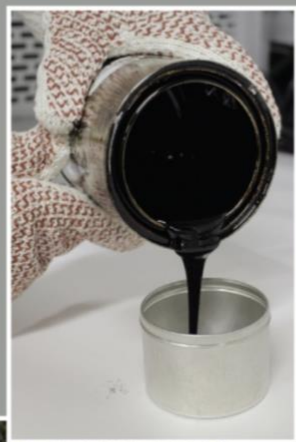

NCAT Report 20-03

BENEFITS OF REHABILITATING CONCRETE PAVEMENTS WITH SLAB FRACTURING AND ASPHALT OVERLAYS

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May 2020

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TABLE OF CONTENTS

LIST OF ACRONYMS

AAIP: Average Annual Incremental Performance
AASHTO: American Association of State Highway and Transportation Officials
a_{FS}: Fractured Slab Structural Layer Coefficient
ANOVA: Analysis of Variance
B&S: Break and Seat
C&S: Crack and Seat
CDOT: Colorado Department of Transportation
CRCP: Continuously Reinforced Concrete Pavement
DF: Dry-Freeze
E_{AC}: Modulus of Asphalt Overlay, Unit: ksi
E_{cr}: Critical Fractured Slab Modulus, Unit: ksi
E_{PCC}: Modulus of Fractured PCC Slab, Unit: ksi
ESAL: Equivalent Single Axle Load
FHWA: Federal Highway Administration
FI: Freezing Index, Unit: °C degree-days
FWD: Falling Weight Deflectometer
HSD: Honestly Significant Difference
IRI: International Roughness Index, Unit: inch/mile
IS: Information Series
JPCP: Jointed Plain Concrete Pavement
JRCP: Jointed Reinforced Concrete Pavement
LTPP: Long-Term Pavement Performance
MRI: Mean Roughness Index, Unit: inch/mile
NAPA: National Asphalt Pavement Association
PCC: Portland Cement Concrete
PSI: Present Serviceability Index
SAMI: Stress-Absorbing Membrane Interlayer
SAPA: State Asphalt Pavement Association
SBS: Styrene-Butadiene-Styrene
SMA: Stone Matrix Asphalt
SPS: Specific Pavement Studies
T_{AC}: Thickness of Asphalt Overlay, Unit: inch
T_{PCC}: Thickness of Fractured PCC Slab, Unit: inch
WF: Wet-Freeze
WNF: Wet-No Freeze
WAAP: Weighted Annual Average Performance

1 INTRODUCTION

The benefits of using asphalt overlays for rehabilitation of Portland cement concrete (PCC) pavements are grounded in economics and long-term performance. The Federal Highway Administration (FHWA) reports that the U.S. has 108,603 lane miles of composite pavements (PCC overlaid with asphalt), which is nearly double the lane miles of PCC-surfaced pavements (FHWA 2015). That means that nearly two-thirds of the concrete pavements in the U.S. have been overlaid with asphalt. However, a persistent problem with asphalt overlays on PCC pavements is reflective cracking of joints and cracks through the asphalt overlays over time. Ultimately, reflective cracking leads to a shortened performance life of the overlay. Rather than removing the concrete, which can be costly to the owner agency and increase delay times for the travelling public, slab-fracturing techniques can be used prior to placement of an asphalt overlay to significantly reduce stress concentrations at concrete joints and cracks. Slab-fracturing techniques include three methods: crack and seat (C&S) for PCC without steel reinforcement, break and seat (B&S) for PCC with steel reinforcement, and rubblization for any type of concrete pavement. C&S is intended to reduce the effective slab length of PCC pavements by producing tight surface cracks. B&S is similar but typically requires greater fracturing effort. The rubblization process typically fractures slabs into fragments with a nominal size of 4 to 8 inches (PCS, 1994). Since the existing pavement remains in-place, there are no hauling or disposal costs, resulting in substantial cost savings for state agencies (Buncher et al., 2008).

In 1994, the National Asphalt Pavement Association (NAPA) released Information Series (IS)-117 *Guidelines for Use of Asphalt Overlays to Rehabilitate PCC Pavements*. This document describes slab-fracturing processes and equipment and provides a procedure, based on the 1993 AASHTO pavement design guide, for determining the thickness of asphalt overlays placed over fractured PCC slabs (PCS, 1994). Since its publication, many states have begun to move toward the mechanistic-empirical based AASHTOWare Pavement-ME design software. Additionally, fractured slab techniques have continued to advance, with new processes and equipment having been successfully used in the rehabilitation of PCC pavements. Consequently, it is time to consolidate current information, guidance, and successful case studies on rehabilitating PCC pavements with asphalt overlays. A comprehensive synthesis of the state-of-the-practice and guidance for these slab-fracturing methods is needed to promote these methods to agencies, road owners, designers, and contractors.

2 RESEARCH OBJECTIVE AND SCOPE

The primary objective of this project was to synthesize both the historical and most recent experiences with C&S, B&S, and rubblization methods for the rehabilitation of PCC pavements with asphalt overlays. These slab-fracturing methods were also compared to alternative concrete rehabilitation treatments such as partial- or full-depth patching, overlays with sawed and sealed joints, geosynthetic interlayers with overlays, and stress-absorbing membrane interlayer with overlays. An extensive literature review was performed, a comprehensive survey of key stakeholders was conducted, and a series of case studies were documented, with the goal of informing agencies and industry of the most effective concrete pavement rehabilitation methods. Additionally, a Phase II project framework was designed and proposed to update and address NAPA's guidelines for slab fracturing and asphalt overlays.

3 LITERATURE REVIEW

3.1 Slab-Fracturing Techniques

The concept of slab fracturing is to spread out the vertical and horizontal movements at joints and cracks in concrete slabs to reduce the concentration of stresses transferred to the asphalt overlay. Slab-fracturing techniques, including C&S, B&S, and rubblization, have been widely recognized as being effective in mitigating reflective cracking distresses.

C&S and B&S minimize the movement of concrete slabs by reducing the effective slab length and seating the broken slab pieces (Freeman, 2002). Both techniques utilize pile drivers, guillotine hammers, whip hammers, or impact hammers to crack the concrete slabs followed by a heavy pneumatic roller to seat the cracked or broken pieces onto the base. Walker (2019) suggested that a test section should be used to establish the fracturing effort of the equipment with a test pit to verify effectiveness. Two roller passes should be required for seating. Excessive rolling might reduce interlock of the slab pieces. The only distinction between B&S and C&S is that C&S is used on jointed plain concrete pavement (JPCP) and B&S is applied to jointed reinforced concrete pavement (JRCP). Figure 1 shows typical fractured PCC slabs using C&S and B&S methods.

Figure 1. Typical Fractured PCC using C&S (left) and B&S (right) Methods (Antigo, 2019)

Rubblization eliminates the movement of old concrete pavement by fragmenting the slabs into 4 to 8 inch pieces, which results in a quasi-unbound aggregate base (PCS, 1994). Two types of equipment, multiple-head breakers and resonant pavement breakers, are typically used for rubblization. The multiple-head breaker rubblizes the slabs using a series of drop hammers. The breaking energy is dependent upon the lift height selected, the impact frequency, and the speed of operation (Antigo, 2018). The resonant breaker uses a resonant beam generating high frequency and low amplitude impacts to fracture concrete pavement. The breaking principle is that the high-frequency, low-amplitude resonant energy delivered to the concrete slab results in failure along a shear plane at a 45-degree angle (Fitts, 2006).

Regarding the degree of slab fracturing, NAPA IS-117 recommends that the maximum crack spacing (or resulting fragment size) be less than 30 inches for C&S projects and less than 12 to 18 inches for B&S projects and that the nominal maximum fragment size be limited to 8 to 12 inches for rubblization projects. In general, rubblization can meet the specified fragment size only when the base and subgrade provide adequate support. If the underlying support is poor, rubblization will yield inadequate support for the asphalt overlay (Antigo, 2014). In the 2000s, Antigo developed a modified rubblization technique that employs less fracture energy to produce a stiffer rubblized concrete layer to support construction operations and asphalt overlays while still effectively eliminating reflective cracking (Buncher et al., 2008). They specified that the maximum particle size should be less than 12 inches at the surface and less than 15 inches at the bottom of the slab, which differs from the recommended maximum size of 12 inches in IS-117 (Antigo, 2015). Figure 2 shows typical fractured PCC slabs using rubblization and modified rubblization methods.

a. Rubblization b. Modified Rubblization

Figure 2. Comparison of Full Rubblization and Modified Rubblization (*Antigo, 2014*)

3.2 Evaluation of Fractured PCC Slab Systems

IS-117 outlined field surveys on over 400 PCC rehabilitation projects with a focus on pavement condition as well as falling weight deflectometer (FWD) results (PCS, 1994). According to this survey, the typical modulus values for C&S slabs was 200-800 ksi, for B&S slabs it was 600-1700 ksi, and for rubblized concrete the moduli ranged from 250-750 ksi. A maximum threshold value of 1000 ksi was recommended for the critical fractured slab modulus (Ecr) to eliminate reflection cracking. However, a minimum value for Ecr to ensure that fractured slabs provide adequate support for asphalt overlay was not provided. Recent FWD analyses typically report moduli for rubblized concrete layers in the range of 50 to 100 ksi, which is much less than the original IS-117 survey results (Antigo, 2014). Therefore, further assessments of the Ecr threshold values are needed to determine if the provisional values are valid.

To assess the performance of different PCC rehabilitation treatments, the Long-Term Pavement Performance (LTPP) program Specific Pavement Studies (SPS)-6 experiment was initiated, including 14 construction projects distributed among three climatic regions (wet-freeze [WF], wet-no freeze [WNF], and dry-freeze [DF]). Figure 3 shows a map of LTPP SPS-6 projects. The sections with green indicate that they are still under evaluation by LTPP, but those with red are no longer monitored. Hall et al. (2002, 2003) conducted an LTPP data analysis of the experiment to quantify the effectiveness of rehabilitation treatments based on changes in performance (international roughness index [IRI], rut depth, and percent cracking area) before and after treatments. In that study, the percent cracking area was calculated by combining the percent area of alligator cracking and block cracking of all severities, but it did not include transverse cracking. Excluding transverse cracking, presumed to be largely associated with reflection cracking, is considered to be a significant oversight of those studies since minimizing reflection cracking is the primary objective of slab fracturing methods. Ambroz and Darter (2005) further investigated the SPS-6 experiment and found that the data availability and completeness were good overall. They suggested performing site-by-site analyses to determine the effects of design factors and treatment methods on the long-term performance of rehabilitated pavements.

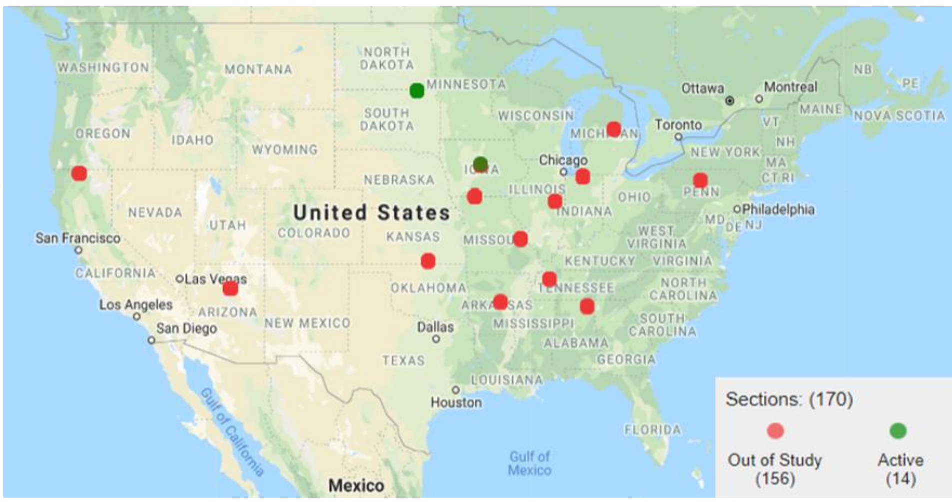


Figure 3. Map of LTPP SPS-6 Sections

To evaluate the effects of design factors, Witczak and Rada (1992) identified 454 field projects that utilized slab-fracturing techniques. They found that fractured slab modulus backcalculated from the FWD test correlated well with crack spacing, which was critical for minimizing reflective cracking distress. They also developed predictive equations to estimate the change in pavement condition index of rehabilitated pavements over time, which included annual average precipitation, annual average air temperature, subgrade modulus, and cracking spacing. Rahim et al. (2013) predicted the performance of cracked, seated, and asphalt-overlaid concrete pavement using service time, traffic volume, and thicknesses of the asphalt overlay and the existing PCC. Marshall (1999) and Ceylan et al. (2008) considered rubblized PCC as a high-quality granular material and suggested using mechanistic-empirical pavement design to predict the long-term performance of rehabilitated pavements.

To quantify the benefits of rehabilitation treatments, the previous studies mainly focused on project-level or local-level analyses. Bemanian and Sebaaly (1999) analysed four-year performance data of C&S and rubblization sections in I-80 in Nevada. The as-constructed asphalt overlay thickness of the C&S section was 6.7 inches, and that of the rubblization section was 8 inches. They reported that both the C&S and rubblization sections performed equally well in terms of ride quality and rut depth, but the 1.4-inch thinner overlay on the C&S section lowered the unit construction cost by approximately $68,780/mile compared to the rubblization section. Morian et al. (2003) evaluated the 10-year performance of Pennsylvania SPS-6 sections. They concluded that rubblization was the most cost-effective rehabilitation treatment, following by C&S or B&S with an 8-inch asphalt overlay. Puccinelli et al. (2013) investigated the long-term performance data of Arizona's LTPP SPS-6 project. They concluded that rubblization and C&S sections yielded similar performance when the asphalt overlay was over 8 inches thick, and slab-fracturing methods outperformed the minimum restoration and maximum restoration treatments for PCC slabs in terms of roughness and cracking performance. Overall, slab-fracturing techniques show promising long-term performance compared to other PCC rehabilitation treatments. However, there has not been a national-level study to quantify the benefits of these techniques or adequately quantify the effects of design factors on rehabilitated pavement performance.

3.3 Asphalt Overlay Mix Design

Asphalt overlays on PCC pavements, particularly those using C&S or B&S techniques, may still be susceptible to reflective cracking. There are several special asphalt mixture technologies, some of which are new to the market, that provide enhanced strain tolerance for inhibiting reflective cracking. When these special mixtures are used in combination with slab fracturing, reflective cracking can be practically eliminated. These technologies include stone matrix asphalt (SMA), asphalt-rubber or rubber-modified asphalt mixtures, and higher levels of polymer modification.

SMA is a special type of gap-graded asphalt mixture containing a modified asphalt binder at an elevated asphalt content, large amounts of high-quality coarse aggregate and mineral filler, and a small amount of cellulous or mineral fibers to inhibit binder drain-down. SMA is typically used as a surface course for high volume roads due to its superior rutting and cracking resistance (NAPA, 2020). In Georgia, a combination of 3/4-inch SMA and 1/2-inch SMA with thicknesses of 2 inches and 1.5 inches, respectively, was used to overlay an existing non-fractured concrete pavement. It was assumed that SMA, at a thickness of 3.5 inches, could replace up to 5.4 inches of conventional dense-graded hot-mix asphalt (Brown, 1997). In Wisconsin, several research projects were initiated to place SMA and dense-graded asphalt mixtures over continuously reinforced concrete pavement (CRCP) and JRCP from 1992 to 1994. After at least four years of performance monitoring, Schmiedlin (1998) found that the SMA mixtures were performing better in terms of crack resistance than the dense-graded mixtures. The cracking data indicated that the SMA surfaces had 40 to 50% less cracking than the dense-graded surfaces. Watson (2003) evaluated the long-term performance of SMA and Superpave projects in the United States and confirmed that SMA mixtures are generally expected to last up to 25% longer than conventional mixtures. He concluded that SMA mixtures significantly reduce the propagation rate of reflective cracking.

Asphalt-rubber is a blend of asphalt binder, reclaimed tire rubber, and additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the asphalt binder sufficiently to cause swelling of the rubber particles (ASTM, 2019). Studies have found that gap and open gradations are better suited for producing asphalt-rubber mixtures than dense gradations, and gap-graded asphalt-rubber mixtures exhibit significantly better cracking and rutting resistance and lower moisture susceptibility (Harvey et al., 2001; Kaloush, 2014; Xiao et al., 2007). For this reason, gap-graded asphalt-rubber mixtures have been widely used over fractured concrete pavements to absorb fracture energy in Arizona and California. LTPP SPS-6 test sections in Arizona demonstrate that this type of mixture has excellent long-term resistance to reflective cracking.

Polymer modified asphalt is a well-established product for improving the performance of asphalt pavements in terms of rutting and cracking resistance. In particular, styrene–butadiene–styrene (SBS) is the most common polymer used in asphalt production (Von Quintus et al., 2007; Anderson, 2007). SBS polymer has a strong interaction with asphalt and absorbs up to ten times its own volume of less polar asphalt components (Morgan and Mulder, 1995). In most cases, 2 to 3% SBS polymer is added to asphalt binder for performance enhancement. Recently, more advanced formulations of highly polymer modified asphalt binder have been developed that allow a high polymer loading up to 7 or 8%. At this content, the SBS polymer forms a more integrated and continuous polymer network in the asphalt, which turns the binder into an elastomer with substantially increased resistance to rutting and cracking (Kraton, 2016). Willis et al. (2016) evaluated the long-term performance of accelerated loading pavement sections with highly polymer modified and conventional polymer modified asphalt mixtures and confirmed that the pavement section with highly polymer modified asphalt had much better rutting and cracking performance. Bowers et al. (2018) assessed the feasibility of using highly polymer modified asphalt mixtures to mitigate reflective cracking distress. Through laboratory performance tests and field trial observations, they concluded that this type of mixture achieved satisfactory cracking performance.

In addition to designing asphalt mixtures that are resistant to reflective cracking, the use of stress-absorbing membrane interlayers (SAMI), open-graded interlayers, geosynthetics, and other similar interlayer systems are reported to be effective in retarding reflective cracking (Dhakal et al., 2016).

There are two types of SAMI used to mitigate reflection cracking. The first type is a seal coat made of asphalt-rubber and coarse aggregate chips. The second type is a polymer-rich dense-graded fine asphalt mixture. In both cases, the SAMI layer is placed on the existing concrete pavement prior to an asphalt overlay. The concept of the SAMI is to create a highly strain tolerant interlayer to dissipate energy generated by movement of the underlying pavement. Morian et al. (2005) assessed the performance of SAMIs over PCC pavements in Pennsylvania and reported that they extended asphalt overlay service lives of asphalt overlays by two years. Bischoff (2007) evaluated the performance of SAMIs used on two concrete pavement rehabilitation projects on I-94 in Wisconsin. She confirmed that the use of SAMIs delayed reflective cracking for two years.

Open-graded interlayers are open-graded asphalt mixtures much like open-graded friction course mixtures that have an interconnected void structure allowing for the dissipation of stresses within the interlayer, thereby reducing the stresses transferred into the above layers.

The Georgia Department of Transportation's Specification for open-graded interlayers (Section 415) requires that the open-graded mixture contain approximately 20 to 25% in-place air voids after compaction and have an asphalt content within the range of 4 to 5%.

Geosynthetics including fabric, geotextile, Glasgrid®, and other composites have also been used as stress-relieving interlayers to reduce reflective cracking. The effectiveness of these products is dependent on installation procedure, material properties, existing pavement condition, and interlayer location. Button and Lytton (2007) suggested that geosynthetic products should not be placed over severely deteriorated concrete pavement. They recommended that suitable concrete pavements for geosynthetic reinforcement should have load transfer efficiencies of 80% or greater. Current practice requires a minimum thickness of 1.5 inches of hot-mix asphalt placed over a geosynthetic interlayer, which ensures that the geosynthetic is fully saturated by the tack coat.

3.4 Asphalt Overlay Thickness Design

IS-117 outlined three approaches to determining the appropriate overlay thickness based on the structural layer coefficient principles used in the AASHTO 1993 pavement design guide. The Level I approach, appropriate for small projects, enables a designer to determine the overlay thickness based on PCC type and thickness, fracture mode, descriptive traffic categories, and descriptive soil categories. Level II requires more engineering effort to set input variables for the design equations. Level III requires the most effort, as the fractured slab structural layer coefficient (a_{FS}) is calculated based on non-destructive testing such as FWD. Ksaibati et al. (1999) conducted a national survey of PCC pavement rehabilitation and found that only three states (Minnesota, Missouri, and Nevada) adopted the IS-117 approaches and Missouri was no longer using them.

Currently, most state agencies utilize the AASHTO 1993 pavement design guide or mechanistic-empirical design methods to determine the asphalt overlay thickness on fractured PCC pavement. Table 1 presents a list of existing structural design approaches for asphalt overlay on fractured PCC pavement.

Table 1. List of Existing Structural Design Approaches for Asphalt Overlay Thickness

Design Approach	Adoption by States	Sources
AASHTO 1972	WI	WisDOT (2019)
AASHTO 1993	AL, AR, CO, FL, IA, KS, LA, MA, MD, MI, MS, ND, NM, OH, OK, OR, PA, SC, VA, WA, WV	AASHTO (1993), Ksaibati et al. (1999), and this study
IS-117	MN, NV	PCS (1994), Ksaibati et al. (1999), and this study
Pavement ME Design	IN, MO, WY	This study
PerRoad Design	N/A	Decker (2006)
State-Specific ME Design	CA, IL, NY, TX	Ullidtz et al. (2010), Hu et al. (2017), and this study

As shown in Table 2, the AASHTO 1993 design method recommends structural layer coefficients for fractured PCC layers based on the slab-fracturing technique and slab condition. Equations 1 and 2 are used to calculate required thickness of the asphalt overlay.

$$D_{OL} = \frac{SN_{OL}}{a_{OL}} = \frac{SN_f - SN_{eff}}{a_{OL}} \quad (1)$$

where D_{OL} is the overlay thickness, SN_{OL} is the overlay structural number, a_{OL} is the structural layer coefficient of the overlay material, SN_f is the total structural number needed to support the traffic for the design period, and SN_{eff} is the total effective structural number of the existing pavement prior to overlay.

$$SN_{eff} = a_2 D_2 m_2 + a_3 D_3 m_3 \quad (2)$$

where D_2 and D_3 are the thicknesses of the fractured slab and base layers, a_2 and a_3 are the corresponding structural layer coefficients, and m_2 and m_3 are the corresponding drainage coefficients.

Table 2. Suggested Structural Coefficients for Fractured PCC (AASHTO, 1993)

Material	Slab Condition	Layer Coefficient
Crack/Seat JPCP	Pieces 1 to 3 ft	0.25-0.35
Break/Seat JRCP	Pieces greater than 1 ft with ruptured reinforcement	0.20-0.35
Rubblized PCC	Pieces less than 1 ft	0.14-0.30

For the Pavement ME design method, the design of an asphalt overlay on fractured PCC slabs is similar to design of a new flexible pavement structure. The key step is to estimate the appropriate elastic modulus for the fractured PCC layer. The Mechanistic-Empirical Design Guide provides two hierarchical input levels for estimating this parameter (Level 1 and Level 3). Level 1 is to estimate the elastic modulus for the fractured PCC layer based on the expected control on slab fracture process. As shown in Table 3, the design guide recommends different design modulus values for fractured PCC layer according to the anticipated coefficient of variation for the back-calculated fractured slab modulus from FWD measurements. The design values are suitable for all methods of fracture. When using these values, the user must ensure that not more than 5% of the in-situ fractured slab modulus values greater than 1000 ksi. If FWD data are not available, the design guide estimates the elastic modulus of the fractured PCC based on the slab fracturing type and fractured slab size. Table 4 presents the recommended design modulus values for the fractured PCC layer at Level 3. In general, the recommended design values at Level 3 are more conservative than those at Level 1 for asphalt overlay thickness design.

Table 3. Recommended Fractured Slab Design Modulus Values for Input Level 1 (ARA, 2004)

Anticipated Coefficient of Variation for the Fractured Slab Modulus, %	Design Modulus, ksi
25	600
40	450
60	300

Table 4. Recommended Fractured Slab Design Modulus Values for Input Level 3 (ARA, 2004)

Slab-Fracturing Characteristics	Design Modulus, ksi
Rubblization	150
12-inch Crack Spacing	200
24-inch Crack Spacing	250
36-inch Crack Spacing	300

4 NATIONAL SURVEY OF CONCRETE PAVEMENT REHABILITATION

This study gathered information on methods used in the United States to rehabilitate concrete pavements with asphalt overlays and identified gaps in knowledge on those approaches. The survey questions are shown in Appendix A, which cover the following aspects:

- Respondent information;
- Current and past concrete rehabilitation projects;
- Concrete slab-fracturing techniques;
- Alternative concrete pavement treatments;
- Overlay mix design guidelines;
- Overlay structural design approaches;
- Field performance of rehabilitated concrete pavements; and
- Recommended successful concrete rehabilitation projects for case studies.

The survey was distributed to state asphalt pavement associations (SAPAs), state and local agency representatives, slab-fracturing equipment manufacturers, and consulting pavement design engineers. A total of 58 quality responses were received. Figure 4 shows the geographical distribution of respondents' organizations. As illustrated, the survey covered the majority of states that had concrete rehabilitation projects in the past 10 years. Several states (i.e., Kentucky, Louisiana, and Texas) with considerable quantity of concrete rehabilitation projects were unfortunately not represented in this study.

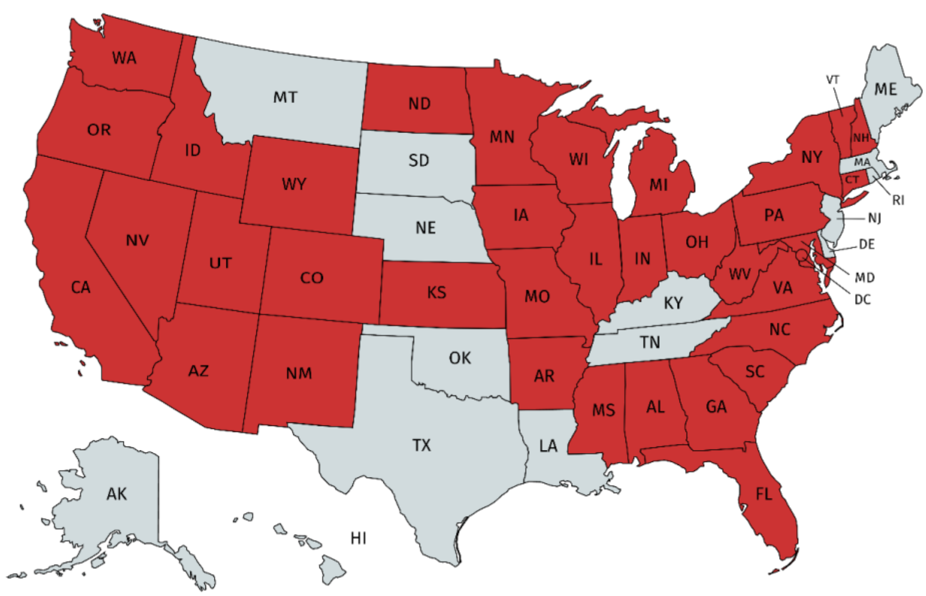


Figure 4. Geographical Distribution of Respondents' Organizations

Figure 5 shows the categories of the respondents' organizations. Majority of respondents were from federal and state agencies, contractors, and design firms. Figure 6 illustrates the years of work experience of the respondents related to concrete rehabilitation. More than 65% of respondents had at least five years of relevant experience.

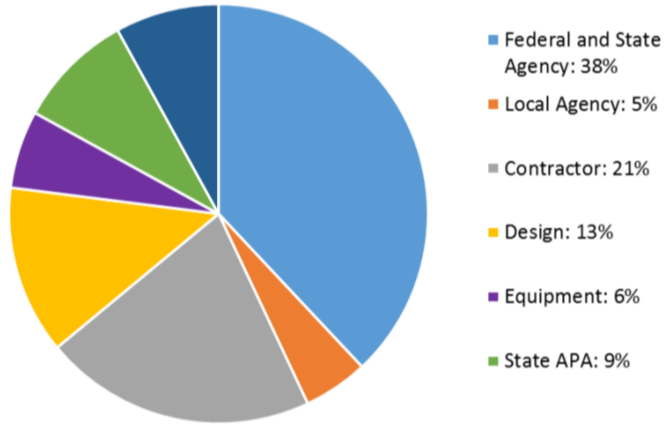


Figure 5. Overview of Respondents' Organizations

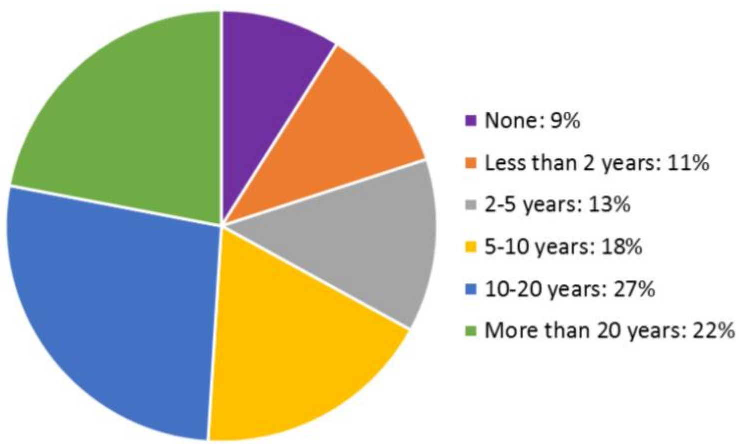


Figure 6. Respondents' Work Experience with PCC Rehabilitation

Figure 7 shows the popularity of PCC rehabilitation techniques used by respondents' organizations in the past decade. The most popular PCC rehabilitation options were minimum and maximum restoration of PCC and rubblization. Minimum restoration includes sealing of joints, surface diamond grinding, etc., and maximum restoration includes full or partial repair of broken slabs and deteriorated joints, retrofit of dowel bar, etc. C&S, stress-absorbing membrane interlayer, and special crack-resistant asphalt mixtures including stone-matrix asphalt, open-graded asphalt, and gap-graded asphalt-rubber mixtures were also frequently used for PCC rehabilitation to retard reflective cracking. Compared to rubblization and C&S, B&S was much less frequently used for PCC rehabilitation.

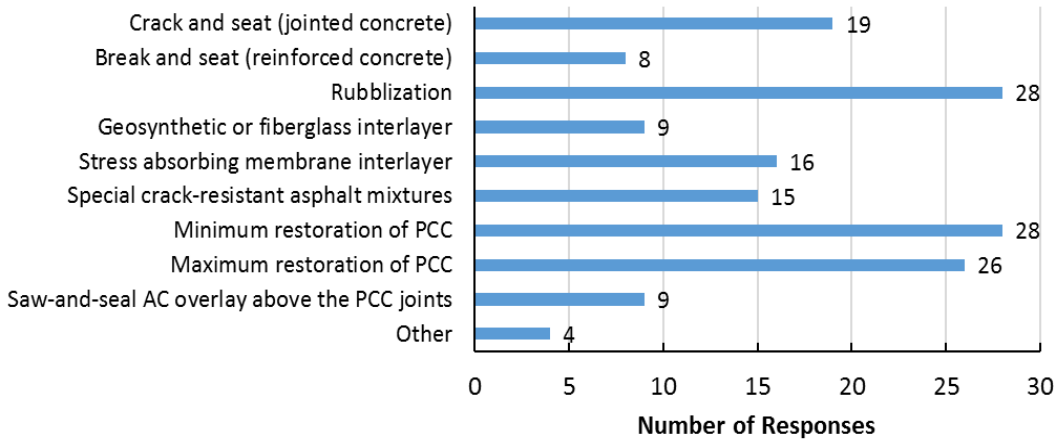


Figure 7. PCC Rehabilitation Techniques Used by Respondents' Organizations in Past 10 Years

Figures 8-10 summarize the number of C&S, B&S, and rubblization projects that were conducted by respondents' organizations in the past 10 years. These results were consistent with the finding from Figure 7 that C&S and rubblization were more popular than B&S for PCC rehabilitation.

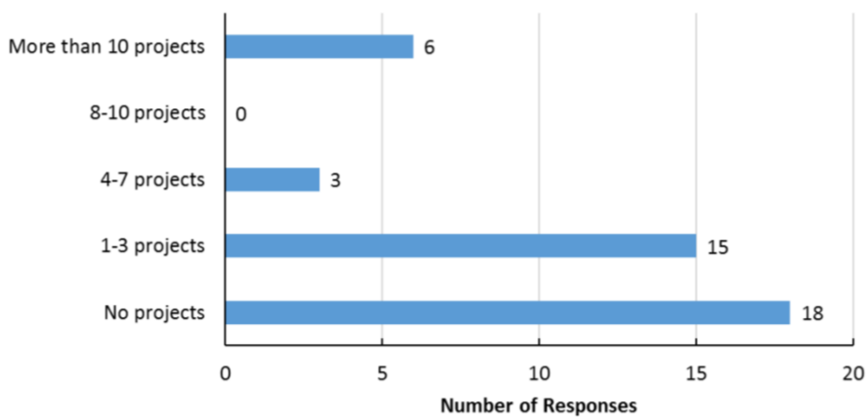


Figure 8. Number of C&S Projects Conducted by Respondents' Organizations in Past 10 Years

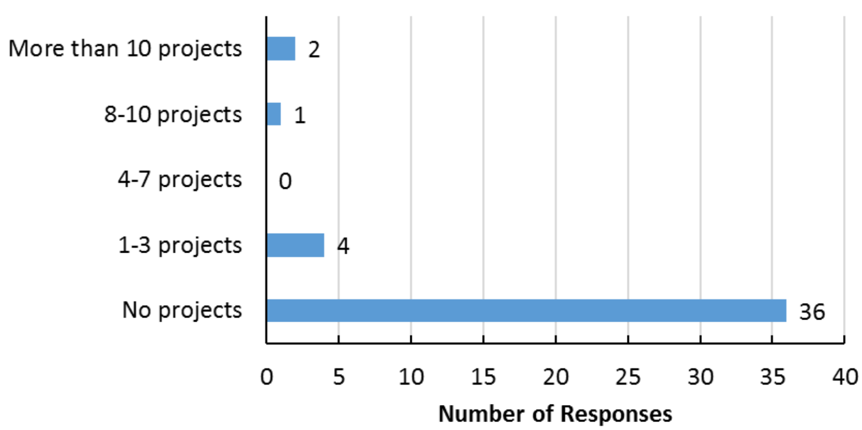


Figure 9. Number of B&S Projects Conducted by Respondents' Organizations in Past 10 Years

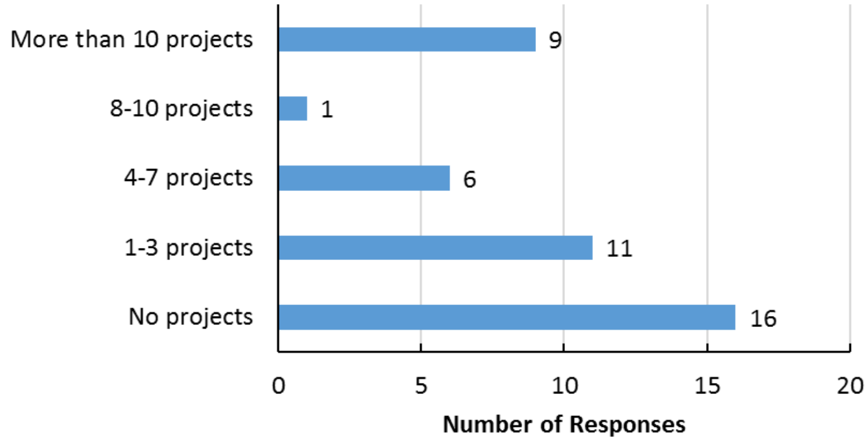


Figure 10. Number of Rubblization Projects Conducted by Respondents' Organizations in Past 10 Years

Figure 11 shows the percentage of PCC rehabilitation projects that included an edge drain system. Note that the installation of edge drain is effective in reducing the moisture damage of rehabilitated pavements. However, the survey results indicate that edge drain systems were not often used in PCC fracturing projects. This contradicted the finding from Ksaibati et al. (1999) stating that the majority of states added edge drain to rubblized pavements.

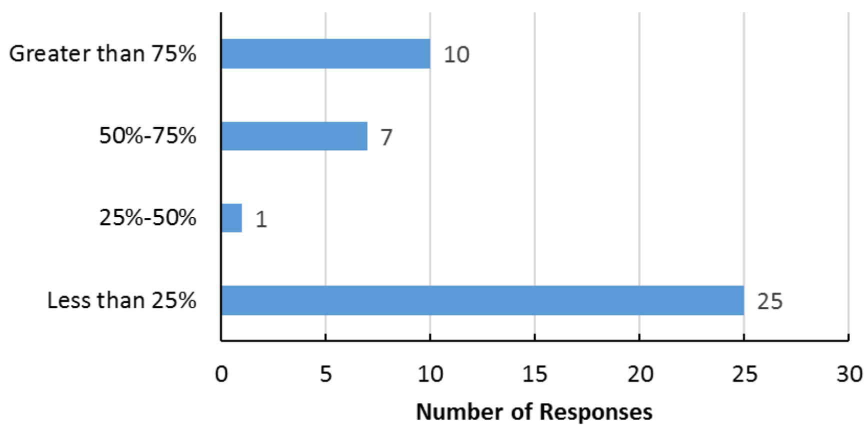


Figure 11. Percent of PCC Rehabilitation Projects Utilizing Edge Drain Systems

Figure 12 shows concerns that prevented respondents' organizations from using slab-fracturing methods to rehabilitate PCC pavements. As shown, the primary reasons were cost concerns, poor performance on a past project, maintenance of traffic concerns, and lack of understanding of slab-fracturing techniques.

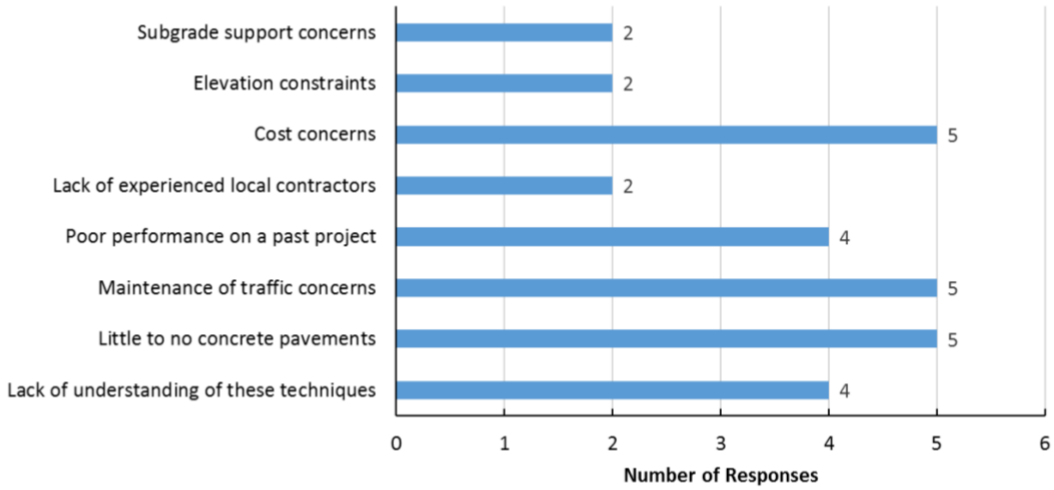


Figure 12. Reasons Preventing Respondents' Organizations from Using Slab-Fracturing Methods

Figure 13 shows the identified challenges faced in performing slab-fracturing methods, including lack of agency specifications, unattainable specification requirements, lack of quality tests with quick results, and difficulty in retrofitting water drainage systems. Some respondents indicated other challenges such as lack of agency experience or specified projects with slab-fracturing techniques.

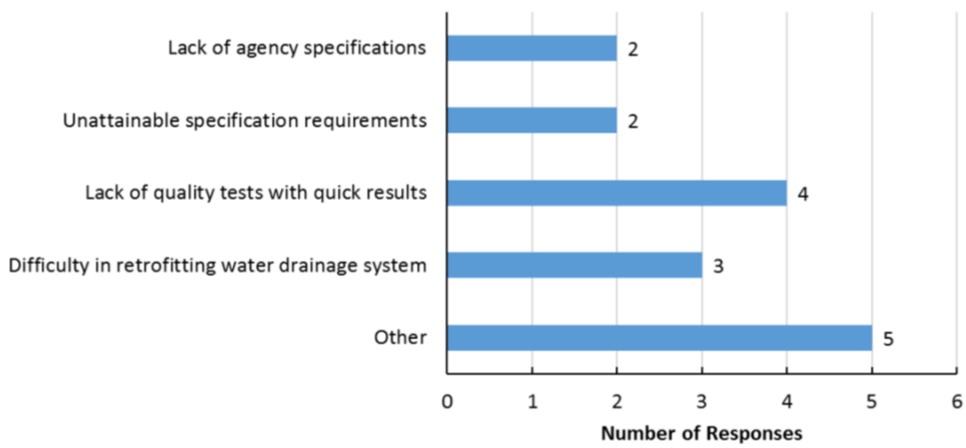


Figure 13. Challenges in Performing Slab-Fracturing Methods

Figure 14 summarizes the types of equipment used for breaking PCC slabs in the past 10 years. As indicated, guillotine-type equipment, multiple-head breaker, resonant pavement breaker, and hydraulic or pneumatic hammer were the most popular types of equipment used. Figure 15 demonstrates the types of equipment used for seating fractured PCC slabs in the past 10 years. Heavy pneumatic rollers, steel vibratory rollers, and a combination of vibratory and pneumatic rollers were mainly used for seating. One respondent indicated other equipment for seating but did not specify the equipment type.

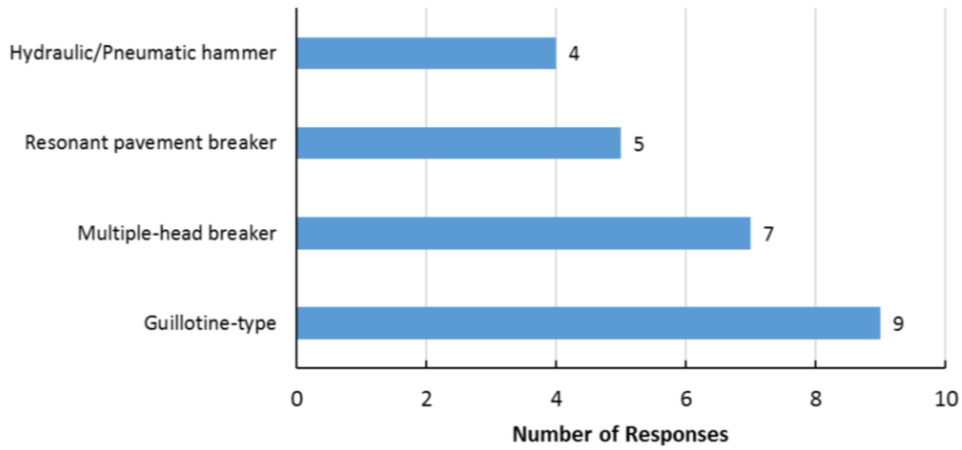


Figure 14. Types of Equipment Used for Breaking PCC Slabs in Past 10 Years

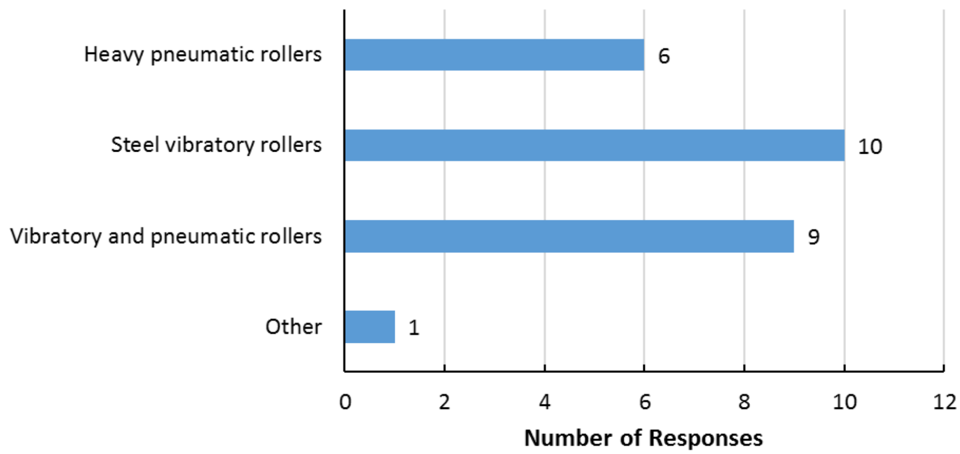


Figure 15. Types of Equipment Used for Seating Fractured PCC Slabs in Past 10 Years

This survey investigated the asphalt overlay mix design, which was used to determine the optimum mixture component materials, including aggregate, asphalt binder, and additives. As shown in Figure 16, only five organizations required or supplied specific mixture for use on fractured PCC pavements. The mixtures used to mitigate reflective cracking were utilized standard dense-graded mixture, modified dense-graded mixture with lower air voids and higher asphalt content, standard open- or gap-graded mixture, and modified gap-graded asphalt-rubber mixture, as presented in Figure 17.

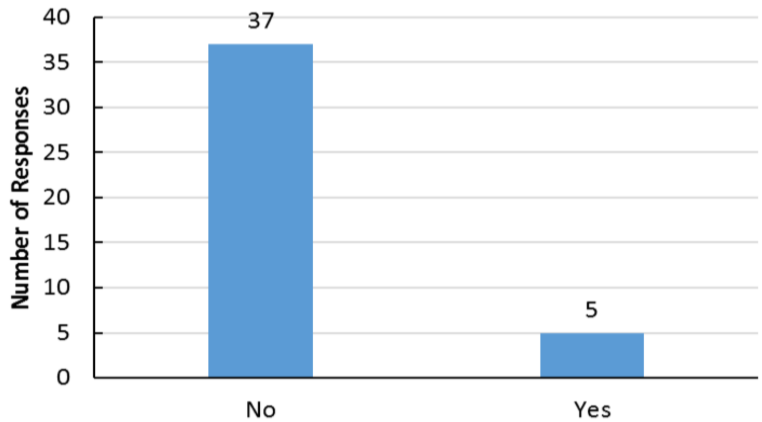


Figure 16. Respondents' Organization Requirement or Supply of Specific Mixture for Use on Fractured PCC

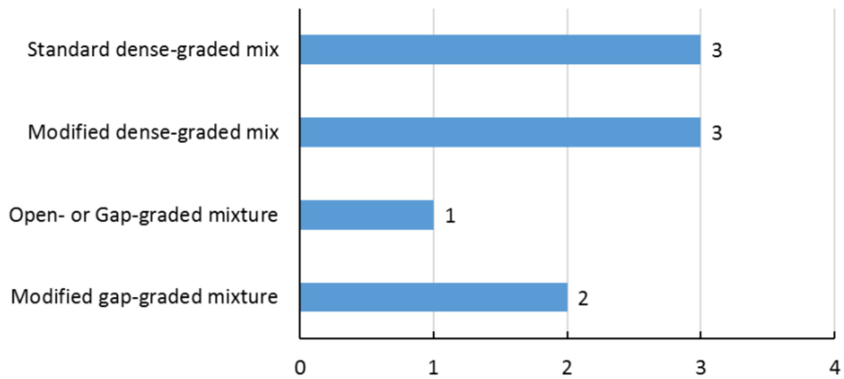


Figure 17. Types of Asphalt Mixture Required or Supplied for Use on Fractured PCC

Figure 18 summarizes the thickness ranges of asphalt overlays for existing projects that used PCC fracturing techniques. As shown, most asphalt overlays had layer thicknesses greater than 3 inches, and about 27% of asphalt overlays had layer thicknesses greater than 8 inches.

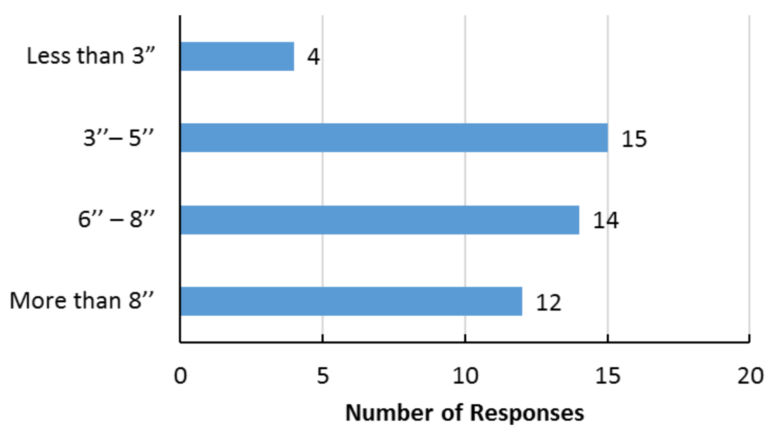


Figure 18. Thickness Range of Asphalt Overlays for Existing Projects Using PCC Fracturing Techniques

This survey also investigated the structural design methods for asphalt overlay, which were used to determine the layer thickness required to accommodate a given loading regime. Figure 19 presents the structural design methods used for asphalt overlays on fractured PCC. The majority of states used the AASHTO 1993 method. It is worth mentioning that Wisconsin used the AASHTO 1972 method; Indiana, Missouri, and Wyoming used Pavement ME design; and California, New York, and Illinois used their own mechanistic-empirical design methods.

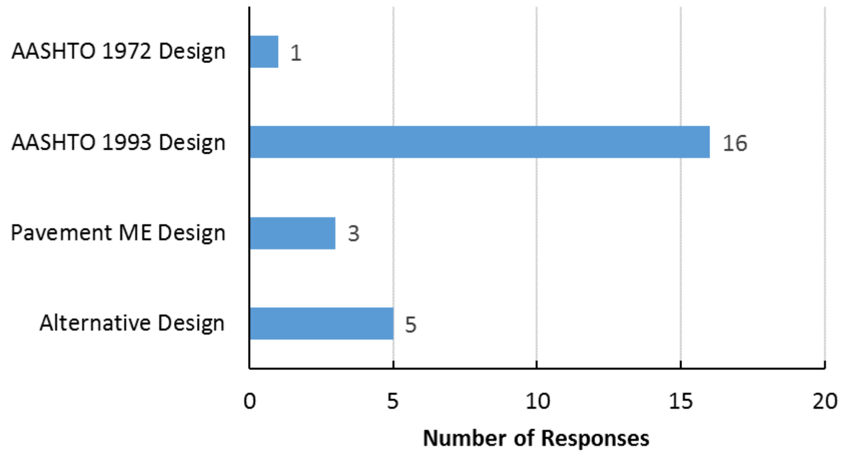


Figure 19. Structural Design Method Used for Asphalt Overlays on Fractured PCC

For those states that used the AASHTO 1993 method, Figure 20 shows the approaches they employed for determining layer coefficients of fractured PCC layers. As demonstrated, most of the states used AASHTO recommended values, which are shown in Table 2. Maryland, Iowa, and Oregon used FWD data; Colorado and South Carolina used aggregate type, size and shape; and South Carolina and Nevada used age and condition to determine the layer coefficients of fractured PCC layers.

Figure 20. Approaches for Determining Layer Coefficients of Fractured PCC Layers

Figure 21 presents the typical distresses observed for rehabilitated PCC pavements with asphalt overlay. As shown, the predominant distress is reflection cracking, followed by drainage failure and delamination or debonding of the overlay. Other distresses were identified by respondents, including thermal cracking, top-down cracking, and longitudinal joint cracking.

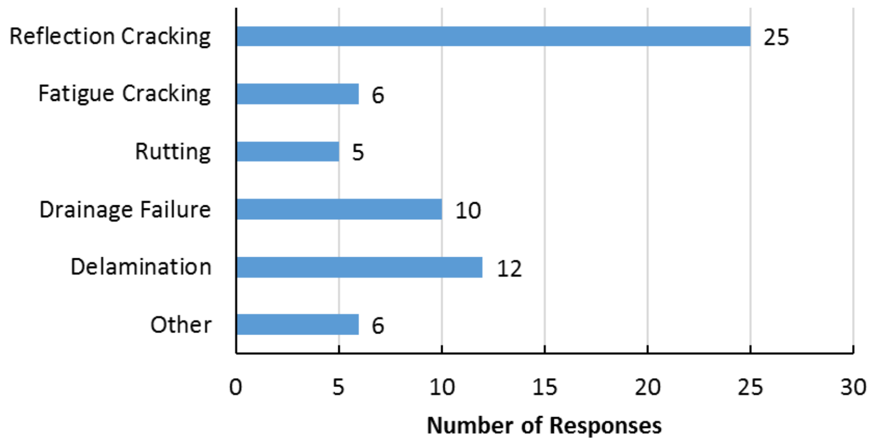


Figure 21. Typical Distresses Observed for Rehabilitated PCC with Asphalt Overlay

5 LTPP DATA ANALYSIS

5.1 LTPP SPS-6 Data Assembly

The LTPP SPS-6 experiment was conducted to assess the effectiveness of different rehabilitation treatments on the life extension of existing jointed PCC pavements. Starting from the early 1990s, there were fourteen SPS-6 projects constructed in the United States. Each project contained eight core pavement sections, which were coded as 601-608 as shown in Table 5 (Ambroz and Darter, 2005).

Table 5. Section Codes of SPS-6 Experiment (Ambroz and Darter, 2005)

Section Code	PCC Treatment	Overlay Treatment	Overlay Thickness (in)	Number of Sections
601	Routine Maintenance	-	-	14
602	Minimum Restoration	-	-	14
603	Minimum Restoration	-	4	14
604	Minimum Restoration	Saw and Seal	4	14
605	Maximum Restoration	-	-	14
606	Maximum Restoration	-	4	14
607	C&S or B&S	-	4	14
608	C&S or B&S	-	8	14
609[1]	Rubblization	-	≤ 6	4
610[1]	Rubblization	-	≤ 8 & > 6	6
611[1]	Rubblization	-	> 8	5

Note: [1] Section codes of 609, 610, and 611 were assigned by this study.

These sections have various PCC treatments (routine maintenance, minimum and maximum restoration, and C&S or B&S), asphalt overlay thicknesses (4-inch and 8-inch), and additional overlay treatment (saw and seal). Minimum restoration is referred to as joint and crack sealing, partial and full-depth patching, and full surface diamond grinding. Maximum restoration includes removing and replacing existing joint and crack sealing, performing additional joint and crack sealing, removing and replacing existing partial and full-depth patching, performing additional partial and full-depth patching, correcting poor load transfer at joints, full surface diamond grinding, retrofitting subsurface edge drains, and undersealing (Ambroz and Darter, 2005).

Since this study only focused on asphalt overlays, the sections coded as 601, 602, and 605 were excluded from the data assembly. In addition to the core sections, most of the projects included sections utilizing the rubblization technique, which were included in the data assembly. As shown in Table 5, the codes of 609, 610, and 611 were assigned to slab rubblization with various asphalt overlay thicknesses. Note that some projects also had other rehabilitation treatments, including geosynthetic interlayer, stress-absorbing membrane interlayer, etc. Given that there were limited projects with these treatments, they were not considered in this study.

Figure 22 shows the number of pavement sections using various slab-fracturing techniques from the LTPP SPS-6 experiment. As presented, there are 24 C&S sections, 14 B&S sections, and 15 rubblization sections. Among them, some C&S and B&S sections have asphalt overlay thicknesses other than 4-inch and 8-inch, which were not included in the data assembly. Figure 22 also demonstrates that C&S was used for JPCP, B&S was applied to JRCP, and rubblization was suitable for both JPCP and JRCP.

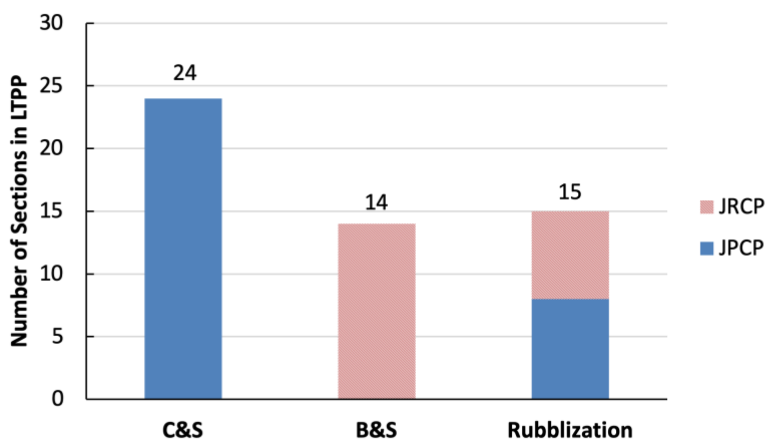


Figure 22. Identified Pavement Sections Using Slab Fracturing Techniques

Table 6 summarizes the extracted data from the LTPP database, which includes climatic data, traffic volume, layer thicknesses, FWD back-calculated layer moduli, and performance data such as IRI, rut depth, longitudinal cracking, and transverse cracking. The climatic conditions were quantified by average annual precipitation, average annual air temperature, average annual freezing index, and average annual number of freezing and thawing days. The annual freezing index was calculated as the annual cumulative average daily air temperatures below 32°F. The annual number of freezing and thawing days was defined as the number of days in a year when the air temperature went from less than 32°F to greater than 32°F. The traffic volume was represented by the annual number of equivalent single axle loads (ESALs). In this study, thickness and back-calculated moduli were extracted only for asphalt overlays and existing PCC.

The effects of underlying layer properties were not considered. Note that FWD back-calculation usually provides multiple solutions. To ensure the rationality of back-calculated results, the LTPP utilized two programs (EVERCALC 5.0 and MODCOMP 6.0) with the internal check of data quality to determine the elastic layer moduli of composite pavements. For performance data, this study collected the average of left and right wheel path IRI indicated as mean roughness index (MRI), maximum average rut depth (Max_Mean_Depth_1_8), longitudinal cracking percent area (MEPDG_CRACKING_PERCENT_AC), and transverse cracking length (MEPDG_CRACKING_LENGTH_AC). Note that LTPP does not differentiate reflective cracking from transverse cracking distress. To evaluate the long-term performance of the treatments considering their unequal application times, two indicators were employed in this study, namely, weighted annual average performance (WAAP) over the analysis period and average annual incremental performance (AAIP). WAAP is the normalized performance under the performance over service time curve, which is calculated by Equation 3 (Gong et al., 2016).

$$WAAP = \frac{\sum_{i=0}^{n-1}\left(P_i + P_{i+1}\right) \times t_i / 2}{\sum_{i=0}^{n-1} t_i} \tag{3}$$

where P_i is the performance value measured at the *i*th survey; P_{i+1} is the performance value measured at the (*i+1*)th survey, t_i is the time (in years) between *i*th survey and (*i+1*)th survey, and *i*=0 represents the first measurement after rehabilitation treatment. AAIP indicates the average performance change per year, which is calculated by Equation 4.

$$AAIP = \frac{P_{final} - P_{initial}}{t_{service}} \tag{4}$$

where $P_{initial}$ is the first performance value measured after the investigated rehabilitation activity, P_{final} is the final performance value before the next rehabilitation activity or the end of monitoring period, and $t_{service}$ is the service time (in years) between the initial and final performance measurements.

Table 6. Summary of Extracted Data from LTPP SPS-6 Experiment

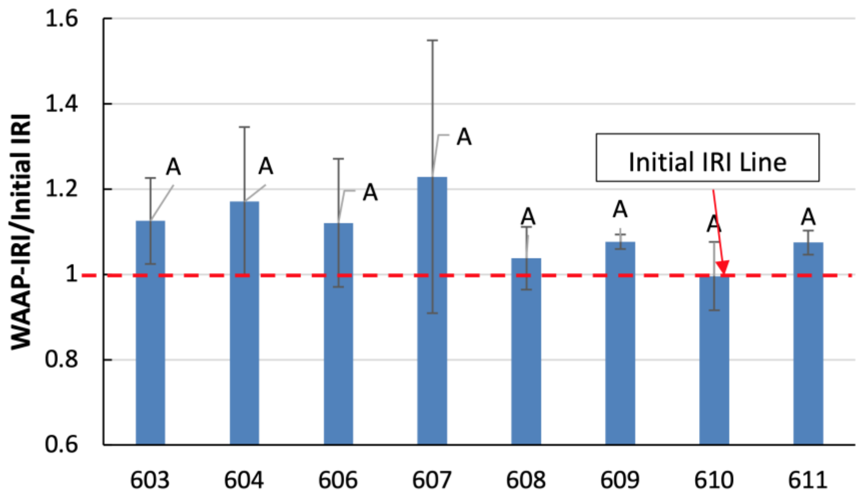
Data Type	LTPP Table Name	LTPP Field Name
Climate	CLM-VWS_PRECIP_ANNUAL	TOTAL_ANN_PRECIP
	CLM-VWS_TEMP_ANNUAL	MEAN_ANN_TEMP_AVG
	CLM-VWS_TEMP_ANNUAL	FREEZE_INDEX_YR
	CLM-VWS_TEMP_ANNUAL	FREEZE_THAW_YR
Traffic	TRF_TREND	ANNUAL_ESAL_TREND
Structure	TST_L05B	REPR_THICKNESS
	BACKCAL_MODULUS_SECTION_LAYER	AVG_MODULUS
Performance	MON_HSS_PROFILE_SECTION	MRI
	MON_T_PROF_INDEX_SECTION	MAX_MEAN_DEPTH_1_8
	MON_DIS_AC_CRACK_INDEX	MEPDG_CRACKING_PERCENT_AC
	MON_DIS_AC_CRACK_INDEX	MEPDG_CRACKING_LENGT_AC

5.2 Effects of PCC Treatments on Pavement Performance

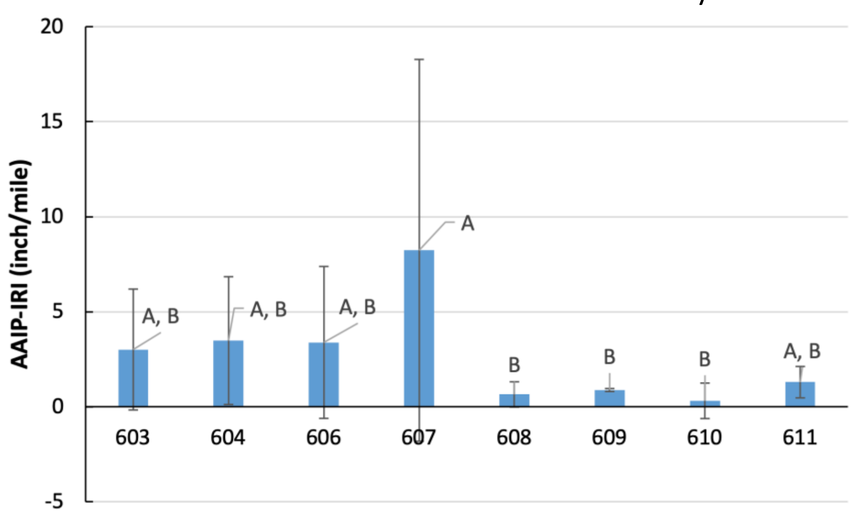
To determine the benefits of slab-fracturing techniques, this study compared the long-term performance of composite pavements that utilized these techniques and other PCC treatments. As mentioned previously, pavement performance data including IRI, rut depth, longitudinal cracking percent, and transverse cracking length were quantified by WAAP and AAIP, denoted as WAAP-IRI, AAIP-IRI, WAAP-RD, AAIP-RD, WAAP-LC, AAIP-LC, WAAP-TC, and WAAP-TC, respectively.

Figures 23a and 23b show the influences of PCC treatments on pavement smoothness. The average WAAP-IRI and AAIP-IRI were calculated for each type of pavement section. A pavement section showing a high WAAP-IRI with a low AAIP-IRI indicates that it has a high IRI within the first several years but a small change in IRI over time, and vice versa. Error bar represents one standard deviation of uncertainty. It can be seen that the variabilities of the WAAP-IRI/Initial IRI and AAIP-IRI values, as indicated by the 95% confidence interval whiskers, were notably higher for this performance measure. As shown in Figure 23a, the average WAAP-IRI was normalized by dividing by the initial IRI after treatment. It is seen that most of the pavement sections had greater weighted IRI values after approximately seven years of service. Pavement sections using C&S or B&S with 4-inch asphalt overlays (section code 607) had the highest weighted IRI and highest change in IRI, indicating that this rehabilitation treatment tended to yield the poorest long-term ride quality. However, those sections using PCC rubblization with 6 to 8-inch asphalt overlays (section code 610) did not exhibit any significant change in weighted IRI through long-term service. This demonstrates that rubblization with a 6 to 8-inch asphalt overlay provided a relatively smooth pavement surface.

An Analysis of Variance (ANOVA) with Tukey's honestly significant difference (HSD) test was conducted to statistically rank these results, as shown in Figure 23a. The confidence level was assigned as 95% (α=0.05). Label A represents the group of sections that had the highest value, label B represents the group of sections having statistically lower value, whereas label A/B represents the group of sections that had the measured value between Group A and Group B. As presented in Figure 23a, all of the PCC treatments were ranked the same in terms of WAAP/Initial IRI. This indicates that there was no statistical difference among these treatments for improving the weighted annual average IRI. Figure 23b shows AAIP-IRI for the different PCC treatments, indicating the average change in IRI per year. As presented, the pavement sections using C&S or B&S with 4-inch asphalt overlays (section code 607) had the highest annual change in IRI, while C&S or B&S with 8-inch asphalt overlays (section code 608) and rubblization with various overlay thicknesses (section codes 609, 610, and 611) yielded much lower annual changes in IRI. Tukey's HSD test was also conducted to rank these results. The ranking results show that pavement sections using C&S or B&S with 8-inch asphalt overlays or rubblization with various overlay thicknesses had statistically lower annual changes in IRI than the other PCC treatments, including minimum and maximum restoration, overlay saw and seal, and C&S or B&S with 4-inch asphalt overlays.



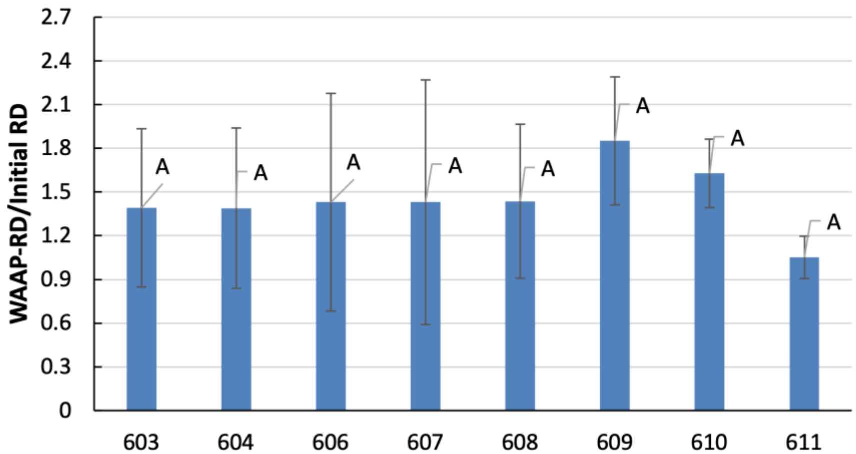
a. Effects of PCC Treatments on WAAP-IRI Divided by Initial IRI



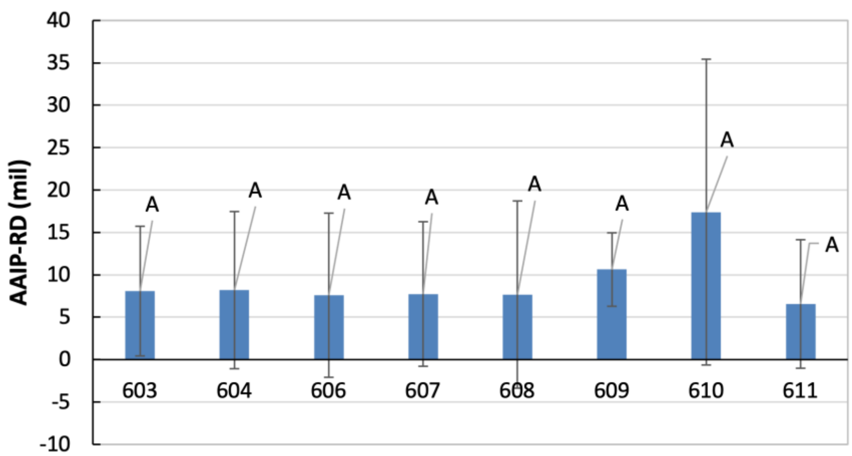
b. Effects of PCC Treatments on AAIP-IRI

Figure 23. Effects of PCC Treatments on International Roughness Index

Figures 24a and 24b present the influence of PCC treatments on rutting performance. As shown in Figure 24a, rubblization with a 6-inch or less asphalt overlay (section code 609) and with more than an 8-inch asphalt overlay (section code 611) provided the highest and lowest weighted rut depths, respectively. Similarly, the pavement sections using these two PCC treatments had the highest and lowest annual change in rut depth, as shown in Figure 24b. The Tukey's HSD test results shown in Figures 24a and 24b indicate that these PCC treatments were not statistically different with respect to long-term rutting performance.



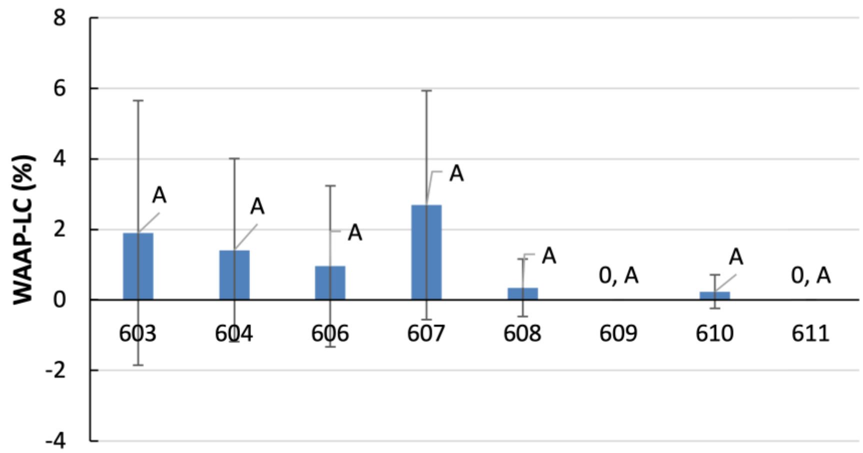
a. Effects of PCC Treatments on WAAP-RD Divided by Initial RD



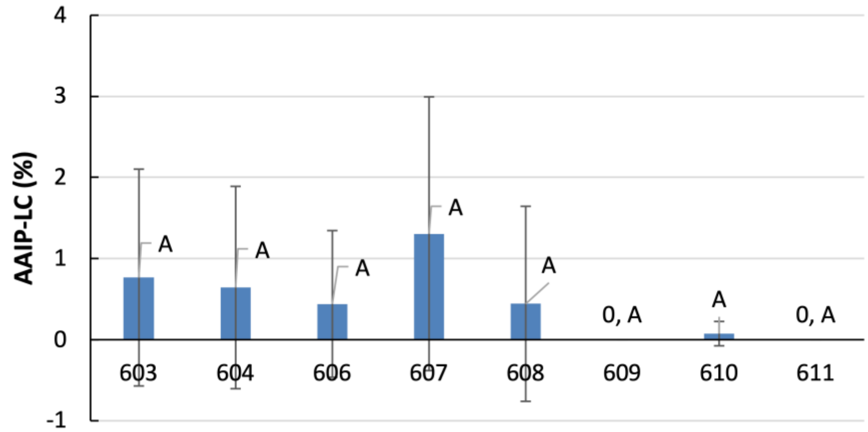
b. Effects of PCC Treatments on AAIP-RD

Figure 24. Effects of PCC Treatments on Rut Depth

Figures 25a and 25b demonstrate the impacts of PCC treatments on longitudinal cracking performance. Since as-constructed asphalt overlays can be assumed to have no cracking distress, the weighted cracking performance does not require normalization for comparisons. As presented in Figures 25a and 25b, all of the sections had relatively low weighted longitudinal cracking and relatively low annual change. Compared to other pavement sections, the pavement sections with C&S or B&S with 4-inch asphalt overlays (section codes 607) had the greatest amount of longitudinal cracking and the highest annual change in longitudinal cracking, while those using rubblization with an asphalt overlay thicker than 6 inches exhibited no longitudinal cracking through seven years of service. The Tukey's HSD results show that the differences in longitudinal cracking performance among these pavement sections were not statistically significant.



a. Effects of PCC Treatments on WAAP-LC



b. Effects of PCC Treatments on AAIP-LC

Figure 25. Effects of PCC Treatments on Longitudinal Cracking

Table 7 presents the effects of PCC treatments on transverse cracking performance. In contrast to the other pavement performance measures, the pavement sections differed significantly with regard to transverse cracking performance. Tukey's HSD test was performed to rank the pavement sections in terms of transverse cracking performance. As shown in Table 7, the grouping labels A, B, C, and D indicate the descending sequences of weighted transverse cracking length or the corresponding annual change in transverse cracking. For instance, the group label A represents the group of sections that had the greatest amount of transverse cracking and the highest annual change in transverse cracking. This analysis shows that pavement sections using minimum restoration of PCC with saw and seal of 4-inch asphalt overlays (section code 604) had the greatest amount of transverse cracking and the fastest annual change, followed by the sections using maximum and minimum restoration of PCC with 4-inch asphalt overlays (section codes 603 and 606). The analysis also indicates that C&S or B&S with an 8-inch asphalt overlay (section code 608) and rubblization with an asphalt overlay thickness greater than 8 inches (section code 611) or less than 6 inches (section code 609) resulted in statistically lower transverse cracking than the other treatments. However, it was found that rubblization of PCC with 6 to 8-inch asphalt overlays (section code 610) had more transverse cracking compared to those with thinner asphalt overlays. This was because LTPP aggregates both thermal cracking and reflective cracking into the transverse cracking category. The sections coded as 610 were mainly from the WF climatic region (Missouri, Illinois, and Michigan), which were expected to have substantial thermal cracking distresses.

Table 7. Effects of PCC Treatments on Transverse Cracking Performance

Section ID	WAAP-TC			AAIP-TC		
	Mean (ft/mile)	Standard Deviation	Grouping	Mean (ft/mile)	Standard Deviation	Grouping
603	1158.9	892.8	B	305.7	172.1	A B C
604	2373.9	1439.9	A	314.2	226.5	A
606	1261.9	852.7	B	372.8	220.7	A B
607	524.8	563.9	B C	188.5	167.9	B C D
608	126.7	146.3	C	86.1	124.6	D
609	76.6	132.5	C	25.3	43.3	D
610	328.9	240.8	B C	92.4	59.7	B C D
611	15.3	19.0	C	10.0	12.7	D

Pavement sections were subdivided according to climatic regions to account for the climate effect. Table 8 compares the transverse cracking performance of pavement sections in WF and WNF zones. Note that the DF zone was not included in the analysis since there was only one project (Arizona) located in this region. Due to the limited sample size, the rubblization sections were grouped in Table 8. It is clear that slab-fracturing techniques, including C&S, B&S, and rubblization, effectively improved the transverse cracking performance of composite pavements in both WF and WNF regions. C&S or B&S with 8-inch asphalt overlays yielded much less transverse cracking than those with 4-inch overlays, especially in the WNF region. Compared to the other treatments, rubblization provided extraordinarily better transverse cracking performance. In particular, this technique resulted in extremely low transverse cracking distresses in the WNF region, where thermal cracking distress is much less common. This implies that rubblization of existing PCC can nearly eliminate reflective cracking distress. Thus, it is appropriate to consider rubblized PCC slabs as an unbound aggregate layer.

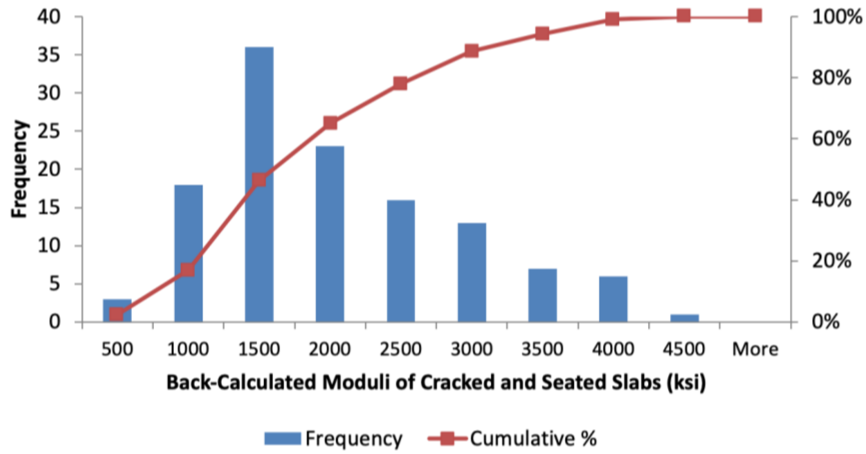
Table 8. Transverse Cracking Performance of Pavements in WF and WNF Regions

Climate Region	Section ID	WAAP-TC		AAIP-TC	
		Mean (ft/mile)	Grouping	Mean (ft/mile)	Grouping
WF	603	1236.0	A B	271.9	A B
	604	2099.9	A	416.6	A
	606	1296.2	A B	354.8	A
	607	678.0	A B	199.6	A B
	608	192.2	B	128.8	A B
	Rubblization	178.5	B	53.9	B
WNF	603	787.8	B	291.5	A B C
	604	2598.8	A	507.9	A
	606	1069.2	B	369.1	A B
	607	218.1	B	137.8	B C
	608	22.2	C	18.0	C
	Rubblization	2.1	C	4.8	C

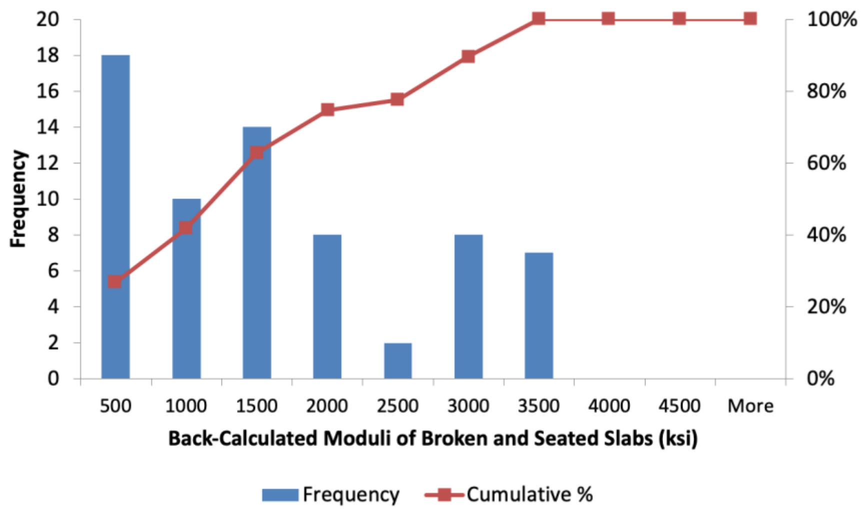
5.3 Backcalculated Moduli of Fractured PCC Slabs

The modulus of a fractured PCC slab (E_{PCC}) is an important parameter to assess the fracturing process, which is more direct and accurate than other indicators such as crack spacing and nominal fragment size (PCS, 1994). Generally, a greater degree of slab fracturing or steel-slab debonding results in a lower E_{PCC}. PCS (1994) recommended that in order to eliminate reflective cracking, a C&S or B&S project should have less than 5% of area exceeding a threshold level of E_{PCC} = 1,000 ksi. In the field, E_{PCC} is typically back-calculated from the FWD deflection basin. LTPP SPS-6 comprehensively recorded the back-calculated moduli of the PCC slabs that were fractured by using the C&S, B&S and rubblization techniques.

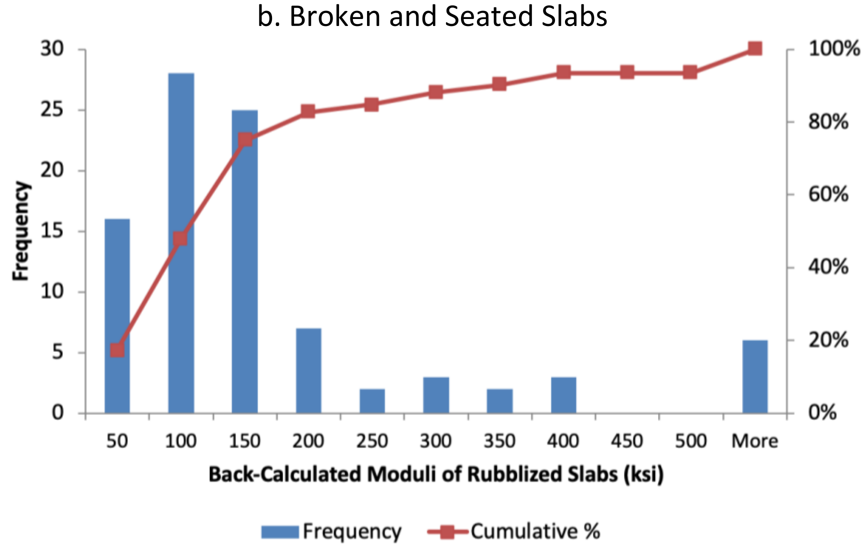
Figure 26 shows the moduli distributions of these fractured slabs. As shown, the majority of C&S and B&S sections had slab moduli ranging from 507 ksi to 3,553 ksi, and most of them exceeded the threshold level (E_{PCC} = 1,000 ksi) suggested by PCS (1994). As described previously, these sections showed satisfactory reflective cracking performance in general. This demonstrated that the existing threshold level of E_{PCC} was not suitable for recent slab-fracturing projects. It is also shown that the broken and seated slabs had slightly lower E_{PCC} than the cracked and seated slabs. This was because B&S usually requires greater fracturing effort, which results in a higher degree of fracturing and debonding. As can be seen from Figure 26c, most of the rubblization sections had slab moduli ranging from 51 ksi to 203 ksi, which were much lower than the C&S and B&S slabs but greater than conventional unbound aggregates (Gu et al., 2015). It is typically considered that rubblization of PCC with thick asphalt overlay could be a candidate for perpetual pavement.



a. Cracked and Seated Slabs



b. Broken and Seated Slabs

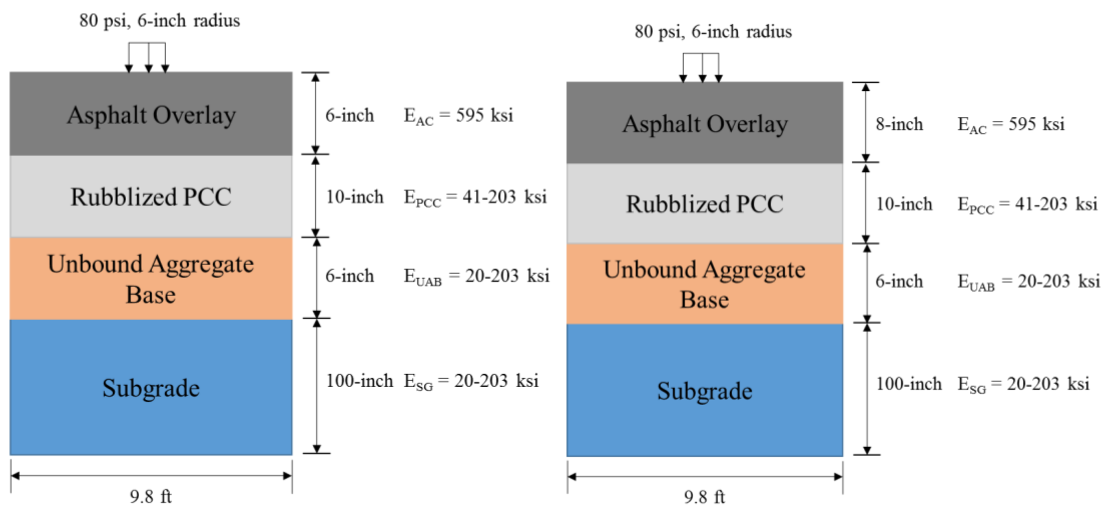


c. Rubblized Slabs

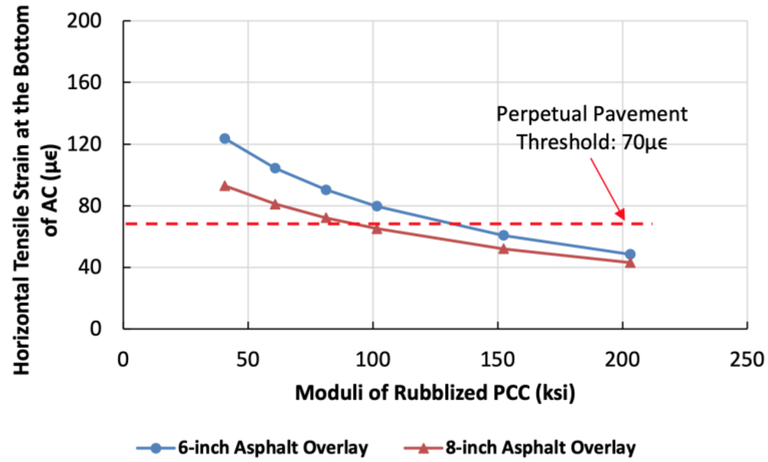
Figure 26. Distribution of Back-Calculated Moduli of Fractured Slabs

As part of this study, a case study was performed to evaluate the structural performance of two rehabilitated pavements using the rubblization technique. Figure 27a shows the layer thicknesses and material moduli of the two pavements. The asphalt overlay thickness varied from 6 to 8 inches, and the rubblized slab moduli varied from 41 ksi to 203 ksi. The pavement structures were subjected to dynamic loading with an amplitude of 80 psi. The circular loading area had a radius of 6 inches. A linear elastic finite element program was used to compute the structural responses. Figures 27b and 27c present the two critical pavement responses of the pavement structures with a variety of material inputs.

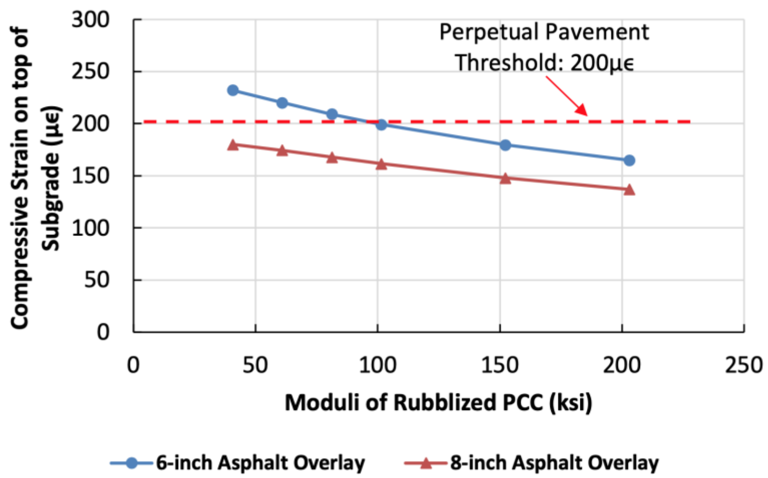
According to perpetual pavement design criteria, horizontal tensile strain at the bottom of the asphalt concrete should be less than 70 με to achieve satisfactory fatigue cracking performance, and compressive strain on the top of the subgrade should be lower than 200 με to eliminate rutting problems. As can be seen from Figures 27b and 27c, the pavement with an 8-inch asphalt overlay could be perpetual when the modulus of the rubblized slab is greater than 81 ksi, and the pavement with a 6-inch asphalt overlay could achieve perpetual status when the slab modulus is higher than 122 ksi. Increasing the moduli of the rubblized slabs was effective in prolonging the fatigue life of composite pavements and reducing their rut depth. However, if slab moduli are too high, it might indicate an insufficient rubblization process, which will result in transverse cracking problems. Therefore, pavement designers should be cautious about balancing the degree of rubblization to achieve satisfactory overall performance.



a. Two Rehabilitated Pavement Structures with Rubblized PCC



b. Tensile Strain at Bottom of the Asphalt Overlay



c. Compressive Strain on Top of the Subgrade

Figure 27. Structural Analysis of Rehabilitated Pavements with Rubblized PCC

5.4 Effects of Design Factors on Transverse Cracking Performance

The design factors that were collected in this study included the layer thicknesses of asphalt overlay and existing PCC, the back-calculated moduli of these two layers, the traffic volume quantified by the average annual number of ESALs, and the climatic parameters such as the average annual precipitation, average annual air temperature, average annual freezing index, and average annual number of freezing and thawing days. Considering the available sample size, only the C&S or B&S sections (section codes 607 and 608) were investigated in this subsection.

A stepwise multiple linear regression analysis was performed to establish the correlation between the design factors and the transverse cracking performance of C&S or B&S sections (AAIP-TC). The p-value obtained from the t-test was used to identify the significant variables in the regression model. A p-value less than 0.05 indicates that the variable is significant at a 95% confidence level. Table 9 presents the results produced by the JMP software. The t-ratio is a ratio of the departure of an estimated parameter from its notional value to its standard error. A higher absolute value of the t-ratio corresponds to a smaller p-value (Gu et al. 2015). As shown in Table 9, the thickness of existing PCC layer (T_{PCC}), modulus of fractured slab (E_{PCC}), the modulus ratio of E_{PCC}/E_{AC}, and freezing index (FI) were identified as the significant variables. Increasing T_{PCC}, E_{PCC}, E_{PCC}/E_{AC}, and FI would result in negative impacts on the transverse cracking performance of rehabilitated pavement. This was reasonable because the increase of T_{PCC}, E_{PCC}, and E_{PCC}/E_{AC} would lead to greater horizontal relative movement between asphalt overlay and existing PCC, which would accelerate the growth of reflective cracking. Compared to precipitation and air temperature, freezing index was a more significant factor affecting pavement thermal cracking. Although the thickness of asphalt overlay (T_{AC}) was not discerned as a significant parameter, it was necessary to be included to improve prediction accuracy. For an individual pavement section, the accumulation of traffic volume undoubtedly leads to more transverse cracking distresses. However, the average annual number of ESALs was not distinguished as a significant variable affecting AAIP-TC when the pavement sections were grouped together. This might be attributed to the fact that the majority of the investigated sections had comparable average annual traffic volume (1 to 1.5 million ESALs).

Table 9. Results of Multiple Regression Analysis

Identified Parameter	Estimated Coefficient	Standard Error	t-Ratio	p-Value
Intercept	-509.082	203.132	-2.51	0.023
T_{AC}	-1.723	1.283	-1.34	0.197
T_{PCC}	6.504	2.925	2.22	0.040
E_{PCC}	0.00179	0.00067	2.69	0.015
E_{PCC}/E_{AC}	44.188	20.249	2.18	0.043
FI	2.059	0.0845	2.42	0.027

Equation 5 shows the regression model to calculate the transverse cracking performance of C&S or B&S rehabilitated pavements.

$$AAIP - TC = -509.082 - 1.723T_{AC} + 6.504T_{PCC} + 0.00179E_{PCC} + 44.188\frac{E_{PCC}}{E_{AC}} + 2.059FI \qquad (5)$$

where AAIP-TC is the average annual incremental transverse cracking length (unit: ft/mile), T_{AC} is the thickness of asphalt overlay (unit: inch), T_{PCC} is the thickness of existing PCC (unit: inch), E_{PCC} is the elastic modulus of the fractured PCC slab (unit: ksi), E_{AC} is the elastic modulus of the asphalt overlay (unit: ksi), and FI is the freezing index (unit: °C degree-days). If the calculated AAIP-TC value is less than 0, then return 0. As can be seen from Figure 28, the calculated AAIP-TC values were in good agreement with those measured from the field, which demonstrated that the developed model had a high prediction accuracy.

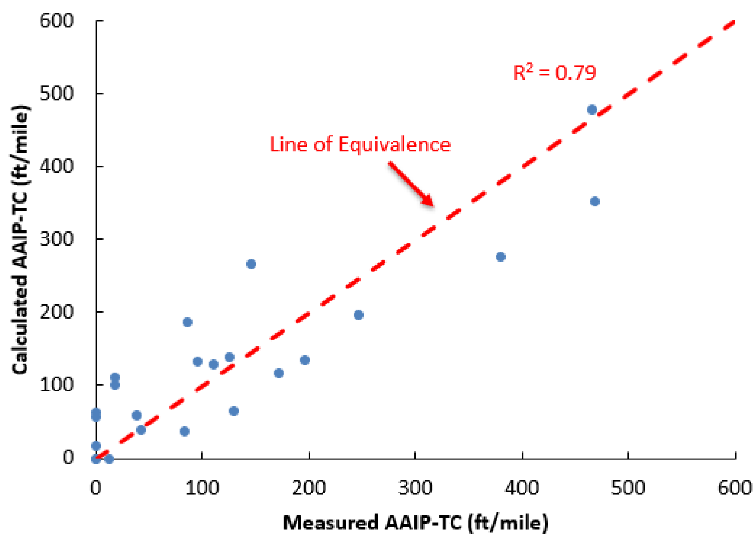


Figure 28. Comparison of Model Calculated AAIP-TC against Field Measured AAIP-TC

6 CASE STUDIES OF CONCRETE PAVEMENT REHABILITATION PROJECTS

Two case studies were selected based on feedback from the survey of the project. The case studies covered C&S in Wyoming and rubblization in Colorado. Each of these projects also had a unique design consideration. The mechanistic-empirical methodology was used for design in Wyoming. Meanwhile, Colorado designed their rubblized section using the AASHTO 1993 design guide and also required stone matrix asphalt be used as the surface overlay. Details of each of these case studies are outlined in the following sections.

6.1 Wyoming Case

Wyoming DOT has used C&S as a method of concrete pavement rehabilitation in multiple locations throughout the state. Two projects were completed within one year of each other, one outside of Laramie in 1997 and a second just outside of Cheyenne in 1998, both along Interstate 80. Table 10 lists the construction details of these two projects.

Table 10. Construction Details of Wyoming Projects

Construction Process	Crack and Seat		
Project Location	Interstate 80, near Laramie and Cheyenne		
Construction Year	Pavement Section	C&S/Overlay	Mill/Overlay
	Cheyenne Marginal WB	1998	2018
	Cheyenne Marginal EB	1997	2017
	Laramie Marginal WB	1997	2016
	Laramie Marginal EB	1997	2016

The Laramie project was originally built in 1963, and in 1997 it was time to either rehabilitate or reconstruct the pavement. The C&S approach was originally designed to serve as a 10-year design, but the pavement performed for 19 and 20 years for Laramie and Cheyenne, respectively. The project in Cheyenne was originally constructed in 1978 and was rehabilitated using crack-and-seat in 1997 (EB) and 1998 (WB). Figure 29 illustrates the pavement condition of the Laramie project before and after rehabilitation in 2016.

(a)

(b)

Figure 29. Laramie Marginal (a) before and (b) after asphalt rehabilitation in 2016 (Photos courtesy of Bob Rothwell, Wyoming DOT)

Design

The pavement was designed following the AASHTO Mechanistic Empirical Design Guide and using the rubblization option, though the modulus was adjusted to range between 175 to 200 ksi to better model the C&S process. After applying C&S, the projects were overlaid with a 1-inch leveling course of dense graded asphalt followed by two 2-inch lifts of a ¾-inch nominal maximum aggregate size asphalt mixture. The surface wearing course is a 3/4-inch thick open graded surface course.

Construction

A guillotine breaker was used for C&S. It is unclear if any drainage measures were taken for the Laramie project, but the Cheyenne project had edge drains added. The Wyoming DOT specification required that the resulting blocks from C&S must be between three and four feet in spacing and a 50 ton pneumatic roller used to ensure that the broken concrete was properly seated. Other quality measures were largely visual such as ensuring that the pavement was level prior to placement of the overlay. Standard quality assurance practices were used for the asphalt concrete mixtures.

Performance

As was previously stated, the rehabilitated pavement in Laramie was expected to be a 10 year design but performed for 19 years with limited maintenance. The Wyoming DOT representative noted that some patching may have occurred, but that pavements on Interstate 80 do not typically perform for 20 years. After 20 years, the Laramie project was resurfaced in 2018 by milling one inch and placing two inches of dense graded asphalt with a 3/4-inch open graded wearing course. It is expected that this pavement will perform for another 10 years. The Cheyenne project was also resurfaced in 2018 by milling two inches and replacing it with three inches of dense graded asphalt with a 3/4 inch open graded wearing course.

The present serviceability index (PSI) is a measure of roughness of the pavement. The pavement with PSI value of 5 is considered perfect, and 2 to 3 is considered poor. The Laramie project had a PSI of 3.5 prior to C&S and a PSI of 4.3 after rehabilitation. The Cheyenne project had a PSI of 3.9 before and a PSI of 4.2 after C&S. To provide a relative comparison, the Wyoming DOT provided a percent rank of its interstate system that consists of approximately 143 sections. The lower the percentage, the worse the pavement is ranked, and higher numbers indicate better performance. Prior to C&S, the Laramie project ranked at 1%, whereas after C&S it ranked 73%. The Cheyenne project ranked 21% prior to C&S and 85% after.

IRI data for the Laramie and Cheyenne projects before and after resurfacing in 2016-2018 are shown in Table 11. In each case, the IRI results were within the FHWA “Good” category (<95) both prior to and after resurfacing (Bureau of Transportation Statistics, 2020). It is important to recognize that the IRI values prior to surfacing represent the performance after 19 to 20 years of trafficking.

Table 11. IRI Data Before and After Resurfacing of Rehabilitated PCC Pavements in Laramie and Cheyenne, WY. (Data from Wyoming DOT)

Section	IRI Before Resurfacing (inch/mile)	IRI After Resurfacing (inch/mile)
Laramie WB	80	50
Laramie EB	85	52
Cheyenne WB	68	48
Cheyenne EB	73	47

6.2 Colorado Case

The Colorado Department of Transportation (CDOT) rehabilitated a section of concrete pavement on Interstate 25 in 2007 using rubblization. This project was particularly interesting because it contained an original 8-inch thick joint concrete pavement, a 2-inch layer of hot mix asphalt or chip seal as a “bond breaker”, and then an 8-inch concrete overlay built in the late 1970’s. When rubblization occurred, only the top 8-inch concrete overlay was rubblized. The lower levels were investigated, but it is postulated that the “bond breaker” layer dampened the impact of the rubblization process and protected the lower layer of concrete. Prior to rubblization, the surface panels were rocking and had four to five full depth cracks per panel. The rocking slabs were a major concern to CDOT and lead them to conclude that rubblization was the appropriate process to use in this design. The rubblization process not only generated smaller particles for better support but helped break up slab transfer. Another challenge for CDOT was traffic, so the contractor limited work between the hours of 10:00 PM and 5:00 AM and required the pavement to be open to traffic each day. This meant that an asphalt overlay also had to be placed on the rubblized pavement each night. The rubblization process was viewed by CDOT as the fastest rehabilitation option that would allow more control in the limited construction window.

Design

CDOT used the AASHTO 1993 design guide to design the pavement. The final structure consisted of the bottom layer of approximately 8 inches of concrete, the 2-inch asphalt concrete or chip seal bond breaker, the rubblized 8 inches of concrete, and 5.5 inches of ½-inch (12.5 mm) NMAS dense graded asphalt containing a PG 76-28 binder with a 2-inch stone matrix asphalt surface.

Construction

CDOT developed a rubblization specification that allowed either resonance or multi-head breakers. The original pavement did not use edge drains, but edge drains were installed for the rubblized pavement with daylighting.

The first day of production required a test pit to check for quality. A sample was excavated and checked to ensure that the rubblization process achieved the target particle size. Gradation tests were then run periodically. An updated specification developed after this project requires that the top three inches of the rubblized layer to have particles no larger than 1.5 inches.

A safety aspect of rubblization was noted in this case study. Because Interstate 25 is such a heavily trafficked route, the adjacent lane to the construction process remained open. Rubblization was considered to be safer compared to other rehabilitation options because vehicles could travel closer to the resonant breaker with lower risk than other techniques that require large drop heights for breaking up the concrete.

Performance

Prior to rehabilitation, the concrete pavement, comprised of 15 x 12 ft. slabs, was in "poor" condition with multiple full depth cracks in each slab along with corner breaks and other forms of distress. The original design anticipated 10 years of performance. After 10 years, some distress started appearing, and at the date of publication the condition is rated as "fair" with some transverse cracking. CDOT noted, however, that higher than anticipated traffic volumes should be considered when evaluating the performance. Overall, maintenance has been considered to be the same as a full reconstruction project with asphalt concrete. Areas with the most distress are under bridges where the overall rehabilitated pavement thickness is thinner due to clearance limitations.

Lessons Learned

Several lessons were learned from this project and others around Colorado. The specification was updated to ensure that the top three inches of the rubblized layer did not have any particles that exceeded 1.5 inches. Smaller particle sizes provided a homogenous surface on which to pave as well as a more uniform density. It was noted that there should be discussion in the preconstruction meeting around what will be done if equipment breaks down, especially if the route is highly trafficked with limited access. Close coordination between the department and the contractor was also highlighted, particularly when high volume routes are being rubblized. The z-bar compactor was found to help achieve target densities in rubblized pavements. Finally, there is an ongoing discussion within CDOT about whether edge drains are effective for rehabilitated concreted pavements that use rubblization. Some preliminary work done by CDOT shows that edge drains are useful, but more work is needed in this area.

7 SUMMARY AND CONCLUSIONS

This study comprehensively synthesized historical experiences with crack and seat (C&S), break and seat (B&S), and rubblization methods for the rehabilitation of PCC pavements with asphalt overlays. The literature review was conducted to document the current engineering practice of PCC rehabilitation, including the existing PCC slab-fracturing process and equipment, evaluation of fractured PCC slab systems, and asphalt overlay mix design and thickness design. A national survey was conducted to address the advancements and gaps for rehabilitating concrete with asphalt overlay. The survey respondents included SAPA leaders, key state and federal agency representatives, slab-fracturing equipment manufacturers, and pavement rehabilitation contractors. From the survey results, three case studies were selected to document the successful practices of slab-fracturing techniques. Additionally, this study utilized data from the LTPP SPS-6 experiment to assess long-term performance of rehabilitated PCC pavements with asphalt overlays. Slab-fracturing techniques were compared against other PCC rehabilitation treatments such as minimum and maximum restoration and saw and seal in terms of pavement smoothness, rut depth, longitudinal cracking, and transverse cracking. The major findings of this study are summarized as follows.

- C&S and rubblization were more popular than B&S for rehabilitation of PCC pavements. The edge drain system was not often used in PCC fracturing projects, although it showed effectiveness in reducing moisture-associated distresses. To mitigate reflective cracking, some agencies required dense-graded asphalt mixture with lower air voids and higher asphalt content and gap-graded asphalt-rubber mixture for overlay material.
- The majority of state agencies adopted the AASHTO 1993 method to design asphalt overlays on fractured PCC pavements, and the structural layer coefficient of the fractured PCC layer was determined based on the recommendation by the AASHTO 1993 design guide. Seven state agencies employed mechanistic-empirical approaches for asphalt overlay structural design. FWD measurements and engineering judgment were used to estimate the elastic modulus of fractured PCC slabs.
- C&S or B&S with an 8-inch asphalt overlay was much more effective than with a 4-inch asphalt overlay in reducing transverse cracking. Rubblized PCC with asphalt overlay had very good performance including resistance to transverse cracking distress, which implies that rubblization practically inhibits reflective cracking. According to the statistical analysis, there were no significant differences in performance measures of IRI, rut depth, and longitudinal cracking for the different treatments involving asphalt overlays on PCC.
- Most of the rehabilitated pavements with fractured slab moduli ranging from 508 to 3,553 ksi showed satisfactory transverse cracking performance. The previously recommended threshold for fractured slab modulus (E_{PCC} = 1,000 ksi) suggested by PCS (1994) does not appear to be suitable. Rubblized PCC slabs can be considered high modulus unbound aggregates. Placing an 8-inch asphalt overlay on top of rubblized PCC was found to meet criteria for a perpetual pavement if the rubblized slab modulus was greater than 81 ksi.
- Increasing the layer thickness of PCC slab (T_{PCC}), modulus of fractured slab (E_{PCC}), modulus ratio of E_{PCC}/E_{AC}, and freezing index (FI) resulted in significantly negative impacts on transverse cracking performance of C&S or B&S pavements. A multiple linear regression model was developed to accurately estimate the transverse cracking performance of the rehabilitated pavements.

REFERENCES

Ambroz, J., and Darter, M. (2005). “Rehabilitation of Jointed Portland Cement Concrete Pavements: SPS-6 – Initial Evaluation and Analysis”. FHWA Report No. FHWA-RD-01-169, McLean, Virginia.

American Association of State Highway and Transportation Officials (AASHTO). (1993). AASHTO guide for design of pavement structures. Washington, D.C.

American Society for Testing and Materials (ASTM). (2019). “Standard Terminology Relating to Materials for Roads and Pavements.” ASTM D8-19, West Conshohocken, PA.

Anderson, R. M. (2007). “Asphalt Modification and Additives.” The Asphalt Handbook MS-4, 7th edition, Asphalt Institute, Lexington.

Antigo Construction, Inc. (2014). Discussions of full rubblization and modified rubblization. Accessed at http://www.antigoconstruction.com/_downloads/Discussion%20of%20Full%20Rubblization%20&%20Modified%20Rubblization-Metric.pdf on September 19, 2018.

Antigo Construction, Inc. (2015). Modified rubblization specification. Accessed at http://www.antigoconstruction.com/_downloads/Rubblization/Modified%20Rubblization%20Specification.pdf on September 19, 2018.

Antigo Construction, Inc. (2018). Rubblization. Accessed at http://www.antigoconstruction.com/rubblization on September 19, 2018.

Antigo Construction, Inc. (2019). Crack & Seat and Break & Seat. Accessed at https://www.antigoconstruction.com/ on December 1, 2019.

ARA, Inc. (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report Part 3. Design Analysis, Chapter 6. HMA Rehabilitation of Existing Pavements. Washington, D.C.

Bemanian, S., and Sebaaly, P. (1999). “Cost-Effective Rehabilitation of Portland Cement Concrete Pavement in Nevada”. Transportation Research Record: Journal of the Transportation Research Board, No. 1684: 156-164.

Bischoff, D. (2007). Evaluation of Strata Reflective Crack Relief System. Final Report No. FEP-01-07, Wisconsin Department of Transportation, Madison, Wisconsin.

Bowers, B., Diefenderfer, B., and Diefenderfer, S. (2018). “Evaluation of Highly Polymer-Modified Asphalt Mixtures: Phase I.” Final Report, No. FHWA/VTRC 18-R14, Virginia Transportation Research Council, Richmond, Virginia.

Brown, D. (1997). “SMA Comes of Age.” Roads and Bridges, Arlington Heights, Illinois.

Buncher, M., Fitts, G., Scullion, T., and McQueen, R. (2008). Development of guidelines for rubblization. Airfield Asphalt Pavement Technology Program Final Report 04-01, Asphalt Institute, Lexington, KY.

Bureau of Transportation Statistics (2020). Road Condition. Accessed Feb 29, 2020. https://www.bts.gov/content/road-condition

Button, J., and Lytton, R. (2007). Guidelines for Using Geosynthetics with Hot-Mix Asphalt Overlays to Reduce Reflective Cracking. Transportation Research Record, No. 2004, 111-119.

Ceylan, H., Gopalakrishnan, K., Coree, B., Kota, T., and Mathews, R. (2008). “Rehabilitation of Concrete Pavements Utilizing Rubblization: A Mechanistic based Approach to HMA Overlay Thickness Design”. International Journal of Pavement Engineering, 9(1): 45-57.

Decker, D. (2006). Rubblization – Design and construction guidelines on rubblizing and overlaying PCC pavements with hot-mix asphalt. National Asphalt Pavement Association Information Series 132, Lanham, MD.

Dhakal, M., Elseifi, M., Zhang, Z. (2016). Mitigation Strategies for Reflection Cracking in Rehabilitated Pavements – A Synthesis. International Journal of Pavement Research and Technology, Vol. 9, No. 3, 228-239.

Federal Highway Administration (FHWA). (2015). “Office of Highway Policy Information: Highway Statistics”. www.fhwa.dot.gov/policyinformation/statistics/2015/hm12.cfm. Accessed July 19, 2019.

Fitts, G. (2006). “Rubblization Using Resonant Frequency Equipment.” Transportation Research Circular E-C087, Transportation Research Board of the National Academies, Washington, D.C.

Freeman, T. (2002). “Evaluation of Concrete Slab Fracturing Techniques in Mitigating Reflective Cracking through Asphalt Overlays.” Final Report No. VTRC 03-R3, Virginia Transportation Research Council, Charlottesville, Virginia.

Gong, H., Dong, Q., Huang, B., and Jia, X. (2016). “Effectiveness Analyses of Flexible Pavement Preventive Maintenance Treatments with LTPP SPS-3 Experiment Data”. Journal of Transportation Engineering, 142(2): 04015045.

Gu, F., Sahin, H., Luo, X., Luo, R., and Lytton, R. (2015). “Estimation of Resilient Modulus of Unbound Aggregates Using Performance-Related Base Course Properties”. Journal of Materials in Civil Engineering, 27(6): 04014188.

Hall, K., Correa, C., and Simpson, A. (2002). “LTPP Data Analysis: Effectiveness of Maintenance and Rehabilitation Options”. National Cooperative Highway Research Program Report Web Document 47, Transportation Research Board, Washington, D.C.

Hall, K., Correa, C., and Simpson, A. (2003). “Performance of Rigid Pavement Rehabilitation Treatments in the Long-Term Pavement Performance SPS-6 Experiment”. Transportation Research Record: Journal of the Transportation Research Board, No. 1823: 64-72.

Harvey, J., Bejarano, M., and Popescu, L. (2001). Accelerated Pavement Testing of Rutting and Cracking Performance of Asphalt-Rubber and Conventional Asphalt Concrete Overlay Strategies. Road Materials and Pavement Design, Vol. 2, No. 3, 229-262.

Hu, S., Basheer, I., Leidy, J., and Zhou, F. (2017). “Development of a universal cracking amount model for fatigue and reflective cracking of asphalt pavements”. Journal of Performance of Constructed Facilities, 31(6): 04017109.

Kaloush, K. (2014). Asphalt Rubber: Performance Tests and Pavement Design Issues. Construction and Building Materials, Vol. 67, 258-264.

Kraton. (2016). “Highly Modified Asphalt (HiMA) Next Generation in Asphalt Pavement Design.” http://kraton.com/products/hima/documents/HIMABroch.pdf. Accessed on 09/21/2016.

Ksaibati, K., Miley, W., and Armaghani, J. (1999). Rubblization of concrete pavements. Transportation Research Record, 1684: 165-171.

Morgan, P. and Mulder, A. (1995). “The Shell Bitumen Industrial Handbook.” Shell Bitumen, Surrey, UK.

Morian, D., Coleman, L., Frith, D., Stoffels, S., and Dawood, D. (2003). “Pennsylvania SPS-6 Performance at 10 Years: Evaluation of Concrete Pavement Rehabilitation Strategies”. Transportation Research Record: Journal of the Transportation Research Board, No. 1823, 28-37.

Morian, D., Zhao, Y., Arellano, J., and Hall, D. (2005). Asphalt Pavement Rehabilitation Treatment Analysis of 20 Years of Performance. Transportation Research Record, No. 1905, 36-43.

National Asphalt Pavement Association (NAPA). (2020). “Stone Mastic Asphalt.” https://www.asphaltpavement.org/index.php?option=com_content&view=article&id=1202&Itemid=100386.

Pavement Consultancy Services (PCS). (1994). “Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavements”. National Asphalt Pavement Association Information Series 117, Lanham, Maryland.

Puccinelli, J., Karamihas, S., Hall, K., and Senn, K. (2013). “Performance Evaluation of Arizona’s LTPP SPS-6 Project: Strategic Study of Rehabilitation Techniques”. Final Report 396-6, Phoenix, Arizona.

Rahim, A., Fiegel, G., Calkins, R., Lim, D., and Holland, J. (2013). “Performance Prediction Models for Cracked, Seated, and Overlaid Concrete Pavements in California”. Transportation Research Record: Journal of the Transportation Research Board, 2013. 2368: 92-101.

Resonant Machines Inc. (RMI) (2018). RMI’s Machine Specs. Accessed at http://www.resonantmachines.com/MachineSpecs/tabid/215/Default.aspx on September 19, 2018.

Schmiedlin, R. (1998). “Stone Matrix Asphalt: The Wisconsin Experience.” Transportation Research Record, No. 1616, 34-41.

Thompson, M. (1999). “Hot Mix Asphalt Overlay Design Concepts for Rubblized Portland Cement Concrete Pavements”. Transportation Research Record: Journal of the Transportation Research Board, No. 1684: 147-155.

Ullidtz, P., Harvey, J., Basheer, I., Jones, D., Wu, R., Lea, J., and Lu, Q. (2010). “CalME, a mechanistic-empirical program to analyze and design flexible pavement rehabilitation”. Transportation Research Record, 2153: 143-152.

Von Quintus, H., Mallela, J., and Buncher, M. (2007). “Quantification of Effect of Polymer-Modified Asphalt on Flexible Pavement Performance.” Transportation Research Record: Journal of the Transportation Research Board, No. 2001, 141-154.

Walker, D. (2019). “Using Fracture Slab Technology to Minimize Reflection Cracking.” Asphalt Magazine, http://asphaltmagazine.com/using-fracture-slab-technology-to-minimize-reflection-cracking/.

Watson, D. (2003). “Updated Review of Stone Matrix Asphalt and Superpave Projects.” Transportation Research Record, No. 1832, 217-223.

Willis, R. J., Timm, D. H., and Kluttz, R. (2016). “Performance of a Highly Polymer-Modified Asphalt Binder Test Section at the National Center for Asphalt Technology Pavement

Test Track." Transportation Research Record: Journal of the Transportation Research Board, No. 2575, 1-9.

Wisconsin Department of Transportation (WisDOT). (2019). "Facilities Development Manual – Chapter 14, Section 10." FDM 14-10, Wisconsin.

Witczak, M, and Rada, G. (1992). "Nationwide Evaluation Study of Asphalt Concrete Overlays Placed on Fractured Portland Cement Concrete Pavements". Transportation Research Record: Journal of the Transportation Research Board, No. 1374: 19-26.

Xiao, F., Amirkhanian, S., and Juang, C. (2007). Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures. Journal of Materials in Civil Engineering, Vol. 19, No. 6, 475-483.

APPENDIX: SURVEY QUESTIONS

The NAPA Pavement Economics Committee (PEC) has funded a study of the benefits of rehabilitating concrete pavements with asphalt overlays. This survey aims to gather information on the methods used in the United States to rehabilitate concrete pavements with asphalt overlays and identify gaps in knowledge on those approaches. The survey covers the following aspects:

- Respondent information
- Current and past concrete rehabilitation projects
- Concrete slab fracturing techniques
- Alternative concrete pavement treatments
- Overlay mix design guidelines
- Overlay structural design approaches
- Field performance of rehabilitated concrete pavements
- Recommended successful concrete rehabilitation projects for case studies

1. Please provide the following information
    a. First and Last Name
    b. Organization Name
    c. Location of your current organization (City, State)
2. Do you have experience with rehabilitating concrete pavements in your current position?
    a. Yes
    b. No
3. Do you have experience with rehabilitating concrete pavements in your prior position(s)?
    a. Yes
    b. No (skip Question 4)
4. Please provide the following information of the organization(s) where you previously gained experience with rehabilitating concrete pavements (list all that apply).
    a. Organization Name
    b. Location of your prior organization(s) (City, State)
5. Please quantify (in years) total time you have spent working on rehabilitating concrete pavements.
    a. none (will skip to the end of the survey)
    b. Less than 2 years
    c. 2-5 years
    d. 5-10 years
    e. 10-20 years
    f. 20 years or more
6. Which of the following best describes your current and prior organization(s) where you gained the experience with rehabilitating concrete pavements (select all that apply)?

a. General Highway Contractor
b. Specialized Equipment Supplier / Subcontractor
c. State Agency
d. Local Agency
e. Design Engineering Firm
f. State Asphalt Pavement Association Representative
g. Other (please specify)

7. Please select all Portland Cement Concrete Pavement rehabilitation options your organization has used in the past 10 years (select all that apply)?
    a. Crack and Seat (jointed concrete)
    b. Break and Seat (reinforced concrete)
    c. Rubblization
    d. Geosynthetic or fiberglass interlayer
    e. Stress absorbing membrane interlayer
    f. Special crack-resistant asphalt mixtures
    g. Minimum restoration of PCC (sealing of joints, surface diamond grinding, etc.)
    h. Maximum restoration of PCC (full or partial repair of broken slabs and deteriorated joints, including dowel bar retrofit)
    i. Saw-and-seal AC overlay above the PCC joints (saw AC and fill sawed joint with crack sealer or equivalent)
    j. Other (please specify)
8. How many “Crack and Seat” projects has your organization conducted in the past 10 years?
    a. No projects
    b. 1-3 projects
    c. 4-7 projects
    d. 8-10 projects
    e. More than 10 projects
9. How many “Break and Seat” projects has your organization conducted in the past 10 years?
    a. No projects
    b. 1-3 projects
    c. 4-7 projects
    d. 8-10 projects
    e. More than 10 projects
10. How many “Rubblization” projects has your organization conducted in the past 10 years?
    a. No projects
    b. 1-3 projects
    c. 4-7 projects
    d. 8-10 projects

e. More than 10 projects

11. What percent of PCC rehabilitation projects has your organization conducted utilizing an edge drain system?
    a. Less than 25%
    b. 25%-50%
    c. 50%-75%
    d. Greater than 75%
12. What has prevented your organization from using slab fracturing methods (crack and seat, break and seat, or rubblization) to rehabilitate PCC pavements (select that all apply)?
    a. Lack of understanding of these techniques
    b. Little to no concrete pavements
    c. Maintenance of traffic concerns
    d. Poor performance on a past project
    e. Lack of experienced local contractors
    f. Other (please specify)
13. What challenges has your company faced in performing slab fracturing methods for an agency (select all that apply)?
    a. Lack of agency specifications
    b. Unattainable specification requirements
    c. Lack of quality tests with quick results
    d. Difficulty in retrofitting water drainage system
    e. Other (please specify)
14. Which equipment has your organization used for breaking the PCC slabs in the past 10 years (select all that apply)?
    a. Guillotine-type
    b. Multiple-head breaker
    c. Resonant pavement breaker
    d. Hydraulic/Pneumatic hammer
    e. Other (please clarify)
15. What types of rollers has your organization used for seating or compaction of the fractured PCC in the past 10 years (select all that apply)?
    a. Vibratory and pneumatic rollers
    b. Steel vibratory rollers
    c. Heavy pneumatic rollers
    d. Other (please clarify)
16. Does your organization require or supply a specific type of asphalt mixture (or additional mix design criteria) for use on slab-fractured PCC?
    a. Yes
    b. No (skip Question 17)

17. What kind of asphalt mixture is required or supplied for use on the slab fractured PCC?
    a. Standard dense-graded mix
    b. Modified dense-graded (modified binder and/or gradation and/or volumetric)
    c. Open- or Gap-graded mixture (e.g. Stone Matrix Asphalt)
    d. Modified gap-graded mixture (Modified binder and/or gradation and/or special volumetric criteria)
    e. Other (please specify)
18. What is the thickness range of AC overlays for the existing projects that used PCC fracturing technique?
    a. Less than 3”
    b. 3’’– 5’’
    c. 6’’ – 8’’
    d. More than 8’’
19. What structural design method has your organization used for asphalt overlays on fractured PCC?
    a. AASHTO 1993 Structural Design Guide (i.e., Structural coefficient method) (skip Question 21)
    b. AASHTOWare Pavement-ME (Mechanistic Empirical) (skip Question 20)
    c. Alternative method preferred (please specify)
    d. I do not know
20. If your organization uses the AASHTO 1993 design method, what approach does your organization use for determining layer coefficients of fractured PCC layer?
    a. Falling weight deflectometer data
    b. Aggregate type, size and shape
    c. AASHTO Design recommended value
    d. Age and condition
    e. Other (please specify)
21. If your organization uses the AASHTOWare Pavement-ME (Mechanistic Empirical) method, how does your organization determine the resilient modulus of the fractured PCC layer? (Check all that apply)
    a. Falling Weight Deflectometer data
    b. Aggregate type, size, and shape
    c. Engineering judgement
    d. Other (please specify)
22. In your jurisdiction/area, what are the typical distresses observed for rehabilitated PCC with AC overlays?
    a. None
    b. Reflection cracking
    c. Fatigue cracking
    d. Rutting

   e. Failure due to drainage
   f. Delamination/debonding of the overlay
   g. Other (please specify)

23. If possible, please identify a concrete rehabilitation project that used a slab fracturing technique (break and seat, crack and seat, rubblization) that would make a good a case study. Candidate case study projects should be at least 10 years old with sufficient project design/construction documentation and/or the ability to contact individuals that could provide information on the design/construction of the project. If so, please fill out the following (otherwise skip to the next question):
    a. Technique [Click down menu: Break and Seat, Crack and Seat, Rubblization]
    b. Location
    c. Approximate date of rehabilitation
    d. Contractor(s) on the project
    e. Contact name
    f. Contact phone
    g. Contact email
24. May we contact you to conduct a telephone interview (30-minute maximum) regarding your responses to this survey?
    a. Yes
        i. Please enter your phone number
        ii. Please enter your email address (optional)
    b. No