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Design and Rehabilitation Strategies for Permeable Friction Course Pavements

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Thousands of miles of permeable friction course (PFC) pavements have performed well for the last 10 to 15 years on Texas highways. PFC pavement reduces hydroplaning, splash and spray, and pavement noise and improves ride quality and safety in wet weather. Hundreds of miles of PFC pavements are now at the end of their service life and need to be rehabilitated. The most common distress observed is raveling. To date, the most widely used method of rehabilitating PFC pavement is to mill the existing layer and replace it with a new wearing layer. This is also the most conservative and most expensive rehabilitation strategy. This project focused on determining if there are less expensive resurfacing options that do not include milling. PFC pavements have many safety-related advantages, but their use is on the decline because of the excessive cost of replacement. The research team conducted a review of literature and state specifications as well as an online survey of Texas Department of Transportation districts to establish the current state of the practice; emerging research and technologies on the design, testing, maintenance, and rehabilitation of PFC pavements; and various laboratory and field techniques that could aid in selecting PFC maintenance and/or rehabilitation options. Different material types and rejuvenator rates were considered to understand their effect on durability and friction. Field performance evaluations of resurfaced PFC pavements were conducted. PFC pavements nearing the end of their life were evaluated as candidate test sections. Three test sections were constructed with a rejuvenating fog seal aimed at extending the life of the PFC, a hot-mix overlay placed over an aged PFC, and a seal coat applied on another aged PFC.

Guidelines were developed for the maintenance and rehabilitation of PFCs. These guidelines focus on how to evaluate a PFC to determine if it still functions as a permeable layer, and a decision tree is provided to offer guidance on maintenance and rehabilitation options.

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DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Edith Arámbula-Mercado, P.E. #108462.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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1. INTRODUCTION

Permeable friction course (PFC) pavements have many safety-related advantages, but their use is on the decline because of the excessive cost of replacement. This project focused on determining if there are less expensive resurfacing options for PFCs. The research team conducted a review of literature and state specifications to establish the current state of the practice and emerging research and technologies on the design, testing, maintenance, and rehabilitation of PFC pavements. A description of this effort is summarized in Chapter 2. The research team also prepared and distributed a short online survey questionnaire to Texas Department of Transportation (TxDOT) personnel to inquire about the state of the practice regarding TxDOT districts' experiences with performance, maintenance, and rehabilitation of PFC pavements. Chapter 3 describes the outcome of the survey.

In addition, the research team conducted field performance evaluations of resurfaced PFC pavements with either Onyx® or seal coat. These projects were identified through the assistance of the TxDOT advisory panel as well as from the survey results. The field performance evaluation efforts are described in Chapter 4. Also, the research team, in coordination with TxDOT districts, identified various candidate PFC test sections that were nearing the end of their pavement life and needed rehabilitation or reconstruction. The field performance evaluation of these candidate sections is detailed in Chapter 5.

Various laboratory and field techniques that could aid in selecting PFC pavement maintenance and/or rehabilitation options and their adequate timing in terms of construction are described in Chapter 6. Different material types and rejuvenator application rates were considered to understand their effect on durability and friction; advanced imaging techniques were used to explore field cores and assess the relationship between ground-penetrating radar (GPR), water flow, and air void content and distribution; and a field moisture inspection method was employed to assess the amount of moisture trapped in the pavement and determine the proper time to apply an overlay to an existing PFC pavement surface.

Chapter 7 details the construction of the test sections, while Chapter 8 summarizes all these efforts and offers conclusions. Recommendations are presented as a set of guidelines for PFC maintenance and rehabilitation, including a decision tree.

2. REVIEW OF LITERATURE

The research team conducted a review of literature and state specifications to establish the current state of the practice and emerging research and technologies on the design, testing, maintenance, and rehabilitation of PFC pavements. Researchers searched multiple databases, including TRID, Compendex, Georef, Geobase, and Inspec, to locate references related to the following topics:

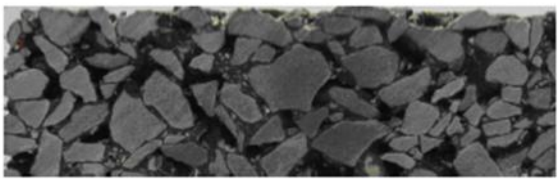
- Innovations in design procedures for PFCs that extend life.
- Test procedures aimed at predicting performance.
- Cleaning of clogged PFCs with water and vacuum techniques.
- Maintenance practices geared to extending the life of a PFC, including spray-applied fog seal products and/or rejuvenators.
- Resurfacing of an old, intact PFC with a new PFC.
- Resurfacing of an old, intact PFC by first sealing the surface with an impermeable layer to close off the voids.
- Guidelines on where and when PFCs should be used.

The search was limited to references published on or after 2010 since other studies have reviewed literature published before that year (Alvarez et al. 2006; Cooley and Brumfield 2009; Estakhri et al. 2008; Hernandez-Saenz et al. 2016; Liu et al. 2010). This chapter summarizes the main findings in several sections. First, the benefits and shortcomings of PFC pavements are highlighted. Then, a synopsis of mix design strategies is presented, including brief one-page summaries of the main component of mix design specifications of several state departments of transportation (DOTs). Next, maintenance strategies are discussed, including timing of maintenance, strategies to restore durability, and strategies to restore functionality.

2.1. BENEFITS AND SHORTCOMINGS

PFC pavements have a track record of successful implementation in the United States and Europe. The main benefit this type of pavement offers is rapid water drainage from its surface, which reduces splash and spray and enhances pavement marking visibility during wet-weather events, consequently diminishing the likelihood of traffic accidents on wet roads (Alvarez-Lugo et al. 2014). In addition, the higher-quality aggregates and binders used in PFC mixes enhance friction and reduce noise, respectively (Nafis and Wasiuddin 2021; Van der Zwan 2011). Another less-touted benefit includes improved water runoff quality, given that the PFC mix acts like a filter when water permeates through its open air void (AV) structure. This benefit is more commonly reached when the PFC mix is used for the surface layer of a full-depth permeable pavement structure, also called porous asphalt (Kayhanian et al. 2019).

In the United States, PFC pavements are primarily pursued because of their drainability, while in Europe, besides the safety benefits, PFCs are desirable for their noise abatement ability. In the Netherlands, for example, which is densely populated, PFC pavements are the standard service course for the main road network, covering more than 80 percent of the freeways (Van der Zwan 2011). This type of pavement became even more prevalent in the late 1980s when the speed limit increased from around 60 mph to 75 mph, which in turn elevated noise levels by about 3 dB, on average, when measured by the close proximity method. Moreover, the Netherlands developed a two-layer porous asphalt (TLPA) to improve noise reduction even more. This system consists of a coarse mix (maximum aggregate size ⅝ inch) layer about 1.8 inch thick placed under a finer mix (maximum aggregate size ¼ inch) layer about 1.0 inch thick. Figure 1 shows a cross section of representative single-layer and TLPA mixes. The TLPA achieves a noise reduction of about 6 dB versus the 4 dB reduction achieved by the single-layer PFC mix when compared to conventional dense-graded hot-mix asphalt (HMA).



(a) (b)

Figure 1. Cross section of representative porous asphalt mixes commonly used in the Netherlands: (a) single layer and (b) TLPA (Van der Zwan 2011).

Noise reduction capabilities of PFC mixes have also been investigated in the United States. A case study in Shreveport, Louisiana, for example, measured the tire-pavement noise for all traffic lanes of a newly constructed PFC pavement and reported a reduction of about 1.2 dB when using the onboard sound intensity method (Nafis and Wasiuddin 2021). In addition, when combining this benefit with reduced roughness and increased friction, a survey distributed among daily road users showed an increase in satisfaction from fair to good or very good when comparing the road before and after the application of the PFC pavement.

Notwithstanding the multiple benefits PFC pavements provide, it is also known that the mix is more expensive; it is only when a PFC mix is used as part of a porous asphalt pavement structure, and stormwater treatment is considered as part of a life-cycle cost analysis, that its total present worth cost over a 20–40 year analysis period is more economical than conventional impermeable pavements such as dense-graded HMA or Portland cement concrete (Rehan et al. 2018).

In addition, winter maintenance treatments are challenging in PFC pavements because of black ice formation, damage caused by snowplows, or clogging of the open AV structure after application of salt, sand, or other deicing products. Proper application of winter maintenance treatments in PFC pavements usually requires the installation of roadway sensors to measure temperature, humidity, dew point, and salt presence coupled with a weather information system to forecast when deicing should be applied (Fay and Akin 2014; Van der Zwan 2011; Yildirim et al. 2007).

More importantly, the average service life of PFC pavements is also shorter than dense-graded HMA. In the Netherlands, for example, the service life of PFC pavements is about 11 years for the driving lane and 16 years for the passing lane versus 15 and 20 years for the driving and passing lanes, respectively, of conventional dense-graded HMA (Van der Zwan 2011). The most common distress that affects PFC pavements is raveling, which is defined as a progressive dislodging of aggregate particles from the surface of the pavement under the influence of environmental factors and traffic. Therefore, raveling may result from aging of the binder causing it to become brittle or by stripping of the asphalt from the aggregate, which can be worsened by the movement of water through the PFC open AV structure.

In Texas, PFC pavements have an average life of 7–10 years, with some projects failing early and others lasting longer. For example, a PFC pavement found on US 281 in Pharr, Hidalgo County, showed excessive amounts of raveling on the outside (far right) lane. A section of the pavement had minor to no distress, while another section had severe raveling. The pavement was constructed in 2004 using river gravel and a design binder content of 9.1 percent AC-10 with 17.7 percent crumb rubber. Pictures captured during the forensic inspection of the pavement conducted in 2010 are shown in Figure 2. Field measurements showed that the raveled section had faster water flow; also, measurements on field cores obtained from the pavement showed higher average AV content (i.e., 24.8 percent versus 19.3 percent) and lower total binder content (i.e., 4.5 percent versus 5.7 percent) in the raveled section (Arámbula et al. 2013).

(a) (b) (c)

Figure 2. PFC pavement located in Pharr: (a) general view of raveled section, (b) detailed view of raveled section, and (c) field core with apparent stripping (Arámbula et al. 2013).

Potential causes of the observed raveling were attributed to the following (Arámbula et al. 2013):

- Aggregate type (i.e., river gravel may be prone to stripping).
- Binder aging.
- Low binder content (i.e., 4.5 percent in the raveled section versus 9.1 percent design binder content).
- Inferior quality control practices during pavement construction.
- Draindown during transport of the PFC mix from the plant to the site (i.e., 35 mi).

Another instance of raveling in Texas after several years in service was a PFC pavement located on US 90 in Houston, Waller County. The pavement was built in 2004 using a design 8.3 percent AC-10 with 18 percent Centex Grade B rubber. The performance of this PFC pavement was adequate during the first years of service; however, after this period, excessive stripping and raveling were observed throughout the pavement surface. Figure 3 illustrates the condition of the pavement. Field measurements showed that the pavement was impervious, and measurements on field cores yielded an average AV content of 11.5 percent. Potential causes of the observed distress were attributed to excess fines in the mix and low AV content on the wheel paths, which likely trapped water on the other areas of the lane, promoting raveling.

(a) (b) (c)

Figure 3. PFC pavement located in Houston: (a) raveling distress near a turning access, (b) raveling distress near a bridge, and (c) close-up view of the pavement surface (Arámbula et al. 2013).

When PFC pavements reach the end of their service life, the most widely used method of rehabilitation is to mill and overlay the existing layer and replace it with a new wearing pavement layer. This method is the most conservative yet most expensive rehabilitation strategy. Therefore, other maintenance and rehabilitation options for PFC pavements that do not necessarily include mill and overlay were documented as part of this literature review effort. In addition, a review of current PFC pavement design procedures was done to compare against the current TxDOT specifications and assess if certain changes could be made to increase service life.

2.2. MIX DESIGN SPECIFICATIONS

The first PFC mix design specification was proposed by the Federal Highway Administration (FHWA) and published in 1974 (Smith et al. 1974). In 1978, the National Cooperative Highway Research Program (NCHRP) published a synthesis of highway practice discussing the design, operation, and performance of open-graded friction course (OGFC) pavements (Halstead 1978). Based on the findings of the synthesis, modifications to the FHWA OGFC mix design specification were released in 1980 and 1990, including recommendations on the selection of optimum binder content, materials, aggregate gradation, and mixing temperature and evaluation of moisture susceptibility (FHWA 1980, 1990). In 1992, a follow-up NCHRP synthesis was published to review performance benefits and limitations of OGFC pavements and to summarize the European experience (Smith 1992). A third NCHRP synthesis was published in 2000, with the objective of documenting performance and use of OGFC pavements and summarizing information about design, materials, construction, maintenance, and rehabilitation strategies (Huber 2000). In this last synthesis, it became clear that the use of OGFC was declining, with states discontinuing the use of this type of pavement due to issues with performance and reduced service life. Therefore, Huber (2000) highlighted mix design advancements in North America (i.e., United States and Canada) at that time, including:

- Use of fiber stabilizers.
- Use of modified binders.
- Increased AV content.
- Increased aggregate size.

In Georgia, for example, the use of OGFC pavements commenced in the 1950s. Like other states, Georgia experienced problems with this type of mix, including excessive draindown, rapid oxidation, raveling, and stripping. In 1982, Georgia DOT (GDOT) placed a moratorium on the use of OGFC pavements. After a few years, several modifications were introduced and were successful in improving performance. These modifications included using hydrated lime as an anti-stripping agent, introducing gibers to eliminate draindown, using a polymer-modified binder, increasing the production temperature to thoroughly dry the aggregates, employing coarser aggregate gradations, and increasing the thickness of the pavement layer (Watson et al. 1998).

Subsequently, the National Center for Asphalt Technology (NCAT) developed a mix design methodology for what it called *new-generation* OGFC mixes (Kandhal and Mallick 1999). Considering findings reported in other studies on the use of modified binders and coarser aggregate gradations in OGFC mixes, NCAT conducted a laboratory study employing different gradations and additives and recommended an improved mix design procedure. The performance evaluation of the mixes was more involved, including draindown, permeability, abrasion, rutting, and moisture susceptibility. NCAT conducted various other subsequent studies on laboratory performance to refine the mix design methodology proposed by Kandhal and Mallick (Watson et al. 2003, 2004). Around that time, the American Society for Testing and Materials (ASTM) also released a standard test method for mix design of PFC mixes, designated D7064 (ASTM 2006).

In a subsequent study sponsored by NCHRP, NCAT developed a performance-based mix design for porous friction courses (Watson et al. 2018). The procedure prescribed the Superpave gyratory compactor to prepare specimens and expanded the array of performance tests to include rutting, cracking, and cohesiveness (besides durability, moisture susceptibility, and permeability). The goal was to achieve a balance between PFC mix durability and functionality. The researchers employed field mixes with known good and deficient performance to establish mix design criteria. Their proposed method was adopted as a draft American Association of State Highway and Transportation Officials (AASHTO) standard mix design method.

In Texas, researchers have also evaluated several aspects of PFC mix design, including volumetrics, permeability, durability, and aging (Alvarez et al. 2008). Based on results from lab experiments, researchers recommended (a) dimensional analysis to estimate the total AV content of the mix; (b) change in density specification from 78–82 percent to 76–80 percent to ensure adequate permeability; (c) field evaluation of permeability during construction; and (d) durability evaluation using the Cantabro abrasion loss and draindown tests. The proposed changes to the TxDOT PFC mix design procedure are summarized in Figure 4.

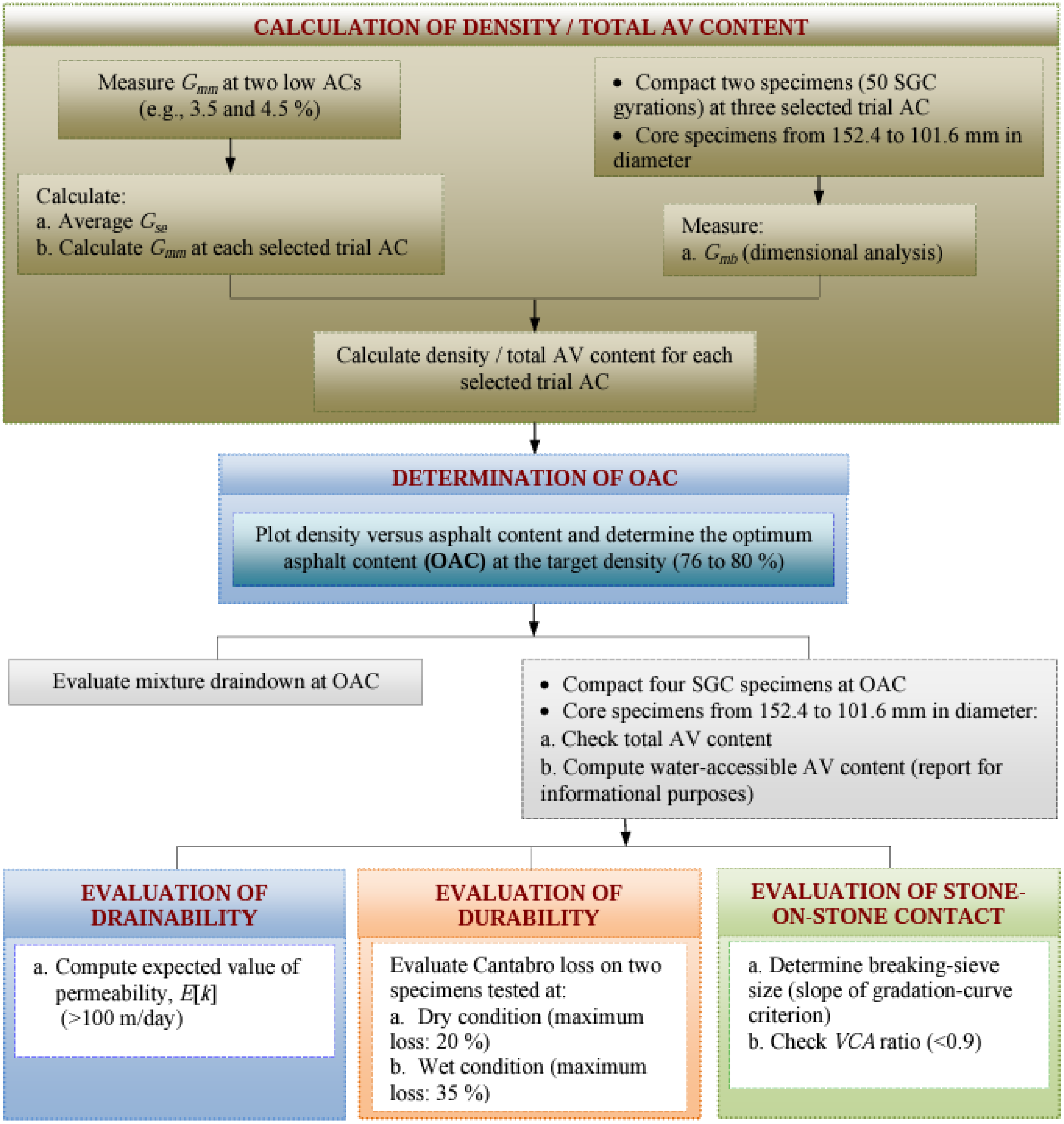


Figure 4. Recommended changes to TxDOT's PFC mix design procedure (Alvarez 2009).

The research team conducted a review of current PFC mix design specifications for multiple DOTs in the United States. The map in Figure 5 shows which states had a PFC mix design specification available and which did not. The main aspects of each available specification, including requirements on aggregate type, aggregate gradation, binder type, binder content, fiber and/or additive use, AV content, tack coat use, layer thickness, and acceptance criteria, were reviewed. The main differences between TxDOT's current PFC mix design specification and that of other states in terms of materials used, optimum asphalt content selection, and performance tests are discussed next.

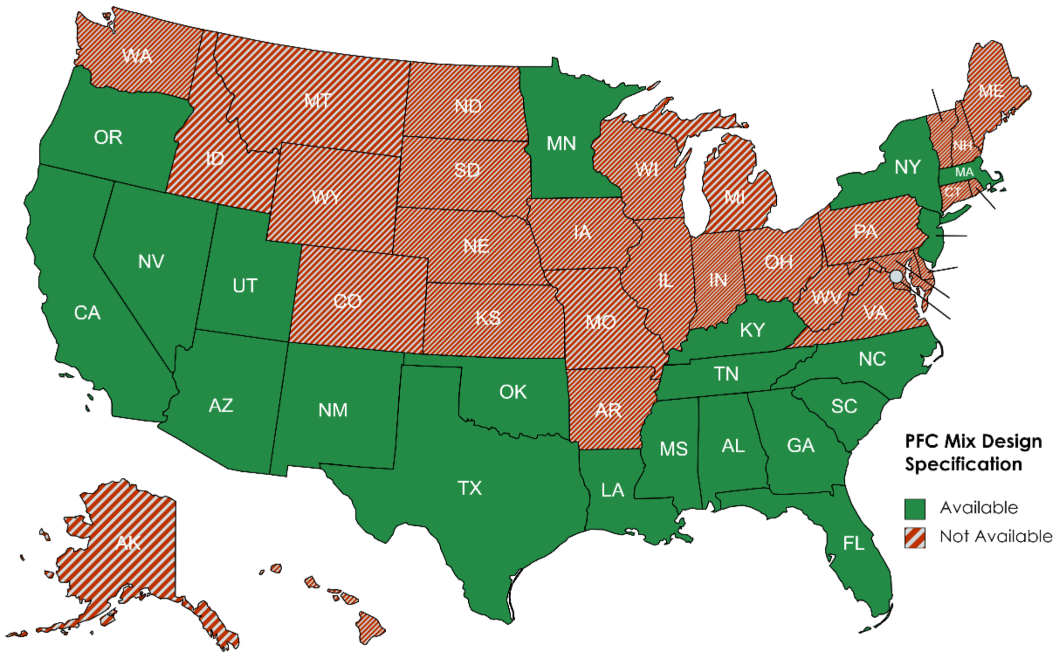


Figure 5. States with and without available PFC mix design specifications.

Most of the states require a polymer-modified performance grade (PG) 76 type binder, while Louisiana also allows a PG 82. A few states use a PG 64-22, but these are generally in the colder climates. In addition to Texas, Arizona, California, and New Jersey allow for an asphalt-rubber (AR) binder.

Other states use similar aggregate quality tests as Texas, such as magnesium sulfate soundness, Los Angeles abrasion, crushed face count, and flat and elongated particles. While Texas allows a 20 percent max loss for soundness, other states that use this test limit the loss to 12 percent. Texas allows a Los Angeles abrasion max loss of 30 percent, which is in line with most others. Alabama limits the aggregates used to granite, quartzite, slag, sandstone, or manufactured lightweight. Mississippi limits the crushed limestone to a maximum of 50 percent of the mix. North Carolina does not allow aggregates produced from crystalline limestone, crystalline-dolomitic limestone, or marble. Louisiana declares that aggregates cannot have more than 2 percent absorption.

Texas PFC mixes are designed to an asphalt content that will meet a specified range and that will produce an AV content of at least 18 percent (or 82 percent maximum density). Other states have similar requirements, though they may note an acceptable range of AVs (i.e., 18 to 22 percent) and a minimum asphalt content. States that do not have an AV requirement are selecting optimum asphalt content using draindown-type test methods (Arizona, California, Utah, South Carolina). For example, Arizona has a target draindown of 0.25 percent and determines the percent of binder as close as possible to the target draindown without exceeding it.

Other performance tests or checks that are done in Texas once an asphalt content has been determined include draindown and Cantabro loss. Hamburg and overlay test requirements are used only for fine PFCs. Most states also have a draindown requirement, and a few have a

Cantabro loss requirement. The draindown percentage that is allowed by TxDOT is 0.1 percent, which is lower than most of the other states. Many states allow a draindown of up to 0.3 percent. Other states may have higher binder contents in their PFC mixes that could potentially improve durability but may negatively affect permeability.

A common performance test used by other states (not used in Texas) is the tensile strength ratio, which provides a measure of the moisture sensitivity of the mix.

2.3. MAINTENANCE STRATEGIES

Maintenance of PFC pavements involves activities conducted to restore durability or functionality (i.e., pavement drainability and noise reduction ability). As previously mentioned, raveling is the main type of distress affecting PFC pavements, but other distresses such as shear failures, cracking, or delamination are also prevalent (Liu et al. 2010). When treatment is needed to restore durability due to a deteriorating pavement condition, the strategies can be classified as (a) preventive maintenance or (b) corrective maintenance. Preventive maintenance includes placing spray-applied products on the surface of the pavement to rejuvenate the mix, while corrective maintenance includes patching or, in cases of extensive or severe distress, full rehabilitation such as milling and overlay.

When treatment is needed to restore functionality, the most common strategy is to clear the AV structure of the PFC mix from any sand, dirt, or debris that may have accumulated with time by applying pressurized water and/or vacuuming the surface of the pavement. These techniques are commonly used in Europe and Japan to restore proper water drainability but are not yet prevalent in the United States for PFC pavements.

Last, activities performed in northern climates, where freeze/thaw or snow accumulation is prevalent, are known as *winter maintenance*. These activities include applying sand or salt (although not recommend for PFC pavements), anti-icers or deicers, or other chemicals, as well as snow plowing. Although technically these activities are considered maintenance strategies, they were not believed relevant to fulfilling the objectives of this project and thus were outside the scope of this literature review.

2.3.1. Timing

The onset and progression of raveling on PFC pavements depends on multiple factors, including material properties, mix design, binder content, AV content, pavement age, environmental conditions, and traffic level (Razzaghmanesh and Beecham 2018). To optimize maintenance timing, researchers have applied automated vehicle-mounted camera and sensor measurement methods and developed statistical models to anticipate the degree of raveling any given PFC pavement may experience (Opara et al. 2015).

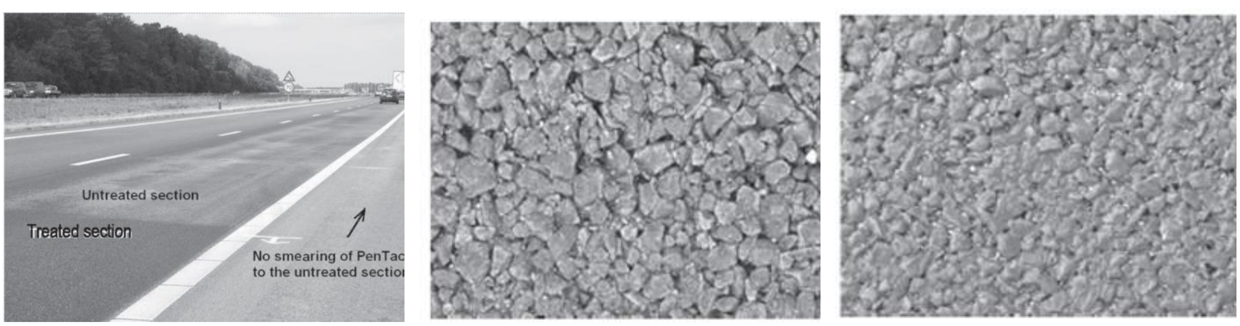
Timing maintenance is applicable to restoring not only durability but also functionality. Wu et al. (2020) recommended using field rut depth measurements as an alternative to permeability measurements to optimize the timing of maintenance strategies that restore drainability. This type of measurement is especially critical because if pressure washing and vacuuming techniques are applied too early, they may exacerbate the onset and/or progression of raveling. Conversely, if these techniques are applied too late, when excessive clogging of the open AV structure of the PFC pavement has already occurred, they may not be as effective (Kinter 2010).

2.3.2. Strategies to Restore Durability

2.3.2.1. Preventive Maintenance

Several options are available to restore durability of PFC pavements. Oklahoma DOT, for example, experimented with several products and procedures to extend the service life of OGFC pavements, including NovaChip, which is an ultrathin surface treatment used to enhance skid resistance and prevent raveling. Researchers applied the product to an existing PFC pavement (without milling) and to a milled and overlay dense-graded HMA construction as a wearing surface (Brewer and Williams 2005). Other than requiring special equipment for laydown, Oklahoma DOT was satisfied with the short-term performance of the NovaChip on the existing PFC pavement and how it also reduced noise and splash and spray during wet-weather events. Thus, Oklahoma DOT further expanded the use of what it calls *spray-applied ultrathin bonded wearing courses*, which are gap-graded friction courses that are bonded to the pavement surface with a polymer-modified emulsion membrane. The membrane seals the existing surface and provides a solid interface, which allows it to be applied directly on top of existing PFC pavements (Kuennen 2011).

In the Netherlands, maintenance of what is labeled porous asphalt, which is equivalent to PFC pavements, is done periodically through the application of rejuvenating products with a spraying truck. The intent is to allow the product to drain through the AV structure of the mix and restore the flexibility of the aged pavement. A laboratory and field study to evaluate a cold-applied emulsion-based product showed improvement in the mechanical performance and functionality (skid resistance and noise reduction), and because of the environmental benefit compared to the conventional maintenance option, it also demonstrated a more favorable life-cycle assessment (Su 2012). Figure 6 shows photographs of the road where the product was applied.



(a) (b) (c)

Figure 6. Application of an emulsion-based rejuvenator in the Netherlands: (a) overview of the field test section, (b) detailed view of the pavement surface before treatment, and (c) detailed view of the pavement after treatment (Su 2012).

Another study on preventive maintenance of porous asphalt with rejuvenators in the Netherlands evaluated three products using cores and beams obtained from the pavement after treatment (Zhang et al. 2012). The products consisted of an emulsion applied at ambient temperature, a binder sprayed at elevated temperature, and an emulsion sprayed at intermediate temperature.

The specimens were obtained after product application and after 1 year and 3 years in service. After testing the mechanical properties of the beam and raveling of the cores with and without treatment, the bending stiffness of the specimens showed mixed results depending on the porous asphalt being a single layer or a TLPA, but the application of the rejuvenators significantly improved the raveling resistance of the porous asphalt in all cases. Furthermore, Zhang et al. (2014, 2015) evaluated the effect of the rejuvenators after application via X-ray computed tomography, optical microscopy, and nanoindentation and verified that the emulsion sprayed at intermediate temperature and the binder sprayed at elevated temperature increased the mortar film thickness around the aggregate particles and filled microcracks to a certain depth (1 inch in the case of the emulsion and 0.2 inch in the case of the binder).

Similarly, in China, preventive maintenance measures for porous asphalt have been investigated. Xu, Chen, et al. (2016) conducted a laboratory study to explore the effect and interaction of four products with the high viscosity modified bitumen traditionally employed in porous asphalt. The four products employed in their study included (a) a reductive material composed of naphthenic oil, (b) a bitumen-based adherence-enhancing material, (c) a polymerized material composed of alpha cyano acrylic resin with organic solvent, and (d) an emulsified binder. Performance was assessed on field cores and laboratory-prepared slabs via Cantabro, permeability, skid resistance, and curing time. Based on the evaluation, the bitumen-based adherence-enhancing material and the polymerizing material with organic solvent showed the best results and cured rapidly. A specially designed maintenance material and the emulsified binder were further explored with aging and evaluated in an equivalent manner, with tests to quantify adhesion and raveling (Xu, Li, et al. 2016). The results showed that the specially designed maintenance material outperformed the emulsified binder and was subsequently applied in a field project to verify sprayability and to establish proper construction techniques. Subsequently, the four products employed in the laboratory study were applied to sections of a 9-year-old porous asphalt in south China (Xu et al. 2018). Based on parameters evaluated before and after the application of the products, including pavement condition index, riding quality index, rutting depth index, skid resistance, permeability, raveling, and low-temperature cracking, it was established that the polymerized material exhibited the best performance.

In the United States, several studies have also been conducted to explore the effectiveness of preventive maintenance strategies on PFC pavements. In Tennessee, a fog seal consisting of a light application of diluted emulsion (i.e., no aggregate) was applied on an existing PFC pavement section of I-40 that was about 3 years old (Huang et al. 2019). Figure 7 illustrates the condition of the pavement surface before and after fog seal treatment. Cores were obtained before and after treatment, and different application rates were considered. Performance was assessed via permeability, texture depth, and abrasion tests. Results indicated that the application of the fog seal reduced the PFC pavement permeability and decreased texture depth yet significantly reduced the abrasion loss (i.e., by about 50 percent compared to the untreated specimens). The reduction in texture depth after the application of the fog seal treatment was temporary since after the abrasion tests, the skid resistance was restored (Song et al. 2021).

(a) **(b)**

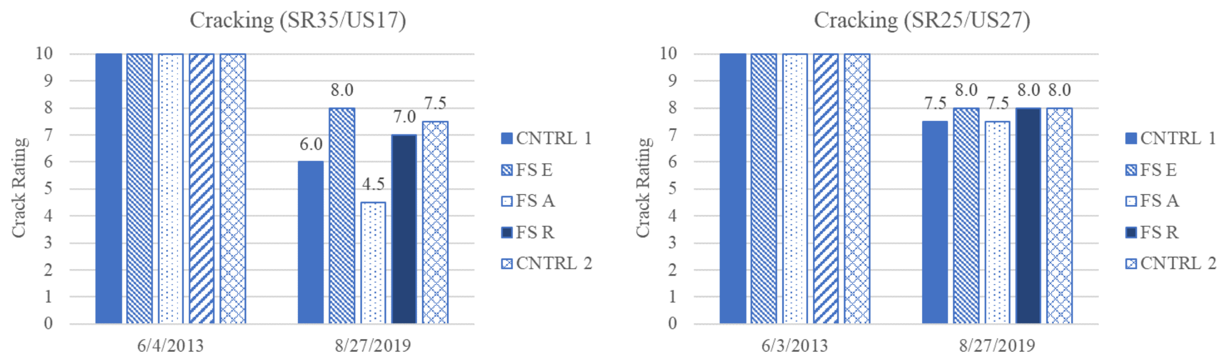
Figure 7. PFC pavement on I-40 in Tennessee: (a) before fog seal treatment, and (b) after fog seal treatment (Huang et al. 2019).

Florida DOT routinely places fog seals on OGFC mixes as a preventive maintenance technique to increase the binder film coating the aggregate particles, reduce the oxidative aging, and delay the onset of cracking and raveling distress. In 2013, the application of fog seals was evaluated in test sections placed on US 17 and US 27 (Kim et al. 2014). The OGFC was constructed in 2009, so the pavement was around 4 years old at the time of the study. Three products were selected for evaluation at that time: Reclamite (emulsion), eFog (CMS 1PF cationic emulsion), and SealMaster AsPen AC (clay-stabilized and mineral-filled emulsion). Details of the application information can be found in Table 1. Two control sections were also placed side-by-side in each location for comparison.

Table 1. Fog Seal Application on US 17 and US 27 Field Sections in Florida (Kim et al. 2014).

Product		**E-Fog (FS E)**	**AsPen AC (FS A)**	**Reclamite (FS R)**
Application Date		4/22/2013	4/23/2013	4/24/2013
Distributor		Palmetto Paving	DuraSeal	Pavement Technologies
Spray Rate (gal/yd^2)	US-27	0.10	0.13	0.07
	US-17	0.10	0.07	0.04
Time to Open to Traffic After Application (min)	US-27	60	120	95
	US-17	65	35	100

Performance was measured based on the condition of the pavement (cracking, rutting, and ride), friction, permeability, and binder viscosity (recovered from field cores). The results showed adequate pavement condition for all sections 6 years after treatment application, with eFog-treated sections showing the best overall cracking performance, as shown in Figure 8 (Nazef 2020). All sections had equivalent raveling performance. Researchers observed a reduced friction right after product application but acceptable values 2 weeks to 3 months after application. The permeability measured right after fog seal treatment versus 6 months after treatment decreased for all test sections (i.e., control and treated). The eFog-treated section showed the highest drop in permeability, while Reclamite had the lowest drop and was similar to the control section. The viscosity of the extracted binder from field cores was less for the treated sections compared to the control section, which proved the rejuvenation ability of the products.



(a) **(b)**

Figure 8. Cracking performance of the control and treated sections: (a) US 17, (b) US 27 (After Nazef 2020).

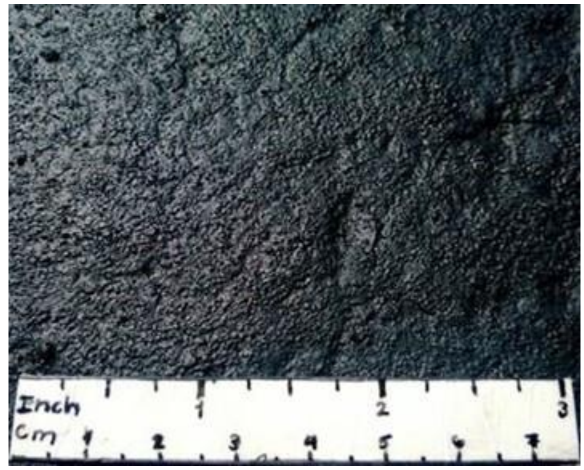
TxDOT has also applied preventive maintenance strategies on PFC pavements throughout the state. A summary of recent experience in various districts is presented next.

2.3.2.1.1. El Paso

The El Paso District placed a seal coat on an older PFC on US 90. The PFC was in good condition, and no adverse performance has yet resulted from sealing off the PFC. This satisfactory performance may also be attributable to the dry climate of the area.

2.3.2.1.2. San Antonio

The San Antonio District also constructed a 1-mi test section in the southbound lanes of IH 35 in June of 2017. This portion of IH 35 is surfaced with an older PFC, which is about at the end of its life and is beginning to exhibit significant raveling. Therefore, the district wanted to see if a product marketed under the name Onyx could hold up the raveling and extend the life of the PFC pavement. Onyx is the tradename for Special Specification (SS) 3028 Frictional Asphalt Surface Preservation Treatment, which is a spray-applied, emulsified binder that also contains an exceptionally fine aggregate or grit to aid in friction. The old PFC surface and the beginning of the Onyx application along with a close-up of the Onyx treatment are shown in Figure 9. Skid measurements taken on the Onyx surfacing and on the existing PFC at either end of the Onyx section are shown in Figure 10. These results are concerning because the skid numbers seem to have dropped by about 10 points and did not recover even after almost 1 year.



(a) (b)

Figure 9. IH 35 in the San Antonio District: (a) beginning of Onyx product application, and (b) surface of the pavement after Onyx application (Scullion et al. 2020).

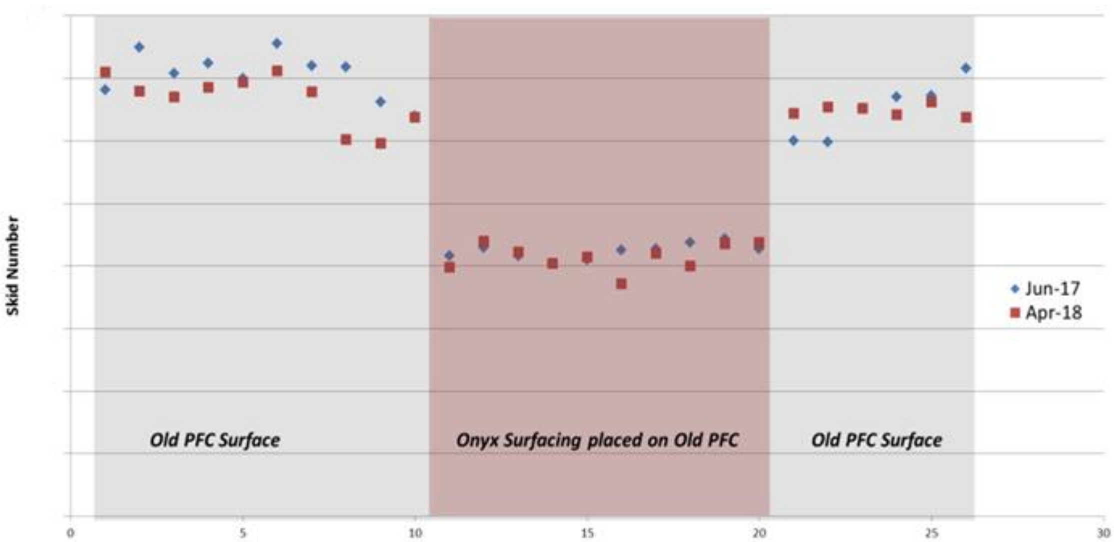


Figure 10. Skid data on IH 35 in the San Antonio District showing the existing PFC pavement and the Onyx test section results (Scullion et al. 2020).

2.3.2.1.3. Brownwood

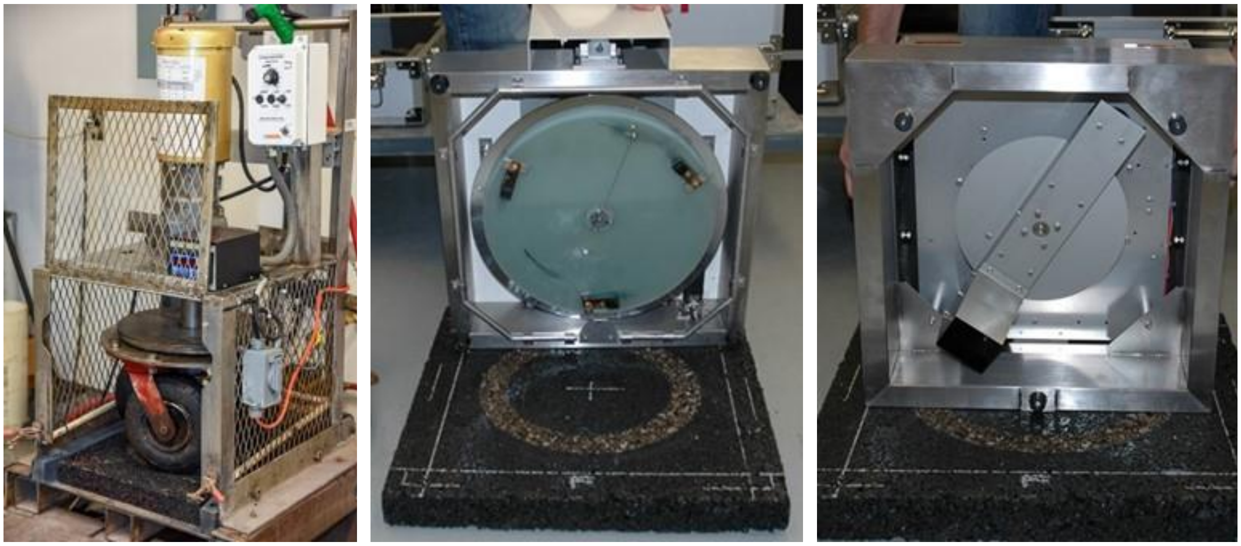
In 2020, the Brownwood District applied a frictional asphalt surface preservation treatment (Onyx, SS 3028) to a PFC pavement on US 183 south of Breckenridge (Figure 11). It would have been difficult to mill off this PFC mix since it was originally placed on a flexible base covered with a surface treatment. The skid results were good, with no noticeable loss in friction observed.

(a) **(b)**

Figure 11. Spray-applied frictional asphalt surface treatment (SS 3028, Onyx) on US 183 in Stephens County: (a) general view of the test section, and (b) detailed view of the pavement surface.

To achieve this acceptable skid performance, the application quantity was optimized. The district worked with the contractor, who obtained 16-inch diameter cores using the equipment shown in Figure 12 and then applied different quantities of Onyx. The cores were then trafficked using a three-wheel polisher (Figure 13a). After 16,000 passes, the friction was measured using a dynamic friction tester (DFT) (Figure 13b), and the texture was measured using a circular track meter (Figure 13c). These two metrics provided a correlation to the skid number obtained with the locked wheel skid trailer. Based on the results of the laboratory testing, 0.12 gal/yd^2 was selected as the application quantity.

Figure 12. Equipment used to obtain 16-inch diameter cores from the PFC pavement.



(a) (b) (c)

Figure 13. Laboratory testing equipment used to evaluate performance of the 16-inch PFC cores: (a) three-wheel polisher, (b) dynamic friction tester, and (c) circular track meter.

2.3.2.1.4. Houston

In 2017, the Houston District attempted to place an AR seal coat on top of an existing PFC pavement on SH 146. Rain had occurred a couple of days prior to the seal coat, trapping water in portions of the PFC. The result was disastrous, with 40 cars and trucks stalled for 5 hours after the AR seal tracked on the tires. An example of an affected truck is shown in Figure 14.

Figure 14. PFC pavement surfaced with AR seal coat tracking on vehicle tires immediately after construction.

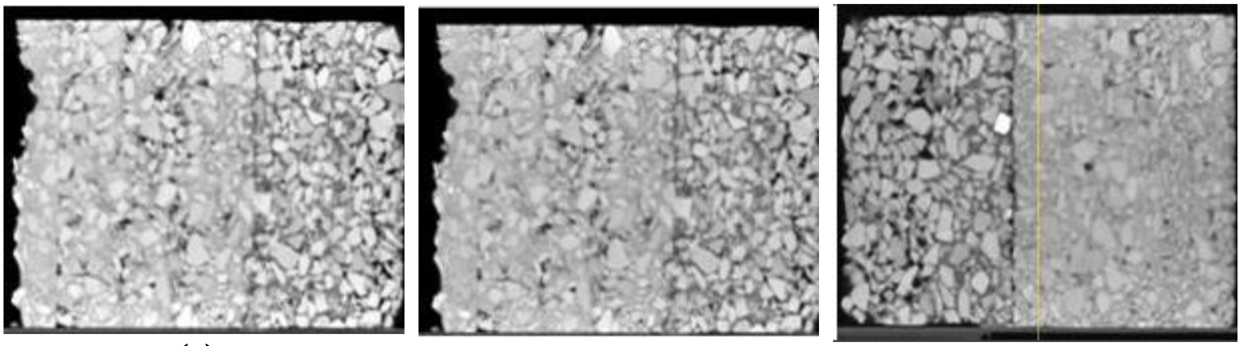
As part of a separate effort, researchers evaluated US 359 in the Houston District to determine if the PFC was a suitable candidate for application of the frictional asphalt surface preservation treatment (Onyx) to seal off the surface to the penetration of water (Scullion et al. 2020). The water flow test was performed at three locations (shoulder [S], inner wheel [WP], and outer wheel [W]), and cores were extracted and taken to the laboratory for computed tomography scanning to estimate existing AVs. Table 2 shows the flow time for the three locations tested in the field. In all, it took a long time for the water to percolate into the PFC pavement (>>20 seconds) at the three locations tested, which means the trafficked PFC no longer drained water.

Table 2. Field Water Flow Test on US 359 (Scullion et al. 2020).

Surface	Existing PFC Pavement Surface		Water Flow
1		Shoulder (S)	13 min and 56.79 sec
2		Outer wheel (W)	11 min and 48.56 sec
3		Inner wheel (WP)	77 min and 17.50 sec

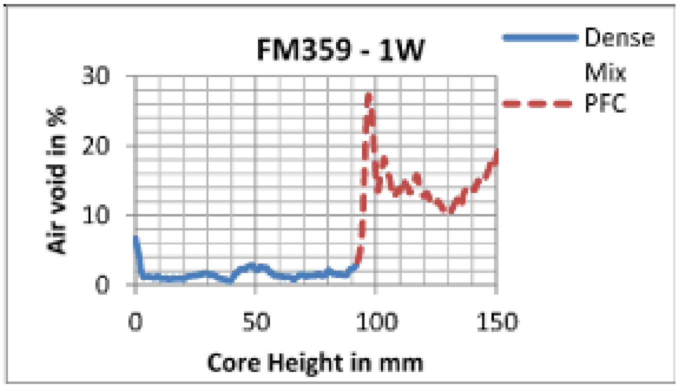
Figure 15 shows images of the computed tomography scans and Figure 16 the estimated AV for the cores extracted from US 359. The results indicate that the estimated AV was higher at the top half-inch of the PFC and reduced toward the center, where the AV detected was below 10 percent (the typical AV of a new PFC pavement is about 20 percent). The reduction was more prominent on the inner lane (3W) than the outer lane (1W) and shoulders (3S). A similar trend was noted during the field flow test. There is a spike in the middle of the AV plot, which represents the joint between the pavement bottom dense layer and the PFC mix. At that point, there was no effect on water flow initiating from the surface.

The recommendation to the district was that no seal was necessary since this pavement had already ceased to drain and was no longer truly functioning as a PFC pavement. While it may have been a suitable candidate to overlay, the district ultimately milled off the PFC pavement.

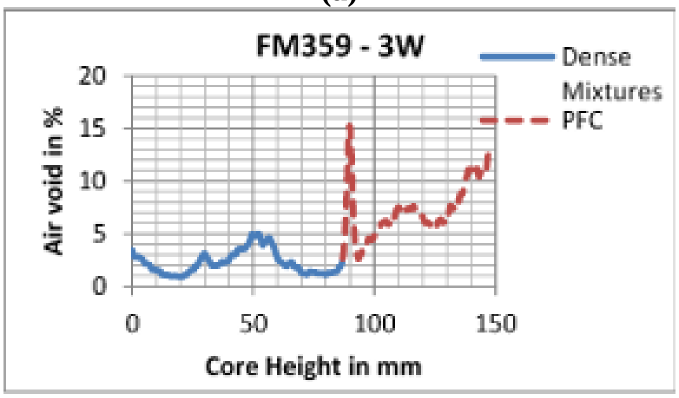


(a) **(b)** **(c)**

Figure 15. Images of the X-ray computed tomography scans obtained from the PFC pavement on US 359: (a) outer lane 1W, (b) inner lane 3W, and (c) Shoulder 3S (Scullion et al. 2020).



(a)



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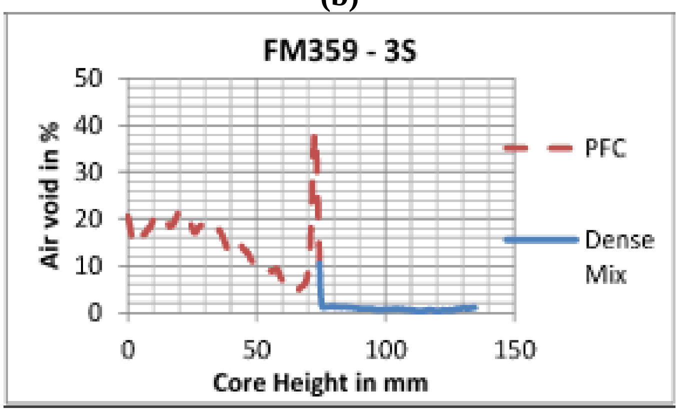


(c)

Figure 16. Air void distribution estimates obtained from X-ray computed tomography images of cores from the PFC Pavement on US 359: (a) outer lane 1W, (b) inner lane 3W, and (c) Shoulder 3S (Scullion et al. 2020).

2.3.2.2. Corrective Maintenance

As previously mentioned, corrective maintenance includes patching for areas of localized distress or, in cases of extensive or severe PFC pavement distress, full rehabilitation such as milling and overlay. Examples of the application of these techniques are summarized next.

2.3.2.2.1. Patching

When localized areas of the PFC pavement need repair due to delamination or potholes, a conventional HMA mix can be used only if the affected area is small and the patch is oriented at a 45-degree angle. However, for larger areas needing patching, another PFC mix is usually furbished (Putman 2012).

In Tennessee, three types of repair material were tested to assess their potential use in patching of PFC pavements (in lieu of a PFC mix)—(a) cold patch, (b) EZ patch, and (c) Aquaphalt—as shown in Figure 17 (Huang et al. 2019). Since previous experience with patching in PFC pavements indicated either partial (i.e., edges) or full disintegration of the patch, clogging of the PFC pavement surface, or impeded later flow of water, Huang et al. conducted a laboratory evaluation that included cohesion of the patching material, adhesion to the existing pavement surface, moisture damage with freeze/thaw, and permeability.

(a) (b) (c)

Figure 17. Patch repair materials used in Tennessee: (a) cold patch, (b) EZ patch, and (c) Aquaphalt (Huang et al. 2019).

The cohesion test followed AASHTO TP 44 (i.e., rolling sieve test), but it was performed at room temperature. The test consisted of molding a specimen with the Marshall hammer, placing it inside a sieve with 1-inch openings, and rolling the sieve back and forth on its side for about 20 seconds. The difference between the initial specimen weight versus the material retained in the sieve was measured and used as an indicator of cohesion.

The adhesion test consisted of taking a compacted PFC specimen, placing the patching material on top, compacting it with 10 blows of the Marshall hammer, extruding the specimen from the mold, waiting 15 minutes, and inverting the specimen to allow the patching material to fall under the effect of gravity. The time required for the patching material to debond from the PFC specimen was measured and used as an indicator of adhesion.

Moisture susceptibility was measured following ASTM D4867 with one freeze/thaw cycle. In this case, the materials were aged for 96 hours at 140°F before Marshall compaction. Then, the specimens were vacuum saturated, frozen, and thawed in a water bath at 140°F. The EZ patch material did not withstand the hot water bath. Therefore, the water temperature was lowered to 77°F for this last part of the procedure.

The permeability was measured using a falling head system equipped with pressure transducers to measure hydraulic head differences. Compacted specimens were placed in an aluminum cell lined with a rubber membrane that was used to apply confining pressure and prevent water from draining through the sides of the specimen. The tube used to introduce water to the specimen was of smaller diameter than the specimen diameter.

The results ranked the materials based on the different performance tests. For example, Aquaphalt had the best cohesion, but EZ patch had the best moisture resistance. Overall, the researchers recommended the cold patch material due to adequate permeability and lower cost but suggested modifying it with 3 percent fast-setting cement to improve its resistance to moisture damage.

2.3.2.2.2. Micromilling and Overlay

GDOT has employed PFC or porous European mixes to maintain pavements since the 1990s. The PFC is placed on top of an existing surface to improve friction and drainage and extend the pavement service life. When the PFC reaches the end of its service life, the pavement layer under it, which is usually a stone matrix asphalt or dense-graded HMA, is generally in good condition and can last for several more years. Traditionally, GDOT mills both the PFC and the mix in the underlayer to improve bond and avoid water entrapment. However, this procedure is expensive and not always available due to maintenance budget constraints. Therefore, GDOT investigated the use of micromilling to remove only the PFC mix on roads with sound underlying pavement structures (i.e., no load-related failures) (Jared and Hines 2014).

Micromilling employs equipment with more teeth that are spaced more closely, which produces a more uniform, smoother, and finer surface texture. Micromilling equipment is shown in Figure 18. To successfully apply this procedure, stringent surface texture and smoothness requirements were established by GDOT, including less than $^{1}/_{16}$-inch difference between ridges and valleys, and a target smoothness index of 825–900 mm/km. A new PFC or porous European mix can be placed directly on top of the micromilled surface, which also represents cost savings. Often, variable-depth micromilling is required to completely remove the existing surface layer. Figure 19 shows an example of a micromilled surface with variable depth.

GDOT has applied this technique on sections of I-75 and I-95 with observed good performance after 4 to 7 years in service and thus has promoted micromilling as a practical corrective maintenance alternative for pavements with sound underlying structures (Lai 2014). Researchers estimate that the cost savings accrued by applying this technique on those two interstate projects amounted to around $11 million (Jared and Hines 2014).

Figure 18. Micromilling equipment teeth (Jared and Hines 2014).

Figure 19. Variable-depth micromilled surface in Georgia (Jared and Hines 2014).

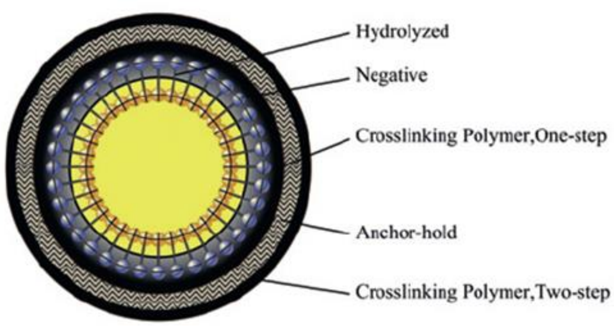
2.3.2.2.3. Recycling

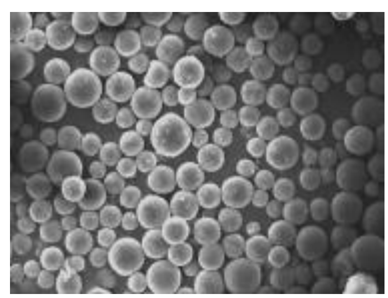
Use of recycled materials in PFC mixes is rarely allowed by state specifications. In fact, recycling of PFC mixes has not been carefully studied until recently. Pratico et al. (2012, 2013) studied the variability of reclaimed asphalt pavement (RAP) obtained from porous European mixes and its feasibility to produce TLPA. Issues of concern included degree of aging of the RAP binder and its ability to blend with the virgin materials, compatibility between the RAP modified binder and the virgin modified binder, and presence of contaminants such as organic as well as inorganic materials. In addition, the variability of the RAP itself was explored with respect to homogeneity of the aggregate gradation and binder content; presence of other types of mixes or materials due to maintenance such as chip seal, crack seal, or patching; milling process; and handling of the RAP stockpile. Two RAP sources were analyzed in terms of aggregate gradation and binder content. Then, mixes were prepared using these two RAP sources and evaluated based on volumetrics, mechanical properties, and permeability with adequate performance.

In a separate study, the use of 15 percent coarse RAP from a PFC mix in a new PFC mix was explored. The laboratory experiment used compaction energy index and cyclic coaxial shear tests in dry and wet conditions to evaluate laboratory-mixed, laboratory-compacted specimens without RAP and with RAP at two total binder contents. In addition, durability (Cantabro) and fracture (indirect tensile strength and semi-circular bending) tests were performed in dry and conditioned (72 hours in water at 104°F) plant-mixed, laboratory-compacted specimens (Frigio et al. 2014). Pavement drainability was also measured in the field. For all performance test metrics, the mixes with RAP showed equivalent or better performance than the mix without RAP. The laboratory mixes performed better than the field mixes, likely due to the size and incorporation of fibers. The drainability of the mixes in the field was not affected by the incorporation of RAP. Overall, the performance of the PFC mixes with 15 percent was satisfactory, and the authors recommended higher amounts of RAP (i.e., 25 percent) for future studies.

2.3.2.2.4. Self-Healing

Other rehabilitation strategies labeled self-healing, including rejuvenator encapsulation, induction heating, and microwave heating, have been explored by researchers in Ireland as an option to furbish PFC mixes that can achieve a longer service life (Tabokovic et al. 2019). Rejuvenator encapsulation consists of adding microcapsules with rejuvenators during PFC mix production; when cracking distress commences in the pavement, the capsules will open, releasing the rejuvenator and restoring the binder properties. The structure of a microcapsule and microcapsule morphology are shown in Figure 20.





(a) **(b)**

Figure 20. Rejuvenator encapsulation: (a) schematic of the structure of a microcapsule (Su and Schlangen 2012), and (b) microcapsule morphology captured by scanning electron microscope (Su et al. 2013).

Induction and microwave heating consists of adding conductive fibers to the PFC mix during production, and then the pavement is heated by either induction or microwave. As the fibers heat, they also heat the binder around them, repairing any existing cracks. Tabokovic et al. (2019) evaluated four PFC mixes with various amounts of steel fibers (i.e., 5 percent, 10 percent, and 15 percent) like the ones shown in Figure 21. Laboratory-prepared specimens were first tested in indirect tensile strength, and then the two halves were put together and placed in a microwave oven for 3 minutes; after cooling the specimen, the same procedure was repeated twice. The researchers employed indirect tensile stiffness modulus and indirect tensile strength to evaluate performance. The mixes with 5 percent steel fibers performed the best because larger amounts caused material clustering that hindered performance. These PFC mixes had the largest indirect tensile strength before and after healing and exhibited full crack healing as shown in Figure 22. A similar but independent study employing 5 percent ferrite powder as filler to prepare PFC mixes yielded parallel results, with an optimum microwave heat time of 2 minutes to achieve a reduction of 50 percent in moisture-induced damage per AASHTO T 283 with one freeze/thaw cycle (Zhu et al. 2019).

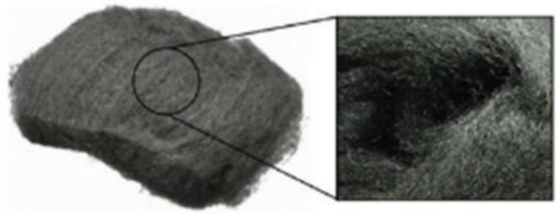
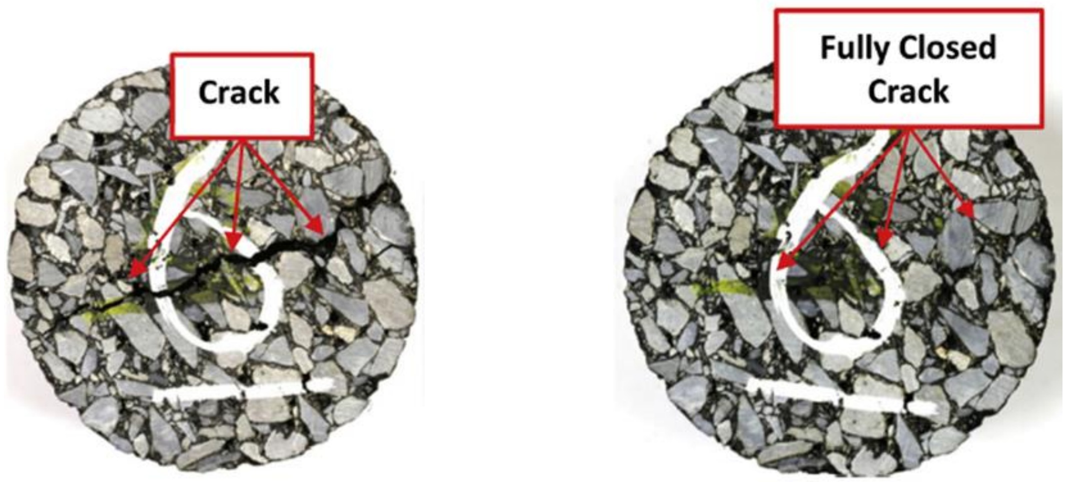


Figure 21. Steel fibers used in PFC mixes by Tabakovic et al. (2019).



(a) **(b)**

Figure 22. PFC mix specimen with 5 percent steel fibers: (a) before microwave-induced healing, and (b) after microwave-induced healing (Tabakovic et al. 2019).

2.3.3. Strategies to Restore Functionality

As discussed before, one of the main benefits of PFC mixes is their ability to minimize splash and spray during wet-weather events and to reduce road noise. This benefit is achieved by the open gradation and high AV content of the mix. The open AV structure, however, is prone to clogging with dust, debris, and other contaminants and susceptible to consolidation (i.e., rutting) under the influence of traffic loads. Therefore, without periodic cleaning of the PFC pavement, the initial permeability and noise reduction ability will diminish with time. In fact, some PFC pavements become essentially dense-graded HMA mixes during their service life.

Although not common in the United States, the most popular methods used to clean PFC mixes and restore their drainability include pressure washing and/or vacuuming. These procedures can be done routinely or less frequently but more in depth. The frequency of cleaning depends on the composition of the soil; for example, in areas with sandy soils, the cleaning frequency will be less than in areas with clay soils (Kinter 2010). There are three basic types of sweepers commercially available in the United States: (a) mechanical broom machines, (b) regenerative air sweepers, and (c) air-based sweepers (Kinter 2010; Kidwell-Ross 2010). In Europe, the most used type of equipment is vacuum sweepers. Usually, high-pressure washing is followed by vacuum sweeping to make the process more efficient, especially if the maintenance is spaced out (Kidwell-Ross 2010).

In Canada, researchers studied the effect of small-scale and full-scale sweepers in restoring the permeability of permeable pavements (i.e., porous asphalt, pervious concrete, and permeable interlocking concrete). The researchers selected eight locations that were at least 3 years old and had been subjected to winter maintenance activities including sand and deicers (Drake and Bradford 2013). Infiltration tests following a modified ASTM D3385 standard test procedure were conducted before and after sweeping for the small-scale treatment sites, and ASTM C1701 standard test method was followed for the full-scale treatment sites. The small-scale treatment consisted of (a) pressure washing followed by 24-hour drying, (b) sweeping with a push broom, or (c) vacuuming with a wet/dry Mastervac (i.e., high or low suction with air flow). Full-sized treatment was conducted with two commercially available sweeper trucks (i.e., Elgin Whirlwind and Tymco-DST 6) like the ones shown in Figure 23.

(a) **(b)**

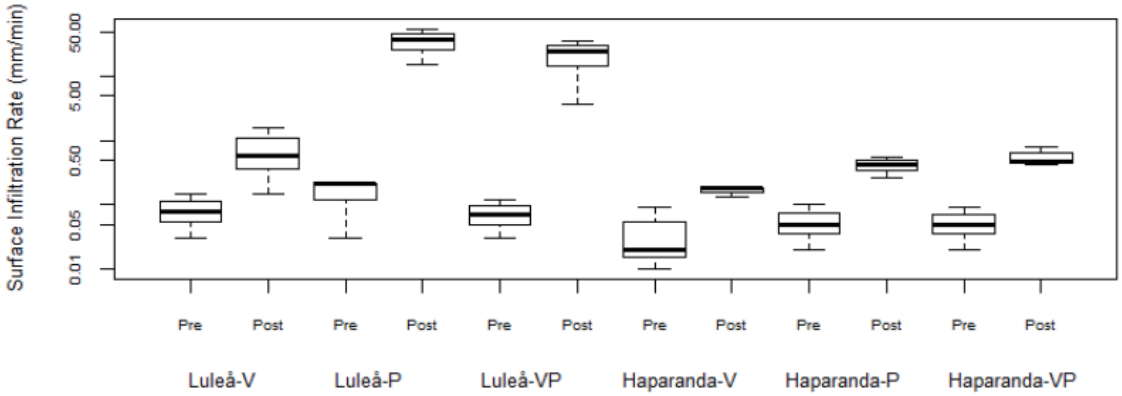
Figure 23. Commercially available sweeper trucks: (a) Elgin Whirlwind (Joe Johnson Equipment 2021), and (b) Tymco-DST 6 (Tymco 2021).

Results regarding restored permeability were mixed. The location with porous asphalt pavement was subjected to only the small-scale treatment and showed minor improvement in infiltration rate, while other locations that had porous concrete or permeable interlocking concrete pavement surfaces had better results. The most effective of the three small-scale treatments on porous asphalt was the Mastervac low suction with air flow. The authors theorized that the small-scale cleaning techniques dislodged the sediment from the porous asphalt surface but were not effective in removing it. Therefore, the sediment redistributed throughout the surface of the pavement, causing a decrease in permeability. If maintenance would have been performed earlier in the life of the pavement, the treatments would have likely been more successful. In addition, some techniques like pressure washing, although effective, were not practical for large pavement surfaces. Therefore, the authors recommended that agencies develop and adopt an operation and maintenance plan to improve the functionality of porous asphalt pavements (Drake and Bradford 2013).

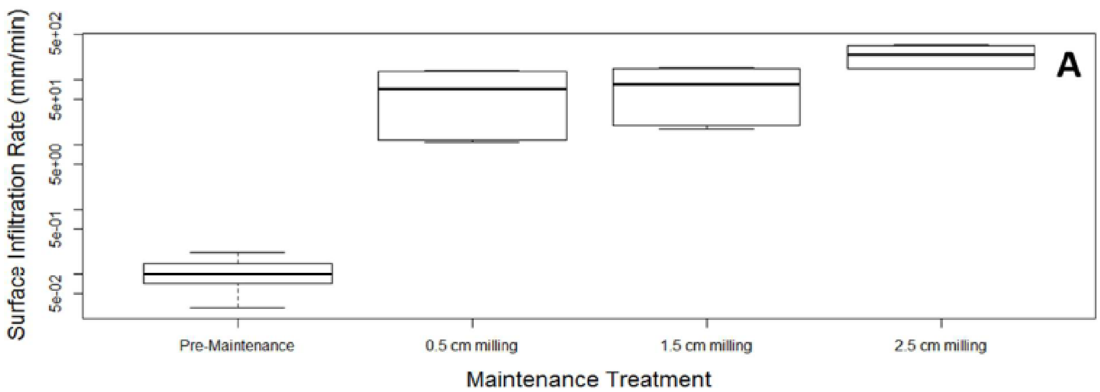
In a joint study between Sweden and the United States, different small-scale and full-scale maintenance techniques aimed at restoring permeability in permeable pavements were evaluated. Two sites located on residential streets paved with porous asphalt that were 21 and 28 years old at the time of maintenance and had not received prior treatment to restore functionality were used in the study (Winston et al. 2016). During winter seasons, these pavements had been subjected to various applications of sand mixed with salt or fine gravel and had very minimal drainability. These two porous asphalt sites were treated with vacuuming using an industrial handheld wet/dry vacuum device (i.e., Dustcontrol DC 50-W), pressure washing with Nilfisk ALTO Poseidon 2-22 XT, a combination of vacuuming followed by pressure washing, and milling. Surface infiltration rate per ASTM C1781 was measured before and after maintenance using equipment like that shown in Figure 24.

Figure 24. Single-ring infiltrometer used to measure water infiltration rate on permeable pavements (Kinter 2010).

Although vacuuming restored the surface infiltration rate, the most effective methods were those involving pressure washing, especially the one that combined pressure washing with vacuuming, as shown in Figure 25a. In one of the two sites, milling at various depths (0.2 inch, 0.6 inch, and 1.0 inch) was tested to verify if this technique would be more effective in removing the sediment accumulated near the surface of the pavement. A 1-inch milling depth produced the best surface infiltration rate, as shown in Figure 25b, as well as an infiltration rate value twice as large as the vacuuming plus pressure washing option.



(a)



(b)

Figure 25. Effects of maintenance strategies on surface infiltration rate at test sites in Sweden: (a) pre- and post-treatment with vacuuming (V), pressure washing (P), and vacuuming plus pressure washing (VP); and (b) milling at various depths (Winston et al. 2016).

In a study by Virginia DOT, three unique protocols to maintain drainability of porous asphalt were evaluated on a park-and-ride facility: (a) regenerative air vacuum at 6-month intervals, (b) conventional vacuuming at 6-month intervals, and (c) regenerative air vacuuming at 12-month intervals. These procedures were applied over a 4-year period. In this case, the researchers did not see a significant effect or improvement on infiltration rates after the treatments (Fitch and Bowers 2018). None of these treatments included pressure washing, which according to other studies (Danz et al. 2020; Kazemi et al. 2017; Winston et al. 2016) is the most effective strategy to restore pavement drainability.

Another study in Wisconsin set up three side-by-side test sections using permeable interlocking concrete pavers, pervious concrete, and porous asphalt near a parking lot and evaluated pavement drainability over a 4-year period before and after regular maintenance (Danz et al. 2020). The parameter of interest was the infiltration rate measured using a modified version of ASTM C1701. The porous asphalt received two types of maintenance: a vacuum-assisted street cleaner (i.e., Elgin Whirlwind equipment shown in Figure 23a) and compressed air plus vacuuming (i.e., Typhoon followed by Pavevac, both from PaveTech Inc.). The results before and after applying the Elgin Whirlwind equipment showed a slight improvement of 16 percent in infiltration rate for the porous asphalt. The compressed air plus vacuuming with the two machines from PaveTech Inc. showed a larger improvement of 40 percent increase in infiltration rate for the porous asphalt.

3. SURVEY OF DISTRICTS

The research team prepared and distributed a short, fact-based online survey questionnaire to TxDOT personnel to inquire about the state of the practice regarding their experiences with performance, maintenance, and rehabilitation of PFC pavements. With input from the advisory panel, the research team developed an online survey, and Eric Lykins, director of operations for the Brownwood District, sent the survey request and link to all the directors of operation and directors of maintenance in the state. The survey was sent on December 15, 2021, with a follow-up reminder on January 5, 2022, and a deadline for completion of January 19, 2022.

Responses were received from two-thirds of the districts (16 total), and respondents included district engineers, directors of operations, directors of maintenance, area engineers, pavement engineers, and senior-level inspectors. The research team received one response per district except for Houston and Dallas, both of which provided two responses. The verbatim questions and responses are summarized in Table 3 through Table 7.

Table 3 summarizes the use of PFCs. While many of the districts have used PFCs in the past, a few reported no plans to continue using PFCs. Some reported not continuing use because of the lack of options available for PFCs at the end of life. The average life of a PFC ranges from 7 to 15 years (Table 4), and most respondents reported that raveling and loss of permeability are the most common failure modes.

Districts were asked to list the types of PFCs used, whether a PG 76 fine gradation, PG 76 coarse gradation, AR binder fine gradation, or AR binder coarse gradation as described in TxDOT specifications, Item 342. They were also asked to list the types of roadways where a PFC is used, and these results are listed in Table 5. Most districts tend to use PFCs on high-volume, high-speed facilities. Table 6 lists the maintenance practices districts have performed on PFCs. Some of the districts have used fog seals and rejuvenators to extend the life of the PFC. Brownwood, Dallas, Houston, and Odessa reported placing a seal coat on a PFC.

An important part of this survey was to identify districts with potential field test sections. Districts were asked to provide a list of projects that were near the end of the pavement service life and that could be candidates for rehabilitation. Table 7 shows that 10 of the districts provided candidate projects. Researchers followed up with these districts to conduct field testing and determine the potential of developing alternative strategies to pavement rehabilitation or removal.

Table 3. District Use of PFCs.

District	Have PFCs been used or are they currently being used in your district?	Do you anticipate an increase of PFC pavement application in your location based on historic performance?
Abilene	Yes, in the past.	No because of winter weather issues.
Atlanta	No. Not yet, but we are about to place some PFC on IH 20 in Harrison County.	Yes.
Austin	Yes, currently.	No. PFC locations are primarily set for our District by the District Pavement SOP.
Beaumont	Yes, in the past.	No. This is a great material, and I personally loved the safety aspect of this material in wet weather. Past administration in BMT did not like the "sacrificial" aspects of this material.
Brownwood	Yes, in the past.	No. We really like the performance of the PFCs however the long-term maintenance of them has caused us to reduce the amount of use. At this point, the only option we have for maintenance is to mill off the PFC and provide another overlay. We have recently placed a seal coat on a 15-year-old PFC, and we will monitor its performance this winter.
Bryan	Yes, currently.	No. We have utilized PFC on many of our main roads and as those main roads are reconstructed, we are converting to CRCP.
Dallas	Yes, in the past.	We are moving to SMA due to performance in the Dallas District. PFC tends to have more failures.
	Yes, in the past.	No. We typically use SMA.
El Paso	No.	No. Most of our arterial network in El Paso is rigid pavement and we get very little rain.
Houston	Yes, currently.	Yes.
	Yes.	Yes.
Lubbock	No. We have a large blowing dirt issue so PFCs were never used in this area because the pavement would fill with dirt. We used CMHB in the past and now we use SMA.	No.
Lufkin	Yes, currently.	Yes.
Odessa	Yes, in the past.	No. We have had good results with PFC w/rubber lasting many years, but there aren't many options at the end of life besides removal.
San Angelo	Yes, currently.	No. Only used in eastern Kimble County on I-10.
Tyler	Yes, currently.	Yes.
Waco	Yes, currently.	Yes.
Wichita Falls	Yes, currently.	Yes.

Table 4. Performance of PFCs in Texas.

District	What is the longevity of PFC pavements in your location? Min–Max, years	What is the average longevity of PFC pavements in your location? Years	What is/are the most common failure mode/modes in PFC pavements in your location?	Other mode/modes of failure?
Abilene	10–16	12	Raveling, loss of permeability.	–
Atlanta	–	–	–	–
Austin	8–12	10	Raveling, loss of permeability.	Winter storm damage.
Beaumont	8–12	10	Other.	We had a few locations with loss of aggregate in areas with high truck turning movements. Other than that, it worked great.
Brownwood	10–15	12	Raveling, loss of permeability.	–
Bryan	10–20	15	Raveling.	–
Dallas	7–10	8.5	Loss of permeability, loss of friction, other.	Base failures.
	5–8	7	Loss of permeability.	–
El Paso	4–10	7	Raveling, loss of permeability, loss of friction.	–
Houston	–	10	Raveling.	Raveling at the turning areas.
	5–15	10	Raveling.	–
Lubbock	–	–	–	–
Lufkin	7–18	9.5	Raveling, loss of permeability, other.	Oxidation.
Odessa	6–10	8	Raveling.	–
San Angelo	? –14	–	Loss of permeability.	–
Tyler	8–15	12	Raveling, other.	Cracking.
Waco	8–8	8	Raveling.	–
Wichita Falls	8–17	12	Raveling, loss of permeability.	–

Note: – indicates no response was provided.

Table 5. Types of PFCs Used and Types of Roadways Where Used.

District	What type of PFCs have been applied in your location?	What type of roadways have PFCs been successfully applied on in your location?
Abilene	PG Coarse, AR Coarse	Interstate and US highways.
Atlanta	As stated earlier, we do not have any PFC in the Atlanta District at this time. However, we have an active contract to put some locations on IH 20 that were identified as part of a study done. We are also looking at possibly putting PFC on a section of US 271.	–
Austin	PG Coarse, PG Fine, AR Coarse	Various (US, SH, FM, etc.) highways with high volumes and speeds. We have even utilized PFCs on RM roadways in our District. Many of these roadways are principal & minor arterials.
Beaumont	PG Coarse, TBPFC	Interstate Highways to Principal Arterials.
Brownwood	PG Coarse, PG Fine	Rural 2 lane 2-way roadways with ADT ranges from 1200–2000.
Bryan	PG Coarse, PG Fine	Controlled access highways (interstate US and state highways).
Dallas	PG Coarse	We have not used a PFC in the past 10+years that I am aware of.
	PG Coarse	IH 30 Interstate, just east of Downtown Dallas.
El Paso	PG Fine, AR Coarse, AR Fine	Interstate and US Highways.
Houston	AR Coarse	State Highway 36 from Freeport to Damon (Fort Bend County Line) and SH 288 between Hwy 6 and BS 288 B. Currently work progress on SH 35 from SH 288 to Matagorda County Line.
	PG Fine, AR Fine	2-lane flexible pavement roadways with moderate ADT.
Lubbock	–	–
Lufkin	PG Coarse	US and SH.
Odessa	AR Coarse, AR Fine	Interstate, Freeways, State highways, Urban corridors.
San Angelo	PG Coarse	I 10 Kimble County.
Tyler	PG Coarse	ALL roadways.
Waco	PG Coarse, PG Fine	Interstate 35 in McLennan and Bell County. Mostly in urban area and at curve sections.
Wichita Falls	PG Coarse, One with SAC B aggregate substituted	Freeway applications and higher volume rural 4 lane conventional sections.

Note: – indicates no response was provided.

Table 6. Maintenance Practices for PFCs.

District	What maintenance practices are performed on PFC pavements in your location?	When applying an overlay over a PFC pavement, is milling done as part of the maintenance strategy?	What do you consider are the dos and don'ts of PFC pavement maintenance in your location?	
			Successful strategies?	Unsuccessful Strategies?
Abilene	None.	Yes. To remove a porous layer from being trapped in the pavement structure that would retain moisture and lead to rutting and distress.	–	–
Atlanta	None.	–	–	–
Austin	Fog seal, rejuvenator.	Yes. To remove existing pavement, reestablish roadway profile, and cross slope.	Minimal maintenance is completed other than addressing typical pavement failures.	NA
Beaumont	Crack seal.	Yes. Was always told not to place anything on PFC. Always considered it "sacrificial." Milled it completely off and placed a new overlay.	Not sure. Would love to start using again in BMT and it will be a lot easier to sell the Administration if we can perform some type of maintenance.	
Brownwood	Seal coat, Onyx.	No. We have not overlaid any of our PFC pavements.	We have recently placed a sealcoat over a 15-year-old PFC (summer of 2021). At this point, the sealcoat is still looking good. We believe the PFC had almost no permeability left.	We placed Onyx on an Ultra-Thin PFC. It helped for about 1 year but doesn't seem to be a long-term PM solution.
Bryan	None. Most successful method has been when it is almost at failure, remove and replace with new PFC.	Yes, to provide opportunities for improved ride quality.	Spot repairs can be performed, but repair areas where wider to tie in with surrounding pavement and avoid creating seams in base repairs.	None attempted.

District	What maintenance practices are performed on PFC pavements in your location?	When applying an overlay over a PFC pavement, is milling done as part of the maintenance strategy?	What do you consider are the dos and don’ts of PFC pavement maintenance in your location?	
			Successful strategies?	**Unsuccessful Strategies?**
Dallas	Seal coat, thin overlay.	Yes, only when cannot raise profile.	–	Any form of patching/repairing shallow or deep distresses.
	None.	Yes, typically mill and inlay PFC.	–	–
El Paso	Fog seal, seal coat, Onyx.	Yes. Milling is done to remove the PFC and provide a stable foundation for the overlay.	Perform base repairs with PFC’s also seal coating existing PFC’s is very effective.	–
Houston	Seal coat, underseal as tack coat.	No. As the surface getting PFC looks good.	If the raveling is observed at the turning areas replace with the hot mix overlay.	–
	None.	Yes. Was always told residual moisture in PFC layer would cause bonding issues.	Don’t use milled-in rumble strips. Causes raveling.	–
Lubbock	–	–	–	–
Lufkin	Fog seal, mill, and inlay.	We have never overlaid a PFC.	Mill and inlay.	Doing nothing and patching with dense grade hot mix.
Odessa	Fog seal. We have tried seal coat without good result with the binder being absorbed causing shelling.	No. We haven’t done an overlay on a PFC to date.	Fog seal to help with raveling towards end of life.	Seal coating.
San Angelo	None.	No. We haven’t overlayed on PFC. We will mill and replace w/ PFC or HMA.	–	–
Tyler	Fog seal, rejuvenator, crack seal.	No. We completely mill and replace.	Crack Seal, mill and replace, some fog seal.	Seal coat.

District	What maintenance practices are performed on PFC pavements in your location?	When applying an overlay over a PFC pavement, is milling done as part of the maintenance strategy?	What do you consider are the dos and don’ts of PFC pavement maintenance in your location?	
			Successful strategies?	Unsuccessful Strategies?
Waco	None.	No. We have not overlayed any PFC.	PFC should be placed on sound sub-surface.	–
Wichita Falls	Shot blast to restore friction on SAC B PFC.	Yes. We have removed PFC prior to overlay to avoid a layer that traps moisture and strips the asphalt.	Attempt to eliminate the use of deicing stone on PFC, it accelerates the loss of draindown in the pavement.	–

Note: – indicates no response was provided.

Table 7. Candidates for Rehabilitation.

District	Are there any PFC pavements in your location that are near the end of their service life that would be candidates for rehabilitation?	Is there any other information relevant to the maintenance or rehabilitation of PFC pavements that you would like to share with the research team?
Abilene	Yes. IH-20 Callahan County Control Section: 0007-02.	Crumb rubber modified PFC's in our district have had great performance with no distress issues.
Atlanta	–	No, but I am looking forward to hearing about maintenance strategies. Although, since our PFC will be brand new in a few months I really hope we don't have to touch it for a long time.
Austin	Yes. US 290 East of Elgin.	More of a question but how do other Districts handle small pavement repair locations where placing a small quantity of PFC may not be reasonable?
Beaumont	Yes. US 90 west of Dayton and SS 380 in BMT. However, both are scheduled for removal.	I am impressed by this material. On US 90 we are losing some of the aggregate in spots. However, it still provides a great "spray" reduction in wet weather since the project was constructed in 2008. This section still shows "Fair" to "Very Good" SKID values. I think BMT Administration decided to stop using this material since we placed this material in so many locations in a short amount of time. A lot of money was spent to remove and replace this material at several locations. We should have looked closer at maintenance of the PFC and spreading out the use of this material. I am still sold on PFC. I love the safety aspects of this material. This section will soon be milled and replaced with Superpave.
Brownwood	Yes. The Ultra-Thin PFC on US183 in Stephens County. This is the same section we placed Onyx on in 2019, I think.	–
Bryan	No.	–
Dallas	No.	Not that I am aware of.
El Paso	No.	–
Houston	No.	Please investigate the underseal instead of seal coat or tack coat in the coastal counties as the material behaves differently due to high relative humidity.
Lubbock	–	–
Lufkin	Yes. US 69/287, US 59 North Nacogdoches County, US 59 Polk County.	–
Odessa	Yes. SH 191—From FM 1788 to LP 250 in Midland County.	–

District	Are there any PFC pavements in your location that are near the end of their service life that would be candidates for rehabilitation?	Is there any other information relevant to the maintenance or rehabilitation of PFC pavements that you would like to share with the research team?
San Angelo	Yes. 1-10 in Kimble County is 14 years old. We are looking at options currently.	There's a reluctance to rejuvenate or fog PFC due to concerns over skid.
Tyler	Yes. Too many to list. Can provide a map of the locations upon request.	No.
Waco	Yes. I 35 north of Waco.	Not that I can think of.
Wichita Falls	Yes. There are two segments of US 287 in Clay and Montague Counties that will likely be addressed in the upcoming years.	We've done limited to no maintenance on PFC pavements in WFS. They have performed very well as a whole in this district.

Note: – indicates no response was provided.

4. EVALUATION OF RESURFACED PFC PAVEMENTS

The research team conducted field performance evaluations of resurfaced PFC pavements. Field projects were identified through the assistance of TxDOT's advisory panel as well as from the survey results described in the previous chapter. Visual and GPR evaluations were conducted to identify the presence of water in the PFC layer. Skid data were reported for the sections where Onyx was applied since this type of treatment has the potential to negatively affect friction.

Two types of surface treatments were placed over aging PFC pavements: Onyx (SS 30238 Frictional Asphalt Surface Preservation Treatment) and seal coat. The following projects were documented.

- Onyx-Surfaced PFC Pavements:
    - Brownwood.
    - San Antonio.
- Seal Coat–Surfaced PFC Pavements:
    - Brownwood.
    - El Paso.
    - Bryan.
    - Houston.

For the pavements surfaced with Onyx, much of the product was worn off after about 2 years of service. For the IH 35 section that had a heavy application of Onyx, the skid was affected negatively, and even with the heavier application, raveling was comparable to the untreated portion of the PFC pavement.

Three of the four seal coated PFCs performed well. Both the Brownwood and El Paso PFC pavements are in an area of low rainfall, and based on the GPR analysis as well as district evaluation, these PFC pavements were not draining at the time of sealing. This was confirmed by the GPR analyses, though some portions of the roadways showed areas of low density at the bottom of the PFC; however, there did not appear to be a negative effect on performance.

The Bryan PFC is in an area experiencing much higher rainfall, and indications from the GPR indicate that the PFC was open and draining when it was sealed. This PFC pavement has been covered with a seal coat for about 10 years and is exhibiting satisfactory performance.

The one failure known to researchers was in the Houston District in 2017. While not a lot is known about this roadway since it was a dramatic failure prompting quick removal at the time, researchers were informed that the failure was due to trapped moisture from a recent rainfall at the time of placing an AR seal coat, which generated steam and caused debonding, with the seal ultimately tracking on vehicle tires.

Table 8 and Table 9 provide a summary of the observations from each roadway followed by a complete discussion of results.

Table 8. Observations from PFC Pavements Surfaced with Onyx.

District, Highway	Observations
San Antonio, IH 35	• There was a moderate amount of raveling at the time of initial application of the Onyx. • After 2 years, the product was still present (probably due to the higher application rate), but raveling seemed comparable to the untreated portion of the PFC. • The skid numbers dropped significantly due to the Onyx. • The increase in skid observed in the Onyx section in 2019 was likely due to an increase in macrotexture from additional raveling.
Brownwood, US 183	• Dielectric is uniform except for a few areas where it looks like there may be some patching underneath. • Signs of distress include minor cracking and raveling. • Most of the Onyx is worn off in the main lanes. • Shoulders still appear to have some of the product. • Onyx has worn off enough in some areas to expose paint striping underneath.

Table 9. Observations from PFC Pavements Surfaced with Seal Coat.

District, Highway	Observations
Brownwood, SH 36	• This was a successful application of a seal coat over a PFC. This past winter had some very harsh conditions, and if there were water trapped in the PFC, it most likely would have shown some serious damage. • Based on the GPR and water flow tests performed by the district, the PFC was most likely not draining at the time of seal coating. There are some isolated areas where the PFC appears to exhibit low density near the bottom of the layer, which could potentially hold water. However, based on the performance observed at the surface, these areas are not causing a problem.
El Paso, US 90	• This was a successful application of a seal coat over a PFC. The seal coat over this PFC has been through three years of service, including three winters, and there does not appear to be any damage to the underlying PFC due to trapped moisture. • Based on the GPR, the PFC was most likely not draining at the time of seal coating. There are some isolated areas where the PFC appears to exhibit low density near the bottom of the layer, which could potentially hold water. However, based on the performance observed at the surface, these areas are not causing a problem. • The seal coat is exhibiting reflection cracking and some flushing in the wheel paths, but overall performance of the seal coat is acceptable.
Bryan, SH 6 FR	• Seal coat and pavement in general is in good condition. • GPR indicates a low dielectric, typical of a PFC that is draining. • There is one area near the bottom of a hill that may be holding moisture in the PFC; however, no performance problems are noted.
Houston, SH 146	• Seal coat exhibited dramatic failure by debonding and picking up on vehicle tires. • Failure was likely caused by trapped water in the PFC at the time of placing the hot membrane at the surface, which then generated steam and caused debonding.

4.1. SAN ANTONIO DISTRICT, ONYX-SURFACED IH 35 (SOUTHBOUND)

This project consists of a1-mi test section in southbound lanes from mile marker (MM) 131 to MM 130. Project information is shown in Table 10.

Table 10. San Antonio District, Onyx-Surfaced IH 35 Project Information.

PFC Project Information	Resurfacing Information
PFC Type: PG 76, PFC-C PFC Age:10 years Traffic: 32,400 AADT Condition of PFC at time of resurface: minor raveling.	Resurface Type: Onyx Resurface Application Rate: 0.28 gal/yd^2 Condition at time of final evaluation in 2019: moderate raveling. Project has since been milled and resurfaced.

The San Antonio District constructed a 1-mi test section in the southbound lanes of IH 35 in June of 2017. This portion of IH 35 was surfaced with an older PFC that was about at the end of its life and beginning to exhibit significant raveling, and the district wanted to see if Onyx could retard the raveling and extend the life of the PFC. Figure 26 shows the treatment soon after application.

The old PFC surface along with the beginning of the Onyx application can be seen in Figure 27. Skid measurements taken on the Onyx surface and on the existing PFC at either end of the Onyx section are shown in Figure 28. These data are concerning because the skid numbers seem to have dropped by about 10 points. Some improvements in skid were noted in the last set of measurements from April 2019, but all measurements were observed to increase, and it was concluded that this increase was attributed to either (a) the slurry wearing off (Figure 29); or (b) the continuation of the raveling (Figure 30), which was visually apparent. Figure 29 and Figure 30 show the pavement surface condition 3 years after placement of the Onyx.

Figure 26. IH 35 PFC surfaced with Onyx.

Figure 27. IH 35 existing PFC and beginning of Onyx application.

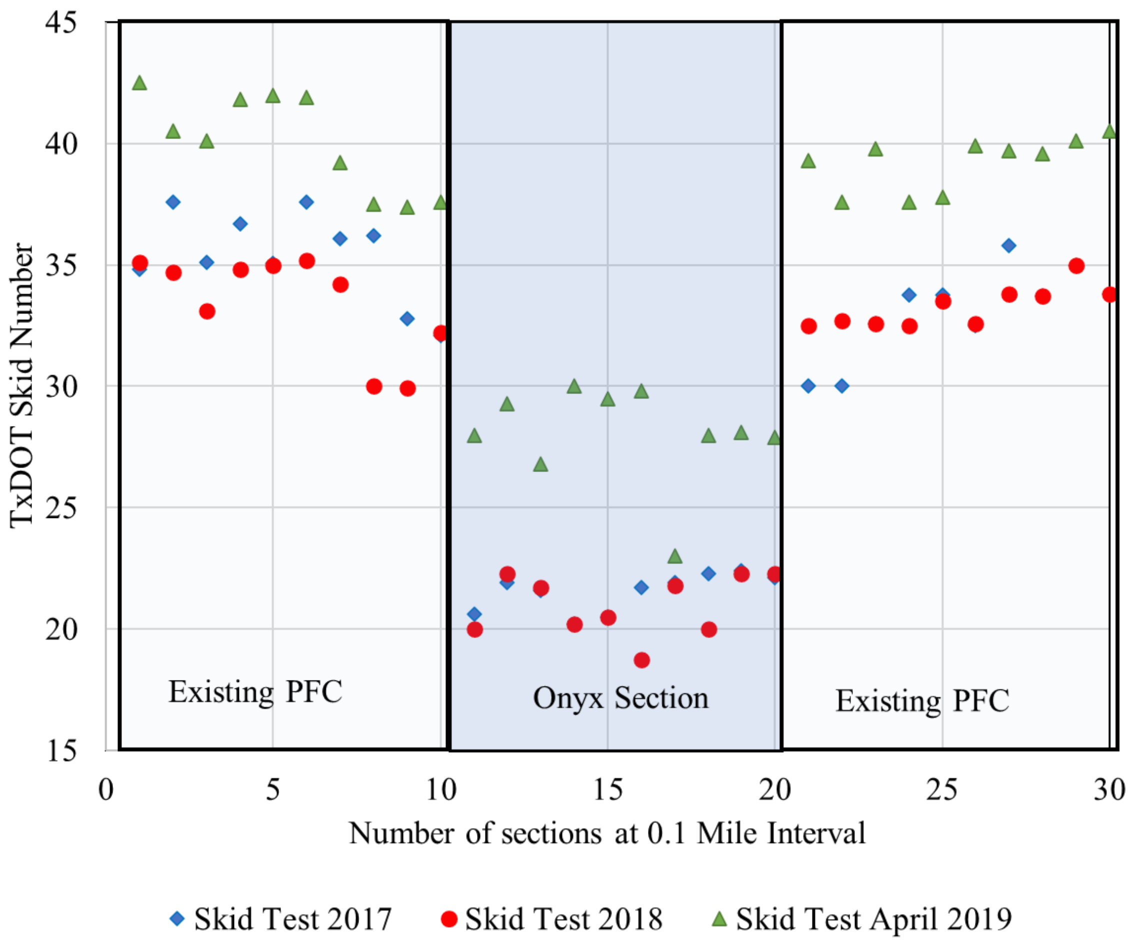


Figure 28. Skid data on IH 35 existing PFC and Onyx test section.

Figure 29. IH 35 after 3 years of traffic showing wear off the Onyx surface treatment.

Figure 30. IH 35 after 3 years of traffic showing signs of raveling.

4.2. BROWNWOOD DISTRICT, ONYX-SURFACED US 183 NEAR BRECKENRIDGE

Project ID: Cont 6231 Sect 69 Job 001, Project ID 025701049

In 2020, the Brownwood District applied a frictional asphalt surface preservation treatment (Onyx, SS 3028) to a PFC on US 183 south of Breckenridge. Project information is shown in Table 11. It would have been difficult to mill this PFC off since it was originally placed on a flexible base covered with a surface treatment. The results were good in terms of friction, as shown in Figure 31. No noticeable loss in friction was observed.

Table 11. Brownwood District, Onyx-Surfaced US 183 Project Information.

PFC Information	Resurfacing Information
PFC Type: Item 342 PG 76, PFC-F	Resurface Type: Onyx
PFC Age: 8 years	Resurface Application Rate: 0.12 gal/yd^2
Traffic: 1,715 to 2,471 AADT Condition of PFC at time of resurface: Still draining and functioning as a PFC, minor raveling, and longitudinal cracking.	Condition of surface at time of evaluation: According to maintenance personnel, it is still draining and functioning as a PFC, minor raveling, and longitudinal cracking. Onyx surface is almost completely worn away in the wheel paths.

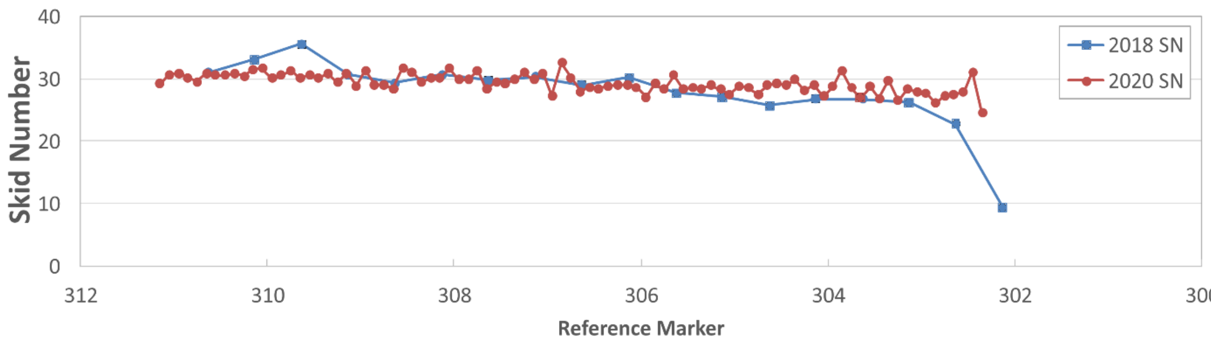
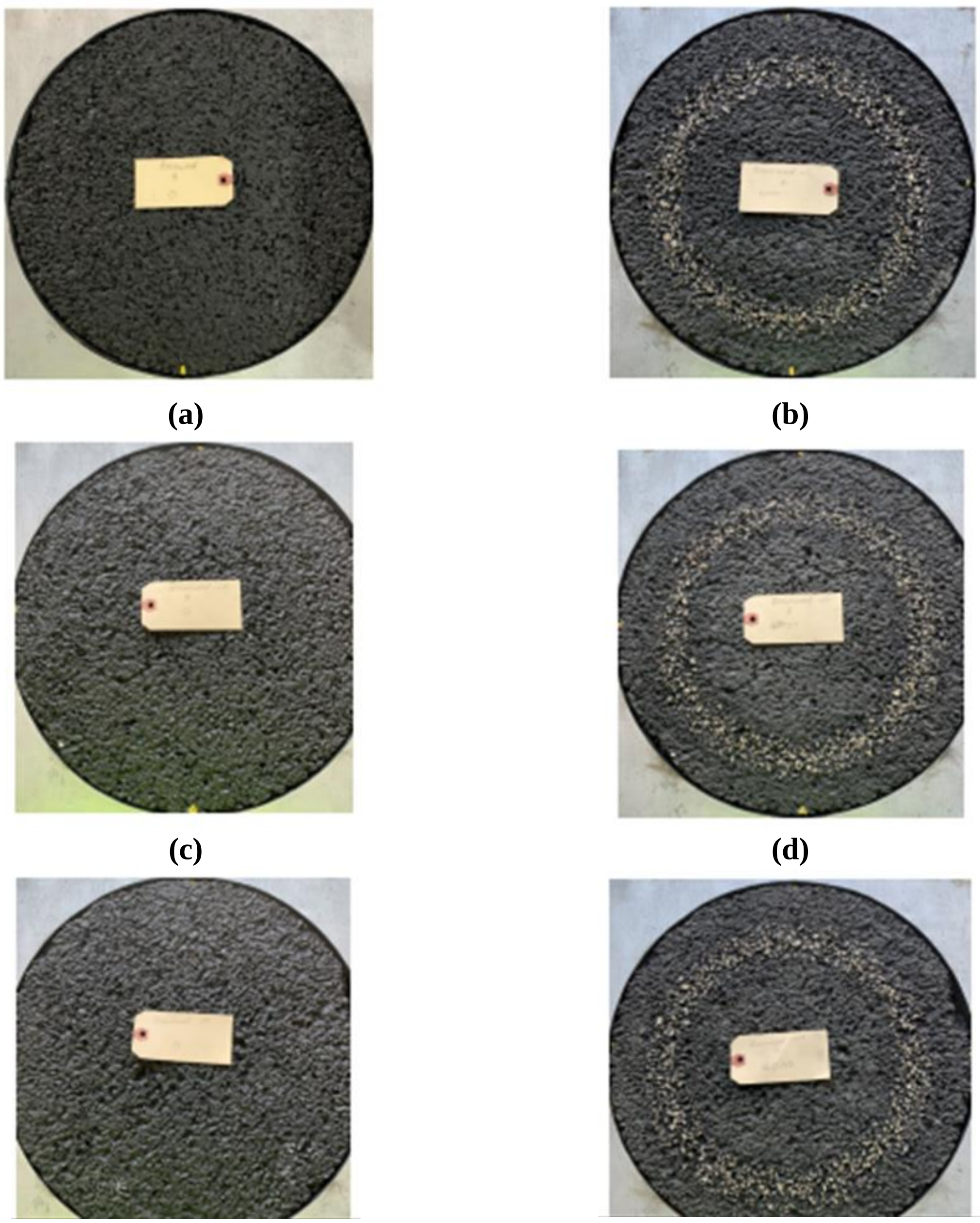


Figure 31. Skid before Onyx application (2018) compared to skid after Onyx application (2020).

To achieve this acceptable skid performance, the application quantity was optimized. The district worked with Hall Brothers, who obtained 16-inch diameter cores and then applied different quantities of the frictional asphalt surface preservation treatment (Onyx). The cores were then trafficked using a three-wheel polisher. Before and after polisher trafficking photos are shown in Figure 32. After 300, 1,000, 2,000, 4,000, 8,000, and 16,000 passes, the friction was measured using the DFT and the texture was measured using the circular track meter. These two measures provide a correlation to the skid number obtained with the locked wheel skid trailer.



(a) (b) (c) (d) (e) (f)

Figure 32. 16-inch cores before and after three-wheel polisher trafficking: (a) core A at zero passes with 0.12 gal/yd^2, (b) core A after 16,000 passes, (c) core B at zero passes with 0.16 gal/yd^2, (d) core B after 16,000 passes, (e) core C at zero passes with 0.20 gal/yd^2, and (f) core C after 16,000 passes.

The laboratory testing revealed that there was a relationship of increasing skid numbers with the increase of passes with the three-wheel polisher. There did not seem to be significant visual differences between the three application rates. The lowest application rate had the quickest skid number recovery. Based on balancing friction needs and sealing the surface, the district selected 0.12 gal/yd^2 as the application rate. The condition of the PFC is illustrated in Figure 33, and details on the GPR evaluation are shown in Figure 34.

Figure 33. Condition of US 183 after about 2 years of traffic (February 2022).

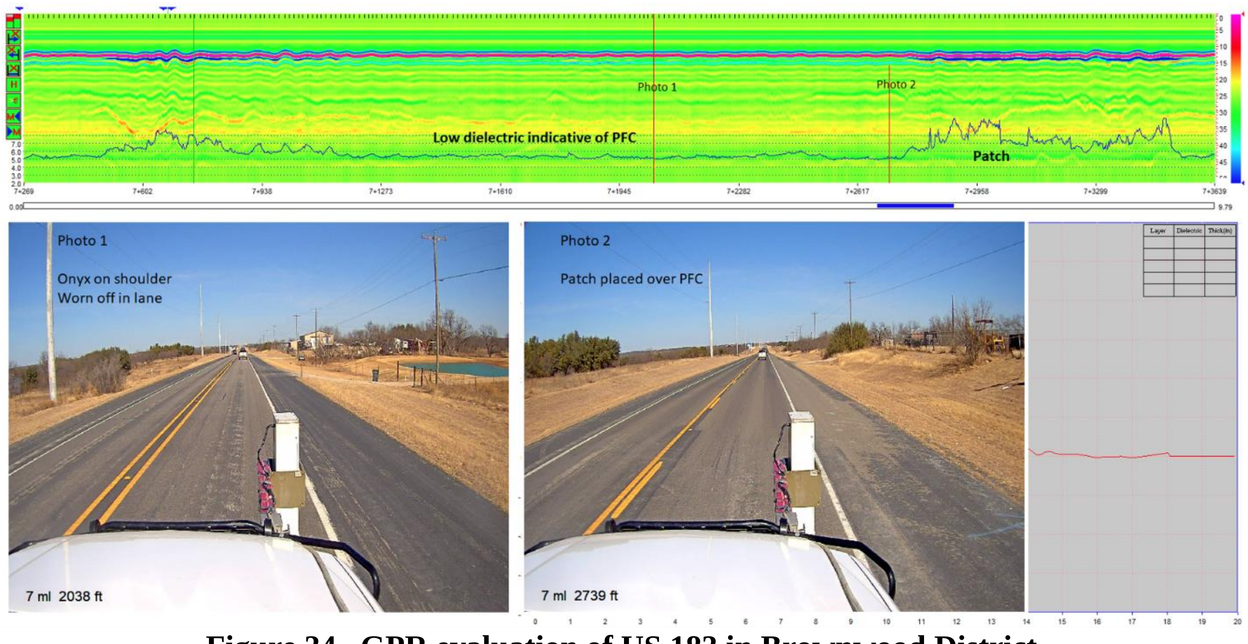


Figure 34. GPR evaluation of US 183 in Brownwood District.

4.3. BROWNWOOD DISTRICT, SEAL COAT–SURFACED SH 36 NEAR RISING STAR

Texas Reference Marker (TRM): ~348+1.93 to TRM: ~352+1.443

In the summer of 2021, the Brownwood District placed a seal coat on a raveling PFC. Project information is shown in Table 12. The district milled some of the worst raveling and did some patching right before the seal coat, but there was still some minor raveling at the time it was sealed. The district also ran some water flow tests the prior fall (of 2020), which showed there was very little to no permeability at that time.

Table 12. Brownwood District, Seal Coat–Surfaced SH 36 Project Information.

PFC Project Information	Resurfacing Information
PFC Type: Type PG 76, PFC-C PFC Age: 10 years Traffic: 1,500 to 2,000 AADT Condition of PFC at time of resurface: minor raveling, not draining.	Resurface Type: Seal Coat Date of Resurface: Summer 2021 Condition of PFC at time of evaluation: seal coat in good condition, some isolated areas of flushing in the wheel paths and raveling outside of wheel paths.

The current condition of the seal coat is shown in Figure 35. It is in relatively good condition, with some minor raveling outside the wheel paths and isolated areas of flushing in the wheel paths.

A GPR survey was conducted in February of 2022, and examples of the GPR survey are shown in Figure 36 and Figure 37. Based on the GPR, most of the project seems to be clogged (not draining) since there is no variation in density with depth, as shown in Figure 36 and schematically depicted in Figure 38. This finding indicates that the pavement was no longer functioning as a PFC at the time of seal coating. However, in some areas (as shown in Figure 37), there appears to be a portion of low density at the bottom of the PFC, meaning that the PFC is clogged in the top portion but open in the bottom portion (as illustrated in the schematic of Figure 39). While this could be an area to potentially hold water, there do not appear to be any surface distresses causing concern.

Figure 35. Current condition of seal coat on SH 36 in Brownwood District (February 2022).

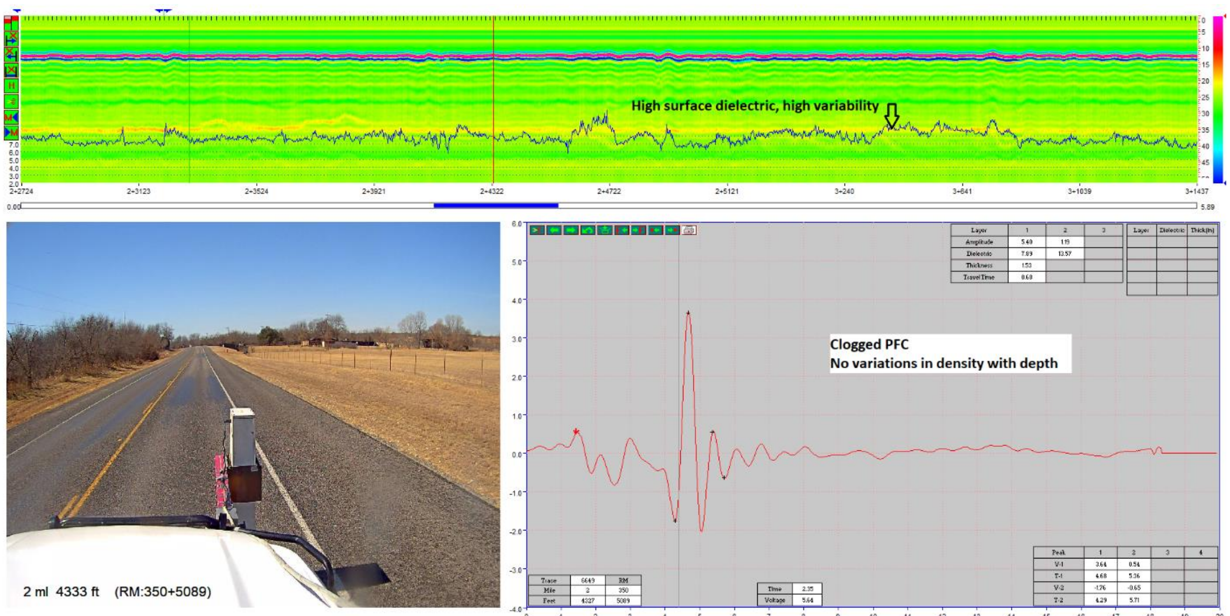


Figure 36. GPR evaluation of SH 36 indicating PFC is clogged.

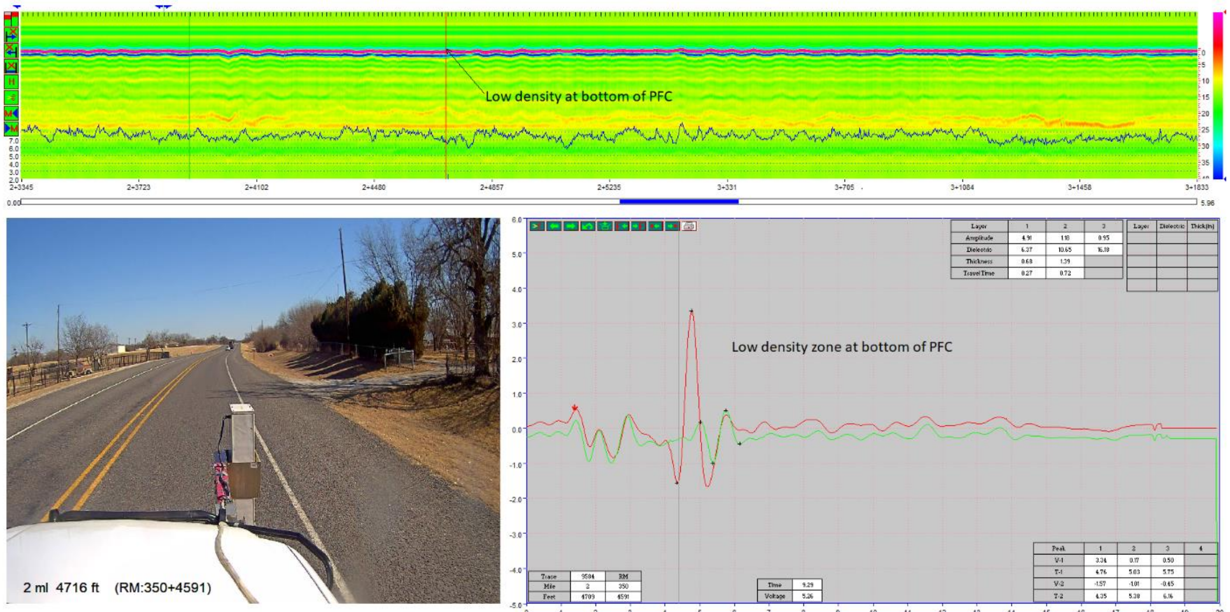


Figure 37. GPR evaluation of SH 36 showing isolated areas of low density at the bottom of the PFC layer.

Figure 38. Schematic depicting clogged PFC observed from GPR.

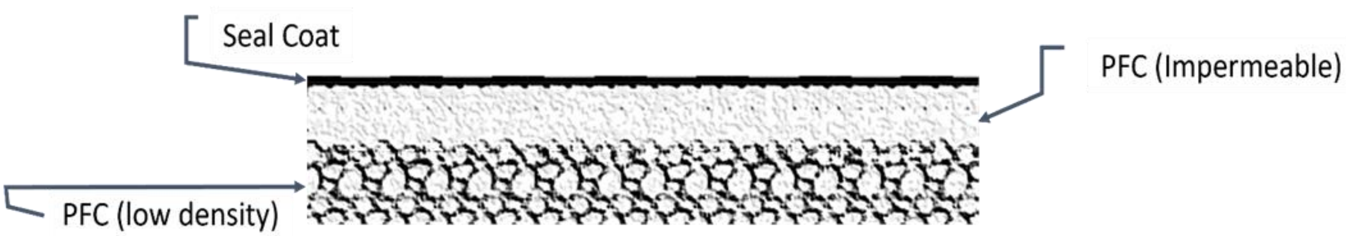


Figure 39. Schematic depicting low density at bottom of PFC observed from GPR.

4.4. EL PASO DISTRICT, SEAL COAT–SURFACED US 90 WEST OF MARFA

Project ID: 002007032

In 2018, the El Paso District seal coated about 27 mi of US 90 from the Jeff Davis/Presidio County Line, east to the Marfa city limits. The project information is shown in Table 13. A 500-ft-long FM roadway with the same PFC was tied into the project and was sealed first to make sure that it worked. Construction photos are shown in Figure 40 and Figure 41. The seal coat is currently exhibiting some cracking that was present in the underlying surface prior to the placement of the PFC. There is also some flushing of the wheel paths in portions of the project (Figure 42).

Table 13. El Paso District, Seal Coat–Surfaced US 90 Project Information.

PFC Project Information	Resurfacing Information
PFC Type: Type PG 76, PFC-C	Resurface Type: Seal Coat
PFC Age:12 years	Date of Resurface: Summer 2019
Condition of PFC at time of resurface: minor raveling, not draining.	Current Condition of PFC at time of evaluation in April 2022: cracking, some flushing in the wheel paths.

GPR imagery is shown in Figure 43. Most of the PFC appears to be clogged since there is no variation in density with depth. However, as on SH 36, there are some isolated areas where the PFC exhibits low density at the bottom of the layer, but there do not appear to be any performance problems associated with the low-density areas.

Overall, the district is satisfied with the performance of the seal coat.

Figure 40. Seal coat construction on US 90 in El Paso District.

Figure 41. Seal coat at time of construction on US 90 in El Paso District.

Figure 42. Current condition of US 90 at western end of project near Presidio County Line (April 2022).

Figure 43. GPR evaluation of US 90 in El Paso District.

4.5. BRYAN DISTRICT, SEAL COAT–SURFACED SH 6 SB FRONTAGE ROAD

The Bryan District placed about a half-mile section of PFC on the SH 6 Frontage Road (FR) south of College Station in about 2006. Project information is shown in Table 14. At the time, this section was not a frontage road but instead encompassed the main travel lanes of SH 6. The PFC was placed in an area that was very flat, without enough slope to achieve good drainage. Correcting the cross slope would have required significant hot mix, so the temporary solution was to place a PFC in this area to help with the drainage. This placement was considered successful by the district, but the section was inadvertently seal coated when the district seal coat program came through a few years later. By this time, the traffic was significantly less on this portion of the roadway since it had become a frontage road.

Table 14. Bryan District Seal Coat–Surfaced SH 6 FR Project Information.

PFC Project Information	Resurfacing Information
PFC Type: PG 76 PFC-C	Resurface Type: Seal coats (2)
PFC age at time of resurface: 7 years.	Date of resurface: Seal coat ~2013, Seal coat 2020.
Condition of PFC at time of resurface: condition unknown.	Current condition of PFC at time of evaluation in April 2022: good condition, no distresses observed.

The current condition of the roadway is particularly good and can be seen in Figure 44. The GPR indicates there are quite a few defects deeper into the pavement but none near the surface. There are no indications of any problems or that the PFC may be holding moisture (Figure 45) except in an area at the bottom of a hill (Figure 46), as indicated by the elevated surface dielectric. However, there are no visual surface indicators that this area has caused any performance problems.

Figure 44. Current condition of SH 6 FR (April 2022).

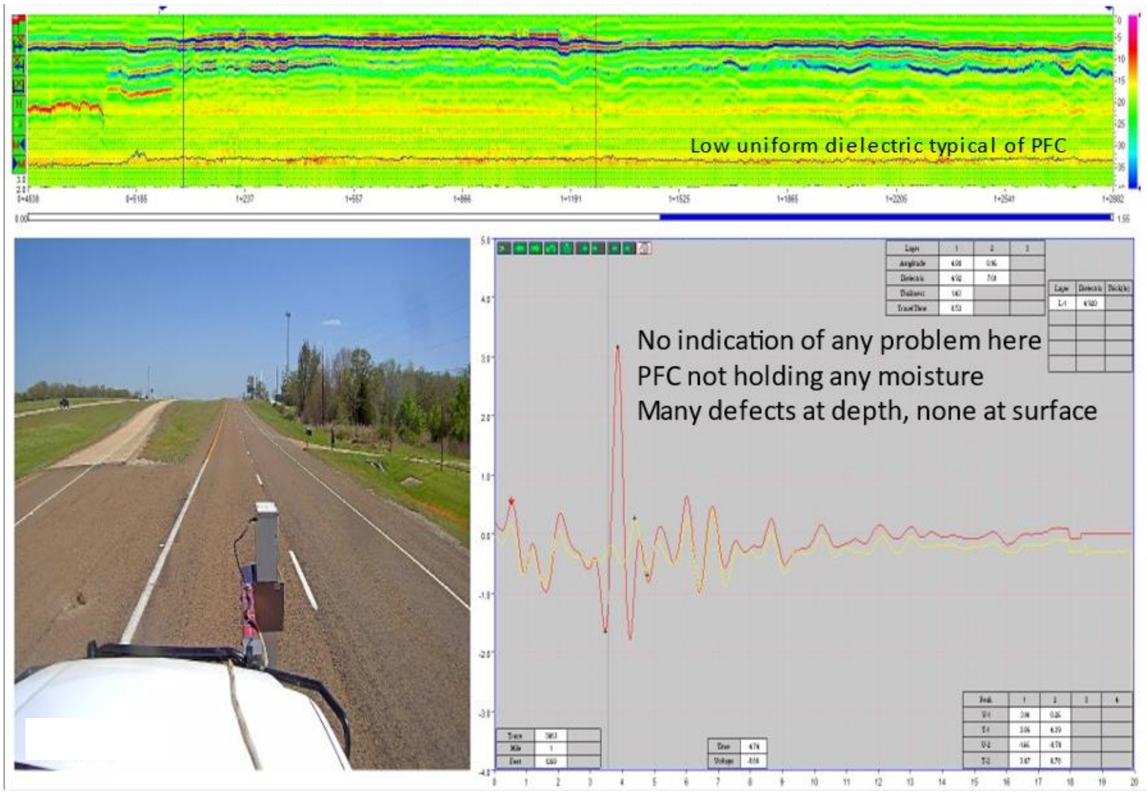


Figure 45. GPR evaluation of SH 6 FR indicating no problem areas.

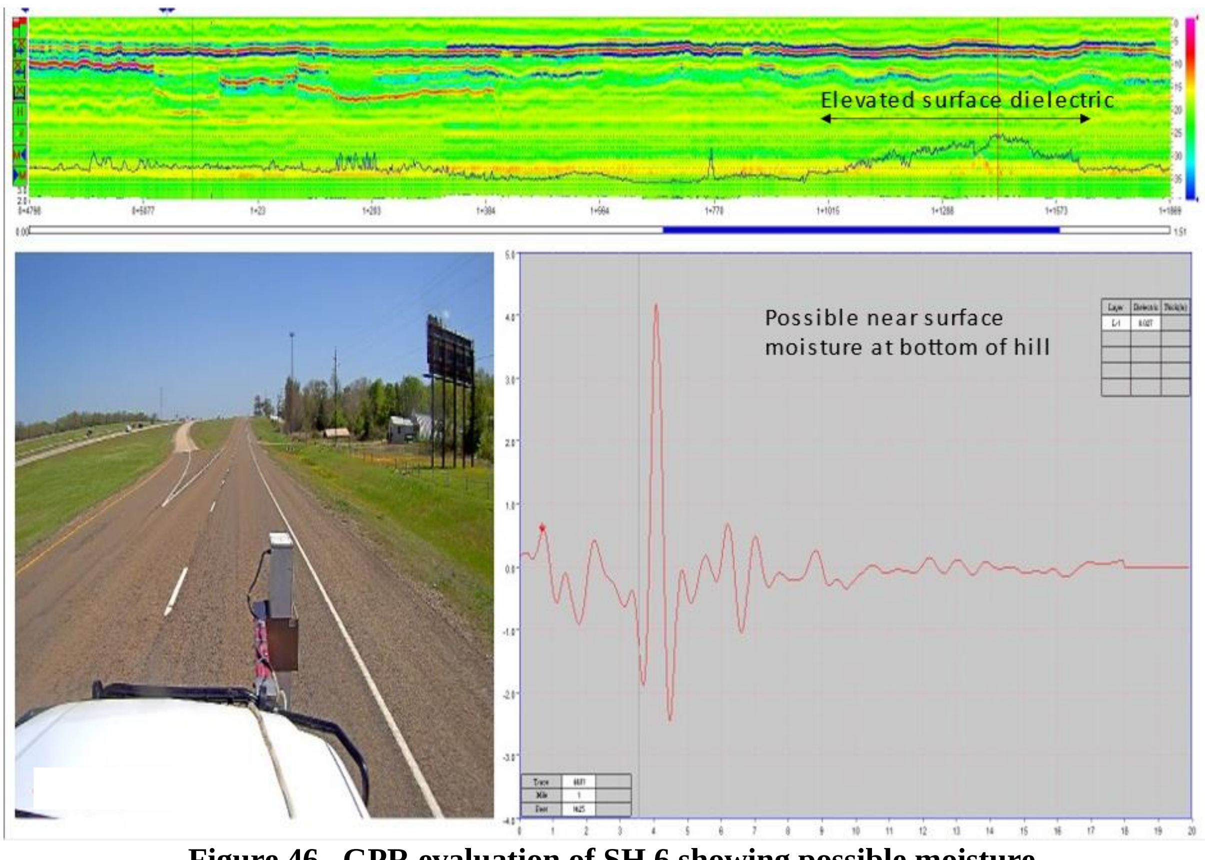


Figure 46. GPR evaluation of SH 6 showing possible moisture.

4.6. HOUSTON DISTRICT, SEAL COAT–SURFACED SH 146

In March of 2017, Texas A&M Transportation Institute (TTI) researchers became aware of the Houston District placing an AR seal coat (intended to be an interlayer) over a PFC on SH 146. Project information is shown in Table 15. This seal coat failed dramatically by not sticking to the surface and peeling up on vehicle tires on the day of placement, as shown in Figure 47 through Figure 49.

Table 15. Houston District, AR Seal Coat SH 146 Project Information.

PFC Project Information	Resurfacing Information
PFC Type: unknown	Resurface Type: AR Seal Coat
PFC Age: unknown	Date of Resurface: March 31, 2017
Condition of PFC at time of resurface: unknown	Sealed with moisture in PFC causing seal coat to pick up on tires.

This was not part of any ongoing research, and no documentation was collected at the time. Based on discussions with the contractor, there had been a recent rainstorm, and it was believed that there may have been moisture trapped in the PFC at the time of the seal coat. AR seal coats are placed at elevated temperatures, and the contractor believed this created steam in the PFC layer, causing the debonding.

Figure 47. Seal coat stuck to vehicle tires (from TV news report).

Figure 48. Seal coat stuck to truck tires (from TV news report).

Figure 49. Seal coat causing damage to cars and tires (from TV news report).

5. FIELD EVALUATION OF EXISTING CANDIDATE PFC PAVEMENTS

The research team identified and evaluated candidate PFC pavements for potential maintenance and/or rehabilitation options and test section construction in the following districts:

- Lufkin.
- Austin.
- Brownwood.
- Bryan.

The activities that were conducted at each site are discussed herein.

5.1. LUFKIN DISTRICT

The Lufkin District provided researchers with a list of PFCs that were nearing the end of their life. TTI collected high-definition video and GPR data on the following roadways:

- US 69.
- SH 7.
- US 59 near Corrigan.
- US 59 near Nacogdoches.
- US 59 near Tenaha.

GPR data are presented for each of these roads.

5.1.1. US 69

In August of 2022, the district let a maintenance contract to do some spot mill and inlay of Superpave mix for the worst sections of the PFC on US 69 in Lufkin. For the purposes of this research project, the district designated a 1,200-ft portion of the road to be a test section. For the test section, workers left the existing PFC in place and overlaid it with a Superpave mix. Figure 50 shows the condition of the PFC test section location prior to the overlay. There was some raveling and cracking, as shown in the photo, and there was also a newer PFC inlaid patch for the last 600 ft in the outside lane. Further details on the specific location of the test section are provided in Figure 51 and Figure 52.

Figure 50. Lufkin US 69 old PFC test section location.

The specific location was US 69 northbound (NB) at the concrete pavement to 1,200 ft southeast, beginning reference marker (RM) 416+0.460 and ending RM 416+0.225.

Figure 51. Google Maps location of the US 69 test section.

Figure 52. Image of test section location on US 69 Lufkin.

The Superpave mix was placed across the full width of the test section. GPR data for the left lane, right lane, and shoulder are shown in Figure 53 through Figure 55. When a PFC becomes clogged and is no longer draining, the GPR dielectric is higher and is more like a dense-graded HMA. Most of this older PFC tended to have a higher dielectric, indicating that it was clogged. The newer PFC inlaid patch (Figure 54) was draining a little better, but because the shoulder was also clogged, there was nowhere for the water to drain off, which created a bathtub effect within the patched area.

Figure 53. GPR data for left lane of US 69.

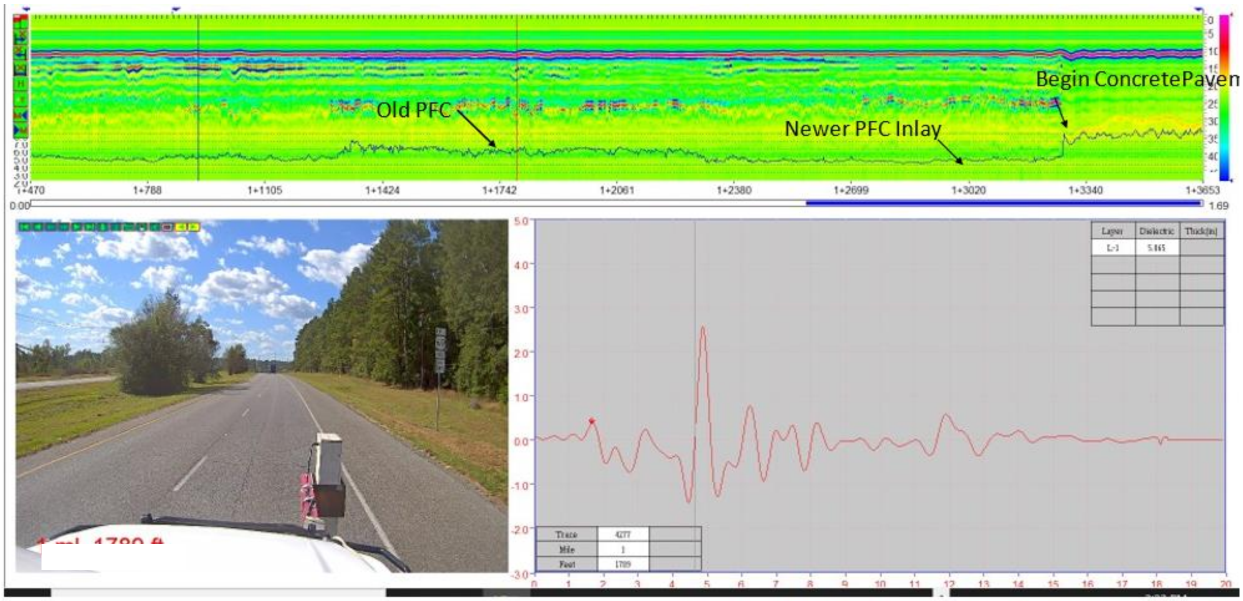


Figure 54. GPR data for right lane of US 69.

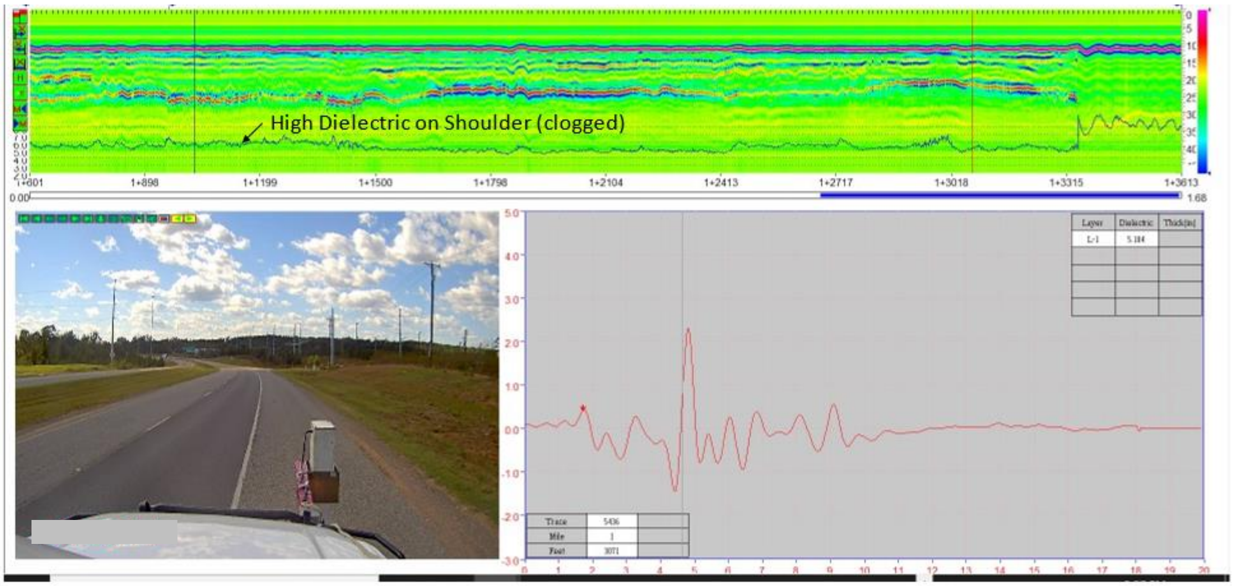


Figure 55. GPR data for shoulder of US 69.

To verify these findings, the Lufkin District provided traffic control for the researchers to conduct field water flow tests and to take cores of the PFC pavement. The older PFC was not draining. At 180 seconds, as shown in the photo in Figure 56, if there was still no water flowing, the test was discontinued. The newer inlaid PFC patch performed better in terms of drainability, and these field tests confirmed the GPR data. A schematic of the test section layout and locations of field water flow tests along with results is shown in Figure 57.

Figure 56. No water flowing in old PFC.

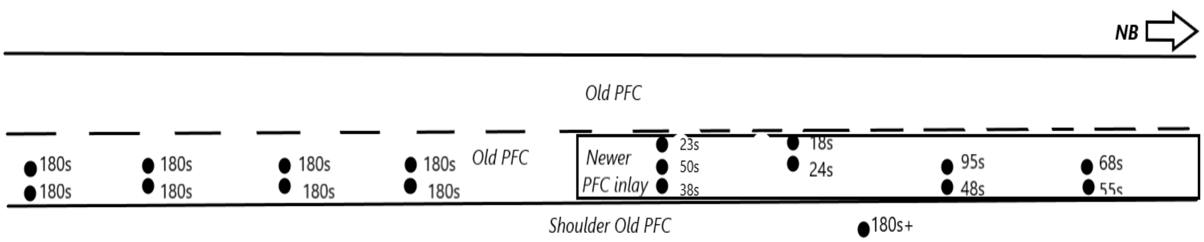


Figure 57. US 69 test section location with field water flow test results.

Cores were also taken of the old PFC and the PFC inlaid patch. The PFCs were well bonded to the underlying HMA layer (Figure 58). The PFCs did not ravel or disintegrate from the coring operation.

Figure 58. Core from US 69 showing PFC bonded to underlying HMA.

A core was also taken over one of the cracked areas of the PFC to determine if the crack was coming from underneath or if it originated in the PFC. Figure 59 shows that the crack originated in a lower layer; however, when it reflected through to the PFC, there tended to be raveling around the crack edges, making the crack more open.

(a) **(b)**

Figure 59. Coring on US 69: (a) coring rig, and (b) core acquired over cracked area of the pavement.

5.1.2. SH 7

The location of this PFC was on SH 7 from SH 96 to Mt. Herman. This PFC was performing well but was exhibiting some minor transverse and longitudinal cracking. There was no indication of significant raveling. GPR data are presented in Figure 60 and Figure 61. Based on the low and uniform dielectric shown in these figures, the PFC appeared to be draining.

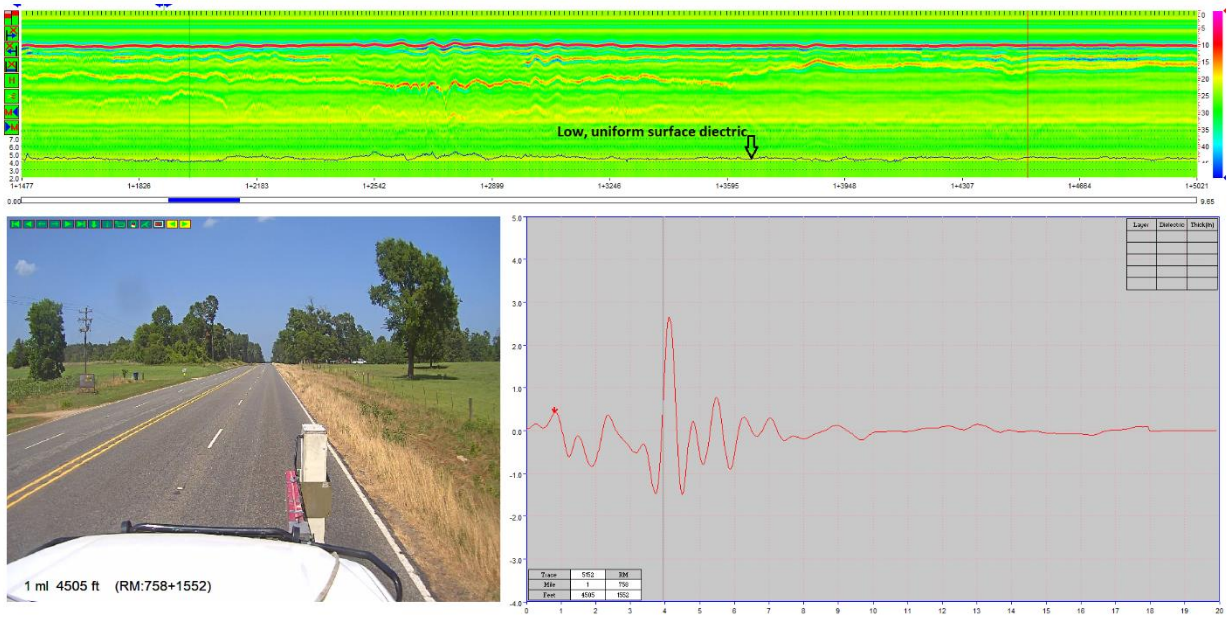


Figure 60. SH 7 PFC eastbound outside lane.

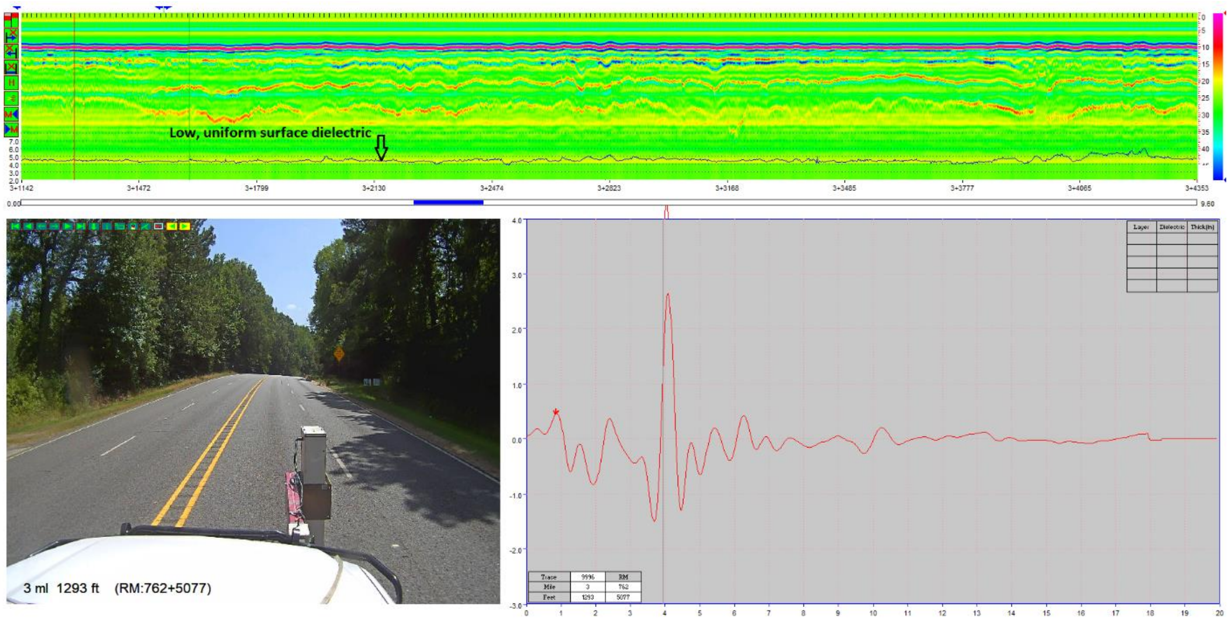


Figure 61. SH 7 PFC westbound outside lane.

5.1.3. US 59 near Corrigan

This PFC was located on US 59, from the Angelina County Line to Corrigan. According to the GPR data in Figure 62, the surface dielectric was around 5 and was uniform, indicating it was still functioning as a PFC (i.e., draining). The overall condition of the PFC was relatively good.

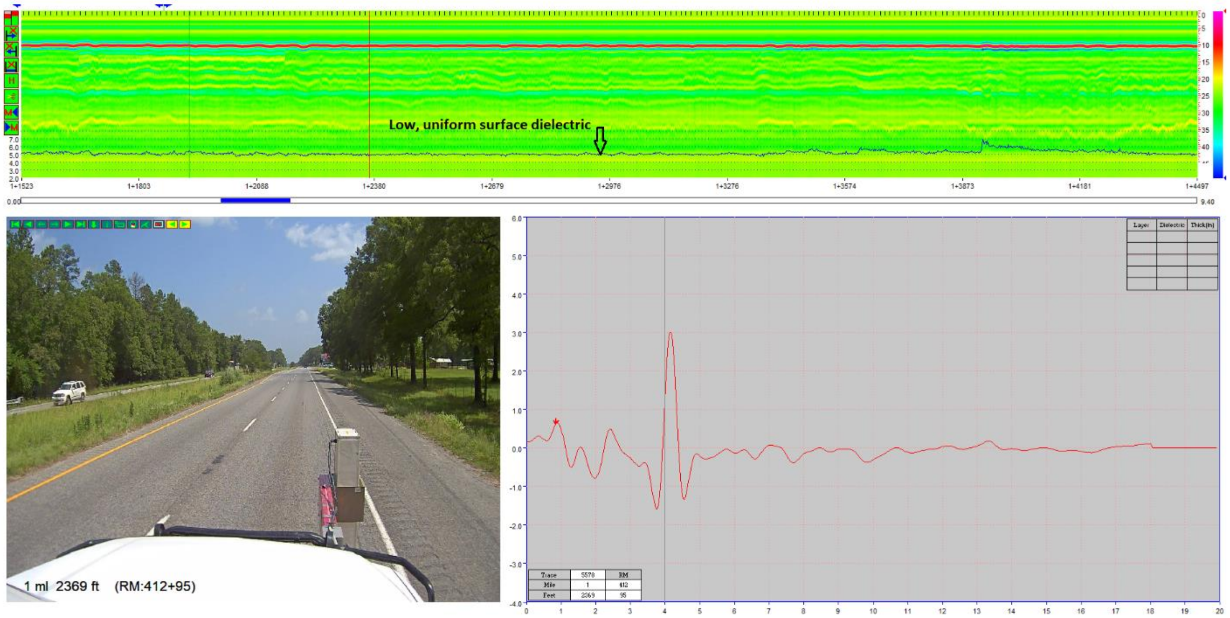


Figure 62. GPR data on US 59 near Corrigan (northbound outside lane).

5.1.4. US 59 near Nacogdoches

This PFC was located on US 59 from the Angelina River to the Nacogdoches city limits. GPR data shown in Figure 63 indicate that the surface dielectric was less than 5 and was functioning as a PFC (i.e., draining). The surface layer was a relatively thin PFC and appeared to have some isolated areas of delamination.

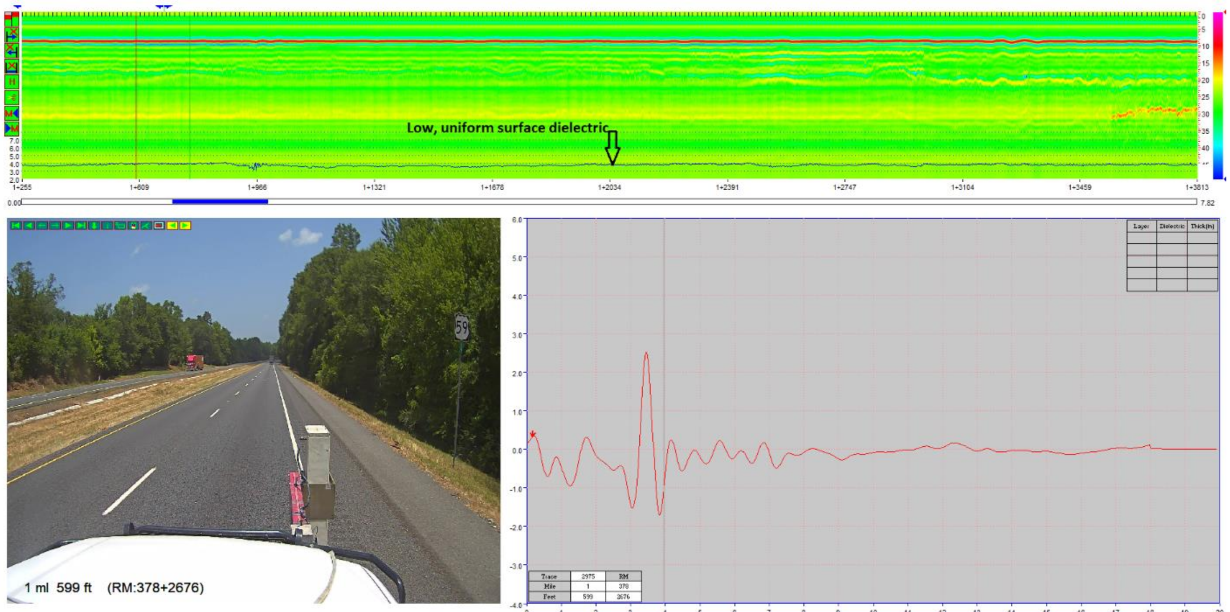


Figure 63. GPR data on US 59 near Nacogdoches (northbound outside lane).

5.1.5. US 59 near Tenaha

This PFC was located on US 59 north, beginning at the cloverleaf intersection of SH 84 and US 59 and going north to the county line about 4 mi. This PFC also had a low, consistent dielectric around 5, indicating that it was still draining, as shown in Figure 64.

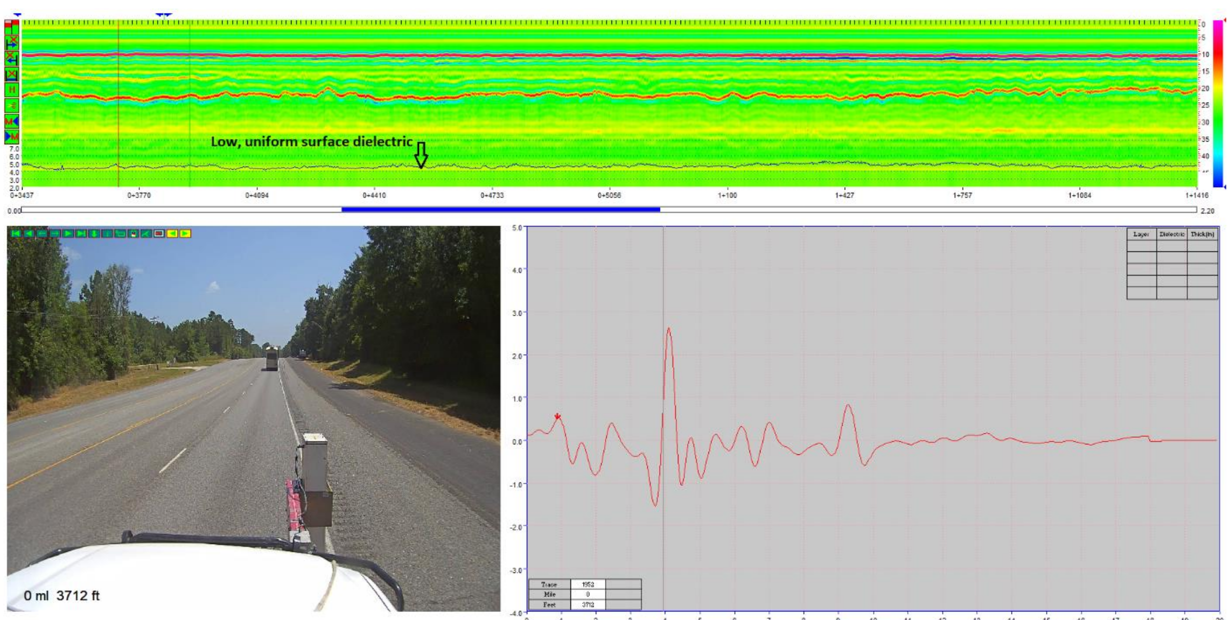


Figure 64. GPR data on US 59 near Tenaha (northbound outside lane).

5.2. AUSTIN DISTRICT REJUVENATING FOG SEAL

5.2.1. SH 195

In 2014, the Austin District constructed a PFC on SH 195 (new construction) near Florence. Prior to opening to traffic, the PFC started to exhibit potential signs of raveling. Even turning a pickup truck tire on the mix caused raveling. Also, the mix looked very aged and oxidized (see Figure 65 and Figure 66). The exact cause of the excess wear was not determined, but this construction occurred when recycled oil engine bottoms were first being identified in asphalt, along with their negative effects on HMA.

(a) (b)

Figure 65. SH 195 PFC in 2014: (a) overview of the signs of pavement distress before opening to traffic, and (b) closeup view of the oxidation and raveling distress.

(a) (b)

Figure 66. Comparison of typical new PFC to the SH 195 PFC mix: (a) typical new PFC; (b) SH 195 new PFC.

To salvage the PFC, the district worked with Ergon Asphalt to apply a rejuvenating fog seal called eFog. This is a polymer-modified, medium-setting emulsion with rejuvenator. It was applied at a rate of 0.12 gal/yd^2.

TTI collected GPR and HD video in August 2022 (8 years later), as shown in Figure 67. While the PFC is showing some signs of raveling and some cracking, it has performed remarkably well given initial concerns.

Figure 67. GPR data for SH 195 collected in August 2022.

5.2.2. MoPac

Based on the success of SH 195, the Central Texas Regional Mobility Authority (CTRMA) worked with the Austin District and the TTI research team to place a test section of rejuvenating fog seal on a 1-mi section of the managed toll lane of MoPac. The surface was in good condition, but CTRMA was looking for a treatment to preserve the PFC and extend its life. The test section location was in the NB express lane from TRM 438.5 to 437.5.

Testing before and after fog seal included skid, GPR, and water flow. The research team also collected GPR data on the test section in October 2022 prior to placement of the fog seal. Some of these data are shown in Figure 68. The video shows the surface to be in good condition, and the surface dielectric is low and consistent, indicating good drainability.

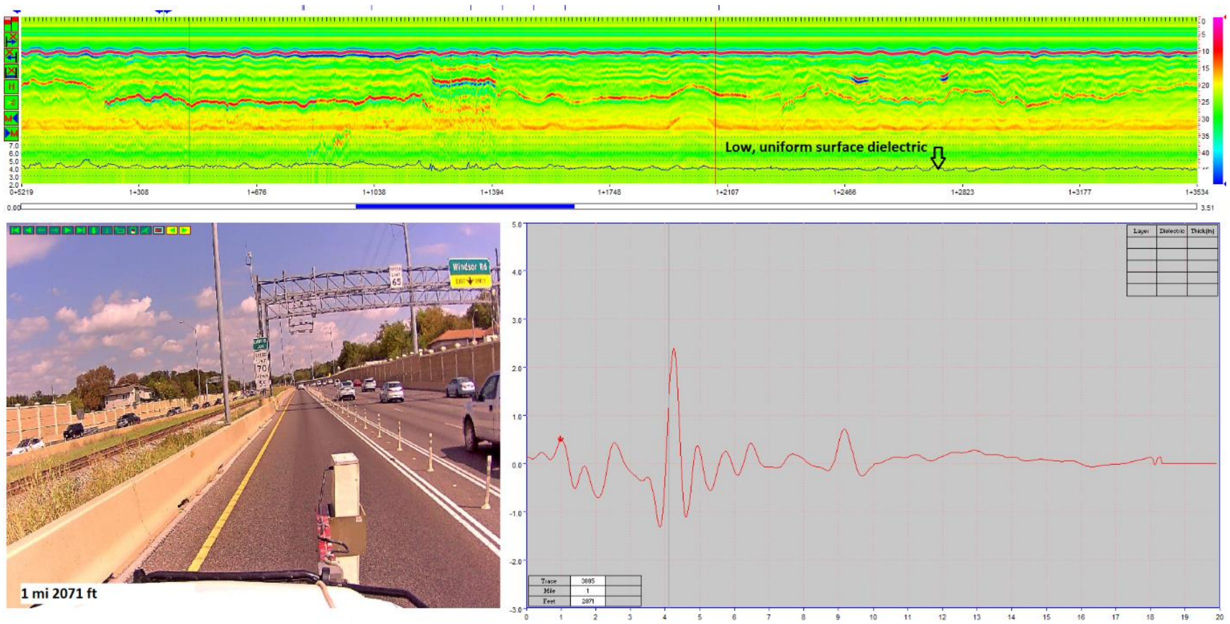


Figure 68. GPR data on MoPac.

5.3. BROWNWOOD DISTRICT

In 2012, the Brownwood District placed a fine PFC on US 183 south of Breckenridge. This section of roadway had a surface treatment exhibiting some flushing, which is why a PFC was selected as the overlay. In 2020, the district applied a frictional asphalt surface preservation treatment (Onyx, SS 3028) to this PFC to extend its life (Figure 69 and Figure 70). After a couple of years in service, the Onyx surface was almost completely worn off.

Since the Onyx surface has worn off, the district is planning to place a seal coat. This PFC cannot be milled off since any milling would probably damage the flex base underneath because it is very thin.

Figure 69. GPR data on US 183 south of Breckenridge.

Figure 70. Condition of US 183 PFC from July 2022, Google Maps.

In March of 2023, TTI researchers conducted field testing on this section of roadway. Five locations were selected for water flow testing and for coring. Water flow tests were conducted in the outside wheel path and between the wheel paths, as shown in Figure 71. For the most part, the PFC was clogged, but there were a few locations where the PFC could be taking in water. The results of the water flow tests are shown in Figure 72.


Figure 71. Water flow testing.

Cores were also taken at each of these five locations and brought back to TTI's laboratory for further evaluation. The coring operation is shown in Figure 73. A close-up of the core is shown in Figure 74. The cross section of the pavement consists of a flex base with a seal coat and then the fine PFC on top of the seal coat. The fine PFC is very thin (less than 1 inch thick).

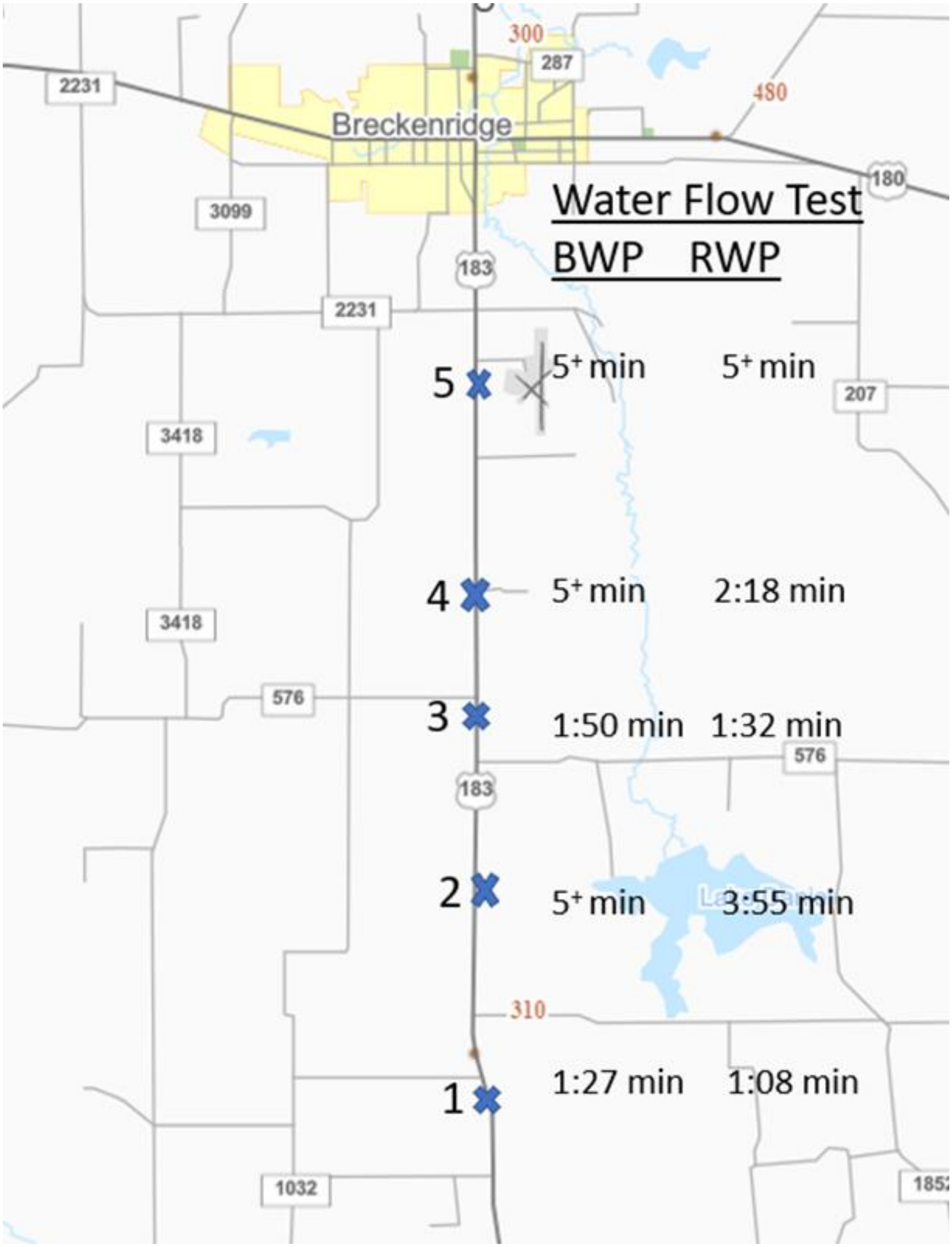


Figure 72. Coring and water flow testing locations along with water flow test results.

Figure 73. Coring of fine PFC.

Figure 74. Close-up of US 183 PFC core.

5.4. BRYAN DISTRICT

The research team reached out to the Bryan District, which is considering maintenance strategies for a PFC on SH 30 in Bryan. This is a relatively short section (less than 1 mi) placed at an intersection to improve safety, and it is starting to show some signs of raveling.

Video and GPR data are shown in Figure 75 and indicate that the surface is still draining.

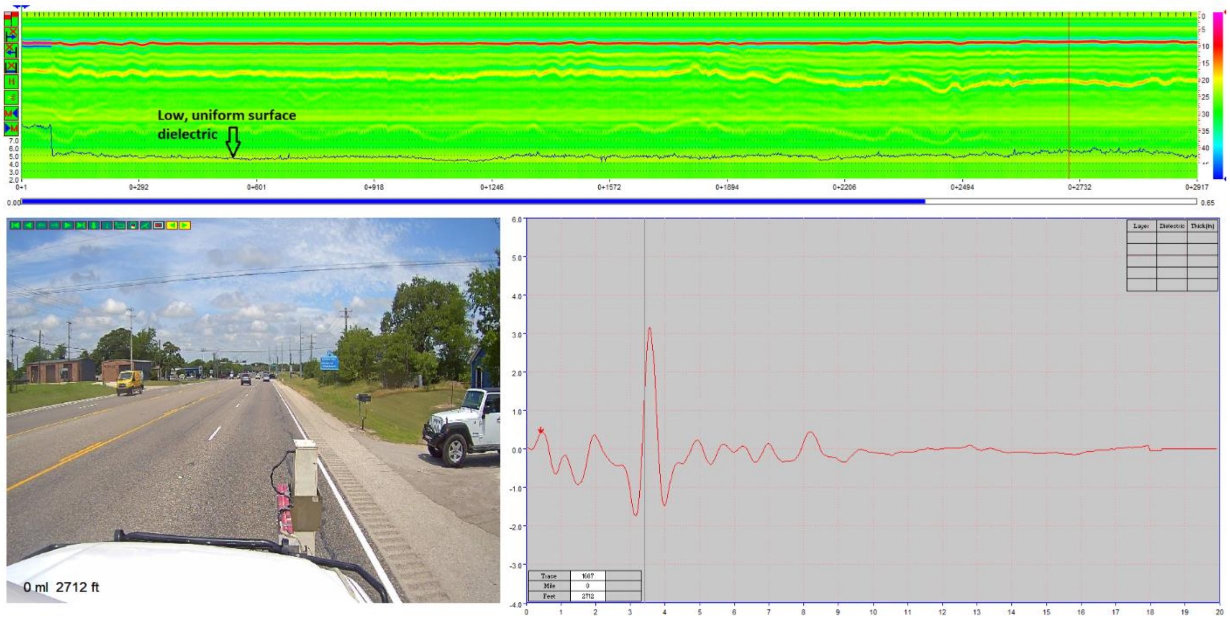


Figure 75. GPR data from SH 30 in the Bryan District.

6. EVALUATION TOOLS FOR PFC PAVEMENTS

Several laboratory and field measurement tools were employed to better understand field observations, assess the effect of mix component materials and rejuvenators on durability and friction, and establish a method to quantify moisture presence in the pavement sublayers and proper rehabilitation timing for PFC projects. These various tools are described next.

6.1. DURABILITY

The Cantabro loss test (Tex-245-F) is conventionally used to assess the durability of PFC mixes. The test consists of testing 5.9-inch (150-mm) diameter by 4.5-inch (115-mm) height specimens compacted to N = 50 gyrations. The specimen weight is obtained prior to testing and is then placed in the Los Angeles abrasion machine (without the steel balls) and subjected to 300 revolutions at 30 rpm. After, any loose material that broke off the specimen is discarded, and the weight of the specimen is obtained again. Further, the mass loss is calculated using Equation 1.

$$CL = \frac{A - B}{A} \times 100 \tag{1}$$

Where:
CL = Cantabro loss, %.
A = initial weight of the test specimen.
B = final weight of the test specimen.

Prior studies have looked at the Cantabro loss test to generate degradation curves by subjecting the specimen to multiple cycles of 300 revolutions each until a certain mass loss is obtained (Arámbula-Mercado et al. 2019). Researchers recommended a stopping criterion of 60 percent mass loss when generating the degradation curves since beyond this point, the rate of mass loss reduced significantly with added Cantabro abrasion loss cycles (Arámbula-Mercado et al. 2019).

In this study, Cantabro loss degradation curves were obtained to verify the durability of the PFC mixes with and without RAP (i.e., virgin) and were subjected to different aging conditions after applying two types of rejuvenators. A loose virgin PFC mix that was at the time being placed on a section of IH 45 and corresponding raw materials (i.e., aggregates, binder, and fibers) were collected from Big Creek Construction's asphalt plant in Corsicana, Texas, for this effort. The virgin mix design is shown in Appendix A. The PFC mix included an igneous aggregate, 1 percent lime, a PG 76-22 binder, 6.2 percent optimum binder content (OBC), an anti-stripping agent, and 0.3 percent fibers.

Samples of RAP were also obtained from the same Big Creek Construction asphalt plant, although they were not being incorporated in the PFC mix being placed on IH 45 at the time. The objective of collecting RAP was to evaluate its effect on the durability of the PFC mix. This was achieved by adjusting the virgin mix design to include 10 percent RAP (which is the maximum currently allowed by TxDOT Item 342, Table 2).

The RAP was characterized by determining its binder content and washed gradation, and the virgin mix design was modified by adjusting the virgin aggregate gradation and reducing the virgin binder content to accommodate the RAP while keeping the target gradation and OBC the same as the virgin mix design. Three replicate RAP samples were subjected to the ignition oven, and the resulting average RAP binder content was 3.39 percent. Therefore, the virgin binder content in the PFC mix was reduced from 6.2 percent to 5.86 percent to account for the binder contribution from the RAP. One of the samples of RAP after being subjected to the ignition oven is shown in Figure 76. Next, the material was washed and sieved to obtain the RAP gradation. The adjusted mix design with RAP is also shown in Appendix A.

Figure 76. RAP sample after the ignition oven.

The loose plant mix was subjected to two aging protocols to assess the effect of aging with and without two types of rejuvenators: CMS and CSS-1H. Both products were provided by Ergon Asphalt. CMS is a cationic medium-setting emulsion and is marketed as eFog. It contains a polymer-modified asphalt base that provides a dense film thickness for increased durability and resistance to traffic. It also contains a rejuvenator aimed at restoring aged asphalt properties. CSS-1H is a cationic slow-setting emulsion with a hard asphalt base. It is a conventional emulsion that is commonly used by maintenance personnel for fog seals.

The aging protocols consisted of subjecting the specimens to 5 days of aging at 149°C (8 hours of aging followed by 16 hours of cooling each day) and 14 days of continuous aging at 95°C.

6.1.1. Effect of RAP

The effect of RAP on durability is illustrated in Figure 77. Each curve represents the average of two or three specimens. The average percent AV of the virgin specimens measured via dimensional analysis was 21.7 percent, while the average percent AV of the RAP specimens was 22.0 percent, which makes them comparable. Trendlines are added to each dataset with a forced intercept (0,0) to assess the degree of degradation for each PFC mix type. This is useful because if only one Cantabro cycle were used, as prescribed in the current standard test method Tex-245-F, both virgin and RAP mixes would show acceptable mass loss with values below 10 percent (maximum Cantabro loss for PFC specimens per current TxDOT specifications, Item 342, is 20 percent). However, when looking at the trend with multiple Cantabro cycles, it is apparent that the degradation of the virgin mix is more accelerated than that of the PFC mix, reaching 60 percent mass loss in about eight Cantabro cycles, while the RAP mix takes about 29 cycles to reach that same mass loss value. This result is likely because the RAP mixes are stiffer and less prone to abrasion.

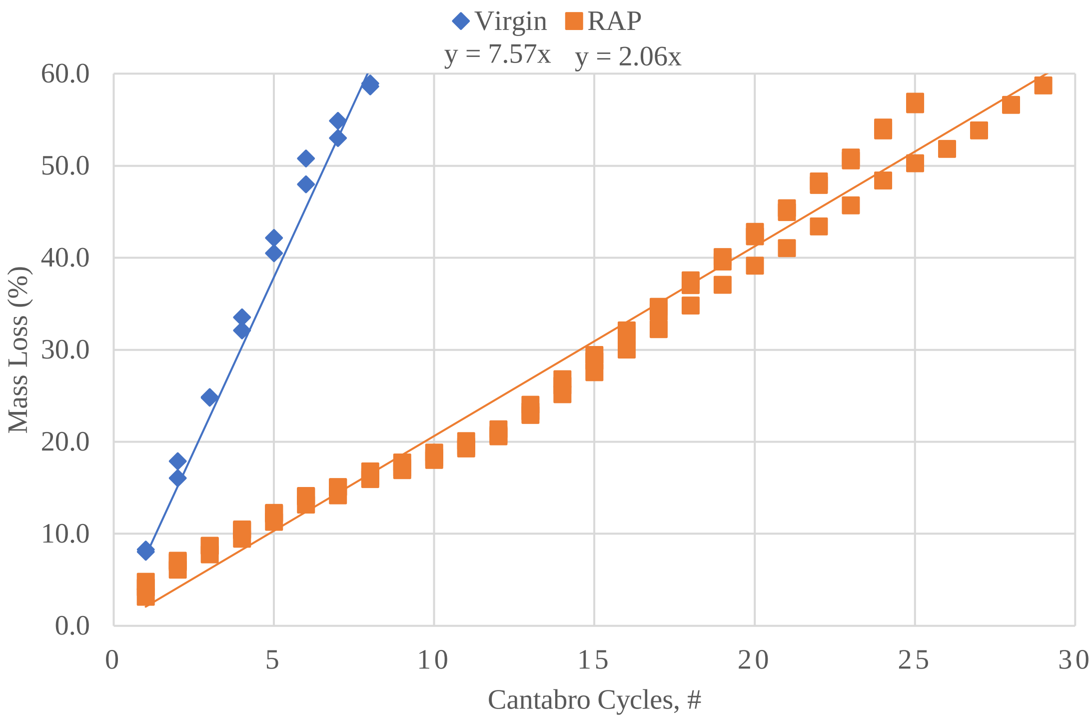


Figure 77. Cantabro loss degradation curves for virgin and RAP specimens.

6.1.2. Effect of Aging

The effect of aging at durability is shown in Figure 78. The average AV of each set of specimens was 21.7 percent for unaged (virgin), 22.4 percent for aged for 5 days at 149°C, and 22.5 percent for aged for 14 days at 95°C. Two aging protocols were selected: a shorter protocol at a higher temperature and a longer protocol at a more moderate temperature. It is apparent that aging did not have a significant impact on the Cantabro loss degradation curve; the mix stiffened with aging, which slowed the rate of mass loss, but the effect was not as significant as what was observed when 10 percent RAP was added to the mix (Figure 77). The difference in slope was about 1.0 between unaged and 5 days aging at 149°C and between 5 days aging at 149°C and 14 days aging at 95°C, which corresponded to 8, 9, and 11 Cantabro cycles to reach 60 percent mass loss for the virgin, 5 days aging at 149°C, and 14 days aging at 95°C, respectively.

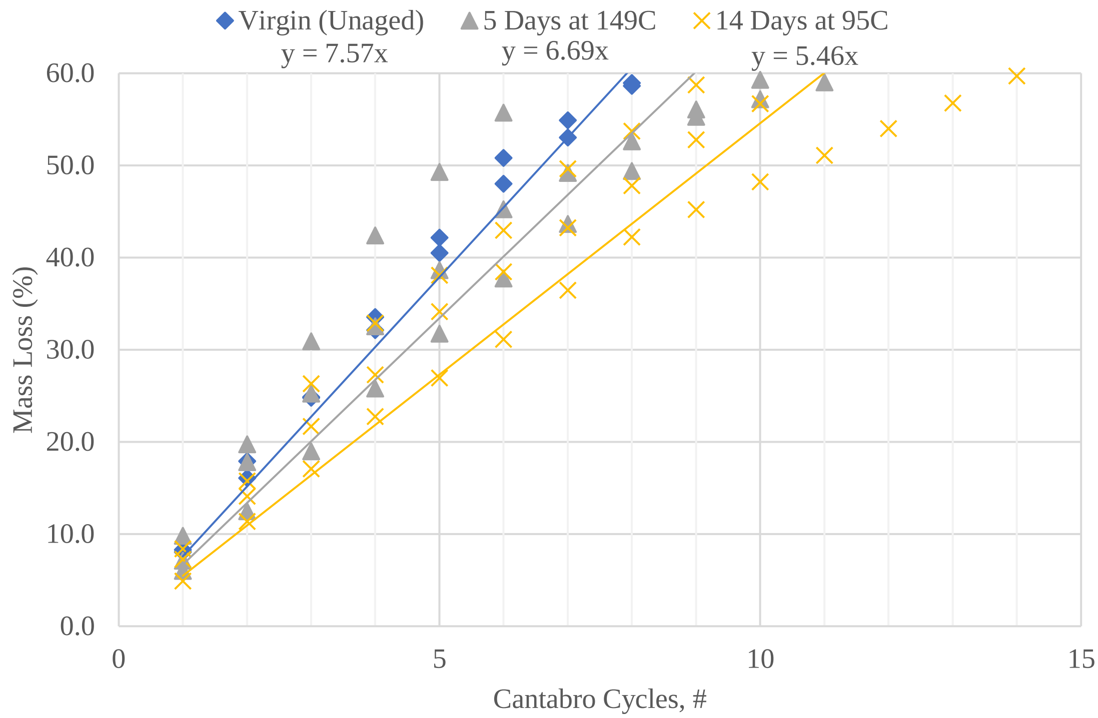


Figure 78. Cantabro loss degradation curves for unaged and aged specimens.

6.1.3. Effect of Rejuvenators

As previously mentioned, two types of rejuvenators, CMS and CSS-1H, were applied to the Cantabro specimens with RAP and the ones that were prepared with aged loose plant mix. The application rate was 0.10 gal/yd^2 for both rejuvenators. The rejuvenators were applied using a Sharpshooter 2.1 drywall hopper gun sprayer like the one shown in Figure 79. To determine the approximate amount of rejuvenator to be applied by the sprayer, a wooden sheet was used. It was weighed without any rejuvenator on it, resulting in a weight of 279.1 grams. Once eight passes of the rejuvenator were applied, the weight on the sheet was 356.2 grams. The approximate amount of material that the device applied in each pass was determined using Equation 2.

$$Sprayed\ Material = 356.2 - 279.1 = 77.1\ \frac{g}{8\ passes} = 9.64\ \frac{g}{pass} \qquad (2)$$

Figure 79. Sharpshooter drywall hopper by Marshalltown.

To spray the material over a larger area, three specimens were stacked on top of each other. The area to be treated was calculated using Equation 3 and considering that the dimensions of each specimen were 6-inch diameter by 4.6-inch height. Note that the area was divided by two because half of the whole longitudinal area was exposed per each pass, as shown in Figure 80:

$$A = \frac{2\pi \mathrm{r}}{2} * \mathrm{L} * \left(3_{samples}\right) = \pi * \left(\frac{6\ in}{2}\right) * \ 4.6\ in * 3 = 41.4\ in^2 = \ \ 0.032\ sqy \tag{3}$$

Based on the selected rejuvenator application rate (0.1 gal/yd^2), Equation 4 was applied to determine the number of passes needed for every set of three stacked specimens.

$$0.1\ \frac{gal}{yd^2}\ x\ \ \frac{0.032\ yd^2}{stack}\ x\ \frac{3{,}785.4\ ml}{1\ gal}\ x\ \frac{1.02\ g}{ml} = 12.36\ \frac{gal}{slab}\ x\ \frac{1\ pass}{9.64\ g}\ \approx 2\ {}^{passes}/_{stack} \tag{4}$$

Figure 80. Cantabro specimens stacked rejuvenator application.

The effect of the rejuvenator on RAP is shown in Figure 81. Each dataset represents the results of three replicate specimens. The average AV of each set of specimens was 22.0 percent for RAP untreated, 23.6 percent for RAP with CMS, and 22.1 percent for RAP with CSS-1H. The results show minimal effect from the rejuvenator on the RAP specimens, with slopes of 2.06 for untreated RAP, 2.02 for RAP with CMS, and 2.45 for RAP with CSS-1H.

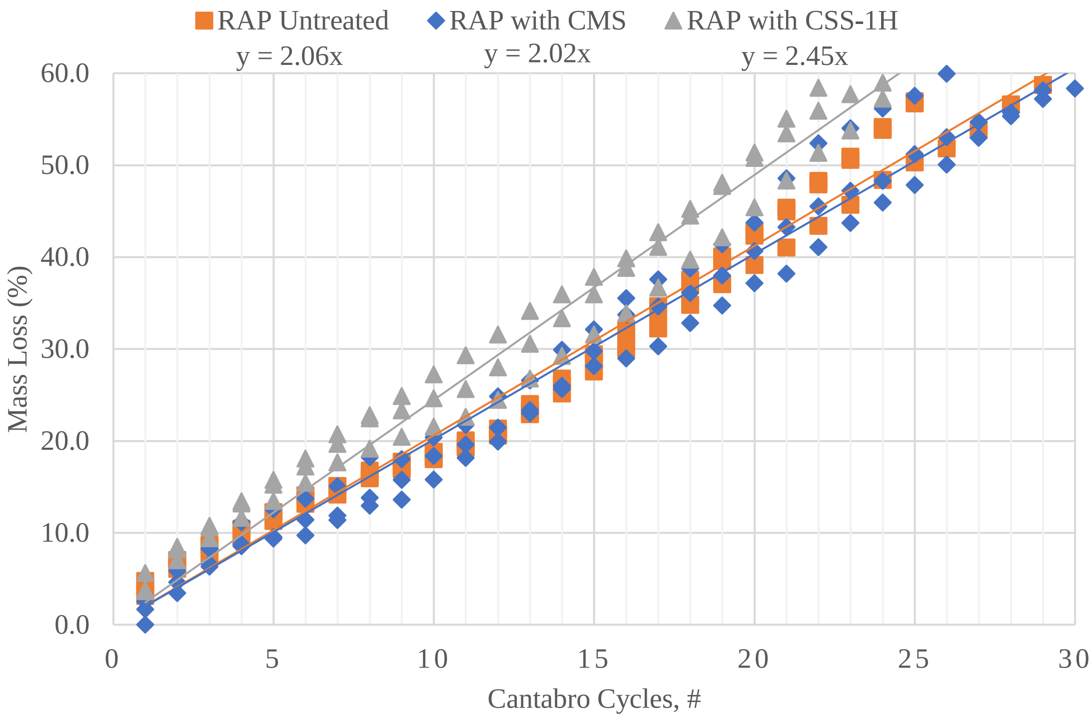


Figure 81. Cantabro loss degradation curves for untreated and treated RAP specimens.

The effect of the rejuvenators on specimens aged for 5 days at 149°C is shown in Figure 82. The average AV of each set of specimens was 22.4 percent for untreated specimens, 23.9 percent for specimens treated with CMS, and 23.6 percent for specimens treated with CSS-1H. In this case, the rejuvenators did seem to have a positive effect on the aged specimens, reducing the rate of mass loss from a slope of 6.69 for the untreated specimens to 5.15 for the specimens treated with CSS-1H, and to 4.42 for the specimens treated with CMS. These values translated to 9 cycles to reach 60 percent mass loss for the untreated aged specimens, about 12 cycles to reach 60 percent mass loss for the aged specimens treated with CSS-1H, and about 14 cycles to reach 60 percent mass loss for the aged specimens treated with CMS.

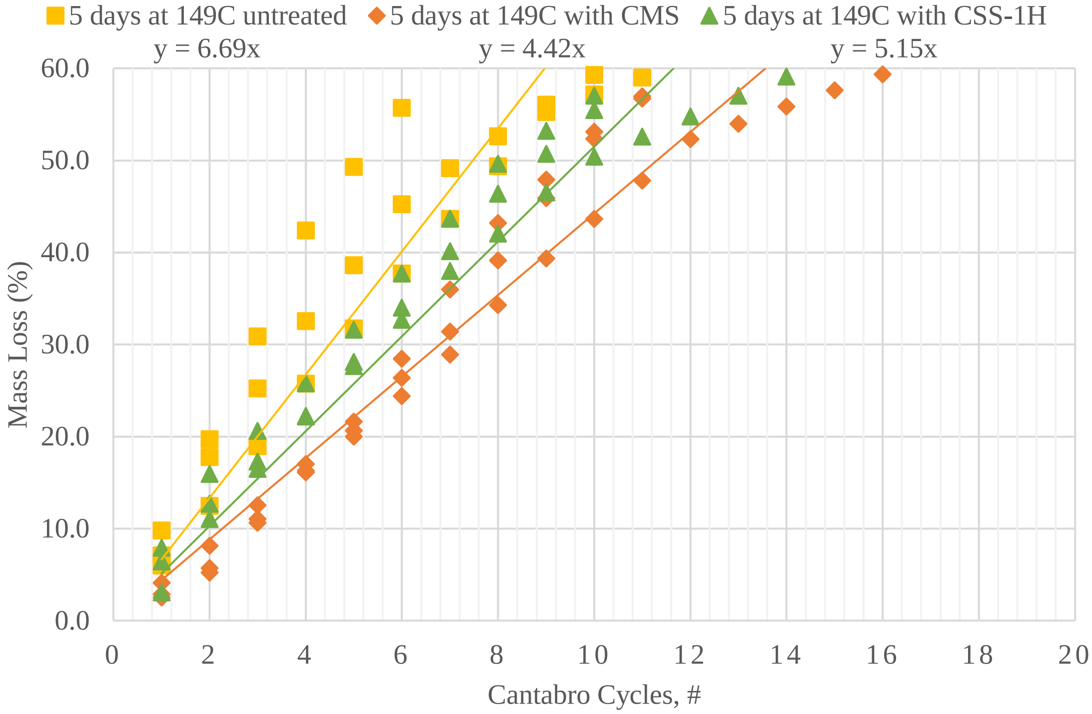


Figure 82. Cantabro loss degradation curves for the untreated and treated specimens aged for 5 days at 149°C.

Last, the effect of the rejuvenators on specimens aged for 14 days at 95°C is shown in Figure 83. The average AV of each set of specimens was 23.9 percent for untreated specimens, 23.5 percent for specimens treated with CMS, and 22.3 percent for specimens treated with CSS-1H. In this instance, the application of the rejuvenators had the opposite effect as the one observed for the specimens aged 5 days at 149°C. For both rejuvenators, the rate of mass loss increased from a slope of 5.46 in the case of the untreated aged specimens to a slope of 9.7 for the specimens treated with CSS-1H, and to 13.83 for the specimens treated with CMS. The initial mass loss (i.e., after one Cantabro cycle) was 12.1 percent for specimens treated with CSS-1H and 16.1 percent for specimens treated with CMS, which is a higher mass loss compared to other types of specimens tested with Cantabro. This behavior is contrary to expectation, and further investigation of the potential causes would be needed before determining the reason behind these trends.

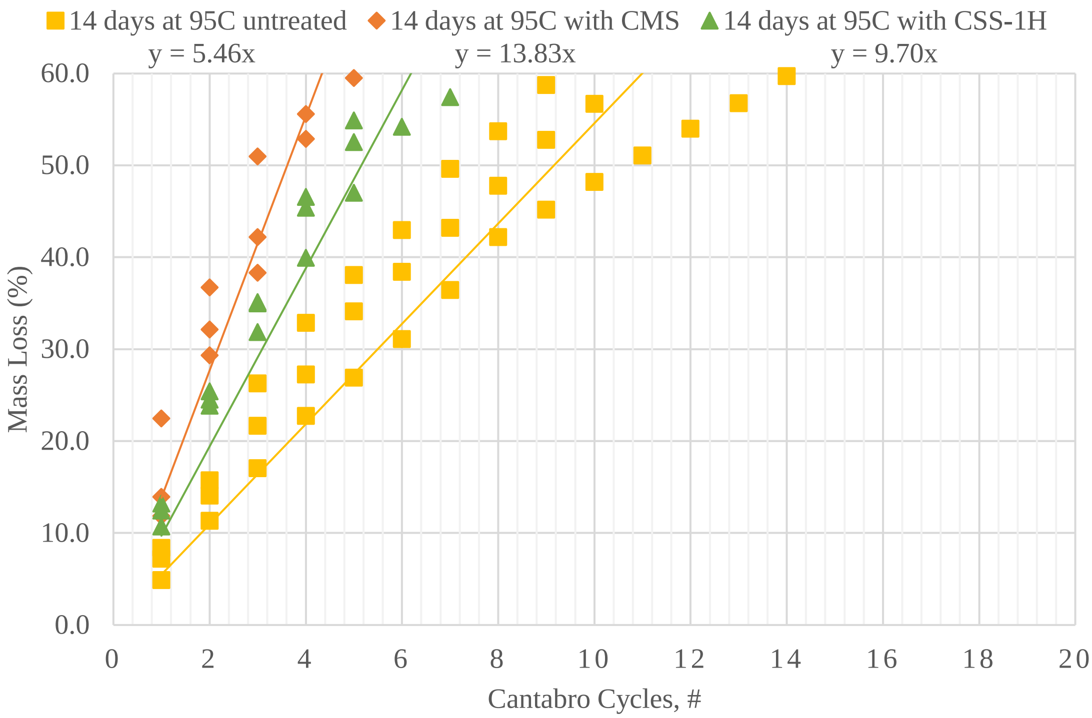


Figure 83. Cantabro loss degradation curves for the untreated and treated specimens aged for 14 days at 95°C.

6.2. FRICTION

Four slabs with dimensions of 12.6 inches long × 10.2 inches wide were prepared to evaluate the effect of two types of rejuvenators and two application rates on the surface friction of PFC mixes. The slabs were prepared with an average 1-inch thickness and target AV content of 20 percent. Molding of the slabs was done using the asphalt roller compactor. Once they were cast, the four slabs underwent polishing and friction tests to obtain a stable or plateau friction value. A plateau in initial friction was reached after approximately 500 cycles in the three-wheel polisher. At that point, the rejuvenators were applied to the surface of each of the slabs. The selected rates for each rejuvenator were 0.1 and 0.14 gal/yd^2. The rejuvenators were applied to the surface of the slab using a Sharpshooter 2.1 drywall hopper gun sprayer (see Figure 79).

The amount of rejuvenator sprayed per pass was determined as previously described in Section 6.1.3 and detailed in Equation 2. To determine the number of passes required to apply the selected application rate for each rejuvenator, it was first necessary to calculate the surface area using Equation 5.

$$A = w\ x\ L = 320\ mm\ x\ 260\ mm = 83200\ mm^2 = 0.0995\ yd^2 \qquad (5)$$

Then, the rate of application (0.10 and 0.14 g/yd^2) was converted to passes using Equations 6 and 7 while assuming the density of the rejuvenator was 1.02 g/ml:

$$0.1\ \frac{gal}{yd^2}\ x\ \frac{0.0995\ yd^2}{slab}\ x\ \frac{3{,}785.4\ ml}{1\ gal}\ x\ \frac{1.02\ g}{ml} = 38.4\ \frac{gal}{slab}\ x\ \frac{1\ pass}{9.64\ g} \approx 4\ {}^{passes}/_{slab} \quad (6)$$

$$0.14\ \frac{gal}{yd^2}\ x\ \frac{0.0995\ yd^2}{slab}\ x\ \frac{3{,}785.4\ ml}{1\ gal}\ x\ \frac{1.02\ g}{ml} = 53.8\ \frac{gal}{slab}\ x\ \frac{1\ pass}{9.64\ g} \approx 6\ {}^{passes}/_{slab} \quad (7)$$

The rejuvenator application process is illustrated in Figure 84.

(a) **(b)**

Figure 84. CMS rejuvenator application: (a) slab enclosed in a plywood box while the rejuvenator is being applied, (b) resulting slab after applying the rejuvenator.

Once the rejuvenator was applied to the four slabs, surface friction using the DFT was measured every hundred cycles of the three-wheel polisher until 1,000 cycles were completed. The results were converted to an equivalent skid number at 50 mph using the following equations (Chowdhury et al. 2017):

$$IFI = 0.081 + 0.732 \times DFT_{20} \times e^{\frac{-40}{Sp}} \tag{8}$$

$$Sp = 14.2 + 9.7MPD \tag{9}$$

$$SN(50) = 4.81 + 140.3 \times (IFI - 0.045) \times e^{\frac{-20}{Sp}} \tag{10}$$

Where:
IFI = international friction index.
DFT_{20} = coefficient of friction at 20 km/h
S_p = speed constant parameter.
MPD = mean profile depth.
SN(50) = skid number measured by a smooth tire at 50 mph (80 km/h).

The results can be observed in Figure 85.

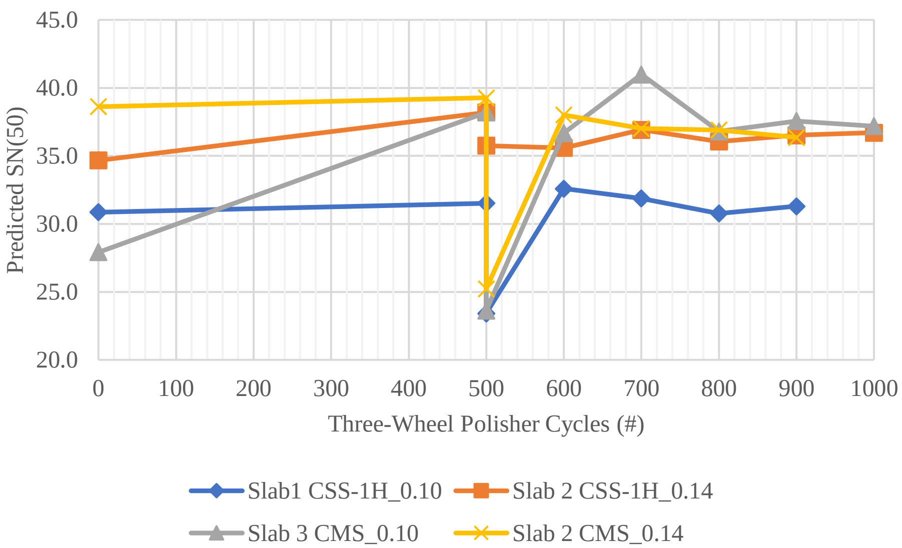


Figure 85. Skid number for different rejuvenators and application rates.

Water flow tests were also conducted initially, after 500, and after 1,000 three-wheel polisher cycles. The results are shown in Table 16. For rejuvenator CMS, the water flow increased after the product application, and more significantly for the lower application rate of 0.1 gal/yd^2. For CSS-1H, there was no meaningful change for the lower application rate and even a reduction in water flow time for the larger application rate.

Table 16. Slab Air Void Content and Water Flow Results.

Slab ID	AV (%)	Cycles (×1,000)	Water flow time (sec)
Slab 1, CSS-1H, 0.1 gal/yd^2	19.6	0	15.5
		500	15.9
		1,000	18.6
Slab 2, CSS-1H, 0.14 gal/yd^2	19.6	0	14.9
		500	12.4
		1,000	15.8
Slab 3, CMS, 0.1 gal/yd^2	19.5	0	17.1
		500	25.0
		1,000	26.0
Slab 4, CMS, 0.14 gal/yd^2	19.7	0	14.2
		500	17.2
		1,000	17.2

Regarding skid resistance, the research team analyzed SN(50) considering variations in rejuvenator type and application rate. The skid numbers calculated through friction testing were compared to understand the influence of material and application rate on skid resistance. The following observations were made based on Figure 85.

6.2.1. Effect of Rejuvenator Type

The study compared the skid resistance of two rejuvenator types: CSS-1H and CMS. Among the provided data for Slab 1 and Slab 4 (CSS-1H), the average SN(50) was approximately 33.71. In contrast, Slab 2 and Slab 3 (CMS) exhibited an average SN(50) of approximately 37.3. Based on this comparison, the CMS material demonstrated higher skid numbers (SN[50]) compared to CSS-1H, suggesting that CMS might offer better skid resistance.

6.2.2. Effect of Rejuvenator Application Rates

The research also investigated the impact of application rates on skid resistance by comparing 0.1 gal/yd^2 versus 0.14 gal/yd^2. Slabs treated with an application rate of 0.1 gal/yd^2 (Slab 1 and Slab 3) showed an average SN(50) of approximately 32.99, while those treated with an application rate of 0.14 gal/yd^2 (Slab 2 and Slab 4) exhibited an average SN(50) of approximately 38.79. This comparison indicated that slabs treated with 0.14 gal/yd^2 tended to have higher skid numbers (SN[50]) compared to slabs treated with a rate of 0.1 gal/yd^2. The results suggest that, in this case, a higher application rate of 0.14 gal/yd^2 yielded better skid resistance than the lower application rate of 0.1 gal/yd^2.

6.2.3. Combined Effect of Rejuvenator Type and Application Rate

The combined effect of rejuvenator type and application rate was also explored. Among the slabs with CSS-1H, Slab 4 treated with an application rate of 0.14 gal/yd^2 had an average SN(50) of approximately 39.43, while Slab 1 treated with an application rate of 0.1 gal/yd^2 had an average SN(50) of approximately 32.99. This finding indicates that increasing the application rate for CSS-1H resulted in a higher SN(50) and potentially better skid resistance compared to a lower application rate.

Similarly, among the slabs treated with CMS, Slab 2 treated with an application rate of 0.14 gal/yd^2 had a slightly higher average SN(50) of approximately 37.19 compared to Slab 3 treated with an application rate of 0.1 gal/yd^2, which had an average SN(50) of approximately 35.12. However, the difference was not as pronounced as what was observed for CSS-1H. This result suggests that while an increase in application rate may positively impact skid resistance, its effect might be less pronounced for rejuvenator type CMS.

6.3. PERMEABILITY

Several cores were acquired in Lufkin on US 69 and in Brownwood on US 183 south of Breckenridge. These cores were used to explore permeability in the laboratory and via imaging techniques and correlate against field water flow observations.

6.3.1. Florida Water Flow Test

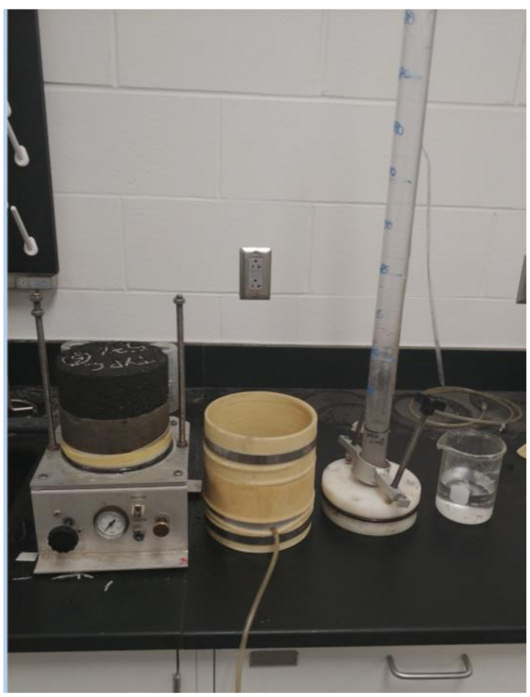
The research team performed a permeability test on 6-inch cores collected from US 69 in Lufkin (Figure 51). The cores had a PFC layer on top of a dense-graded HMA. The research interest was to determine the permeability of the PFC surface layer; therefore, the cores' dense-graded part was removed by a saw cut. The remaining PFC layer, about 1.5 inches thick (Figure 86), was used for measuring water permeability via the Florida method, FM 5-565. The research team tested two PFC cores from Lufkin US 69 obtained from the newer PFC inlay (Figure 57). Cores obtained from the older PFC were too thin and could not be tested.

Figure 86. Lufkin core before and after saw cut.

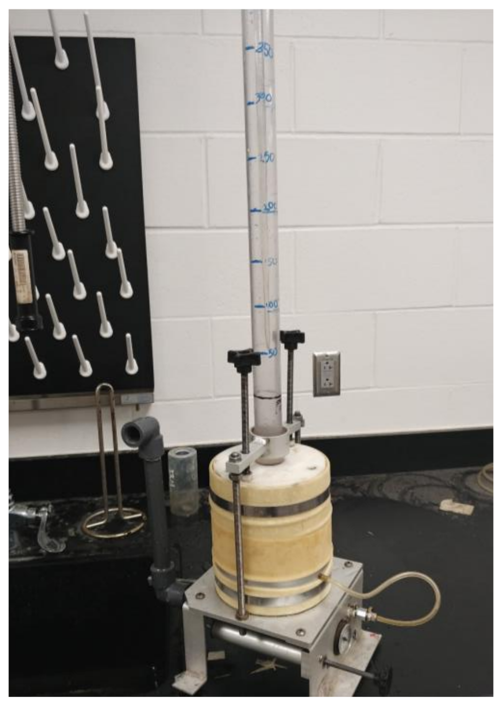
According to FM 5-565, before the cores are subjected to the permeability test, they must be fully saturated. The cores were placed under water for over 3 hours to attain complete saturation conditions (Figure 87). Another way of achieving saturation is by subjecting the samples to 15 minutes of vacuum saturation.

Figure 87. Lufkin cores being saturated under water.

After soaking, the cores were placed on a porous pedestal plate at the base of the permeameter (Figure 88). A housing sealing tube and a graduated cylinder were assembled to cover the pedestal and the test cores according to the FM 5-565 protocol (Figure 88). Then water was added to the upper mark of the graduated cylinder (500 ml mark). Before releasing the water (through the bottom orifice), the operator checked for leaks or water loss due to under saturation. The water was then released, and the time taken to drop from the 500 ml mark to the 0 ml mark was recorded.



(a)



(b)

Figure 88. Florida permeameter: (a) specimen setup on top of porous stone and equipment parts, and (b) equipment assembly during testing.

The field cores' coefficient of permeability (k) was calculated using Equation 11.

$$k = \frac{aL}{At} ln\left(\frac{h1}{h2}\right) \tag{11}$$

The parameters used to calculate the coefficient of permeability are shown in Table 17. The constant parameter listed at the end of the table represents the relationship of all values without the elapsed time, which may vary slightly from one operator to another.

Table 17. Permeability Test Parameters.

Specimen ID	LFK #11	LFK #16
a (area of standpipe), cm^2	8.0384	8.0384
L, thickness of test specimen, cm	3.7617	3.4420
A (area of test specimen), cm^2	180.485	180.6829
h_1, initial hydraulic head (cm)	71.98	71.98
h_2, final hydraulic head (cm)	8.89	8.89
Constant parameter (cm)	0.3504	0.3203

Table 18 shows the permeability coefficient of the PFC cores collected from Lufkin US 69. The observed permeability coefficient is lower than the recommended minimum permeability (0.11 cm/s) for PFC mix design per AASHTO PP 77.

Table 18. Permeability Coefficients of Lufkin US 69 PFC Cores.

Specimen	LFK #11	LFK #16
Constant parameter	0.3504	0.3203
Elapse time (t)	10.20	23.44
K (constant/time) (cm/s)	0.034	0.014

The research team compared the permeability of the field cores with other treated and untreated specimens prepared in the laboratory. The results indicate that the permeability of field cores was lower than typical PFC specimens prepared in the laboratory, yet the field cores' permeability was slightly higher than Type D HMA mixtures (Figure 89). In general, the permeability measurements indicate that the newer PFC inlay on US 69 in Lufkin was relatively sealed. However, the water flow measurements obtained in the field suggest that the PFC inlay had moderate drainability (Figure 57), which may indicate that the Florida permeameter may not be the best candidate to measure permeability of thin field cores.

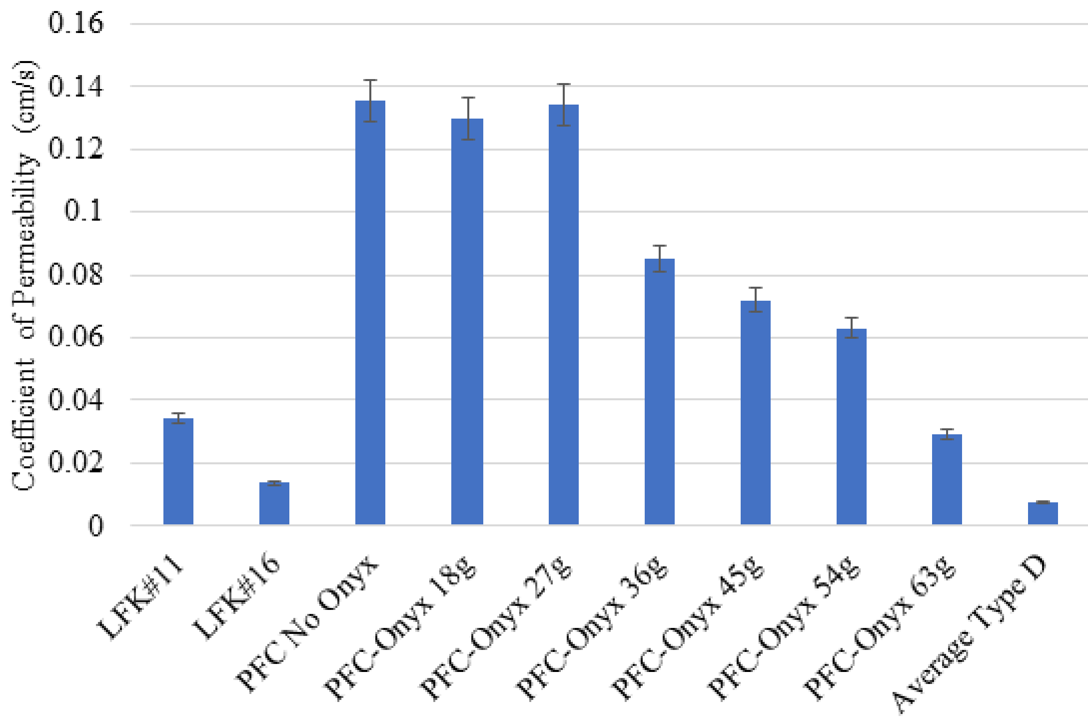


Figure 89. Coefficient of permeability of Lufkin US 69 cores versus other mix types.

6.3.2. Image Analysis

Cores were extracted at two distinct locations, Breckenridge US 183 and Lufkin US 69. In the latter, there were two sections, an older PFC and a newer inlaid patch, as previously shown in Figure 57. X-ray computed tomography (CT) analyses were conducted on one core from each location. To analyze the data, it was necessary to measure the maximum specific gravity and calculate the AV content for each core per Tex-207. The results are listed in Table 19. Figure 90 displays the device used to conduct the X-ray CT scans of the cores.

Table 19. Sample Data for Maximum Specific Gravity Calculation.

Core ID	SC3 S2 (US 183) BR	5 LFK	15 LFK	Units
Diameter	151.96	151.34	151.53	mm
Height	25.49	21.32	40.46	mm
Weight	968.30	721.90	1366.40	g
Maximum Specific Gravity	2.31	2.39	2.38	NA
Volume	462.40	383.52	729.51	cm^3
Density	2.09	1.88	1.87	g/cm^3
Air Voids	9.50	21.20	20.90	%

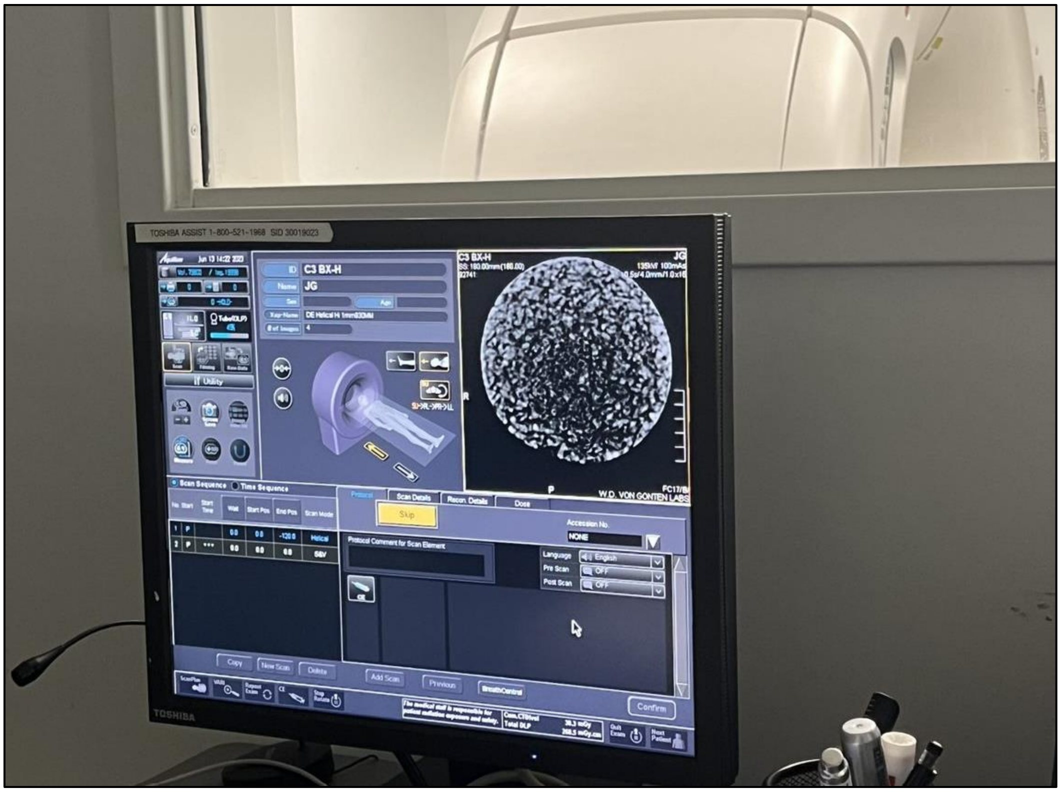


Figure 90. X-ray CT scan equipment.

The software ImageJ was utilized to analyze the images by matching the measured AV content listed in Table 19 to the average porosity obtained while fixing a grayscale image threshold. The porosity resulting from the image analysis for each core (i.e., %Area) is displayed in Table 20.

Table 20. ImageJ Analysis Results.

	Area	Mean	StdDev	Mode	Min	Max	Median	%Area	MinThr	MaxThr
1	898.012	1893.622	103.556	1789	1770	2404	1869	9.372	1770	32767
2	2046.985	1778.970	126.454	1637	1637	2404	1748	21.363	1619	32767
3	1939.800	1787.477	124.465	1637	1637	2404	1757	20.244	1632	32767

The upper layer of the core (i.e., the PFC layer) was the area of interest. Sample images obtained from the X-ray CT scan for the three cores are shown in Figure 91. These results seem to align well in terms of water flow with the field observations previously described in Chapter 5.

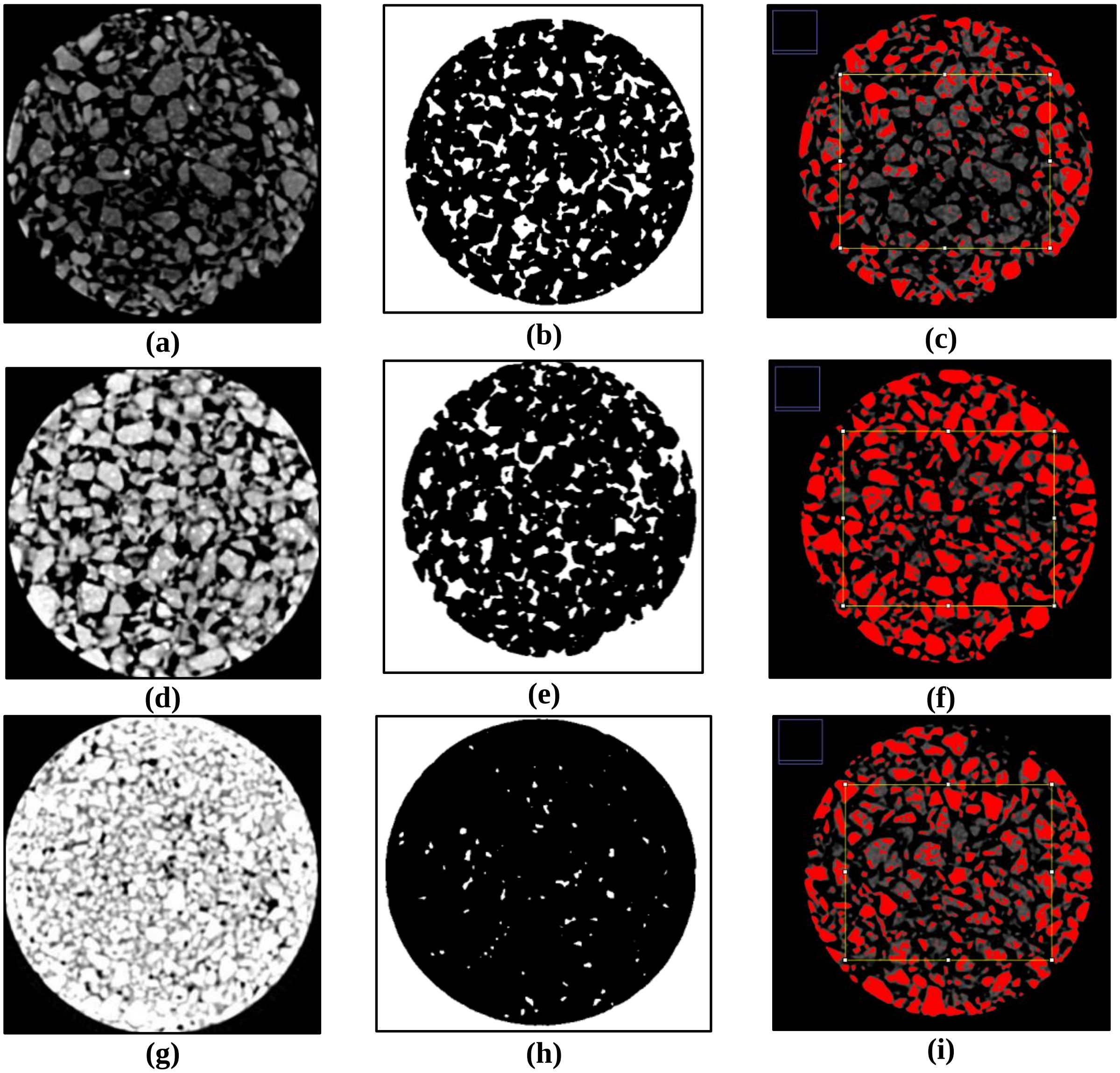


Figure 91. Images from the X-ray CT scan: (a), (d), and (g) show grayscale images; (b), (e), and (h) show black and white images; (c), (f), and (i) show images after ImageJ analysis; (a), (b), and (c) are the Lufkin US 69 core on the inlaid patch; (d), (e), and (f) are the Lufkin US 69 core of the older PFC; and (g), (h), and (i) are the Breckenridge US 183 core.

6.4. MOISTURE INSPECTION

One of the key concerns with covering an old PFC with either HMA or a seal coat is trapping moisture in the PFC. If moisture becomes trapped and a hot material such as HMA or seal coat binder is applied to the PFC, the trapped moisture could create a vapor that tries to escape and potentially cause a debonding of the new surface. One simple, promising test to check for moisture is the plastic sheet test. This test is also recommended by TxDOT's statewide seal coat coordinator to check for moisture prior to sealing cold-mix patches, which tend to have higher air voids than conventional hot-mix pavement.

The plastic sheet test is a low-cost, low-technology method of determining surface moisture. It is mostly used as a warning for pavement markings to ensure excess moisture prevents adequate bond. The moisture testing is described in TxDOT Item 668 (Section 3.2.1) for prefabricated pavement markings as follows: "***Moisture***. *Apply material to pavement that is completely dry. Pavement will be considered dry if, on a sunny day after 15 min., no condensation occurs on the underside of a 1-sq. ft. piece of clear plastic that has been placed on the pavement and weighted on the edges.*"

The test is performed by placing a 12-inch × 12-inch piece of transparent plastic on the pavement and weighting down the edges, usually with duct tape. The pavement is considered dry if when inspected after 15 minutes, no condensation has occurred on the underside of the plastic. An alternative to using a plastic sheet is using roofing felt paper in combination.

Researchers conducted field testing to determine if this was an effective test to measure the presence of moisture in a PFC. Testing was performed on a very dry PFC and at an air temperature of 95°F. The pavement surface was at TTI's RELLIS Campus and is one of the surfaces used to calibrate profilometers. A 5-gal bucket of water was poured onto the pavement surface (Figure 92). The PFC was draining very well, and all the water penetrated the PFC within 5 seconds. The surface was then allowed to dry, which took about 10 minutes. Two types of moisture barriers were then duct-taped to the surface: a plastic sheet and roofing paper (Figure 93).

Figure 92. Water poured onto the PFC surface.

Figure 93. Roofing paper (left) and plastic sheeting (right) taped to the PFC surface.

Within 5 minutes, moisture became visible on the underside of the plastic sheet, as shown in Figure 94. Some condensation was also observed under the roofing paper (Figure 95); however, it was much easier to see the condensation through the plastic as it began to appear. After 10 minutes, a significant amount of moisture was visible on the underside of the plastic, as shown in Figure 96, after it was removed from the pavement surface.

Figure 94. Moisture condensation on the underside of the plastic.

Figure 95. Moisture condensation on the underside of the roofing paper.

Figure 96. Plastic sheeting after removal from pavement surface after 10 minutes.

7. CONSTRUCTION OF TEST SECTIONS

Three full-scale test sections were constructed within this research project:

- Lufkin District, US 69, Superpave Overlay: The district let a contract to include a test section for this research project. A Superpave mix was placed over an existing old PFC (clogged) pavement plus existing newer PFC (still draining) inlaid patch. This section was constructed in May 2023.
- Brownwood District, US 183, Seal Coat: This test section was constructed in July 2023. The existing PFC was about 10 years old and had previously been surfaced with Onyx to extend its life. The Onyx layer had worn off and a seal coat was applied.
- Austin District, MoPac Express Lane, Rejuvenating Fog Seal: This test section was constructed in November 2022. The surface was in good condition, but CTRMA was looking for a treatment to preserve the PFC and extend its life.

7.1. LUFKIN TEST SECTION—CONTRACT NO. RMC 6401-22-001 MILL AND INLAY (ANGELINA)

The Lufkin District constructed a 1,200-ft test section consisting of a Superpave C mix placed over an old PFC. This test section was part of a larger contract that included milling sections of the old PFC and inlaying with Superpave C. The test section was located in the NB lanes of US 69 just north of FM 2251, and it extended across the travel lane, passing lane, and shoulder. In the last 600 ft of the travel lane, there was a newer PFC inlaid patch that can be seen in Figure 97 and Figure 98. The condition of the old PFC included a moderate amount of cracking and raveling, as shown in Figure 99. The newer PFC patch was in excellent condition and had no distress. Based on GPR and water flow testing, as reported in Chapter 5, the older PFC was clogged and not draining, including on the shoulder, but the newer inlaid PFC patch was still draining. Unfortunately, this created a bathtub situation since the water trapped in the newer PFC inlaid patch had nowhere to drain.

This test section was constructed on May 8, 2023. The mix was produced and placed by East Texas Asphalt in Lufkin. The weather leading up to construction had produced a significant amount of rain in the area. In fact, construction occurred on Monday, and the prior weekend saw enough rain that there were standing puddles on the sides of the road.

Since the test section consisted of a 2-inch overlay on an existing surface, construction began with milling the old surface at each end of the section to provide a transition to and from the new overlay (Figure 100). A non-tracking tack coat was then applied at a rate of 0.08 gal/yd^2 (Figure 101). Material was placed in windrows on the pavement surface ((Figure 102a) and picked up with a material transfer vehicle (Figure 102b) and moved into the laydown machine (Figure 103a). A steel-wheel roller was used to compact the mix using three vibratory passes and one static pass (Figure 103b).

On one portion of the mat, for a length of about 150–200 ft, anomalies started to appear. There were several transverse bulges that showed up *after* the roller operator had completed compaction and moved up to the next section. Once these anomalies appeared, the roller operator came back to re-roll these bulges, which only made the situation worse. The mix started behaving as if it were tender or unbonded and was moving laterally, causing the edges to crack (Figure 104). The roller operator immediately ceased all rolling, paving was halted, and the district lab was called out to take cores to check the bond. Cores were taken immediately over the bulged areas (Figure 105). The cores came out intact, and the bond was secure. Later, the district lab measured the shear strength of the bond (Table 21), and the bond strengths of the two cores were 21.8 and 11.9 psi. While this may not be a great bond, nonetheless there was a bond of the new surface to the old, so the bond did not appear to be the culprit for the problems seen in the field. A photo of the core after shear testing is shown in Figure 106. After this occurred, the tack rate was also increased to 0.1 gal/yd^2 for the rest of the test section construction.

After coring, and after the mat had cooled significantly, a few more static passes of the roller were made in the problem areas, which smoothed the mat (Figure 107). There was still a slight visible crack on each edge of the mat (Figure 108).

This specific mix design had been produced by this plant and placed by this crew many times previously without these types of issues showing up. In fact, the only time the problem showed up in this entire contract was on this noticeably short section. It is not clear what caused this problem; however, researchers theorize that this portion of the paving was on top of the newer PFC inlaid patch, which may have been holding water at the time of paving. When the mat was placed on the surface of this patch, steam was created and tried to escape through the new mat, causing the mix to behave as if it were tender.

Figure 108 shows the overlay 1 week after traffic, and a crack was visible but did not appear to have gotten any worse. A GPR test was also performed about a week later, and based on the radar (Figure 109), there did not appear to be any moisture trapped in the underlying PFC (Figure 110).

Figure 97. Newer PFC inlaid patch in the travel lane.

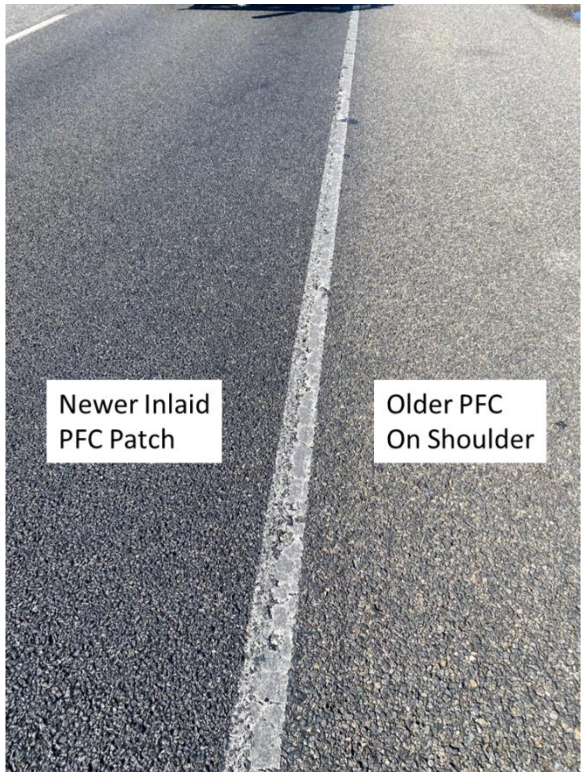


Figure 98. Close-up of newer PFC patch next to older PFC in shoulder.

(a) **(b)**

Figure 99. Typical distress shown in test section area of the old PFC: (a) raveling, and (b) cracking.

Figure 100. Milling the old surface to provide smooth transition to new overlay.

Figure 101. Non-tracking tack coat applied first to travel lane and then shoulder.

(a) (b)

Figure 102. Superpave mix laydown: (a) windrows placing mix on the pavement surface, and (b) material transfer vehicle picking up the mix to move it to the laydown machine.

(a) (b)

Figure 103. Paving and compaction of Superpave mix over PFC: (a) laydown machine, and (b) steel-wheel roller.

Figure 104. Bulges and cracking appearing after additional rolling in an isolated section.

(a) **(b)**

Figure 105. Coring operation over bulged pavement area: (a) coring rig, and (b) cores taken showing the new overlay bonded to the old PFC.

Table 21. Results of the Shear Test on Cores Measuring Bond between Superpave C Mix and Old PFC.

Test	Sample ID	Maximum Load (lbs)	Sample Diameter (in)	Shear Strength (psi)
1	1	615.0	6.0	21.8
2	2	337.0	6.0	11.9
Average		476.0	6.0	16.9

Figure 106. Photo of core after shear test.

Figure 107. Additional static rolling on the problem areas after mat cooled down.


Figure 108. After 1 week of traffic.

Figure 109. GPR taken 1 week after construction showing overall satisfactory performance and no trapped moisture.

(a) **(b)**

Figure 110. Other portions of the greater contract where old PFCs were milled and inlaid with Superpave C: (a) general view, (b) closeup view.

7.2. BROWNWOOD DISTRICT TEST SECTION (BRECKENRIDGE)—CONTRACT NO. 0011-09-075 2023 DISTRICT-WIDE SEAL COAT

This test section consisted of a seal coat placed over a fine-graded PFC located on an 8-mi section of US 183 just south of Breckenridge. As described previously, this PFC was mostly closed up and not draining, although there were a few areas that did still seem to drain based on water flow testing conducted in March 2023. The PFC extended across the main lanes but not into the shoulder. A few years ago, an Onyx application was placed over the main lanes and the shoulder to extend the life. After a couple of years, most of the Onyx had worn off the main lanes but was still very visible on the shoulders. Even though the Onyx may have worn off the surface of the main lanes, it more than likely contributed to filling in some of the voids in the PFC, thereby clogging it up.

Because there were some locations in this PFC that still could take on water, it was critical that the weather be monitored by the district prior to placement of the seal coat to ensure that the pavement was completely dry. Other projects in Texas where a seal coat was placed on a mix that was holding moisture showed that when asphalt binder is shot at 375°F, steam is created, causing the seal not to bond and traffic to start picking up the seal coat. This outcome is a worst-case scenario and should be avoided at all costs.

Prior to placement of the seal coat, there had been no rain for many days, and temperatures were in triple digits for most of those days, so the pavement was very dry. For these 8 mi of pavement, the seal coat was placed on the afternoon and evening of July 7 and completed on the morning of July 8, 2023.

The contractor placing the seal coat was Brannon Paving. Materials used for the seal coat consisted of a precoated Grade 3 limestone aggregate from Zach Burkett. The asphalt binder was an AC-20-5TR from Wright Asphalt.

The existing surface condition is shown in Figure 111 and Figure 112. The PFC looks very dry, with some moderate cracking and minor raveling. Maintenance crews had placed some cold-mix level-up patches at several locations throughout the project, as shown in Figure 113. Photographs of the construction process are documented in Figure 114.

Initial asphalt application rates were selected at 0.45 gal/yd^2 for the main lanes and 0.48 for the shoulder. While these rates were thought to be high compared to what the district was shooting on other roadways for this contract, it still did not seem to be quite enough. Initial embedment depth after rolling is shown in Figure 115. It looks to be about 25 percent. Asphalt rate was eventually increased for the main lanes to 0.5 gal/yd^2. The district seal coat specialist who was setting the rates did not think that asphalt was soaking into the PFC; he believed that the surface was very aged and hard and there was zero penetration of the aggregate into the old surface after rolling. The aggregate application rate started out at 125 yd^2/yd^3 but was increased to 120 yd^2/yd^3 (Figure 116).

This seal coat was being placed during extreme triple-digit temperatures. When these temperatures occur during seal coat placement, it is not uncommon to experience tracking under traffic. For the 2023 summer, the state seal coat specialist had recommended backing off slightly on the asphalt rate during extremely hot weather. Brownwood, however, chose to use a transverse variable asphalt rate whether the underlying pavement was showing flushed wheel paths or not. This means that smaller nozzles were used in the wheel paths so that outside the wheel paths, the asphalt rate was about 20 percent higher than the wheel path rate.

Figure 111. PFC in March of 2023 prior to seal coat showing typical distresses and evidence of the Onyx still visible on shoulder.

(a) **(b)**

Figure 112. Pavement distress observed in the PFC surface: (a) cracking, and (b) slight raveling.

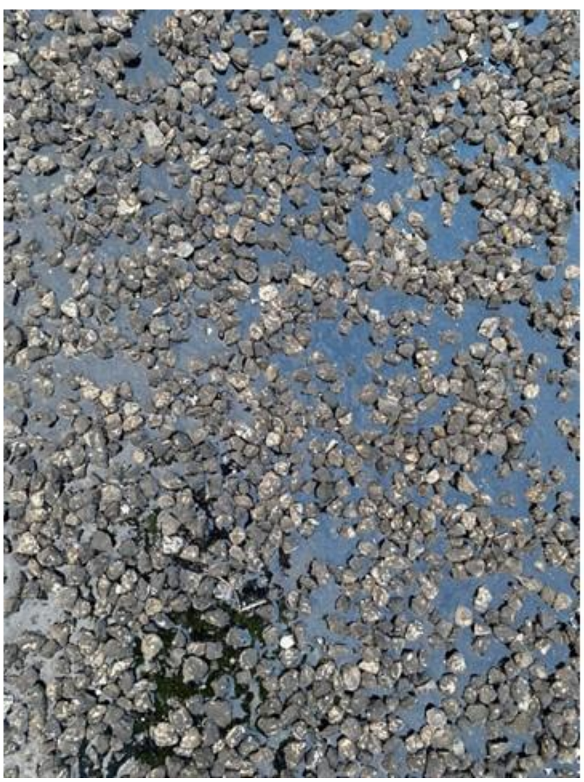
Figure 113. Several level-up cold-mix patches located throughout the project.

(a) **(b)**

(c) **(d)**

Figure 114. Construction of Grade 3 seal coat over PFC: (a) asphalt distributor truck, (b) asphalt application, (c) aggregate application, (d) rolling.

Figure 115. Initial embedment after rolling.



(a)

(b)

Figure 116. Aggregate application rates: (a) initial, and (b) final.

Some districts have recently had problems with AC-20-5TR in that the tire rubber content has been variable, in some cases as low as 2 percent rather than the required 5 percent. The Brownwood District was experimenting with a handheld XRF to measure the tire rubber content in the asphalt binder. The Brownwood District seal coat specialist took samples throughout the construction of the district-wide seal coat contract and performed the XRF test in the field (Figure 117 and Figure 118). He reported that this supplier was consistently providing a product with 5 percent tire rubber, as required.

The seal coat surface compared to the old PFC is shown in Figure 119 and Figure 120. Thus far, this test section has been successful. At the time of this report, it had seen about 3 weeks of traffic and extremely hot temperatures and had performed well. All current indications are that this PFC may remain in place indefinitely for future resurfacings.

(a) **(b)**

(c) **(d)**

Figure 117. Field XRF testing to verify tire rubber content in AC-20-5TR: (a) sampling from the distributor truck, (b) preparing the test specimens, (c) inserting the test specimens in the equipment, and (d) acquiring the XRF measurement.

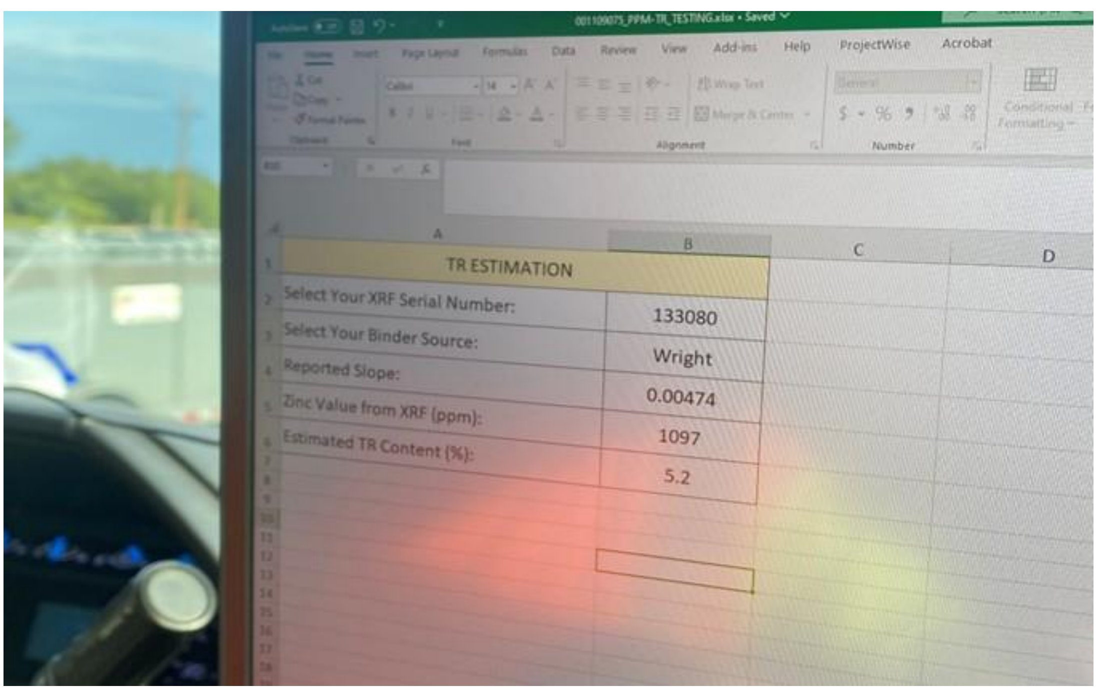


Figure 118. Computer display of XRF data showing tire rubber content of 5.2 percent.

Figure 119. Close-up of seal coat next to PFC surface.

Figure 120. View of seal coat and PFC surface.

7.3. AUSTIN DISTRICT REJUVENATING FOG SEAL

The Austin District had previously placed a rejuvenating fog seal on SH 195 with good success, as discussed in Chapter 5. Based on this success, CTRMA worked with the Austin District and TTI researchers to place a test section of rejuvenating fog seal on a 1-mi section of the managed toll lane of MoPac. The surface was in good condition, but CTRMA was looking for a treatment to preserve the PFC and extend its life. The test section location was in the NB express lane from TRM 438.5 to 437.5.

Testing performed included skid, GPR, and water flow testing before and after fog seal.

As discussed in Chapter 5, TTI collected GPR data on the test section in October 2022 prior to placement of the fog seal. As shown in Figure 68, the surface at that time was in good condition, and the surface dielectric was low and consistent, indicating good drainability.

TTI performed water flow tests before and after placement of the fog seal (Figure 121). Seven stations were evaluated, and at each station, water flow in the right wheel path and between the wheel paths was tested. These results are shown in Figure 122 and Figure 123. The fog seal reduced the water flow in the right wheel path an average of almost 5 seconds and reduced the water flow between the wheel paths by an average of 3 seconds.

Figure 121. Water flow testing on MoPac.

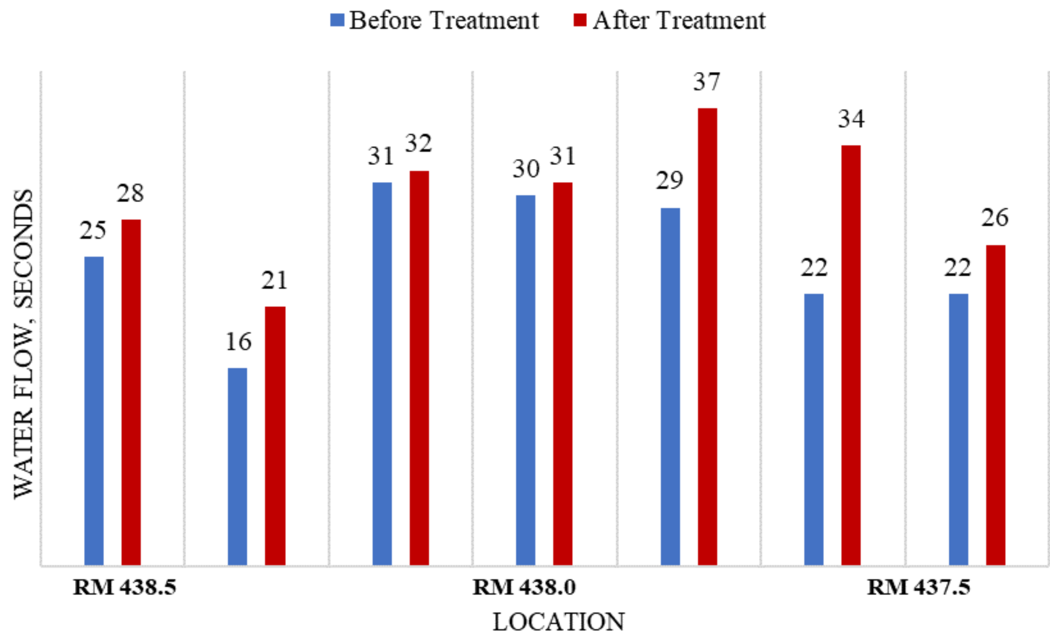


Figure 122. Water flow results before and after treatment for right wheel path: average before 25.0 seconds, average after 29.8 seconds.

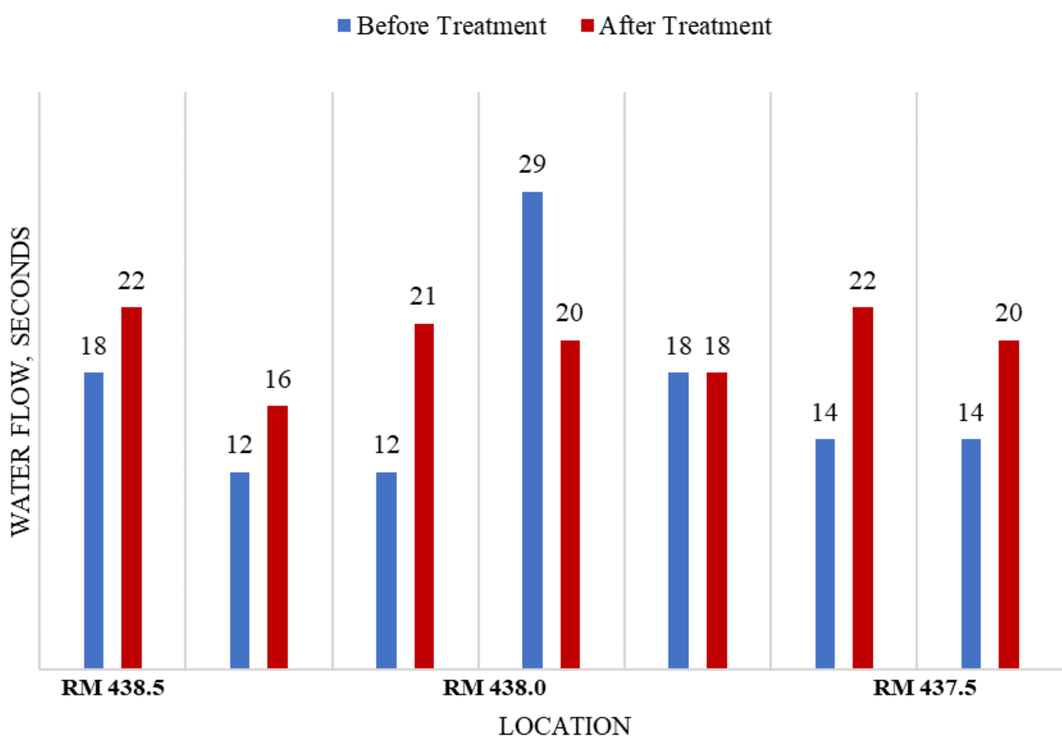


Figure 123. Water flow results before and after treatment for between wheel paths: average before 16.7 seconds, average after treatment 19.8 seconds.

On November 9, 2022, the 1-mi rejuvenating fog seal was placed on MoPac (Figure 124). TxDOT was on site to observe and collect skid data, CTRMA coordinated events and traffic control, and TTI personnel were on site to do water flow testing and document construction. Ergon donated the product for the test section. The product was applied at a rate of 0.14 gal/yd^2, which provided a relatively thick, sticky film of asphalt on the surface (Figure 125). The test section was opened to traffic approximately 1.5 hours after placement.

Figure 124. Construction of fog seal on MoPac.

Figure 125. Close-up of fog seal application on PFC.

TxDOT conducted skid testing before the fog seal and then at three other times after application. Table 21 includes the reduction in skid observed after the application (actual skid numbers available upon request).

Table 22. Reduction in Skid after Application of Rejuvenating Fog Seal.

Time after Fog Seal Application	Reduction in Skid Number from before Treatment
One hour (before traffic)	75%
Next day (morning)	28%
Next day (afternoon)	28%
Six days later	21%

8. SUMMARY AND CONCLUSIONS

PFC pavements provide multiple benefits, including reduced splash and spray during wet-weather events, improved road marking visibility, and reduced road noise. Conversely, this type of mix also faces challenges because it is more costly and yields a shorter service life compared to conventional dense-graded HMA. At the end of service life, the most common rehabilitation strategy for PFC pavements is to mill and overlay. Although this method is highly effective, it is also expensive and sometimes out of reach due to budget constraints.

In fact, a survey of directors of operations and directors of maintenance within TxDOT revealed that many of the districts that have used PFCs in the past have no plans to continue using PFCs, in part because of the lack of options available for PFCs at the end of their service life.

To gather information about alternative rehabilitation strategies for PFC pavements, researchers conducted a review of maintenance strategies to restore durability and functionality. Among the strategies to restore durability, research studies (including case studies in Texas) that have applied fog seals or rejuvenators to the surface of the pavement as preventive maintenance were reviewed. In addition, corrective maintenance practices such as patching, micromilling and overlay, recycling, and innovative methods called self-healing were examined. Finally, strategies to restore functionality, although not prevalent in Texas, were documented since some of these methods may be of interest to TxDOT.

Through the survey of TxDOT directors of operations and directors of maintenance, the research team identified PFC pavements that had been resurfaced with either Onyx or seal coat. The research team conducted field performance evaluations (i.e., visual inspections and GPR) on these resurfaced PFC pavements and observed that those treated with Onyx, especially a section with heavy application, had a significant initial skid reduction, but after about 2 years in service, the product on the two PFC pavements that were resurfaced with Onyx was worn off, and raveling was comparable to the untreated portions of the PFC pavement. Most of the seal coat treatments worked well regardless of the amount of rainfall at the given location or if the PFC pavement was draining or closed off prior to the application of the seal coat. There was only one instance of a failing seal coat treatment on a PFC pavement that was attributed to the presence of trapped moisture, which was due to a rainfall event that happened near the time of construction and the use of an AR seal coat that caused debonding of the seal and tracking of the product after opening the treated section to traffic.

The research team worked with four TxDOT districts that had identified PFC pavements nearing the end of their service life as candidates for rehabilitation. The research team performed visual inspections and conducted field measurements, including high-definition video, GPR, and water flow, on the various candidate field projects.

Ultimately, three districts agreed to place test sections. The Lufkin District placed a Superpave C mix over an aged PFC. Overall, this construction was successful, but there were some issues that occurred during the compaction process that may be attributed to the presence of moisture in the PFC. The weather leading up to construction included a significant amount of rain in the area, and this moisture may have caused the new Superpave mix to act tender. Once the surface cooled somewhat and was rolled again, the mat was fine. The Brownwood District constructed a

Grade 3 seal coat over an aged PFC. Weather had been extremely hot and dry leading up to this construction, and no problems occurred. The research team also worked with the Austin District, CTRMA, and Ergon Asphalt to construct a short test section on the managed lane of MoPac in Austin. The goal of CTRMA was to extend the life of the PFC while maintaining the permeability. Ergon provided a rejuvenating fog seal. Water flow tests conducted before and after application showed a slight reduction in permeability. TxDOT performed skid testing before and after application, which showed a significant reduction in friction immediately after application. By the next morning, the friction was back to about 75 percent of its original value.

In addition to field work, researchers explored several tools to evaluate PFC mixes on the inclusion of RAP, aging, and the use of rejuvenators at various application rates. The first evaluation related to durability using the Cantabro loss test. The effect of adding RAP significantly reduced the mass loss compared to virgin specimens. Aging and the inclusion of rejuvenators did not seem to have a significant effect on Cantabro mass loss. With regard to the effect of rejuvenators on surface friction, CMS showed the highest equivalent skid number (i.e., SN[50]) and was less affected by the rejuvenator application rate compared to CSS-1H, which showed lower equivalent skid numbers after application, especially at a lower application rate, and more sensitivity to the rejuvenator application rate. Permeability measured via the Florida water flow test was challenging on thin field cores and did not match field observations, which may indicate that FM 5-565 is not the best test for measuring permeability of thin field cores. Conversely, X-ray CT image analysis of cores showed more promising results and better alignment with field water flow measurements. The plastic sheet test, a simple on-site, low-cost test, was used to detect the presence of moisture below the surface of an old PFC and proved effective after only 5 minutes of the sheet being taped to the surface of the pavement. This could be an effective method to assess the presence of moisture on existing PFC pavements before covering them with either HMA or seal coat to prevent trapping moisture and having issues with compaction or debonding.

Recommendations resulting from this research are presented in Appendix B as a set of guidelines focused on how to evaluate PFCs to determine what type of maintenance and rehabilitation is needed. A decision tree is included to provide guidance on different maintenance and rehabilitation options.

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APPENDIX A. MIX DESIGNS

VIRGIN MIX DESIGN

Table 23. Virgin Mix Design Aggregate Bin Fractions and Combined Gradation.

	AGGREGATE BIN FRACTIONS									
	Bin No.1		**Bin No.2**		**Bin No.3**					
Aggregate Source:	Igneous		Igneous		–					
Aggregate Pit:	Mill Creek (Grnt), OK.		Mill Creek (Grnt), OK.		–					
Aggregate Number:	0050433		0050433		–					
Sample ID:	MM_C Rock		MM_D Rock		Hydrated Lime					
							Combined Gradation			
Hydrated Lime?:					Yes		Total Bin			
Individual Bin (%):	90.0	Percent	9.0	Percent	1.0	Percent	100.0%			
Sieve Size:	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum. % Passing	Lower Spec Limit	Upper Spec Limit	Within Spec's
3/4"	100.0	90.0	100.0	9.0	100.0	1.0	100.0	100.0	100.0	Yes
1/2"	79.2	71.3	99.3	8.9	100.0	1.0	81.2	80.0	100.0	Yes
3/8"	54.6	49.1	91.2	8.2	100.0	1.0	58.3	35.0	60.0	Yes
No. 4	12.6	11.3	38.5	3.5	100.0	1.0	15.8	1.0	20.0	Yes
No. 8	3.4	3.1	9.5	0.9	100.0	1.0	4.9	1.0	10.0	Yes
No. 200	0.4	0.4	1.4	0.1	100.0	1.0	1.5	1.0	4.0	Yes

Table 24. Virgin Mix Design Asphalt Binder Type and Content.

Binder Substitution?	No	Binder Originally Specified:	PG 76-22		
Asphalt Source:	Jebro	Binder Percent, (%):	6.2	Asphalt Spec. Grav.:	1.030
Antistripping Agent:	Lhoist	Percent, (%):	1	Fiber Content, %:	0.30

ADJUSTED RAP MIX DESIGN

Table 25. Adjusted Design Aggregate Bin Fractions and Combined Gradation.

	AGGREGATE BIN FRACTIONS						"RECYCLED MATERIALS"					
	Bin No.1		**Bin No.2**		**Bin No.3**		**Bin No.8**					
Aggregate Source:	Igneous		Igneous				Fractionated RAP					
Aggregate Pit:	Mill Creek (Grnt), OK.		Mill Creek (Grnt), OK.									
Aggregate Number:	0050433		0050433									
Sample ID:	MM_C Rock		MM_D Rock		Hydrated Lime							
							Recycled Asphalt Binder (%)					
							3.4		Combined Gradation			
Hydrated Lime?:					Yes		10.0	% of Tot. Mix	Total Bin			
Individual Bin (%):	81.4	Percent	7.3	Percent	1.0	Percent	10.3	% of Aggregate	100.0%			
Sieve Size:	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum. % Passing	Lower Spec Limit	Upper Spec Limit	Within Spec's
3/4"	100.0	81.4	100.0	7.3	100.0	1.0	100.0	10.3	100.0	100.0	100.0	Yes
1/2"	79.2	64.5	99.3	7.2	100.0	1.0	96.4	9.9	82.6	80.0	100.0	Yes
3/8"	54.6	44.4	91.2	6.7	100.0	1.0	74.0	7.6	59.7	35.0	60.0	Yes
No. 4	12.6	10.3	38.5	2.8	100.0	1.0	25.1	2.6	16.7	1.0	20.0	Yes
No. 8	3.4	2.8	9.5	0.7	100.0	1.0	15.2	1.6	6.0	1.0	10.0	Yes
No. 200	0.4	0.3	1.4	0.1	100.0	1.0	1.1	0.1	1.5	1.0	4.0	Yes

Table 26. Adjusted Design Asphalt Binder Type and Content.

Binder Substitution?	No	Binder Originally Specified:	PG 76-22		
Asphalt Source:	Jebro	Binder Percent, (%):	6.2	Asphalt Spec. Grav.:	1.030
Antistripping Agent:	Lhoist	Percent, (%):	1	Fiber Content, %:	0.30

APPENDIX B. TXDOT GUIDELINES FOR MAINTENANCE AND REHABILITATION OF PERMEABLE FRICTION COURSE (PFC) PAVEMENTS

BACKGROUND

Over the past several years, the Texas Department of Transportation (TxDOT) has adopted the use of permeable friction courses (PFCs) as an asphalt pavement surface layer primarily because of safety and environmental benefits. A PFC is defined in TxDOT Specification Item 342 as a surface course of a compacted permeable mixture of aggregate, asphalt binder, and additives mixed hot in a mixing plant. This hot-mix asphalt (HMA) exhibits several characteristics that translate into benefits to the traveling public.

- Reduced wet-weather splash and spray.
- Reduced risk of hydroplaning and wet skidding.
- Increased pavement marking visibility during heavy rain events.
- Reduced noise levels.
- Increased resistance to rutting.
- Cleaner water runoff when compared to dense-graded HMA.

In general, PFC durability performance is limited by the presence of distresses generated by moisture sensitivity, aging potential, and inadequate compaction. PFC functionality is limited by the loss of permeability. Regarding durability, raveling is the distress most frequently reported as the cause of failure in PFC mixtures. The mixture service life as defined by its durability is highly variable and can range from 7 to 10 years. The high air void (AV) content of a PFC corresponds to its main functional characteristic and defines its primary advantages related to safety, economy, and environmental benefits. Unfortunately, the AV content is reduced during service because of clogging. Therefore, the initial permeability and noise reduction capacity are expected to decrease such that, at the end of the functional life (when the functional characteristics are lost), a PFC behaves more like a conventional dense-graded HMA. This begs the question, "If the PFC eventually behaves like a conventional dense-graded HMA, is it necessary to mill it off instead of overlaying it?"

TYPICAL PFC DISTRESSES

When PFC pavements begin to reach the end of their serviceable life, the most common distress is raveling, as shown in Figure 1. Cracking is also sometimes observed to reflect from lower layers. When cracking occurs in a PFC, the edges of the cracks begin to ravel as well, causing the cracks to appear quite wide (Figure 2).

Figure 1. Raveling distress in aged PFC.

Figure 2. Cracking distress in aged PFC.

Evaluate Functionality of PFC

When determining maintenance and rehabilitation options for an aged PFC surface, one important consideration is to evaluate its functionality as a PFC. Is the surface still permeable? There are two methods that may be used to evaluate the permeability of the surface:

- Ground-penetrating radar (GPR).
- Permeability or water flow of hot-mix asphalt, TxDOT test method TEX 246-F.

A PFC mix that still has open air voids and is draining will typically have a uniform and low surface dielectric. An example of the surface dielectric of this type of mix is shown in Figure 3. The dielectric trace shown for the draining PFC in Figure 3 is very uniform and has a value of less than 5. A PFC that is clogged and not draining will have a nonuniform and higher dielectric, which resembles a surface dielectric more typically seen with dense-graded mixes like the one shown for the clogged PFC in Figure 3.

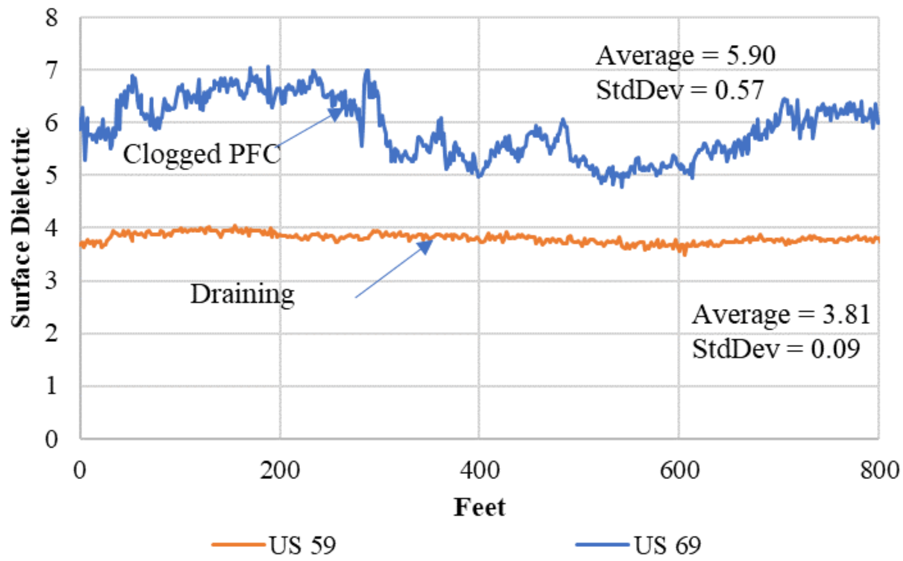

Figure 3. GPR surface dielectric when it is low and uniform it indicates the PFC pavement is still open and draining and when it is high and nonuniform indicates the PFC pavement is clogged and not draining.

In addition to GPR analysis, water flow testing can be performed to determine if the PFC is still draining. This test is used during the construction of new PFC mixes to verify that the mix has adequate permeability to drain water off the pavement surface. It is also used on thin overlay mixes (TOMs, TxDOT Item 347) during construction to verify that the compacted mixture is impermeable since the primary purpose of the TOM is to seal off the underlying pavement layers from moisture infiltration.

Figure 4 shows the water flow test being conducted in the field. A cylindrical permeameter is used along with plumber's putty to create a watertight seal. The permeameter is filled with water, and the time that it takes the water to travel from the top marking on the pipette to the bottom marking on the pipette is recorded.

For new PFC mixtures to be considered permeable, immediately after construction they are expected to have water flow time less than 20 seconds. For a TOM to be considered impermeable, it is expected to have a water flow value greater than 120 seconds. Thus, if an old PFC has a water flow greater than 120 seconds, it could be considered clogged.

A water flow value less than 120 seconds may indicate the PFC is still draining, though maybe not as effectively as when it was new.

Figure 4. Water flow testing.

Maintenance and Rehabilitation Options

Historically, there have been very few options for maintaining or rehabilitating PFCs. The prevailing wisdom has always been that the PFC mix is a sacrificial layer to be removed once it reaches the end of its service life. Many TxDOT districts consider this as a negative feature to using PFCs.

As part of research project 0-7110, other options for maintenance and rehab were explored. These other options included the following if the PFC was still draining:

- Fog seal the surface with either conventional fog seal or rejuvenating fog seal to prevent or prolong raveling and extend service life. Figure 5 shows a rejuvenating fog seal being placed on PFC on MoPac in Austin.
- Overlay the PFC with a new PFC.

Figure 5. Rejuvenating fog seal application on PFC.

If the PFC was not draining, the following options were explored:

- Overlay the PFC with hot-mix asphalt.
- Place a seal coat over the PFC.

While placing a seal coat or hot-mix overlay on a PFC is somewhat controversial, several districts have done so successfully (Figure 6). The Brownwood, Bryan, and El Paso Districts have placed a seal coat on a PFC. The Lufkin District has overlayed a PFC with a Superpave C mix as part of a research test section (Figure 7). The critical aspect of sealing or overlaying a PFC is to do an adequate field evaluation to determine whether or not it is still draining. If it is clogged and not draining, it behaves similarly to a dense-graded mix.

To aid in evaluating options, a decision tree is shown in Figure 8.

Figure 6. Seal coat application on PFC.

Figure 7. Hot-mix application on PFC.

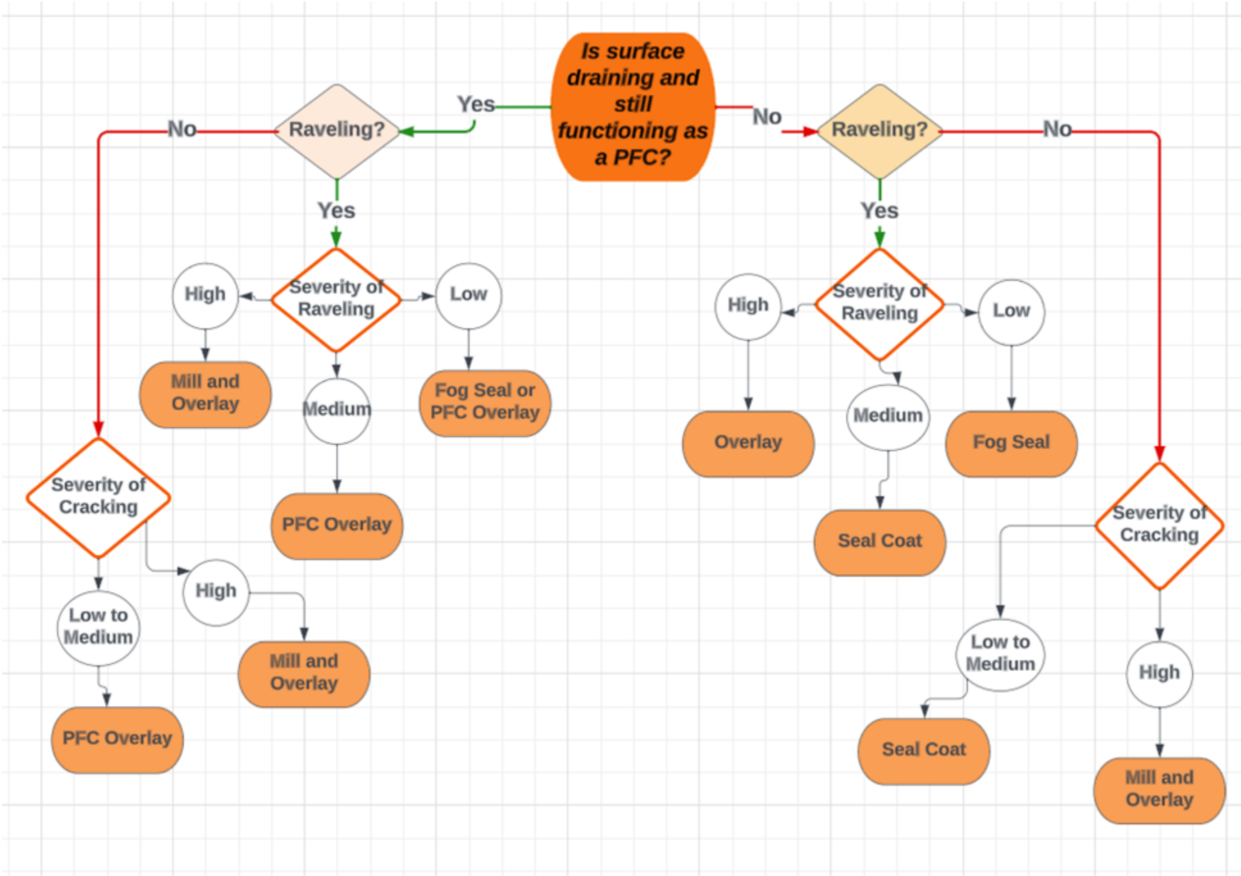

Figure 8. Decision tree for maintenance and rehabilitation options for PFCs.

Another maintenance option that is often used for PFCs that are starting to exhibit distress is to do spot repairs consisting of milling and inlaying. It has been standard practice when milling and inlaying a PFC surface that the inlay material also be a PFC to ensure that the entire PFC drains to the shoulder. However, there are cases where this may not be the best practice. In Figure 9, for example, there was an old PFC across both the main lanes as well as the shoulder. The old PFC was completely clogged including on the shoulder. Milling and inlaying the travel lane with new PFC would create a bathtub effect since the new inlaid PFC would have nowhere to drain. In this case, it was better and more cost effective to use a dense-graded mix for the inlaid material.

Figure 9. PFC repaired with inlaid, dense-graded hot-mix asphalt since PFC on shoulder was clogged.

Weather Considerations When Covering Old PFC with New Surface

If it is determined that a PFC is clogged and no longer draining, there still may be some locations within the surface with the potential to hold water. Before placing a seal coat or hot-mix surface over an old PFC, it is recommended that the weather be monitored several days prior to construction to ensure that no rain has fallen. If there is water in the old surface, placing hot spray-applied asphalt binder or placing hot mix could generate steam in the old surface and cause the new surface to debond.

To ensure optimal weather conditions at the time of resurfacing, a plan note restricting construction may be required at the discretion of the engineer.

In addition to weather monitoring, a simple moisture test is recommended. This is a test that is required in TxDOT Specification Item 668 for prefabricated pavement markings to ensure a good bond is achieved. The specification states:

Apply the material to pavement that is completely dry. Pavement will be considered dry if, on a sunny day after 15 minutes, no condensation occurs on the underside of a 1-sq. ft transparent plastic that has been placed on the pavement and weighted on the edges.

Figure 10 shows a transparent plastic sheet duct-taped to a PFC pavement surface. Researchers poured water into the pavement surface and waited for the surface to dry before taping the plastic to the PFC. Within a few short minutes, moisture appeared on the underside of the plastic sheet.

Figure 10. Moisture test on PFC pavement surface.

Mitigating the Cost Associated with PFC Use

It has not been customary practice in TxDOT to include the use of RAP in PFC mix designs, but according to TxDOT Item 342, Permeable Friction Course, up to 10% fractionated RAP is allowed. According to contractors interviewed by researchers in project 0-7110, including the use of 10% RAP in designs would offset the cost of milling the old PFC.

As part of this research project, laboratory tests were conducted on a virgin PFC mix and compared with tests on the same mix with a 10% aggregate replacement with RAP. There were no measurable detrimental performance effects noticed with the addition of 10% RAP.

APPENDIX C. VALUE OF RESEARCH

Project #	0-7110		
Project Name:	Develop Cost Effective Design and Rehabilitation Strategies for Permeable Friction Course		
Agency:	TTI	Project Budget	$ 399,957
Project Duration (Yrs.)	2.0	Exp. Value (per Yr.)	$ 7,769,667
Expected Value Duration (Yrs.)	10	Discount Rate	2%

Economic Value

Total Savings:	$ 85,066,375	Net Present Value (NPV):	$ 73,598,193
Payback Period (Yrs.):	0.051477	Cost Benefit Ratio (CBR, $1 : $___):	$ 184

Years	Expected Value
0	$0
1	$1,553,933
2	$3,107,867
3	$4,661,800
4	$6,215,733
5	$7,769,667
6	$9,323,600
7	$10,877,533
8	$12,431,466
9	$13,985,400
10	$15,539,333
11	$0
12	$0
13	$0
14	$0
15	$0
16	$0
17	$0
18	$0
19	$0
20	$0
21	$0
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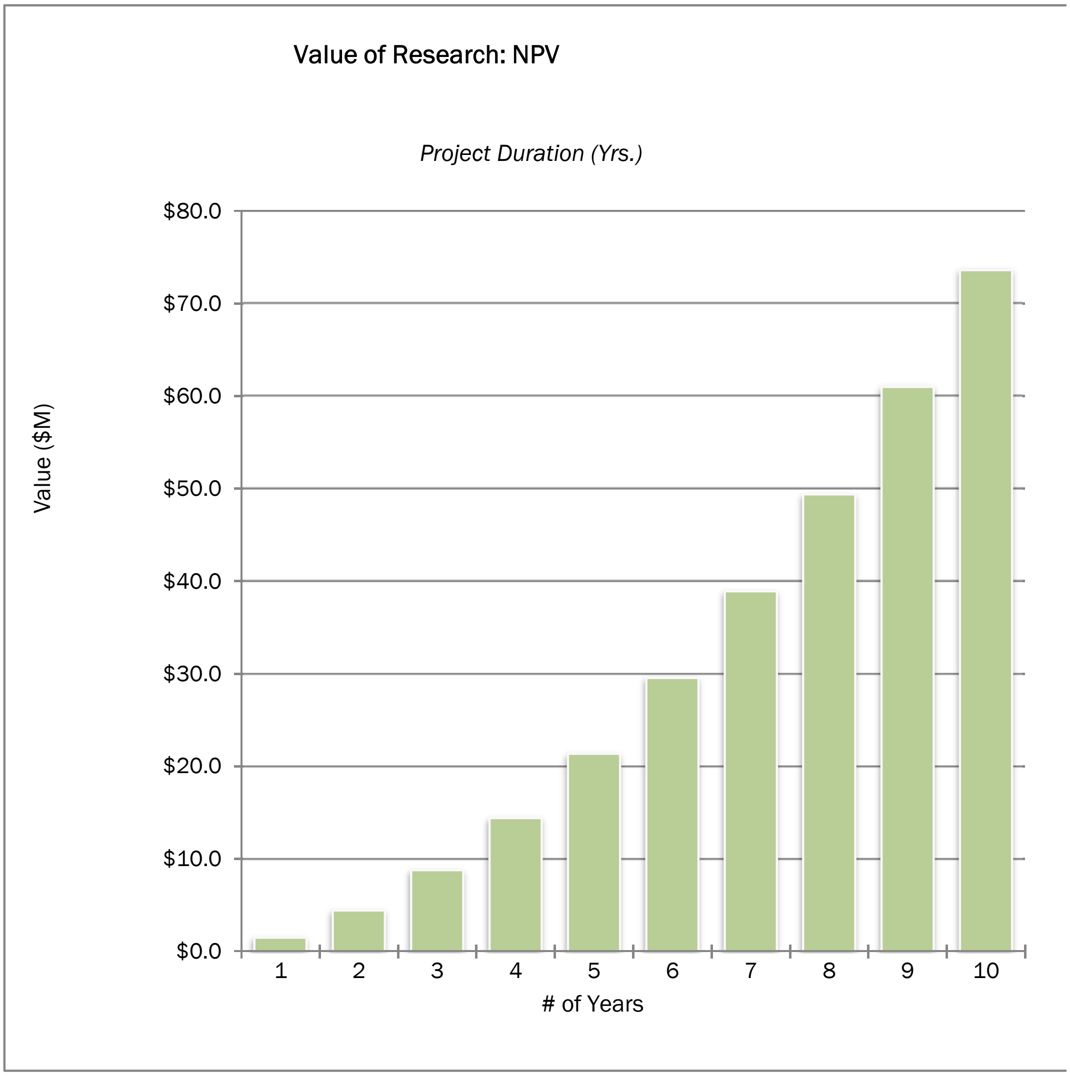
24	$0
25	$0
26	$0
27	$0
28	$0
29	$0
30	$0



Notes:

Amounts on Value of Research are estimates.
Project cost should be expensed at a rate of no more than the expected value per year.
This electronic form contains formulas that may be corrupted when adding or deleting rows, by variables within the spreadsheet, or by conversion of the spreadsheet. The university is responsible for the accuracy of the Value of Research submitted.

Variable Justification

The estimate takes into account the average life of a PFC pavement in Texas, which ranges between 7 and 15 years, with an average of 10 years, and assumes that each year a portion of the total lane-miles of PFC pavements in need of maintenance will be treated with a fog seal instead of milling and overlaying. Average Low Bid Unit Prices for 2022 were used to quantify the amount of PFC (in tons) applied in one year and Bid Item Averages for 2022 were used to obtain the costs of fog seal, milling, PFC mixture (Item 342), and tack coat. The application rate for the fog seal and tack coat was assumed 0.10 gal/sy. For the calculation, it was also considered that each year an additional 1.5% of the total amount of PFC pavements needing maintenance was going to be fog seal instead of milled and overlaid, to a total of 15% of the PFC pavements needing maintenance being treated with a fog seal by year 10. Thus, monies spent on mill & overlay maintenance are going to reduce and the total amount spent on maintenance is going to decrease as the research is implemented. The discount rate is based on OMB Circular No. A-94 for the 7-year Nominal Interest Rates on Treasury Notes and Bonds.

Qualitative Value

Benefit Area	Value
Level of Knowledge	This project will significantly increase TxDOT's understanding of maintenance options for PFC.
Management and Policy	This project will promote improving PFC service life, reducing the burden on TxDOT's maintenance and rehabilitation budgets.
Customer Satisfaction	The travelling public will spend significantly less time waiting in construction zones saving money, reducing congestion, reducing emissions, and improving safety.
Environmental Sustainability	Less PFC mixtures will be used in overlays, reducing the carbon footprint in acquisition and transportation of virgin materials and reducing emissions caused by mixture production.
Increased Service Life	Treating an existing PFC can extend its service life from 3 to 5 years at a reduced cost.
Materials and Pavements	Alternative PFC maintenance treatments provide a low cost strategy for treating existing PFC roadways. Promoting alternative maintenance strategies will incentivize innovation and emergence of new products for this purpose.
Infrastructure Condition	Providing alternatives to more expensive maintenance & rehabilitation treatments that can extend the service life of PFCs, allow for monies to be applied in other areas of infrastructure, and improve the overall pavement network condition.