this work is very labor intensive since extreme care must be taken when removing panels so as to not cause damage to adjacent panels that are to remain in place.

Dowel Bar Retrofit – Observed Distress

The following summary provides a brief description of pavement distress that has been observed on WSDOT dowel bar retrofit projects, specifically on interstate pavements. While the performance of DBR sections has been very good, areas of isolated distress have occurred. The majority of these distresses occurred on projects constructed between 1992 and 1997. Experience gained during the early years of WSDOT's dowel bar retrofit projects has led to significant improvements in construction practices and specifications. As a result, distress on dowel bar retrofitted pavements has been greatly reduced.

The following distresses have been observed: studded tire damage, cracking of the grout material in the dowel bar slot caused by retrofitting over an existing longitudinal crack, 45 degree cracking, and spalling. Each of these distresses are discussed below.

Studded Tire Damage

This type of distress (Figure 5) was common on the first two projects, with the majority of the dowel bar slots exhibiting accelerated wear. The primary cause of the slot wear was due to the use of studded tires and chains in this area of Washington state (vicinity of Snoqualmie Pass) and an insufficient quantity of large stone aggregate. To reduce surface wear, WSDOT modified the aggregate size in the patching material from AASHTO Grading No. 57 (*7*) to AASHTO Grading No. 7. This change occurred in 1997, and since that time, no appreciable wear has occurred on any of the dowel bar slots.

Longitudinal Cracking

Existing longitudinal cracks that intersect dowel bar slots (Figure 6) have caused isolated problems on several projects. This problem occurs when a dowel bar slot is located over an existing longitudinal crack. The failure mechanism is typically the debonding of the pour back material from the walls of sawed slots. To eliminate this distress, WSDOT recommends either aligning the slots to miss any existing longitudinal cracks or by not placing a dowel bar in this location.

45-degree Cracking

Normally, 45-degree cracking is not seen on WSDOT dowel bar retrofit projects, however, several hundred instances (Figure 7) of this distress were found on an eight-kilometer (five-mile) section. A forensic investigation was conducted to determine the cause(s) of the 45-degree cracking. The results of this investigated determined the following causes:

- The slots were cut too deep causing cracking in the bottom of the dowel bar slot and placement of the dowel bar below the mid depth of the slab. Cores showed that slots were cut up to 178 mm (7 inch) deep on a 230 mm (9 inch) slab.
- Heavy (27 kg (60 lb)) jackhammers were used for concrete removal. Heavy jackhammers can punch through the bottom of slots during concrete removal.

As a result of these findings, WSDOT revised the dowel bar retrofit special provision to prohibit the use of any jackhammer greater than 14 kg (30 lb) and to ensure dowels are placed at mid depth of the concrete slab.

Spalling

Spalling is another common, but infrequent, distress (Figure 8). Approximately 19 joints per kilometer (12 joints per mile) are typically affected. In most cases, spalling is caused by the misalignment of the core board.

Diamond Grinding versus Roto-Milling of Concrete Pavements

The use of a roto-mill machine (using a triple head carbide mandrel) for re-establishing PCC pavement ride and texture has been suggested on a number of dowel bar retrofit projects in Washington state. This treatment has been evaluated on two separate projects, with similar results. As shown in Figure 9a, the diamond ground surface (diamond ground in 1995, photo taken in 1998) shows no damage to the transverse or longitudinal joint. While the amount of spalling that occurs on the transverse joint with the roto-milled surface, shown in Figure 9b, (roto-milled in 1996, photo taken in 1998) is unacceptable for long-term performance. In the roto-milled surface photo, the right lane (in the foreground) was roto-milled while the adjacent lane (in the background) received no treatment. As can be seen, the roto-milling process causes significant joint spalling. Over time, typically 3 to 5 years, the roto-milled surface develops an unacceptable ride. Therefore, due to the poor performance and the high risk of distress that occurs in the longitudinal and transverse joints (and potential damage to the dowel bar slots), roto-milling of PCC pavements is not a viable treatment.

LESSONS LEARNED (DOWEL BAR RETROFIT DO'S AND DON'TS)

Based on the construction difficulties and performance review of all dowel bar retrofit projects in Washington state, the following information summarizes construction related recommendations for minimizing premature failures of dowel bar retrofit.

Cutting Slots

- Ensure that saw cuts are sawed to sufficient depth to place the center of the dowel bar at the mid-depth of the pavement. Saw cuts that are sawed too deep will contribute to corner cracks when traffic loads are applied.
- Slots should be aligned to miss existing longitudinal cracks.
- For ease of construction when gang saws are used, slots may be sawed but not retrofitted to miss any existing longitudinal crack. Non-retrofitted saw cuts should be cleaned and sealed with an epoxy resin.
- The alignment of sawcuts must be parallel to the roadway centerline. Dowel bar slots placed perpendicular to skewed joints will cause joint lock up and lead to cracking.
- Based on FHWA recommendations (*7*), sawcuts should be cut and prepared so that the dowel bars are placed within the following tolerances:
  - Placed within 25 mm (1.0 inch) of the center of the existing pavement depth.
  - Centered over the transverse joint with a minimum embedment of 200 mm (8 inches).
  - Placed parallel to centerline and within the plane of the roadway surface.
  - Horizontal position ± 13 mm (1/2 inch), vertical position ± 13 mm (1/2 inch), skew from parallel (per 457 mm (18 inch)) ± 13 mm (1/2 inch).

Removing Material from Slots
Jackhammers should weigh less than 14 kg (30 pounds). Jackhammers should not be used in a plane vertical to the PCC pavement surface. If used vertically, the jackhammer may punch through the bottom of the slot.

Sand Blasting Slots
- All exposed surfaces and cracks in the slot should be sand blasted and cleaned to bare concrete to remove saw slurry, parting compound, or other foreign material.
- A high-pressure water blast has been successful in cleaning the slots.

Cleaning Slots and the Adjacent Area
- Compressed air should be used to remove concrete chunks, dirt, debris, water, and slurry from the sides and bottom of the slots.
- A physical check of the slots cleanliness (using a tool such as a scraper) should be made to ensure no slurry residue remains on the sides of slots.
- Concrete chunks, dirt, debris, and slurry residue should be cleaned 1 to 1.2 meters (3 to 4 feet) away from the slots perimeter. Otherwise, dirt is easily reintroduced into the slot during subsequent operations.
- All free water must be removed.

Silicone Sealant in Slots
- Once the slots are cleaned, silicone sealant must be placed on the existing transverse joint within the slot area. The sealant should not extend 13 mm (1/2 inch) beyond the joint because excessive sealant will not allow the concrete pour back material to bond to the sides of the slot.
- Sealant should be placed to prevent any of the patching material from entering the joint/crack at the bottom or sides of the slot.
- Concrete surfaces, including the bottom of the slot must be dry.

Dowel Bars/Chairs/End Caps
- The epoxy coating on dowel bars should be free of nicks and abrasions prior to use. To date, there has been no evidence (based on core samples and pavement performance) to indicate that corrosion of the epoxy coated dowel bars will occur over the 10 to 15 year design life.
- Dowel bars should be completely coated with an approved parting compound prior to placing into chairs. Dowel bars that have a factory-applied coating should be protected and free of dirt and debris. The factory-applied coating should be clearly visible, otherwise an additional application of an approved material must be applied. Dowel bars should not be coated once they have been placed in the slots as the sides and bottom of the slots will become contaminated.
- The core board that is positioned on the dowel bar is used to ensure that a joint is formed directly in line with the existing joint and to allow for the expansion of the pour back material. The core board (closed cell foam with plastic or poster board faced material) should be of sufficient quality to allow a tight fit to all edges of the slot during placement of the pour back material. Care should be given to ensure the core board extends beneath the dowel bar to the slot bottom.

- The chairs placed on the dowel bars should be strong enough to allow full support of the dowel bar. Chairs should allow at least a 13 mm (1/2 inch) clearance between the bottom of the dowel bar and the bottom of the slot.
- End caps should allow at least 6 mm (1/4 inch) of movement at each end of the bar. End caps placed on each end of the bar reduce the risk of dowel bar lockup and are considered to be insignificant to the overall cost.

Placement of Grout
The pour back material should be placed in a manner that will not cause movement of the dowel bar within the slot. Pour back material should not be dumped onto the slots. Placing the pour back material on the surface adjacent to the slot and shoving it towards the slot allows the least movement.

Consolidating Grout
A 25 mm (1.0 inch) or less diameter vibrator should be used to consolidate the patching material. Steps should be taken to ensure that the grout material is not over consolidated and that the dowel bar does not move during consolidation.

Striking Off Excess
The patching material in the dowel bar slots should not be overworked; this will cause mitigation of the fine material to the surface. The grout should be finished 3 to 6 mm (1/8 to 1/4 inch) above the pavement surface. The diamond grinding operation should remove the high spots and smooth the surface.

Diamond Grinding
Restoration of the surface should be done by diamond grinding. Diamond grinding cuts into the concrete aggregate to improve the surface and ride. Use of a roto-milling machine impacts the surface and results in the "popping" out of aggregate rather than cutting it. The roto-milling process causes significant damage to the joint.

Slurry Removal
The agencies environmental section should be consulted during the dowel bar retrofit design regarding concrete slurry removal. Some areas allow slurry to be placed on roadway slopes while in some areas, depending on environmental requirements, the slurry must be removed to an off site location.

Patching Material Requirements
Concrete patching materials should be prepackaged cementitious patching material and meet the ASTM requirements as shown in Table 2. The amount of aggregate filler should conform to the manufacturer's recommendation and the aggregate used for extension material should be AASHTO Grading No. 7.

ADDITIONAL DOWEL BAR RETROFIT RESEARCH
A pooled fund project was established between the states of California, Minnesota, Texas, and Washington (*9*). The intent of this pooled fund study is to:

- Share information on pavement practices including new design, rehabilitation, decision-making, and research

- Discuss how pavement-oriented research studies are identified, conducted, and implemented
- Discuss potential pavement-oriented studies of mutual interest

One research project that developed out of the pooled fund study was the characterization of dowel bar retrofit performance. The primary contributors to this study will be the states of California and Washington, since both of these states have a substantial number of lane miles of plain jointed PCC pavement that were built twenty to thirty years ago, with similar designs. WSDOT has significant construction experience with dowel bar retrofit. Caltrans, through a well-established pavement research program with the University of California, has the ability to perform accelerated pavement testing with a heavy vehicle simulator. Therefore, a partnered research project to evaluate the performance capabilities of dowel bar retrofit was created in 2000 between the states of California and Washington.

The research project (*10*), constructed in January 2001 in Ukiah, California, retrofitted the existing transverse joints with dowel bars. The objectives of the research project are as follows:

- Feasibility of dowel bar retrofit based on the condition of the existing slabs.
- Evaluate the load transfer restoration provided by dowel bar retrofit.
- Determine the expected life of dowel bar retrofit.
- Determine the mechanism of failure.
- Develop best practice procedures in the areas of design, materials, and construction.
- Identify appropriate rehabilitation treatments based on life cycle costs.

A variety of tests are being conducted on this test pavement which include, but are not limited to, load transfer efficiencies, faulting measurements, curling measurement due to temperature changes, in-place material testing, deflections, and weather information (temperature, humidity, wind speed, and rainfall).

The primary benefits of this project are to provide information and tools to design and construct dowel bar retrofit projects for maximum performance and to determine whether and under what conditions dowel bar retrofit is the most cost-effective strategy for rigid pavement rehabilitation. In addition, this project will provide information regarding the most effective dowel materials, and the number of dowels to place in each wheel path.

CONCLUSIONS

WSDOT has significantly modified the design and construction of dowel bar retrofit based on 10 years of experience. Construction inspection is one of the primary factors for ensuring the success of dowel bar retrofit. One of the more critical construction activities is cutting the slot and removing the existing PCC. Cutting the slot too shallow or too deep (i.e. not placing the dowel bar at mid-depth) may contribute to increased stress on the bar resulting in corner cracking. Also, the use of heavy (more than 14 kg (30 pound)) jackhammers can cause punching through the bottom of the slot, resulting in increased joint failure. The other critical factor for successful dowel bar retrofit is in project selection. Dowel bar retrofit is appropriate on PCC pavements with less than 10 percent slab replacement and average faulting between 3 mm (1/8 inch) and 13 mm (1/2 inch). Based on these modifications and enhancements, dowel bar retrofit is considered to be a successful and viable alternative for rehabilitating faulting concrete pavements in Washington state.

REFERENCES

1. AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 1 Specifications*, M 145-91, AASHTO, 2001.

2. FHWA. *Improving Load Transfer in Existing Jointed Concrete Pavements, Final Report*, FHWA-RD-82-154. FHWA, U.S. Department of Transportation, 1983.

3. Pierce, Linda M. PCCP Rehabilitation in Washington State (A case study). In *Transportation Research Record 1449*, TRB, National Research Council, Washington, DC, 1994, pp. 189-198.

4. Hall, K. T., Darter, M. I., Armaghani, J. M. *Performance Monitoring of Joint Load Transfer Restoration*. DTFH61-91-P-001198, December 1992.

5. American Concrete Pavement Association. *Pavement Rehabilitation Strategy Selection*. TB-015.P, Skokie, Illinois, 1993.

6. Larson, R. M., Petersen, D., Correa, A. *Retrofit Load Transfer – Special Project 204*. FHWA-SA-98-047. FHWA, U.S. Department of Transportation, 1998.

7. FHWA. *Pavement Notebook.* FHWA-PD-96-037. FHWA, U.S. Department of Transportation, 1996.

8. AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 1 Specifications*, M 43-88, AASHTO, 2001.

9. Mahoney, Joe P., Pietz, Martin D., and Anderson, Keith W. *Summary Report on the State Pavement Technology Consortium*. Washington State Department of Transportation, WA-RD 487.1, February 2000.

10. University of California at Berkeley Pavement Research Center, Dynatest Consulting, Inc., Washington State Department of Transportation, University of Washington Seattle. *Goal 7 Test Plan: Dowel Bar Retrofit Rehabilitation of Rigid Pavements.* Partnered Pavement Research Test Plan prepared for California Department of Transportation. August 2001.

LIST OF FIGURES AND TABLES

Figures

Tables

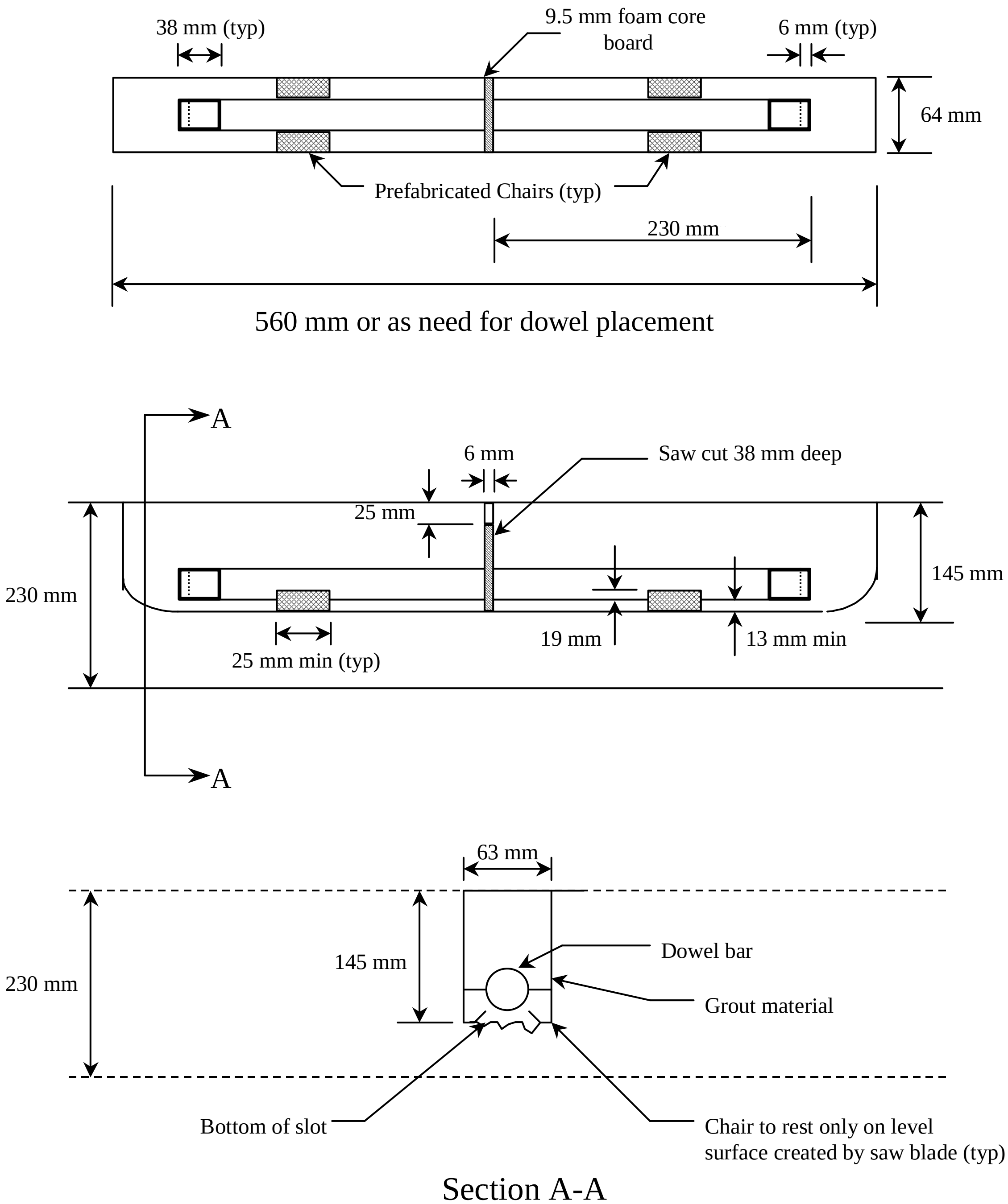

FIGURE 1 Dowel bar retrofit placement specifications.

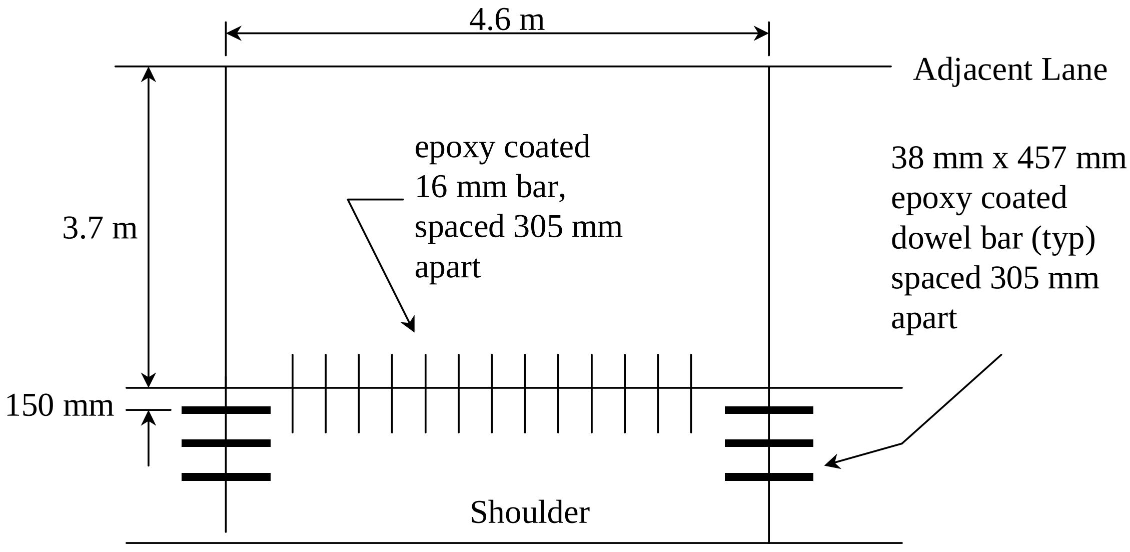

FIGURE 2 Tied dowelled concrete shoulder layout.

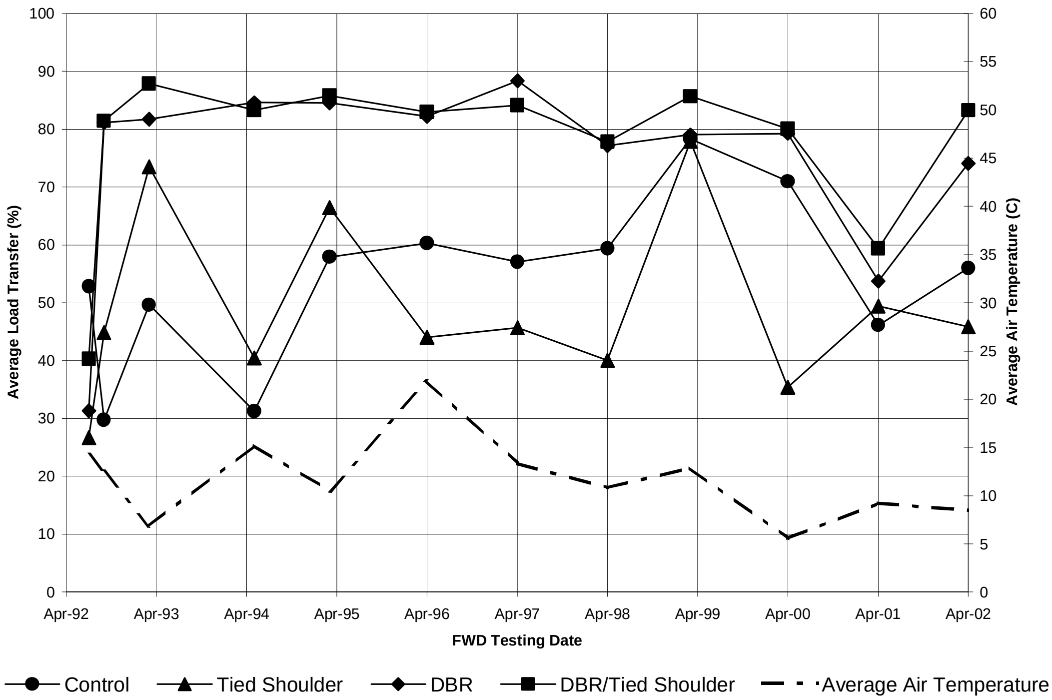

FIGURE 3 Average load transfer analysis.

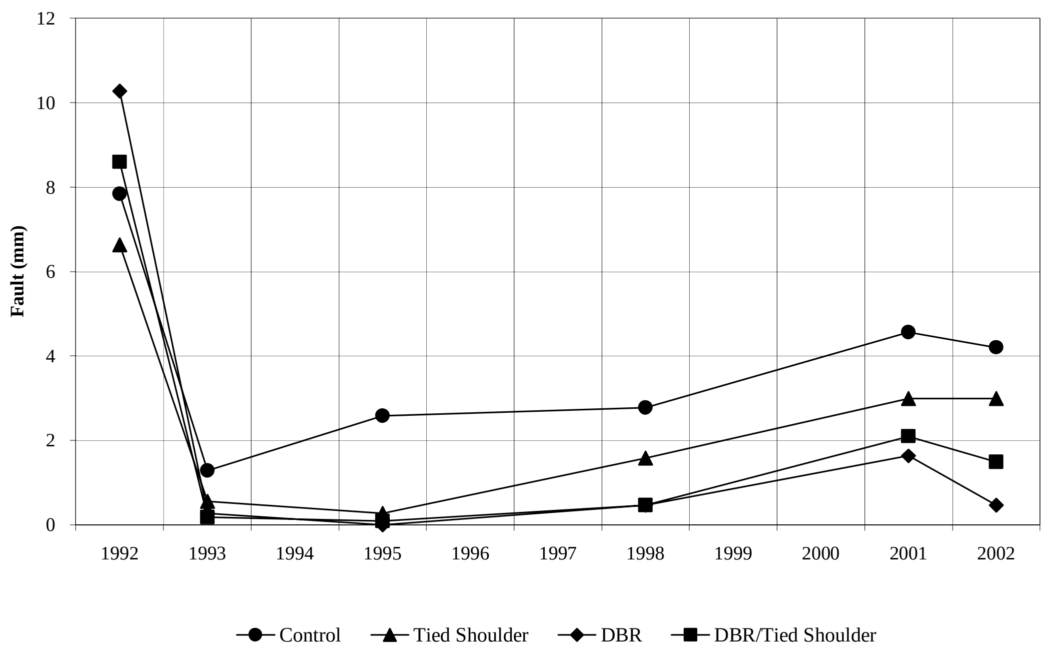

FIGURE 4 Average fault measurements.

FIGURE 5 Example of accelerated wearing of grout in dowel bar slot.

FIGURE 6 Longitudinal cracking in dowel bar slots.

FIGURE 7 45-degree cracking.

FIGURE 8 Joint spalling due to misaligned core board.

FIGURE 9(a) and (b) Surface texture for diamond grinding and roto-milling.

TABLE 1 Summary of Dowel Bar Retrofit Projects

State Route	Project Name	Year	Dowel Bar Retrofit Lane km	Dowel Bar Quantity (each)	Grinding Quantity (m^2)
90	Kachess River to Yakima River	1992	0.61	1,067	19,056
90	Easton Hill to Yakima River	1993	43.39	61,698	248,748
90	Top of Easton Hill to Silver Creek	1994	5.71	12,225	20,581
5	Martin Way Overcrossing to Mounts Road	1995	8.50	10,850	43,788
5	Joe Leary Slough Bridge to Nulle Road SB	1996	18.62	24,220	161,460
90	Hyak Vicinity to Ellensburg - Phase 1	1997	62.75	84,334	484,154
82	SR 821 to Selah Creek Bridges	1997	65.08	98,358	254,936
5	Martin Way to Mounts Road	1997	11.76	15,207	53,989
195	Bridge 195/34 to Bridge 195/38	1997	17.00	20,912	52,944
5	North Lake Samish River Road to 36th St	1997	20.28	26,787	72,658
5	NW 319th Street to East Fork Lewis River Bridge	1998	2.59	3,432	N/A
5	Sunset/SR 542 Vicinity to Nooksack River Bridge 5/828	1999	24.75	20,358	117,797
5	Gravelly Lake Interchange Vicinity to Puyallup River Bridge	1999	53.11	43,040	133,173
5	Blakeslee Junction Railroad Bridge to Thurston County Line	2000	7.24	2,814	N/A
5	Stanwood/Bryant Vicinity	2000	0.11	138	421
5	Pierce County Line to Tukwila Interchange - Stage 2S	2001	10.53	2,040	121,680
5	Pierce County Line to Tukwila - Stage 3	2002	7.13	4,536	25,403
5	Federal Way SB WIM Weigh Station	2001	1.17	300	675
5	Nooksack River to Blaine Vicinity	2002	2.12	4,470	40,320

TABLE 2 WSDOT Patching Material Requirements

Property	Test Method	Requirements
Mortar		
Compressive Strength		
at 3 hours	ASTM C-109	Minimum 3,000 psi
at 24 hours	ASTM C-109	Minimum 5,000 psi
Length Change		
at 28 days	ASTM C-157	0.15 percent maximum
Total Chloride Ion Content	ASTM C-1218	1 lb/yd^3 maximum
Bond Strength		
at 24 hours	ASTM C-882 (modified by ASTM C-928)	Minimum 1,000 psi
Scaling Resistance (at 25 cycles of freezing and thawing)	ASTM C-672	1 lb/ft^2 maximum
Concrete		
Compressive Strength		
at 3 hours	ASTM C-39	Minimum 3,000 psi
at 24 hours	ASTM C-39	Minimum 5,000 psi
Length Change		
at 28 days	ASTM C-157	0.15 percent maximum
Bond Strength		
at 24 hours	ASTM C-882	Minimum 1000 psi