LONG-TERM PERFORMANCE OF DOWEL BAR RETROFIT IN WASINGTON STATE

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ABSTRACT

In 1993, Washington State Department of Transportation (WSDOT) initiated its first full-scale dowel bar retrofit (DBR) project for the repair of a severely faulted concrete pavement. To date, WSDOT has DBR approximately 280 lane miles (450 lane km) or approximately 600,000 bars of concrete pavements in Washington State. Upon review of DBR pavement condition, it was noted that projects with lower average faulting levels (< ½ in [3 mm]) prior to DBR appear to have superior performance as compared to all other DBR projects. For example, projects with lower faulting levels, after 10 years of service had average International Roughness Index (IRI) of 145 in/mi (2.3 m/km) and average faulting of 0.01 in (0.3 mm) compared to all other DBR projects with an average IRI of 210 in/mi (3.3 m/km) and average faulting of 0.16 in (4.1 mm). Based on this performance, WSDOT considers DBR to be a cost effective rehabilitation treatment for faulted concrete pavements.

INTRODUCTION

Load transfer across transverse joints of jointed plain concrete pavements is essential for long-term performance, especially in the presence of heavy truck traffic loadings. Sufficient load transfer reduces tensile stress and deflections thereby reducing the potential for joint spalling, base and/or subgrade pumping, transverse joint faulting, and cracking. Load transfer may be obtained through aggregate interlock, treated bases, and/or dowel bars placed at transverse joints. Depending on truck traffic loadings, aggregate interlock alone may not provide sufficient load transfer to minimize tensile stress and deflections. In general, load transfer efficiencies between 70 to 100 percent are considered to be adequate, while load transfer below 50 percent can lead to joint faulting, panel cracking, and poor ride quality (1).

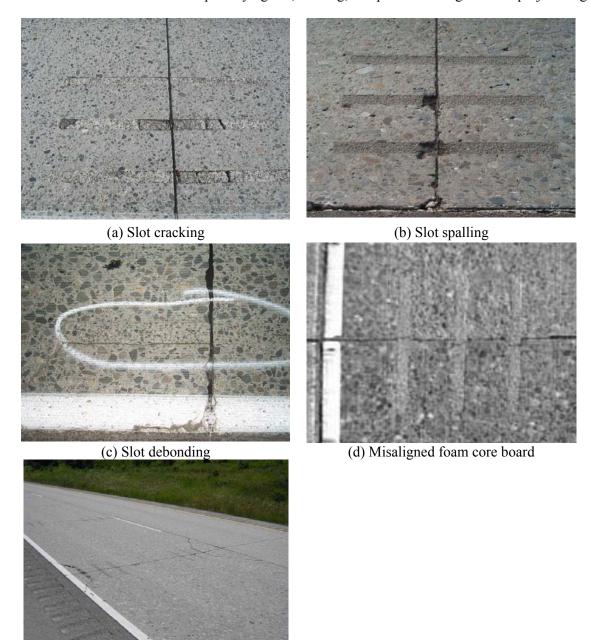
In Washington State, plain jointed concrete pavements constructed prior to the 1990's did not contain dowel bars across the transverse joints. After being in-service for 30 more years, a significant number of the Washington State concrete pavements have developed transverse joint faulting, many with average faulting > ½ in (13 mm). Since sufficient funding was not available to reconstruct the faulted and rough concrete pavements, in 1992 the Washington State Department of Transportation (WSDOT) initiated a study (2) to investigate the cost effectiveness of load transfer restoration techniques. Since then WSDOT has dowel bar retrofitted (DBR) more than 280 lane miles (450 lane km), or approximately 600,000 bars, of faulted concrete pavements.

Since its inception in Washington State, DBR has also included diamond grinding of the entire project length, and to the extent necessary full-depth replacement of concrete panels with two or more cracks, partial-depth spall repair, crack sealing, and for all but one project, resealing transverse and longitudinal joints. It must also be noted, that when WSDOT initiated DBR there existed a sizeable (approximately 600 to 800 lane miles [970 to 1290 km]) backlog of concrete pavements in need of rehabilitation. Due to this backlog, the majority of which were on the heavily traveled interstate system, WSDOT conducted DBR in a worst-first manner, implying that projects that received DBR first, were in the worst condition (primarily heavily faulted).

PAVEMENT DISTRESS EVALUATION

As part of the Washington State Pavement Management System (WSPMS), WSDOT has been collecting pavement condition data since the late 1960s. From the late 1960s to the 1990s, pavement condition surveys were conducted via windshield surveys (rating teams driving along the roadway shoulder at 10 mph [16 kph] and noting the distress). From 2001 to present, WSDOT has used a pavement condition vehicle (operating at highway speed) capable of collecting IRI, rutting/wear, faulting, and digital images for quantifying surface distress (e.g., cracking, spalling, and raveling). From this, two data sources were available for determining the performance of DBR in Washington State:

- Digital surface images from approximately 180 lane miles [290 lane km] or 380,000 DBR slots. The digital images were used to quantify DBR specific distress which included: cracking (Figure 1a), spalling (Figure 1b), debonding (Figure 1c), misaligned foam core board (Figure 1d), and 45-degree cracking (Figure 1e).
- 2006 WSPMS for quantifying IRI, faulting, and panel cracking over the project length.



(e) 45-degree cracking **FIGURE 1 DBR slot distress.**

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Over the span of DBR construction in Washington State, WSDOT has changed its equipment for collecting and processing pavement condition data. The summary of pavement performance discussed in the next section is based on condition data collected from 1992 through 2006 with no data adjustments due to the varying equipment types. The impact of this is that data collected in more recent years (2001 to present) may contain a higher level of accuracy than data collected between 1992 and 2001.

As described previously, with such a large backlog of concrete pavements in need of rehabilitation or reconstruction, WSDOT did not establish performance criteria (e.g., IRI, faulting, and panel cracking) for selecting and prioritizing DBR projects. Today, however, WSDOT uses the following criteria for wear (due to studded tire damage) and roughness, and is in the process of determining appropriate criteria levels for faulting and panel cracking.

- Roughness greater than 170 in/mi.
- Wear depths greater than 0.40 in.

Though load transfer efficiencies have long been used to characterize the performance of concrete pavements and many studies (1, 3-7) have quantified levels for the application of load transfer restoration, measurement of load transfer can be problematic especially on heavily traveled roadways (due to lane closure requirements during falling weight deflectometer testing). In addition, load transfer efficiency is not a routine test conducted by WSDOT and beyond specific case studies is not available for any of the DBR projects. One performance measure that is routinely collected by WSDOT is joint faulting and will be one of the measure used in the evaluation of DBR projects.

PERFORMANCE OF DOWEL BAR RETROFIT IN WASHINGTON STATE

The following summarizes the performance of DBR projects constructed between 1993 and 2006. Figure 2 illustrates each of the DBR projects according to PCC age at the time DBR was applied, as well as the in-service age of the DBR projects as of 2007. On average, the age of the existing PCC prior to dowel bar retrofit was 32 years (ranging from 17 to 46 years) and the average in-service age of DBR, as of 2007, is 9 years (ranging from 1 to 14 years).

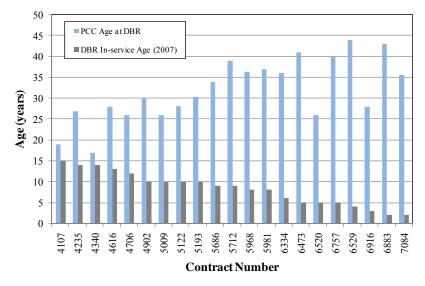


FIGURE 2 Age of PCC at time of DBR and DBR in-service age.

From the review of the digital images, it was determined that Washington State has experienced very little DBR slot related distress, with less than 3 percent of all DBR slot distress combined on any given project and typically less than 1 percent on all projects (Figure 3). Figure 3 shows the percent of slots along the vertical axis and contract number, with in-service age of DBR in parenthesis, along the horizontal axis.

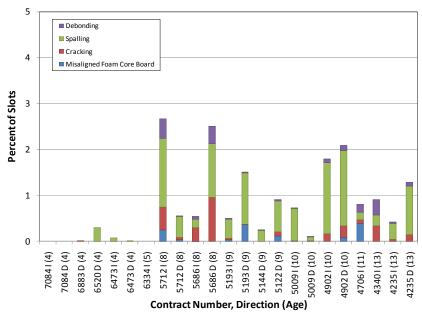


FIGURE 3 DBR slot distress by DBR contract (DBR age in parenthesis).

Though considered minor, the most predominant distress is DBR slot spalling. This distress is likely related to construction technique and not failure of the patching material. This performance can be attributed to clear construction specifications, consistent presence of WSDOT inspectors during construction, and the contractor's commitment to quality construction practices.

One of the reasons for reviewing the WSPMS was to determine the development of panel cracking of the existing concrete panels after DBR. For this summary it was assumed that standard WSDOT practice was followed for each DBR rehabilitation project. That is: the DBR rehabilitation process also replaced all multi-cracked panels, sealed all longitudinal cracks, and all transverse panel cracks received DBR.

Pavement performance data (IRI, panel cracking, wear, and faulting) from 22 DBR projects was extracted from the WSPMS and is shown in Figure 4. Year 0 represents the pavement condition prior to DBR. It should be noted that in Figure 4 condition data (specifically IRI and wear) for year 1 is higher than for year 2, ideally, the opposite would be true. One potential reason for this anomaly may be due to the timing of the annual pavement condition survey in relation to the construction season in Washington State. WSDOT conducts the annual pavement condition survey between July and October, while the typical construction season runs from May through October. Therefore, it is probable that for some projects, the pavement condition survey was conducted prior to DBR construction resulting in higher than expected performance values in year 1. It is fully understood that other factors may also be affecting pavement condition and the intent of Figure 4 is to illustrate the longer-term performance of DBR not the year to year change in pavement condition. As seen in Figure 4, on average IRI just prior to DBR was slightly more than 160 in/mi (2.5 m/km) and after 13 years of performance has returned to levels almost

equal (154 in/mi [2.4 m/km]) to pre DBR conditions. This increase in IRI has been determined to be predominately related to the use of studded tires and not the return of joint faulting (8). Pavement wear depths, which are also related to studded tire wear, had a pre DBR average of 0.14 in (3.6 mm) and after 13 years have shown a steady increase. Panel cracking (includes all types of cracks regardless of the number of cracks per panel) prior to DBR was approximately 6 percent and after 13 years has reached 19 percent of total panels. Upon closer review, it appears that the majority of the increased percentage of cracking is due to cracking within panel replacements, propagation of existing cracks to adjacent panels, and cracking associated with DBR (to be explained further below). Finally, prior to DBR average faulting was 0.11 in (2.8 mm) and after 13 years of performance has stayed well below 0.05 in (1.3 mm). Quite a bit of variability has been noted in faulting measurements over the 13 year period, which may in part be due to measurement error, error in calculating average faulting values, and/or the relatively fewer miles of DBR in more recent years.

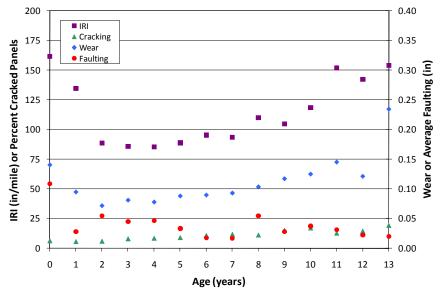


FIGURE 4 Dowel bar retrofit pavement performance.

From the review of DBR performance, it was found that 5 projects showed superior longer-term performance as compared to all other DBR projects (see Table 1 and Figure 5). Prior to DBR, these 5 projects had an average IRI of 262 in/mi (4.1 m/km) and average panel cracking of 5 percent, which is comparable to the condition of all the other DBR projects. However, after 10 years of service, these 5 projects showed superior performance over all other DBR projects with average joint faulting of 0.01 in (0.3 mm) versus 0.16 in (4.1 mm), average IRI of 145 in/mi (2.3 m/km) versus 210 in/mi (3.3 m/km), and average panel cracking of 5 percent versus 24 percent. A two tailed Student's t-test was conducted to determine if the performance means (both prior to and 10 years after DBR application) of the 5 projects are significantly different than the performance means of all other DBR projects. Performance after only 10 years was selected due to the relatively few number of lane miles (lane km) on the 5 projects with pavement performance beyond 10 years. A significance level of $\alpha = 0.05$ was used with a null hypothesis that there is no significant difference in the performance of the 5 projects compared to all other projects. Table 1 provides the results of this statistical analysis and indicates that:

- Prior to DBR construction
 - o A significant difference did not exist in pavement roughness.

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- A significant difference does exist in the amount of panel cracking.
- Unfortunately, WSDOT did not begin measuring more accurate (high speed profiler) levels of joint faulting until 2001. Therefore, for the majority of pavement sections evaluated, faulting measurements were unavailable and an assessment of significant difference could not be determined.
- After 10 years of service
 - A significant difference exists in pavement roughness.
 - A significant difference exists in the amount of panel cracking.
 - A significant difference exists in the amount of joint faulting.

TABLE 1 Pavement performance prior to and 10 years after DBR

	5 Projects		All Projects		Null
Distress Condition	Avg.	Std. Dev.	Avg.	Std. Dev	Hypothesis
Prior to DBR					
Roughness, in/mi (m/km) ¹	262 (4.1)	32 (0.5)	272 (4.3)	82 (1.3)	Accept
Cracking (%)	5	4	8	7	Reject
Faulting, in (mm)					
After 10 years of service					
Roughness, in/m (m/km)	145 (2.3)	16 (0.3)	210 (3.3)	59 (0.9)	Reject
Cracking (%)	5	3	24	24	Reject
Faulting, in (mm)	0.01 (0.3)	0.01 (0.3)	0.16 (4.1)	0.49 (12.4)	Reject

¹ Standard WSDOT practice includes diamond grinding after DBR.

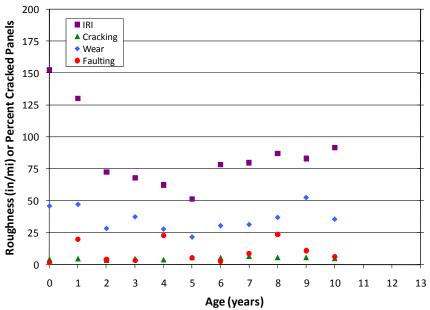


FIGURE 5 Dowel bar retrofit pavement performance – 5 projects only.

From this analysis, there is a significant difference in the performance means of the 5 projects compared to all other projects. Unfortunately, more accurate faulting levels were not available prior to DBR construction, but based on personal knowledge (9) of all the projects prior to DBR, the 5 projects had less faulting. Based on the statistical analysis and the personal knowledge of each DBR project in Washington State it can be concluded that applying DBR prior to significant fault development (> 1/8 in [3 mm]) can result in improved longer-term DBR performance (lower IRI, less faulting, and lower percent of cracked panels).

For comparison purposes, the same analysis as shown in Figure 4 was conducted on all non-DBR concrete pavements. To be somewhat equivalent, pavement condition on the non-DBR sections from 1993 to 2006 were evaluated, which is the same time period of the DBR project evaluation. Since the majority (94 percent) of the DBR projects is on interstate pavements, the analysis of non-DBR sections was also limited to the interstate. This also allows for an equitable comparison of similarly aged pavements since most of the interstate in Washington State was constructed between the early 1960s and mid 1980s. The result of this analysis (which includes approximately 375 lane miles [600 lane km]) is shown in Figure 6. On average, the non-DBR projects have lower IRI, lower levels of faulting, and few percent of cracked panels. Interestingly, the depth of wear is somewhat comparable between the non-DBR sections and the DBR projects. Keep in mind that for the most part, all of the DBR projects had obtained higher levels of faulting, roughness, and wear prior to DBR construction. So it is not necessarily surprising that the non-DBR projects have improved performance over the same time period.

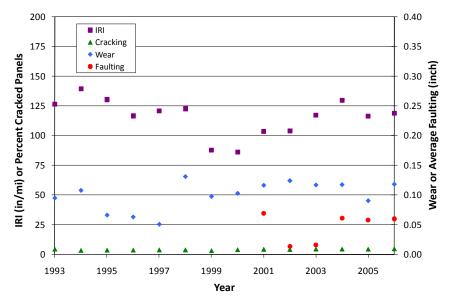


FIGURE 6 Non-dowel bar retrofit pavement performance.

Upon review of panel cracking (45-degree, corner, longitudinal, and transverse) it was found that 5 projects (all with an in-service DBR age of 10 years or more) showed a significant increase (approximately 10 to 35 percent) in panel cracking (majority of which was longitudinal cracking) after DBR application. However, all of these projects are located in an area that is subjected to high freeze-thaw damage and prone to cracking due to the failure of an improperly installed longitudinal tape joint during original construction (see Figure 7). For all other DBR projects, the percent of panel cracking (Figure 8) are relatively minor (less than 3 percent). Figure 8 shows the percent of panels along the vertical axis and contract number, with age of DBR in parenthesis, along the horizontal axis. From this

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183 184 summary it was also determined that the predominant increase in panel cracking is associated with longitudinal cracking (Figure 9). At this time it is uncertain the exact cause of the increase in longitudinal cracking and additional analysis will be necessary.



FIGURE 7 Failed longitudinal tape resulting in longitudinal cracking.

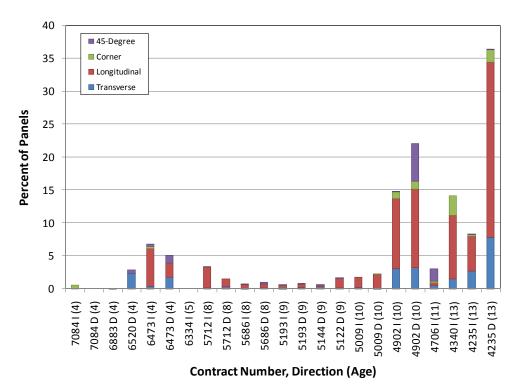


FIGURE 8 Percent of panel cracking by DBR contract (DBR age in parenthesis).

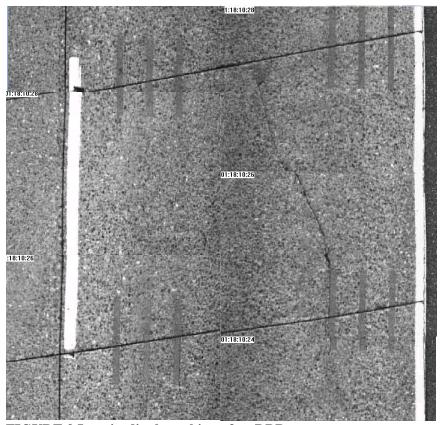


FIGURE 9 Longitudinal cracking after DBR.

During the review of the digital images from the 2006 annual pavement condition survey, it was noticed that a large percentage of panel replacements, conducted during DBR application, had experienced some form of panel cracking (transverse, longitudinal, or multiple). An evaluation indicated that approximately 30 percent of the new panel replacements (average age of 1 to 14 years) had cracked prematurely (Figure 10). Considering that very few panels from the original construction had experienced cracking over a 25 year period, this rapid increase in panel cracking on the panel replacements was considered significant. A number of potential causes of the increased panel replacement cracking includes: (1) weakened subgrade condition; (2) panel replacement removal process; (3) inadequate consolidation and/or selection of base material; (4) improper concrete placement; and (5) the presence of existing distress and the development of sympathy cracking. Based on the results of a forensic investigation of premature panel cracking (10) WSDOT modified its panel replacement construction specification by providing clearer language for requiring and ensuring that full-depth saw cuts are conducted and the inclusion of relief cuts prior to concrete removal. This specification has been in place since 2008 and will be monitored on future projects to ensure that the modifications have resulted in improved panel replacement performance.

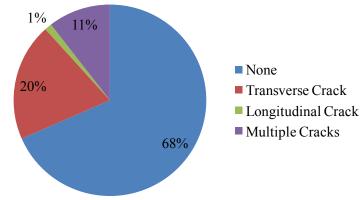


FIGURE 10 Cracking in new panel replacements.

SUMMARY

DBR application, in conjunction with panel replacements and diamond grinding, has proven to be an effective rehabilitation treatment for faulted concrete pavements. The following summarizes DBR performance in Washington State:

- Projects that were DBR prior to significant fault development (< 1/8 in [3 mm]) showed superior longer-term (10 years) performance over all other DBR projects. Superior performing versus all other DBR projects showed average joint faulting of 0.01 in [0.3 mm] versus 0.16 in [4.1 mm]), average IRI (145 in/mi [2.3 m/km] versus 210 in/mi [3.3 m/km]), and average panel cracking (5 versus 24 percent), respectively.
- During DBR construction, it is standard WSDOT practice to conduct full-depth replacement on all panels that contain 2 or more cracks. Based on the review of all DBR projects, approximately 30 percent of the panel replacements cracked prematurely. This premature cracking is not considered to be attributable to DBR; however, it is part of WSDOT rehabilitation process that needs to be resolved for long-term performance. Recently, WSDOT has made modification to the panel replacement specifications that should minimize the premature cracking.
- Based on the review of approximately 380,000 DBR slots, the presence of cracking, spalling, and debonding of the patching material is nearly non-existent, indicating superior construction and inspection practices leading to long-term performance.
- Based on the review of pavement digital images and the WSPMS, the primary form of distress occurring 10 years after DBR construction appears to be longitudinal cracking; reasoning for this cracking requires additional study.

To date, WSDOT has completed approximately 280 lane miles (450 km) and has over 17 years of experience in DBR design and construction. WSDOT has achieved a high level of knowledge and success, through appropriate specifications and construction inspection processes. In addition, a number of contractors have established themselves as competent in DBR construction. Therefore, it is envisioned that future dowel bar retrofit projects in Washington State will be well constructed and perform accordingly.

REFERENCES

1. American Association of State Highway and Transportation Officials (AASHTO) (1993). AASHTO Guide for Design of Pavement Structures. American Association of State Highway and Transportation Officials.

- Pierce, L. M. and A. Korynta (1994). *Dowel Bar Retrofit I-90, Kachess River to Yakima River*,
 Research Report WA-RD 346.1, Washington State Department of Transportation.
- Reiter, M. J., Darter, M. I. and S. H. Carpenter. (1988). Restoration of Joint Load Transfer.
 Transportation Research Record 1183, Transportation Research Board, pp. 46 58.
- Hall, K. T., Darter, M. I. and J. Armaghani. (1993). Performance Monitoring of Joint Load Transfer Restoration, *Transportation Research Record* 1388, Transportation Research Board, pp. 129 – 139.
- Ambroz, J. K., Seiler, W. J. and M. I. Darter. (1996). Load Transfer Design and Benefits for Portland Cement Concrete Pavements. Report Number 96-128-E1, ERES Consultants, Inc.
- Federal Highway Administration (FHWA). (1997). Concrete Pavement Rehabilitation: Guide for Load Transfer Restoration. Publication No. FHWA-SA-97-103, Federal Highway Administration.
- Roberts, J. H. and J. W. Mack. (2001). Dowel Bar Retrofit in Portland Cement Concrete Pavement.
 National Pavement Preservation Forum II: Investigation in the Future. FHWA-IF-03-019, Federal Highway Administration.
- Pierce L. M. (2009). Evaluation of Dowel Bar Retrofit for Long-Term Pavement Life in Washington
 State, PhD Dissertation, University of Washington, Seattle, Washington.
- Pierce, L. M and J. S. Uhlmeyer. (2008). Personal communication on faulting condition prior to dowel bar retrofit based on a low, medium to high ranking, July 2008.
- Pierce, L. M., Uhlmeyer, J. S., Weston, J. and K. W. Anderson. (2009). Forensic Evaluation of Cracking in Panels Adjacent to Panel Replacements on Interstate 5 in Washington State, ,
 Proceedings, International Society on Concrete Pavements, National Conference on Preservation,
 Repair, and Rehabilitation of Concrete Pavements, St. Louis, Missouri.

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