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16. Abstract

Permeable Friction Course (PFC) mixes have proven to be excellent mixes that exhibit a number of desirable characteristics: rut resistance, crack resistance, reduced wet weather splash spray, reduced tire noise, and increased visibility of pavement markers during heavy rain. The Texas Department of Transportation pays a premium price for these benefits, which are sometimes short-lived, and several districts have restricted their use because of premature raveling problems.

This study was initiated to address these performance issues. It focused on the following three topics:

- Developing new laboratory test protocols to be used at the design stage to potentially eliminate mixes with stripping susceptibility.
- Monitoring the performance on sections constructed with new specifications with changes aimed at minimizing performance problems such as the new coarse graded asphalt rubber PFC.
- Construct an automated splash spray monitoring system to measure how existing PFC pavements are performing, thereby helping to optimize future designs.

17. Key Words
Permeable Friction Course, PFC, Splash and Spray, MIST Conditioning, Fine PFC, Raveling, Field Testing, Lab Testing

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DISCLAIMER

This research was performed in cooperation with 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 the 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 (researcher) in charge of the project was Tom Scullion, P.E. #62683.

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CHAPTER 1. INTRODUCTION

Permeable Friction Courses (PFC) mixes have proven to be excellent mixes that exhibit the following desirable characteristics:

- Rut resistance.
- Crack resistance.
- Reduced wet weather splash spray.
- Reduced tire noise.
- Increased visibility of pavement markers during heavy rain.

The Texas Department of Transportation (TxDOT) pays a premium price for these benefits, which are sometimes short-lived as documented by Project 0-5836, Permeable Friction Courses over Time. Recently, several projects had performance problems with surface fusion, loss of permeability, and raveling. Three districts (Pharr, Corpus, and Lubbock) have reported that they do not plan to use any more PFCs.

Project 0-6471 was initiated to explore the potential for better optimizing the PFC design to minimize the risk of these performance problems occurring, and to develop a new test to minimize the risk of premature raveling and stripping. Furthermore, the study was to focus on developing new tools to rapidly monitor the performance of PFCs in the field.

In Chapter 2, the results from a laboratory evaluation of PFCs that had performed poorly in the field were evaluated. The focus is on mixes that had premature raveling problems. Efforts were made to determine if there is a laboratory conditioning test that could be used to eliminate mixes that might ravel. Substantial work was undertaken with the moisture-induced stress tester (MIST™) moisture conditioning system. Samples were made to run performance tests such as Cantabro Loss, Hamburg Wheel Tracking Test (HWTT), and Indirect Tension Test (IDT) before and after MIST conditioning. A detailed study was also conducted on the concept of introducing a "locking point" parameter during mix design as a means for design mixes to retain their good drainage properties with time.

As part of this and other studies, changes have been made to the current PFC specifications. This includes adding a new coarse gradation to the Asphalt Rubber PFC specification and incorporating a new Fine PFC specification. In Chapter 3, field investigations were done on sections constructed with these new specifications. As will be shown, the new coarse gradation on the asphalt rubber (AR) PFC is working well on a section on IH 45 in Houston. The new fine PFCs are also performing very well. Future use of both of these mixes should be encouraged. Recommendations are also given to the Pharr District, which has had poor PFC performance.

Chapter 4 describes the efforts to develop field equipment to measure the main objective of PFCs—that of reducing the roadways splash and spray performance. The deployment of this equipment will be useful in optimizing the design of future PFC's by monitoring the long-term performance of the current generation of PFCs and how their drainage properties change with time.

CHAPTER 2. LABORATORY EVALUATION OF KEY PERFORMANCE ISSUES

INTRODUCTION

Districts in Texas experience the following two key performance issues associated with PFCs:

- Loss of permeability.
- Premature raveling.

One of the biggest concerns regarding the performance of PFCs is the loss of permeability. While it is commonly thought that PFCs become clogged, clogging with roadside debris does not seem to be the main issue. The loss of permeability appears to be related to one or more of the following issues:

- Poor aggregate gradation (the more single-sized, the better).
- Excessive aggregate crushing.
- Too much compaction during construction.
- Consolidation under heavy truck traffic.
- Too much asphalt (particularly when AR is used, which calls for as much 8 to 10 percent binder).

Several of the above factors are related to the quality of the aggregate used in the mix.

When PFCs reach the end of their life, the failure mode typically occurs in the form of raveling. If raveling occurs early in the life of the PFC (say, less than 5 years), then it is typically a result of a bonding issue between the binder and the aggregate (i.e., stripping). Since PFCs are designed to allow water in the mix, it is very important to assess and eliminate materials that are prone to stripping.

DETAILS OF THE LABORATORY WORK COMPLETED

The objective of this project was to evaluate and recommend enhancements to TxDOT's laboratory test methods to address the following key performance issues:

- Raveling.
- Clogging.
- Aggregate crushing.

These three factors have been related to poor performance in several districts such as Pharr (raveling), Houston (raveling and surface fusion), Lubbock (raveling), and Austin (aggregate crushing). Several PFCs with distinct characteristics were used to identify what laboratory test methods were sensitive to problematic mixtures. The ultimate goal is to recommend the use of laboratory test methods during the mix design phase as part of the PFC specification.

A test method using the locking point in the Superpave™ Gyratory Compactor (SGC) was used to evaluate the mixture design and crushing resistance of the aggregates. The Aggregate Crushing Value (ACV) test was also used to evaluate mixture aggregate quality.

Raveling is one of the most common distresses affecting PFCs due to their high void content and oftentimes open gradation. It is common for these mixtures to exhibit adequate performance for a period of several years, then fail rapidly once raveling sets in. Raveling is primarily a moisture susceptibility issue, and thus more prevalent in mixtures with high air voids, low binder content, or placed in areas of the pavements with limited lateral drain (e.g., wheel paths).

The research team proposed a series of laboratory tests to identify raveling-susceptible mixtures, including:

- Hamburg Wheel Tracking Test per Tex-242-F.
- Cantabro Loss per Tex-245-F.
- Indirect Tension Test per Tex-226-F after MIST.

PRELIMINARY EVALUATION OF LABORATORY TEST METHODS

An initial evaluation of the laboratory test methods listed above was conducted to assess their practicality in testing PFC mixtures. MIST was used to condition the specimens. Based on the initial results, researchers decided to discard the Overlay Test (OT) and the pull-off test from the list of candidate tests to evaluate raveling-susceptible mixtures, as explained below.

Mixture Designs

Most of the materials were sampled from the Pharr District for this portion of the study and include the following mixture types:

- Mixture 1: 100 percent A Gravel (SAC A)—Fordyce Showers Pit.
- Mixture 2: 100 percent B Limestone (SAC B)—Martin Marietta Beckman.
- Mixture 3: 100 percent B+ Limestone—Border Pacific Matrimar.
- Mixture 4: 50/50 Gravel/B Limestone.
- Mixture 5: 50/50 Gravel B+ Limestone.

Table 1 shows the physical properties of the three aggregate types as reported in *the Bituminous Rated Source Quality Catalog*. Both of the limestone aggregates shown in Table 1 represent a SAC B material; however, the Matrimar limestone has significantly better qualities, particularly in terms of soundness.

PFC mixtures with the above aggregate combinations were designed in the laboratory using a performance graded (PG) 76-22 binder from Martin Asphalt (Houston Terminal). Table 2 presents mix design data for the five different mixtures.

Table 1. Properties of Aggregates Used in Mix Designs.

Aggregate	Los Angeles Abrasion % Loss	$MgSO_4$ Soundness, % Loss	Micro Deval, % Loss
Fordyce Gravel (Showers)	19	4	4
Beckman Limestone	31	29	29
Matrimar Limestone	25	3	12

Data obtained from TxDOT's Bituminous Rated Source Quality Catalog

Table 2. Mix Design Data.

Mix Parameter	TxDOT Specification PG 76 Coarse (PFC-C)	Mixture 1: 100% Fordyce (F)	Mixture 2: 100% Beckman Limestone (BLs)	Mixture 3: 100% Matrimar Limestone (MxLs)	Mixture 4: 50% Fordyce + 50% Beckman Limestone (F+BLs)	Mixture 5: 50% Fordyce + 50% Matrimar Limestone (F+MxLs)
Sieve Size	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing
½″	80.0–100.0	88.1	86.4	84.9	87.3	86.5
3/8″	35.0–60.0	42.4	46.9	49.8	44.5	46.2
No. 4	1.0–20.0	8.0	4.1	5.8	6.1	6.9
No. 8	1.0–10.0	3.5	2.6	2.8	3.1	3.2
No. 200	1.0–4.0	1.5	2.2	2.2	1.9	1.9
Asphalt	6.0–7.0%	7.0% PG 76-22	6.9% PG 76-22	7.1% PG 76-22	7.1% PG 76-22	7.1% PG 76-22
Lime	1.0% max	1.0%	1.0%	1.0%	1.0%	1.0%
Fibers	0.2–0.5%	0.3%	0.3%	0.3%	0.3%	0.3%
Lab Molded Density	82.0% max	72.3%	75.5%	75.8%	75.7%	76.0%
Cantabro Loss	20% max	16.5%	11.4%	8.0%	34.8%	15.8%
Drain-Down	0.1% max	N/A	N/A	N/A	N/A	N/A
Hamburg	For Information Only	2,690	11,075	13,750	13,400	20,000
Overlay Test	For Information Only	N/A	N/A	N/A	N/A	N/A
Mixture Composition	–	60% Grade 3 and 39% Grade 4 Fordyce (Gravel)	60% Type C and 39% Grade 4 Beckman Limestone	60% Grade 3 and 39% Grade 4 Mexican Limestone	30% Grade 3 and 19.5% Grade 4 Fordyce; 30% Grade 3 and 19.5% Grade 4 Beckman Limestone	30% Grade 3 and 19.5% Grade 4 Fordyce; 30% Grade 3 and 19.5% Grade 4 Mexican Limestone

Locking Point Results

Solutions to key performance issues such as long-term permeability and raveling require careful evaluation of both the recommended aggregate type and gradation and binder content. To evaluate the mix designs, researchers employed ideas developed in Florida to determine a locking point for the aggregate skeleton. The concept is that the combination of mostly single-sized PFC aggregates should readily lock in place, and during compaction in the SGC very small changes in density should be observed with the additional number of cycles. If the mix continues to consolidate, then either the aggregates are crushing under the applied load or the aggregate gradation needs to be revised. The compaction curves for each of the five different mixtures are presented in Figure 1 through Figure 5. Mixtures were subjected to 300 cycles in the SGC and the mixture using the highest quality aggregate (Figure 1) showed the best performance with little to no change in density early in the compaction process. In contrast the mixture using the poorest quality aggregate (Figure 2) exhibits a slope in the curve throughout the process indicating the aggregate is crushing. All of the mixtures had similar asphalt contents ranging from 6.9 to 7.1 percent.

Vavrik and Carpenter (*1*) defined the actual locking point: the first three gyrations that are at the same height preceded by two gyrations at the same height (height is in millimeters and rounded to a single decimal place). Figure 6 shows the locking point for each mixture. The following is a ranking of the mixtures from best to worst:

1. 100 percent Fordyce Gravel.
2. 50 percent Fordyce Gravel/50 percent Matrimar Limestone.
3. 100 percent Matrimar Limestone.
4. 50 percent Fordyce Gravel/50 percent Beckman Limestone.
5. 100 percent Beckman Limestone.

The use of the gravel improved the performance of either of the limestone mixtures alone in terms of the locking point. Based on these data and the known quality of the materials being used in the mixes, a locking point maximum limit of 100 gyrations is proposed as a preliminary criterion.

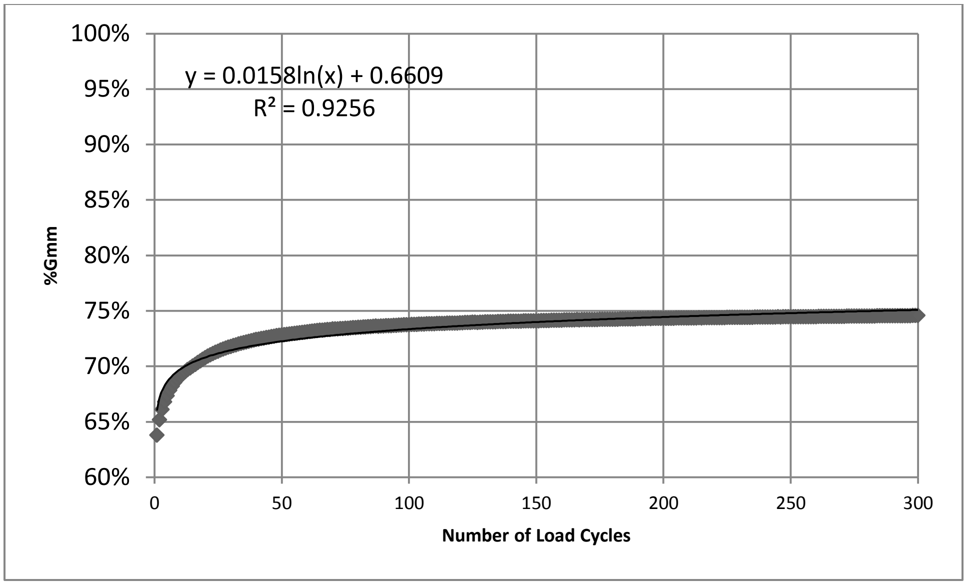


Figure 1. SGC Compaction Curve for 100 Percent Fordyce Gravel Mix.

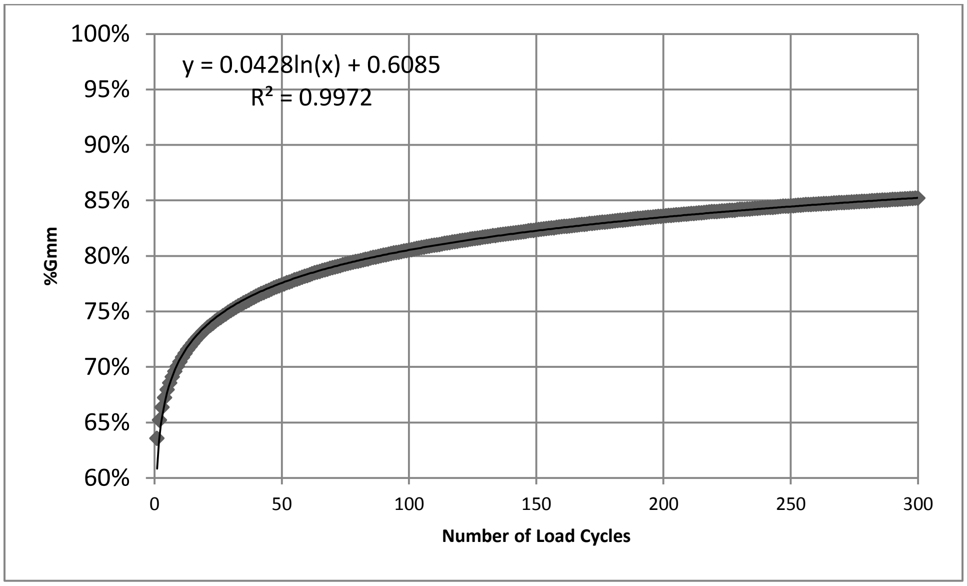


Figure 2. SGC Compaction Curve for 100 Percent Beckman Limestone Mix.

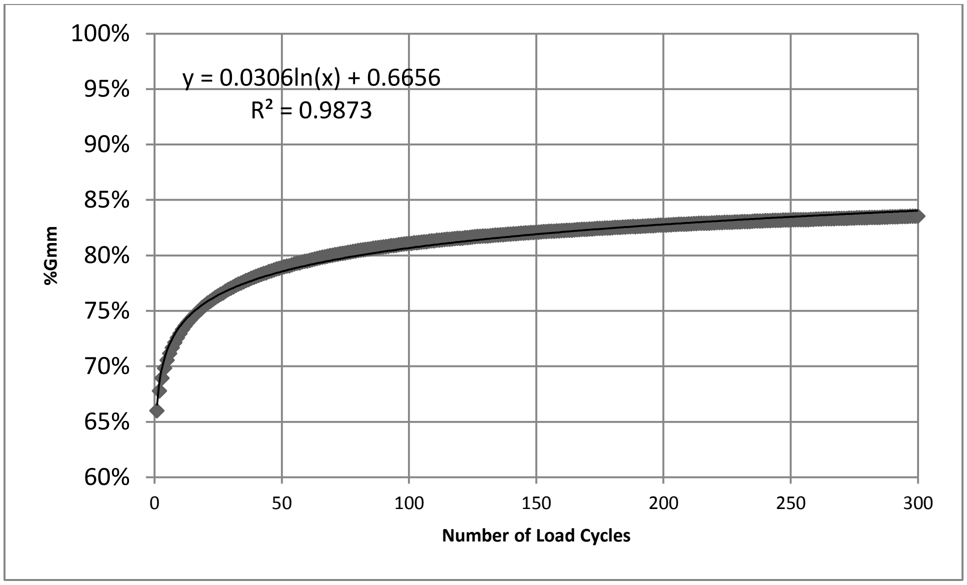


Figure 3. SGC Compaction Curve for 100 Percent Matrimar Limestone Mix.

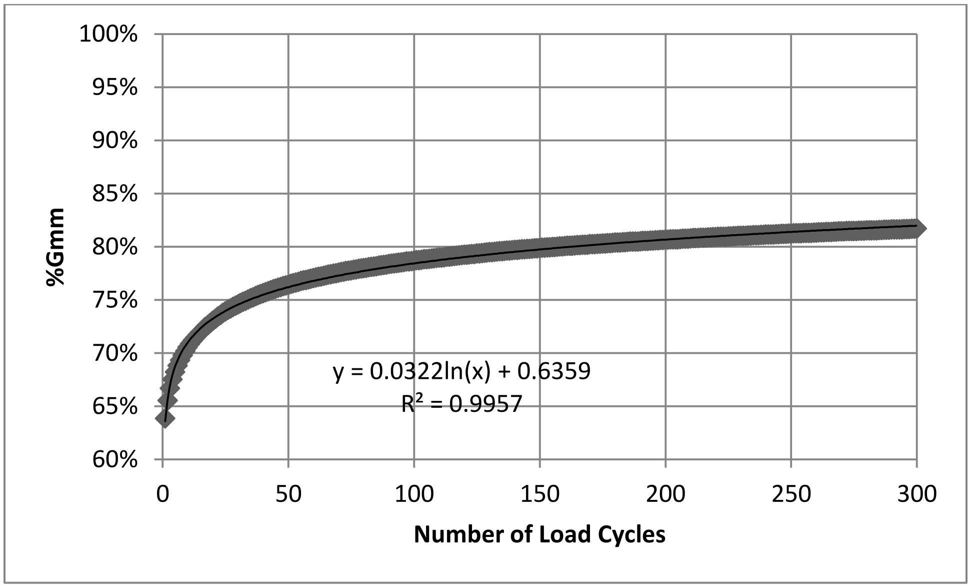


Figure 4. SGC Compaction Curve for 50/50 Fordyce Gravel/Beckman Limestone Mix.

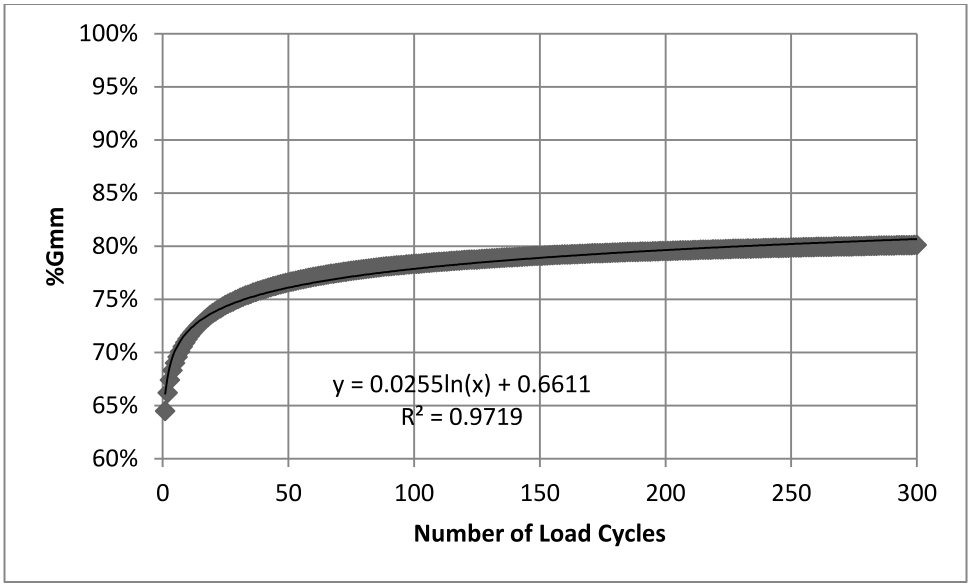


Figure 5. SGC Compaction Curve for 50/50 Fordyce Gravel/Matrimar Limestone Mix.

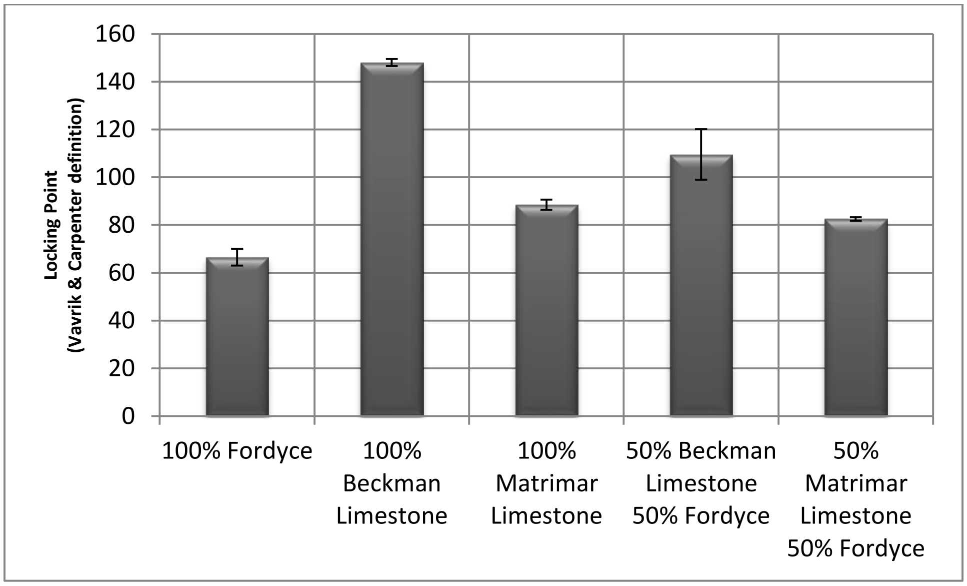


Figure 6. Locking Point Results.

Aggregate Crushing Value

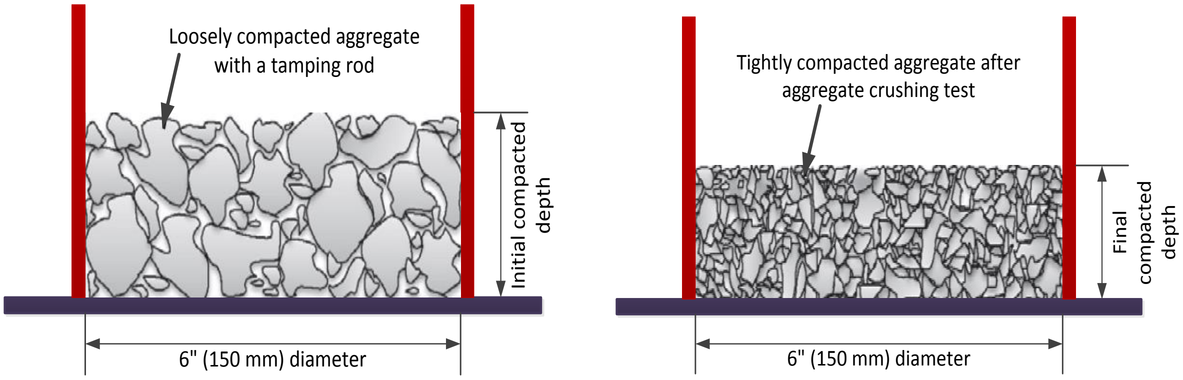
ACV is also a measure of aggregate quality but uses only the coarse aggregate fraction alone. ACV was measured in accordance with the British Standard 812-110. As shown in Figure 7, the main principle of the test is to compact and crush a loose aggregate specimen in a test cylinder by applying a constant load rate of 40 kN/min (4 ton/min) through a plunger. After the load reaches 400 kN (40 tons), the applied load was removed and the aggregates were emptied from the test cylinder and sieved to determine the extent of crushing, which the amount of crushed particles passing a 2.36 mm (No. 8) sieve has established.

The total percent mass loss was represented as ACV. The rankings of the aggregates from best to worst are as follows:

1. 100 percent Fordyce Gravel.
2. 50 percent Fordyce Gravel/50 percent Matrimar Limestone.
3. 100 percent Matrimar Limestone.
4. 50 percent Fordyce Gravel/50 percent Beckman Limestone.
5. 100 percent Beckman Limestone.

This ranking is the same as that for the locking point results.

After crushing, the aggregates were separated into +⅜, +No. 8 and −No. 8. These fractions for each aggregate and aggregate blend are shown in Figure 8 and Figure 9. Figure 10 and Figure 11 show only the +⅜ material after crushing and separated into the gravel and limestone fractions. These photos show that most of the crushing that occurs in the blended aggregates occurs in the limestone portions of the blends. Even though there is a significant difference in the soundness values of the Beckman and Matrimar limestones, the crushing occurring in each type seems to be similar.



(a) Before crushing (b) After crushing

Figure 7. Schematic Diagram before/after ACV Test.

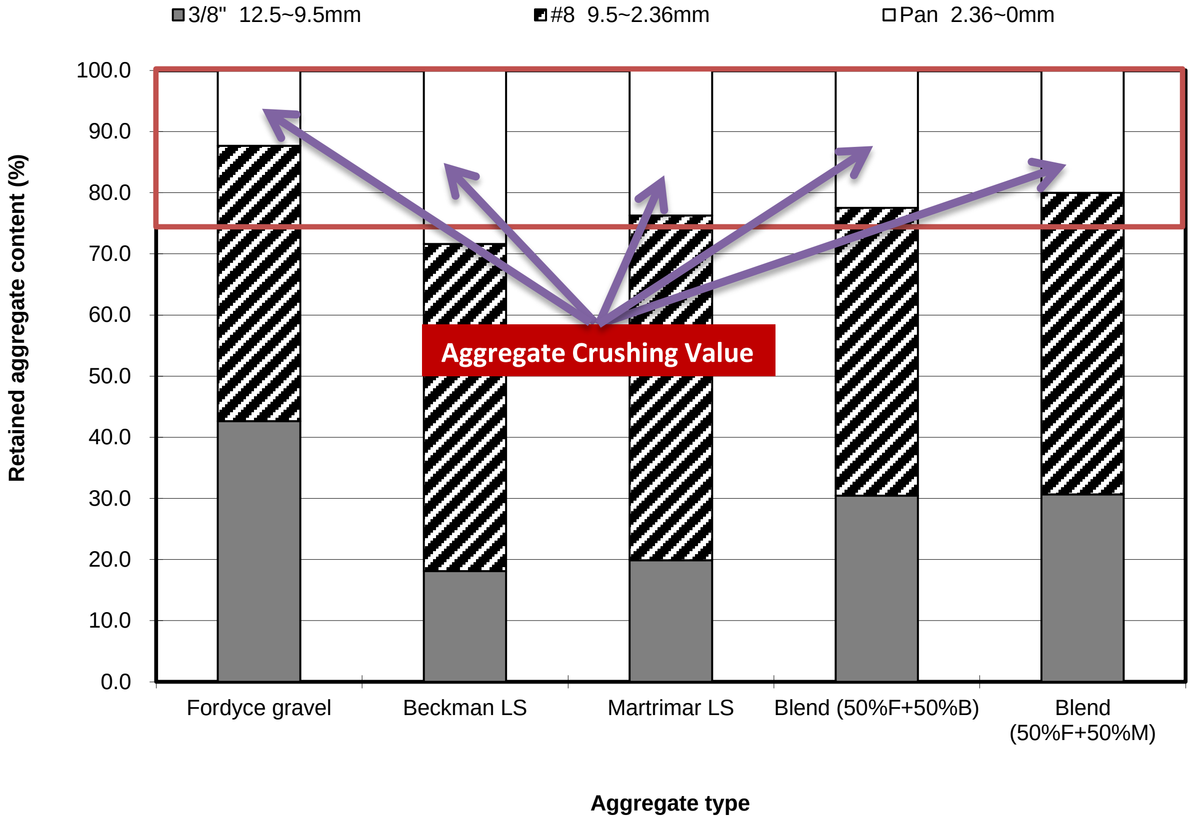


Figure 8. Aggregate Crushing Values.

(a) Fordyce Gravel **(b) Beckman Limestone**

(c) Matrimar Limestone **(d) 50/50 Fordyce/Beckman**

(e) 50/50 Fordyce/Matrimar

Figure 9. Aggregate Samples after ACV Test Separated into ⅜ Inch, +No. 8, and −No. 8 Mesh Fractions.

Figure 10. Remaining ⅜-Inch Materials after ACV Test from Original 50/50 Blend of Fordyce Gravel and Beckman Limestone.

Figure 11. Remaining ⅜-Inch Materials after ACV Test from Original 50/50 Blend of Fordyce Gravel and Beckman Limestone.

PERFORMANCE TEST RESULTS

All five mixtures were subjected to the performance tests that had been identified earlier in this project as showing promise for predicting field performance. In particular, a test to identify premature raveling is needed and this was the main objective of this work. These tests evaluated include the following:

- Cantabro Loss (before and after MIST).
- HWTT.
- IDT before and after MIST.

Researchers chose to run the MIST (Figure 12) at 40 psi, 140°F, and 1000 cycles as the moisture condition method most appropriate for PFC mixes since it most closely approximates field conditions.

Figure 12. Moisture-Induced Stress Tester Equipment.

Cantabro Loss

This test was performed following TxDOT procedure Tex-245-F on 6-inch (152 mm) diameter by 4.5-inch (115 mm) height specimens. After the compacted specimen was weighed, it was placed in the Los Angeles Abrasion (LAA) testing machine without the steel balls (Figure 13). The machine was run at 30–33 revolutions per minute for 300 revolutions. After the 300 revolutions, the test specimen was weighed, and any loose material was discarded. The Cantabro loss was recorded as the relative difference between the initial and final weights. Current TxDOT Special Specification #3269 requires a maximum Cantabro loss of 20 percent for all types of PFC mixtures.

Figure 14 presents both dry and MIST condition Cantabro results. The Fordyce Gravel mixture has exhibited premature raveling in the field due to stripping. This property seems to be reflected in the MIST-conditioned 100 percent Fordyce specimens. All of the mixtures showed significant increases in Cantabro loss after MIST with the exception of the 50/50 Fordyce/Beckman mixture, which had even a failing dry Cantabro. The 100 percent Fordyce mixture is the only mixture that had an acceptable dry Cantabro but had more than a 30 percent loss after conditioning, indicating it is prone to stripping as has been observed in the field.

Figure 13. Los Angeles Abrasion Testing Equipment (www.pavementinteractive.org).

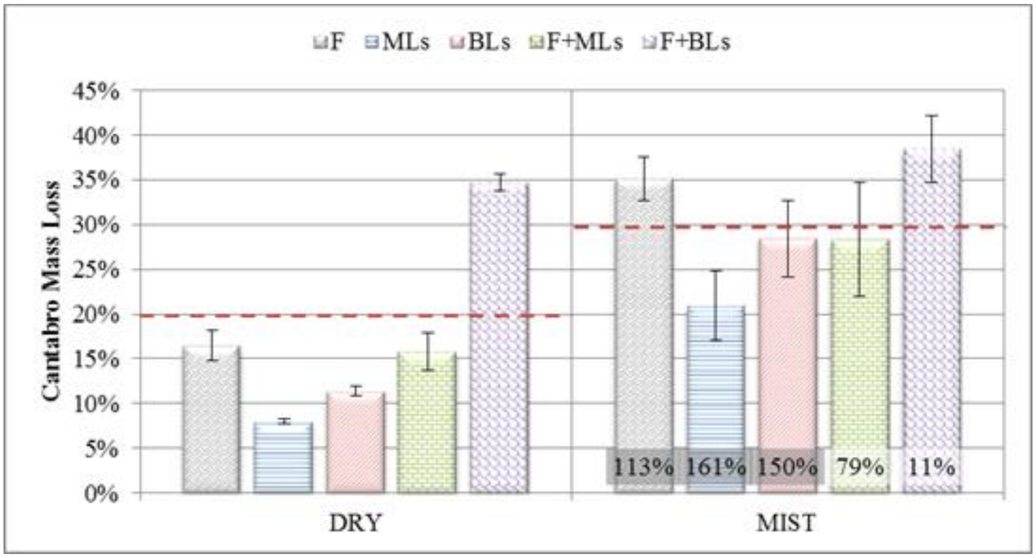


Figure 14. Cantabro Loss for Dry and MIST-Conditioned Specimens.

Hamburg Wheel Tracking Test

HWTT is a common test procedure that TxDOT uses to determine mixture susceptibility to rutting and moisture damage. A minimum requirement of 10,000 load cycles to 12.5 mm rut depth is now part of the Special Specification # 3269 for fine PG-PFCs. This test was performed according to TxDOT procedure Tex-242-F on 6-inch (152 mm) diameter by 2.5-inch (64 mm) height specimens. Figure 15 shows the results of HWTT. This test seems to clearly indicate that the 100 percent Fordyce mixture is susceptible to stripping. All of the other mixtures exceeded 10,000 cycles. The best performing mix (which lasted 20,000 cycles) was the 50/50 blend of Fordyce/Matrimar limestone. These data seem to indicate that the stripping susceptibility of an aggregate such as gravel can be significantly improved with the addition of a good quality limestone. Photographs (Figure 16) after testing of the Fordyce/Beckman blend compared to the Fordyce/Matrimar blend show some evidence of stripping in the Fordyce/Beckman specimens.

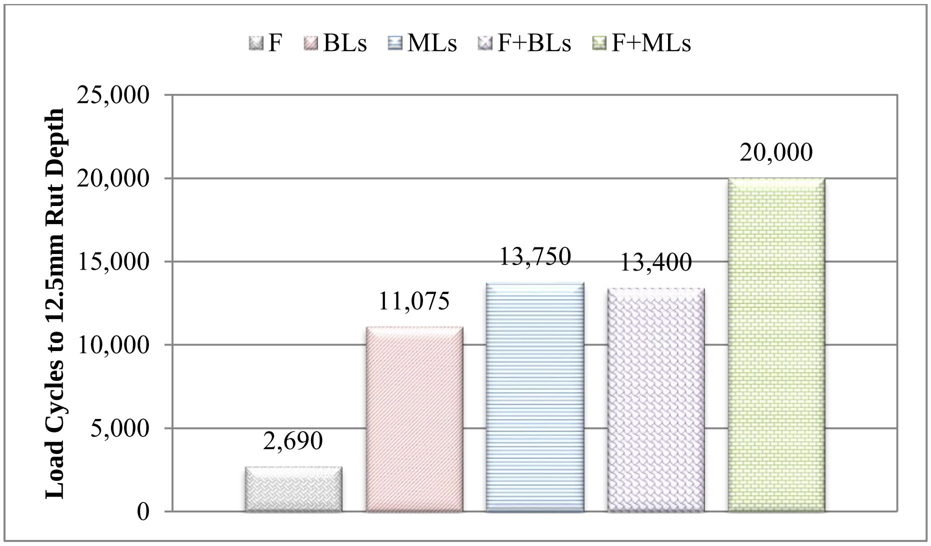


Figure 15. HWTT Number of Load Cycles to Failure.

(a) Failed at 13,750 cycles (b) Lasted to 20,000 cycles

Figure 16. HWTT Specimens after Testing for (a) 50/50 Blend of Fordyce Gravel and Beckman Limestone, and (b) 100 Percent Matrimar Limestone.

Indirect Tensile Strength

The IDT strength test was performed following TxDOT procedure Tex-226-F on 6-inch (152 mm) diameter by 2.5-inch (64 mm) height specimens. The specimens were set up in a loading frame between two 0.75-inch (19 mm) square steel loading strips as shown in Figure 17. A constant compressive load at a controlled deformation rate of 2 inches (50 mm) per minute was then applied until failure. The maximum vertical load at failure was used to calculate the tensile strength of the specimen. In addition, the ratio of the average IDT strength of the MIST conditioned specimens to the average IDT strength of the dry specimens or tensile strength ratio (TSR) was calculated.

Figure 17. IDT Strength Test Setup.

Figure 18 and Figure 19 present the results for all five mixtures. Except for the 100 percent Beckman Limestone mix, all of the mixes suffered a decrease in IDT after MIST. However, this test is not distinguishing the Fordyce gravel as a stripping-susceptible mix as in both Cantabro and HWTT testing results. Previously, researchers recommended an IDT ratio of 80 percent after MIST for PFC mixtures. However, these data do not support that recommendation since the 100 percent Fordyce Gravel mix would pass that requirement yet based on field performance and Hamburg/Cantabro results the mix is clearly prone to stripping. The IDT test is therefore not recommended for PFC performance evaluation.

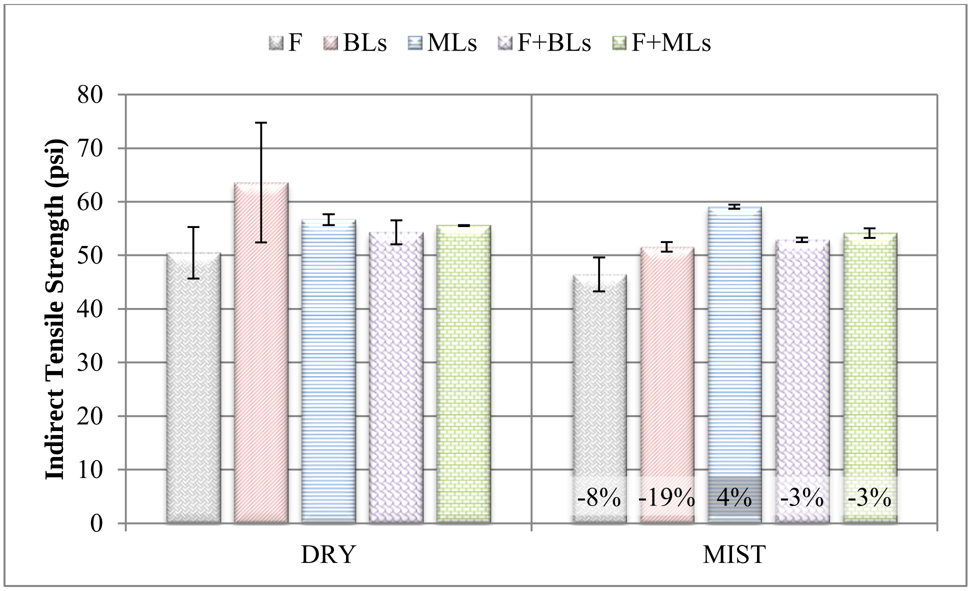


Figure 18. Indirect Tensile Strength Results for Dry and MIST-Conditioned Specimens.

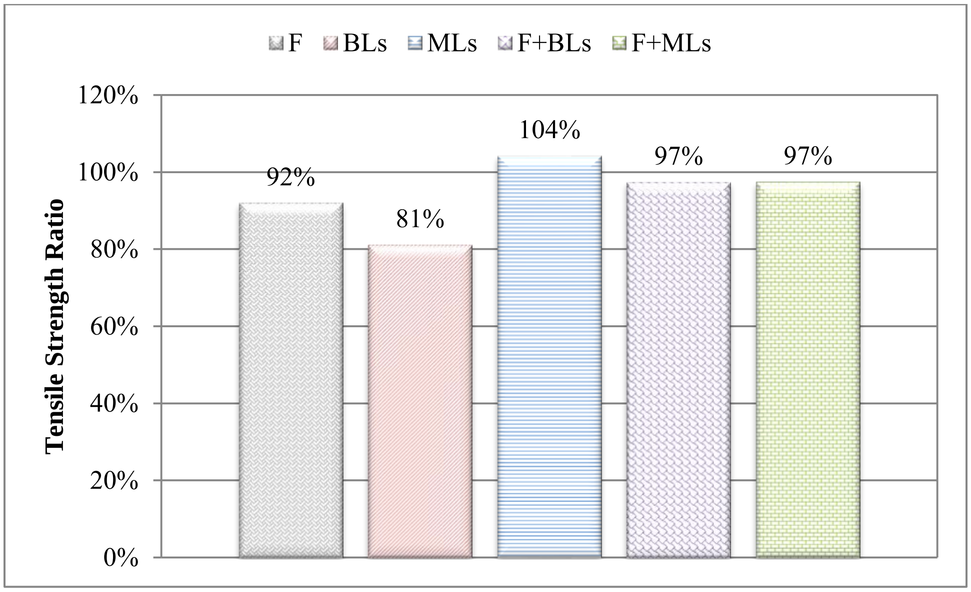


Figure 19. TSR Results.

CONCLUSIONS AND RECOMMENDATIONS FROM THE LAB TESTING

Based on the results presented in this chapter, the following tests are recommended to address, in part, these two performance issues.

Maintaining Permeability

To ensure that a mix has an adequate aggregate skeleton and does not crush or break-down under the application of traffic, *a locking point maximum value of 100 gyrations* is recommended. The concept of this simple test is that the combination of mostly single-sized PFC aggregates should readily lock in place, and during compaction in the SGC, very small changes in density should be observed with an additional number of cycles. If the mix continues to consolidate, then either the aggregates are crushing under the applied load or the aggregate gradation needs to be revised.

Eliminate Premature Raveling

Due to the inherent presence of water within a PFC mixture, a moisture susceptibility test is needed. The following two tests are proposed to identify a mixture that is prone to moisture damage:

- A maximum of 10,000 cycles in the Hamburg Wheel Tracking Test.
- A maximum of 30 percent Cantabro loss after MIST conditioning of 40 psi, 140°F, and 1000 cycles.

CHAPTER 3. CONSTRUCTION AND MONITORING OF PFC TEST SECTIONS

INTRODUCTION

Project 0-6741 promoted the use of the following three alternative PFC designs:

- Opening up the AR PFC gradation to minimize the risk of surface fusion that was found on sections in the Houston District and elsewhere. This was adopted and incorporated into the latest PFC specification and is included in the new FY 14 spec book.
- Adopting the move to the new fine PFC. This can be placed at thicknesses between 0.75 and 1 inch, with no loss in drainability.
- Adoption of a more rigorous upfront lab testing on moisture susceptibility to eliminate mixes, which will be prone to delamination.

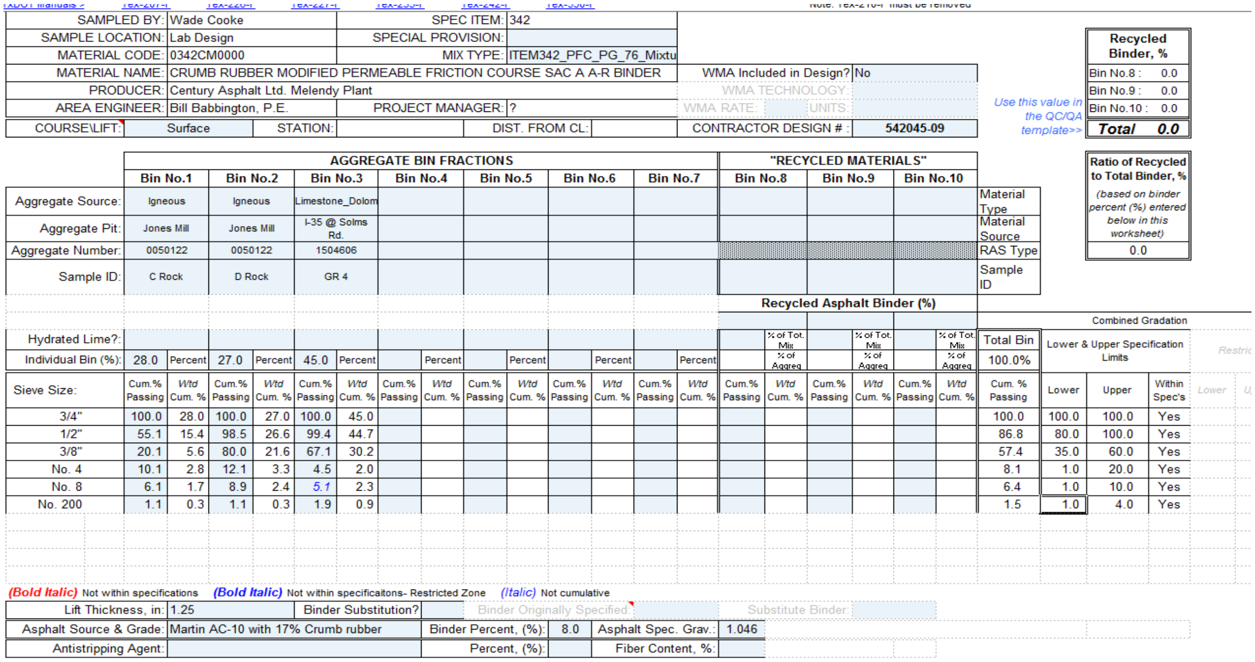
Sections were constructed to evaluate the performance of the first two design proposals above, and recommendations were made to the Pharr District to construct sections that meet the requirements of the third design proposal with their locally available aggregates.

DESIGN RECOMMENDATION 1−OPENING UP THE AR PFC GRADATION BAND (IH 45 HOUSTON)

For several years, the Houston District has reported inferior long-term performance for AR PFCs designed according to the prevailing Item 342 spec with the required fine master gradation shown in Table 3 of that spec and with a binder content ranging from 8 to 10 percent. For these PFCs, Jeff Volk, the current Area Engineer in Waller County, measured water flows in excess of 5 minutes shortly after placement. These were not acting as PFC, and several sections started to ravel severely. Figure 20 shows photos of a closed and raveled AR PFC.

Figure 20. Nondraining and Raveling PFC Reported by Houston with AR PFC Binders.

The problems shown in Figure 20 have generally not been reported with the PG binder PFCs. Visually it appears that the asphalt in the PFC has migrated to the surface of the mat. In an experiment to evaluate if modified gradation would improve the performance of the AR PFCs, the coarse PG 76 gradation mix design shown below was placed on the main lane of IH 45. The section is approximately 0.7 miles long and starts at TRM 3 just north of Galveston. As shown in Figure 22, this section is now over two years old and is performing very well.



SAMPLED BY:	Wade Cooke	SPEC ITEM:	342
SAMPLE LOCATION:	Lab Design	SPECIAL PROVISION:	
MATERIAL CODE:	0342CM0000	MIX TYPE:	ITEM342_PFC_PG_76_Mixtu
MATERIAL NAME:	CRUMB RUBBER MODIFIED PERMEABLE FRICTION COURSE SAC A A-R BINDER	WMA Included in Design?	No
PRODUCER:	Century Asphalt Ltd. Melendy Plant	WMA TECHNOLOGY:	
AREA ENGINEER:	Bill Babbington, P.E.	PROJECT MANAGER:	?

WMA RATE: UNITS:

COURSE\LIFT: Surface STATION: DIST. FROM CL: CONTRACTOR DESIGN # : 542045-09

Note: Tex-210-F must be removed

Recycled Binder, %	
Bin No.8 :	0.0
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***0.0***

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
0.0

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
	Bin No.1	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.5**	**Bin No.6**	**Bin No.7**	**Bin No.8**	**Bin No.9**	**Bin No.10**	
Aggregate Source:	Igneous	Igneous	Limestone_Dolom								Material Type
Aggregate Pit:	Jones Mill	Jones Mill	I-35 @ Solms Rd.								Material Source
Aggregate Number:	0050122	0050122	1504606								RAS Type
Sample ID:	C Rock	D Rock	GR 4								Sample ID
								Recycled Asphalt Binder (%)			
Hydrated Lime?:											

Combined Gradation

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	28.0	Percent	27.0	Percent	45.0	Percent		Percent		Percent		Percent		Percent		% of Tot. Mix % of Aggreg		% of Tot. Mix % of Aggreg		% of Tot. Mix % of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum.% Passing	*Wtd* Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	28.0	100.0	27.0	100.0	45.0															100.0	100.0	100.0	Yes
1/2"	55.1	15.4	98.5	26.6	99.4	44.7															86.8	80.0	100.0	Yes
3/8"	20.1	5.6	80.0	21.6	67.1	30.2															57.4	35.0	60.0	Yes
No. 4	10.1	2.8	12.1	3.3	4.5	2.0															8.1	1.0	20.0	Yes
No. 8	6.1	1.7	8.9	2.4	*5.1*	2.3															6.4	1.0	10.0	Yes
No. 200	1.1	0.3	1.1	0.3	1.9	0.9															1.5	1.0	4.0	Yes

Restric Lower U

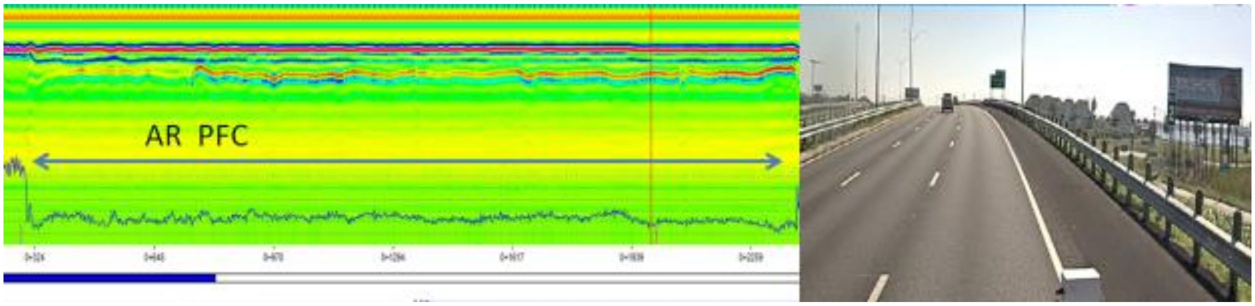
(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	1.25	Binder Substitution?		Binder Originally Specified:	Substitute Binder:
Asphalt Source & Grade:	Martin AC-10 with 17% Crumb rubber	Binder Percent, (%):	8.0	Asphalt Spec. Grav.:	1.046
Antistripping Agent:		Percent, (%):		Fiber Content, %:	

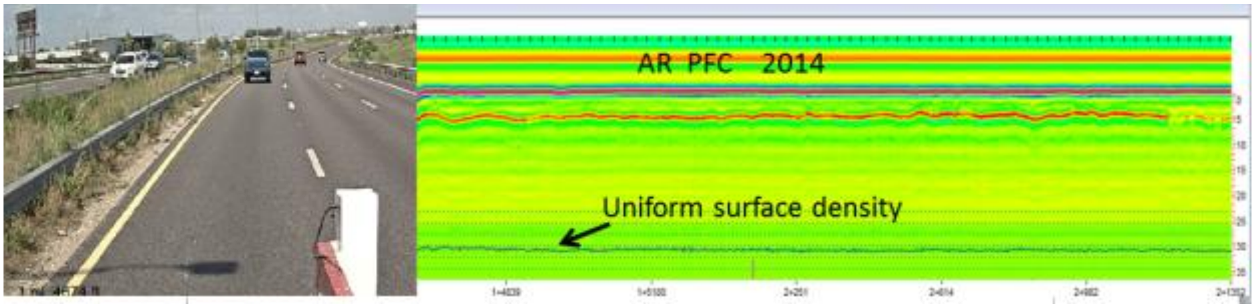
Figure 21. Modified Gradation for the AR PFC Placed on IH 45 in Houston.

Figure 22. Coarse Graded AR PFC in Service on IH 45 in Houston.

During construction, water flows on this section were measured to be less than 20 seconds, and unlike other AR PFC in Houston, it is draining well after two years in service. Figure 23 shows that ground penetrating radar (GPR) data were collected on the section in both 2013 and 2014. The measured surface dielectric is an indicator of mat density and uniformity; the measured dielectrics found in IH 45 are very low and uniform. This shows that the surface densities are uniform and not changing. The coarser gradation appears to be part of the answer. Researchers propose more monitoring and more sections for construction.



a) 2013 GPR data

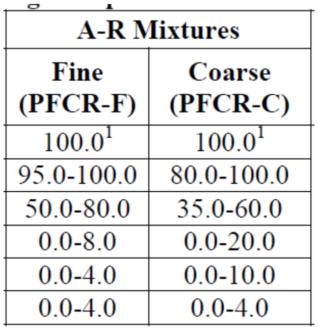


b) 2014 GPR data

Figure 23. GPR Data from the Coarse PFC on IH 45 in Houston.

To address the surface fusion concern with AR PFCs, TxDOT has modified the allowable gradations. Table 3 shows the two allowable gradations; the PFCR-C is the new coarse gradation.

Table 3. Showing Existing Fine and New Coarser Gradations for AR PFCs.



A-R Mixtures	
Fine (PFCR-F)	Coarse (PFCR-C)
100.0[1]	100.0[1]
95.0-100.0	80.0-100.0
50.0-80.0	35.0-60.0
0.0-8.0	0.0-20.0
0.0-4.0	0.0-10.0
0.0-4.0	0.0-4.0

Districts that wish to use the AR binder because of assumed improvements in cracking resistance and reported low noise characteristics should be encouraged to use the coarse gradation shown in Table 3. It is working well under the heavy traffic conditions on IH 45.

DESIGN RECOMMENDATION 2−MOVE TO THE FINE GRADED PFC

Early in this study, the initial work on the fine PFC found them to be a viable option to both save money and increase water flow. To ensure that these mixes have the correct quality of materials and desired performance, researchers recommend increased performance requirements in the lab design phase. Consequently, the fine PFC must pass both a Hamburg requirement (last more than 10,000 passes) and an Overlay Tester cracking requirement (more than 300 cycles). The Hamburg requirement is still under review and it is recommended that it be permitted to be waived where appropriate. However more work is needed as several mixes that historically passed the Hamburg are now failing. But this may because of recent unreported changes to the PG binders. The initial recommendations were adopted and incorporated as part of temporary spec 3269, and will be in the new specification book under Item 342. These requirements are not applied to the traditional coarse graded PFC's. All of the fine PFCs placed during this study had to meet these additional lab requirements.

To evaluate the constructability and performance of the fine PFC mixture, field trials were conducted in the following five locations and mixtures were designed for each location using materials local to the area:

- Fine PFC placed at the Pecos Test Track.
- Exit Ramp in the Lufkin District.
- Exit Ramp in the Bryan District.
- US 183 in the Brownwood District.
- Loop 338 in the Odessa District.

Construction and Monitoring of the Fine PFC Section at the Pecos Test Track

Researchers developed specifications and let a contract to Reece Albert Construction of Midland to construct two fine-graded PFC mixtures on the entrance to the facility. They used a relatively good quality limestone from Vulcan Materials in Eastland and a rhyolite gravel from Capital Aggregates' Hoban Pit.

Texas A&M Transportation Institute (TTI) designed the mixes using a single aggregate fraction from each source (Table 4). Researchers specified a minimum asphalt content of 6.5 percent that was also selected as optimum for both mixtures, and used 0.3 percent fibers. Lime was not included in the mix design since the plant did not have the capability to add it. The mixtures were designed according to TxDOT procedure Tex 204-F, Part V.

Table 4. Mix Design Compositions for Field Testing at Pecos.

	PFC Mix Design No. 1	PFC Mix Design No. 2	Draft Specification Lower and Upper Specification Limits	
	Capital Aggregates Hoban	Vulcan Materials Eastland Limestone		
Sieve Size	**Cum. % Pass**	**Cum. % Pass**		
No. 1/2	**100.0**	**100.0**	100	100
No. 3/8	**94.5**	**97.8**	94	100
No. 4	**30.2**	**46.4**	20	55
No. 8	**4.8**	**3.4**	0	15
No. 16	**1.0**	**1.9**	0	12
No. 30	**0.4**	**1.6**	0	8
No. 50	**0.3**	**1.5**	0	8
No. 200	**0.2**	**1.3**	0	4

Asphalt Type: PG 76-22 Binder Percent: 6.5% Lime: 0% Fibers: 0.3%

Selecting Optimum Asphalt Content

As discussed previously, since these mixes had higher air void contents than conventional PFC mixes, additional tests (Hamburg and Overlay) were added to ensure adequate field performance. These tests were also used to aid in selecting the asphalt content. Table 5 presents the results. Samples were molded at 6.0, 6.5, and 7.0 percent asphalt, and evaluated for density, Hamburg, and Overlay Tester characteristics. The Hoban rhyolite mixture failed the Hamburg requirement of no more than 12.5 mm rut depth at 10,000 cycles but passed these criteria at 6.5 percent asphalt. Overlay Test data exceeded the minimum of 300 cycles for all three asphalt contents. All three asphalt contents met the density requirements of between 70 and 74 percent. Based on the Hamburg criteria, the acceptable asphalt content was selected as 6.5 percent.

The Eastland mix had acceptable Hamburg and Overlay Test results at all three asphalt contents but the least rut depth was at 6.5 percent asphalt. The density results for all three asphalt contents exceeded the proposed specification values of between 70 and 74. The aggregate gradation controlled this density value, and since the aggregate is from a single fraction (or stockpile), no change in the gradation could be made, given that this type is what was available from this quarry. A goal of the research was to determine if the proposed specifications were acceptable based on field performance characteristics. So allowing a mix to be constructed that was outside of the density specifications provided additional information that may be used to validate and/or modify the specifications. An asphalt content of 6.5 percent was selected for the Eastland limestone mix.

While considered a good quality limestone, the Eastland material still did not meet TxDOT polish value requirements for a Class A in the Surface Aggregate Classification System. A Class A aggregate must also have a Los Angeles Abrasion loss of less than 30 and a Magnesium Sulfate Soundness loss of less than 20; both aggregates met these values. The final specification requirement for the fine-graded PFC required 100 percent class A aggregates. Soundness values for the Eastland and Hoban materials were:

- Eastland: LAA = 25 percent, Soundness = 13 percent.
- Hoban: LAA = 20 percent, Soundness = 10 percent.

Table 5. Mix Design Performance Test Results at Different Asphalt Contents.

Mixture Type	Asphalt Content, %	Density, %	Hamburg Results, Rut depth @ No. of cycles	Overlay Test Results		Performance Testing Outcome
				Max Load, lb	Number of Cycles to Failure	
PFC-1 Hoban Rhyolite	6.0	73.1	12.5 mm @ 4,900	336.3	402	Fail
	6.5	73.5	8.1 mm @ 10,000	367.0	450	Pass
	7.0	73.7	12.5 @ 7,000	317.0	1000	Fail
PFC-2 Eastland Limestone	6.0	76.3	9.12 @ 10,000	478.4	337	Pass
	6.5	77.8	6.29 @ 10,000	419.0	300	Pass
	7.0	78.4	8.50 @ 10,000	494.5	1000	Pass

The mixtures were placed side by side on the entry road to the facility as shown in Figure 24. Standard equipment for asphalt concrete pavement construction was used, including a material transfer vehicle, paver equipped with an infrared monitoring system, and three passes with a 13.5-ton tandem steel wheel roller operated in static mode.

Figure 24. PFC Mix on Pecos Facility Entrance Road.

Monitoring Performance

The PFC mixtures were evaluated immediately after construction for drainage characteristics using a field water flow test shown in Figure 25 (Tex 246-F). The test evaluates the time required to discharge a given volume of water channeled onto the pavement surface through a 6-inch diameter opening. The time corresponds to the water flow value (WFV) and is expressed in seconds.

Figure 25. Test Method Tex-246-F, Field Water Flow Test.

For conventional PFC mixtures, TxDOT recommends WFVs of less than 20 seconds. The Hoban PFC had an average WFV of 9 seconds while the Eastland mix had a WFV of about 27 seconds. This indicates that the higher-than-desired lab-molded density of the Eastland PFC translated to poorer drainability in the field.

TxDOT measured skid resistance on the mixtures a few days after construction. The wet skid number was measured at 50 mph using a smooth tire. Values obtained were 39 for the Hoban mix and 31 for the Eastland mix. These values are expected to increase as the asphalt on the surface is eventually worn away by traffic and weathering.

The direct tire-pavement noise was measured on each section using an on-board sound intensity (OBSI) system. The OBSI measures sound intensity at different frequencies, which can then be used to calculate an overall noise level. The Hoban PFC mix had a noise level of 100.1 dBA, and the Eastland PFC mix had a noise level of 98.7 dBA. Recent measurements made by TxDOT on eight of the conventional coarse graded PFCs using the PG 76 binder produced an average overall noise level of 102.2 dBA. The higher air voids and/or finer texture for the fine graded PFC should be contributing to the lower noise level.

Lufkin Construction Project

Researchers worked with the Maintenance Engineer of TxDOT's Lufkin District to place the experimental fine-graded PFC on an exit ramp of US 59 as shown in Figure 26. This ramp had an existing chip seal surface and a number of accidents had occurred when drivers exited too fast and skidded off the ramp while trying to make the sharp curve during wet weather. The district personnel said they were pulling vehicles out of the ditch every time it rained. None of the surfaces that the district’s maintenance personnel had tried could withstand these high shear forces exerted by traffic on the surface.

The mixture design for this project was the sandstone design presented earlier. Traffic speeds on the exit ramp prohibit skid and noise testing.

The mix held up very well during one of the hottest summers Texas has seen (over 30 consecutive days of 100°F+ temperatures in 2013) and the district was happy to report no accidents even during a 6-inch rain event. An inspection conducted six weeks after placement found the section looked identical to the day it was placed, with no flushing or closing up of the open surface. Testing performed on the mix showed that it met the specification requirements (Table 6).

Table 6. Test Results on Lufkin Fine Graded PFC Plant Mix.

	Lufkin PFC Mix Plant Sampled Material	**Lower and Upper Specification Limits**		**Additional Testing on Field Mix**
	Sandstone			Target Asphalt Content: 6.5 % Actual Asphalt Content: 6.1% Hamburg Test: 7.4 mm at 10,000 cycles Overlay Test: 356 cycles to failure Cantabro Loss: 5.4% Field Water Flow: 19 seconds (Avg. of 6 readings taken on pavement surface immediately after construction)
Sieve Size	**Cum. % Pass (Ignition Oven Sample)**			
No. 1/2	100.0	100	100	
No. 3/8	99.2	94	100	
No. 4	37.4	20	55	
No. 8	8.7	0	15	
No. 16	6.2	0	12	
No. 30	5.3	0	8	
No. 50	4.7	0	8	
No. 200	3.2	0	4	

Very Thin, Fine-Graded PFC Placed on Cloverleaf Exit Ramp of US 59 Near Lufkin District Office. Maintenance needed a mix to address the numerous wet weather accidents occurring on this ramp.

Figure 26. Cloverleaf Exit Ramp of US 59 of the TxDOT Lufkin District.

Bryan Exit Ramp PFC

The Bryan District used the fine PFC as a test section to surface the newly constructed exit ramp off SH 6 to the district office. This design was the same as that used in Lufkin, but was placed with a local Bryan contractor, Knife River. Researchers observed a similar performance to that seen in Lufkin (Figure 27).

Figure 27. Construction of the Bryan Fine PFC Exit Ramp.

Brownwood US 183 Fine PFC

The Brownwood District let the first full-scale construction project of the fine PFC. This was on US 183 just south of Breckenridge. The existing pavement was a relatively new surface treatment that was prematurely bleeding (Figure 28). Maintenance was continually treating the bleeding surface with lime water and limestone rock asphalt patches. Therefore the fine PFC was selected to resurface this roadway since the high air void content of the fine PFC could potentially accommodate the excess underlying bleeding asphalt.

The target thickness was ¾-inch and the shoulders were left unsurfaced. Researchers worked with TxDOT and contractor personnel to set roller patterns and evaluate water flow characteristics.

Figure 28. US 183 Bleeding Surface Treatment prior to PFC Surfacing.

Since there were no Class A materials available in the area, researchers wrote the specs to allow a higher quality Class B material. Local limestone aggregates were used to produce the mix, and water flow measurements taken during construction were less than 20 seconds (Figure 29).

Figure 29. Water Flow Testing on US 183 Fine PFC.

Recent discussions with the district engineer have revealed that after nine months of service, the PFC is in excellent condition and TxDOT is pleased with the performance. The surface has also given the district good public relations with the local citizens because the previous project had performed so poorly and was a source of many public complaints. Figure 30 shows the surface three months after construction.

Figure 30. US 183 PFC Three Months after Construction.

Loop 338 Odessa District

The construction of the fine PFC on Loop 338 was completed in August 2014. Based on discussions with the Odessa District personnel, their highest priority was to develop a cost-effective overlay mix that could be used to cover up badly bleeding chip seals.

Figure 31 shows the highway selected for the test section. This is on Loop 338 around Odessa and starts just north of the intersection with 87th Street. The concern is the low skid as the existing seal is badly flushed and in many locations there is free asphalt on the surface. There are no easy fixes for this problem as the free asphalt will bleed through any traditional overlay mix and quickly reappear on the surface. Based on the work at Pecos described earlier, the following two options are possible:

- Option 1. Place a high air void PFC (>20 percent air voids) so that any free asphalt will not migrate to the surface and the PFC will increase skid resistance and reduce noise.
- Option 2. Micro-mill the bleeding seal and place a thin lift of Ultra-Thin Dense mix (similar to the mix placed at Pecos).

For Loop 338, the district selected the fine PFC option. Researchers proposed that the district use the best performing PFC placed on the test track, which was the PFC made with the Grade 5 Hoban rock. This is 100 percent Grade 5 rock with 0.3 percent fibers and 6.5 percent Alon PG 76-22 asphalt.

Figure 31. Preexisting Condition for Loop 338 Odessa District.

A contract was awarded to Reece Albert Inc. to place the fine PFCs; this company did the original construction at the test track. The Loop 338 construction was completed on August 8, 2014. Figure 32 shows photos of the construction sequence.

a) Belly dump trucks with RoadTec pickup

b) One pass of two steel wheel rollers, (no backing up)

c) Sprinkling before opening the PFC to traffic

Figure 32. Construction Sequence on Loop 338.

The target lift thickness was 0.75 inches. The contractor assumed there would be some roll down, so initially the lift was placed at 1-inch thickness. However, there was little or no roll down, so the initial lift was slightly thicker than the target. No problems were experienced with the placement. The mix temperatures at the back of the lay down machine were consistent throughout the whole placement and found to be between 260° and 265°F. Only a single forward pass was made with the two rollers in non-vibratory mode. The one concern was when to open the PFC to traffic. Since PFCs have a thicker film thickness than normal mixes, there is concern that there will be problems if the mat is opened too early, especially if the heavy truck traffic stops on the mat. To cool the mat off, a single pass was made with the water truck as shown. After the mat wetting, researchers found the temperature of the surface of the PFC to be 130°F, which was deemed adequate for opening to traffic. As anticipated, as soon as the roadway was opened up, several large trucks did stop on the mat because of the construction activities. No problems were observed with any rock pickup.

To check the adequacy of the mix, researchers run the water flow test shown in Figure 33. The measured flow time was 9 seconds, which is identical to that measured at the Pecos test track. This proved that the single-pass rolling was adequate.

Figure 33. Water Flow Being Conducted on the New PFC.

Researchers anticipate that this mix will have a very good skid resistance and excellent noise characteristics. Skid and noise tests were conducted on the PFC section and on both the leading and trailing chip seal section. Skid measurements were made on the 500-ft section both before and after the PFC test section as well as on the new PFC section. The skid measurements on the existing bleeding chip seal were 6 and 7, whereas the new PFC were 29 and 30. These measurements were taken when the surfacing was new; they will be expected to increase once traffic polishes asphalt off the new PFC surface.

DESIGN RECOMMENDATIONS 3−IMPROVED MOISTURE SUSCEPTIBILITY TESTING

In January 2014, the Pharr District banned the use of PFCs on highways because of the poor performance of PFCs over the past 10 years. The major concern is raveling and the district has experienced numerous failures with its main aggregate source crushed gravel. Figure 34 shows photos of a typical raveling issue.

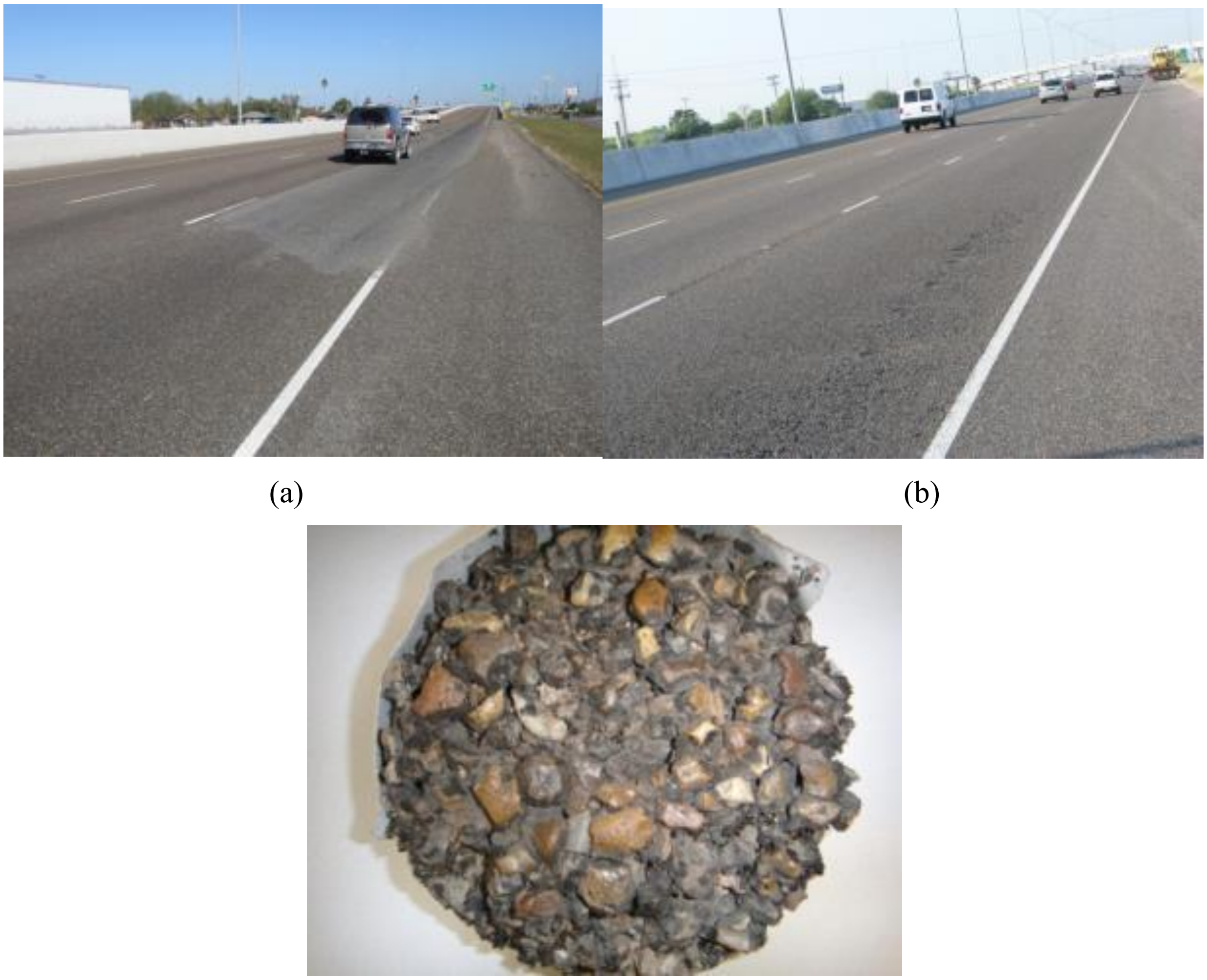

(a)
(b)
(c)

Figure 34. Raveling of a 5-Year-Old PFC on US 281 in Pharr: (a) Section North of SH 107, (b) Section between SH 495 and Trenton Road, and (c) Core Exhibiting Severe Stripping.

The concern expressed was that these mixes performed adequately for several years, but then failures occurred very suddenly and very dramatically, requiring the district to divert all maintenance funds to these specific locations. The worst raveling failures have been with AR binders, but the district has also experienced issues with gravel PFCs made with PG 76 binders.

At the time of this writing, PFCs are still banned in the Pharr District. This is somewhat surprising as Pharr with its mild winters has the best climate for long-lasting PFCs. One of the goals of this Task was to use the recommendations developed in this study to develop an improved PFC design for implementation on the Pharr District's major highways. The implementation effort is described next.

LABORATORY INVESTIGATION OF PHARR DISTRICT' S MATERIALS To provide recommendations for design of test sections for the Pharr District, researchers evaluated the following four PFC mixtures in the laboratory:

- Mixture 1 (F): Coarse PFC with 100 percent Fordyce Gravel (SAC A).
- Mixture 2 (MLs): Coarse PFC with 100 percent Matrimar Limestone (SAC B+).
- Mixture 3 (F+MLs): Coarse PFC with 50 percent Fordyce Gravel + 50 percent Matrimar Limestone.
- Mixture 4 (Fine MLs): Fine PFC with 100 percent Matrimar Limestone.

The Fordyce gravel from Showers Pit is the most commonly used aggregate type in the Pharr District. The raveled section on US 281 (Figure 34) employed this type of aggregate. The Matrimar limestone is an alternative material available in the area. Although it is classified as SAC B in the *Bituminous Rated Source Quality Catalog*, the Matrimar limestone has very good qualities, especially with regard to soundness. Mixtures 1–3 were designed as coarse PFC mixtures (PFC-C), while Mixture 4 complies with TxDOT Fine PFC gradation requirements (PFC-F). Details on all four mixes were provided earlier in Chapter 2.

Based on the results of previous tasks, researchers proposed a series of laboratory tests to identify raveling-susceptible mixtures, including:

- Cantabro Loss per Tex-245-F.
- HWTT per Tex-242-F.
- IDT Test per Tex-226-F.

Cantabro Loss and IDT were done on specimens with and without moisture conditioning. Based on the recommendations from Task 3 and Task 5, researchers used the MIST equipment to subject the PFC specimens to moisture conditioning under the following test conditions:

- 40 psi (75 psi).
- 140°F (60°C).
- 1000 test cycles.

Cantabro Loss

Figure 35 shows both dry and MIST-conditioned Cantabro Loss results. In the figure, each bar represents the average of three values (except for Mixture 3 that had only two values). The error bar spans ± 1 standard deviation from the average value. The values over the MIST results represent the relative difference between the average dry and average MIST results. An Analysis of Variance (ANOVA) with a significance level of 5 percent showed that the relative differences for Mixtures 1 and 2 were statistical significant (highlighted in gray in Figure 35). Mixtures 3 and 4 had also had important differences between the MIST and dry values; although they were not statistical significant, they are considered practically different.

Cantabro Loss is currently included in TxDOT Special Specification #3269 with a limit of 20 percent. All four mixtures had less than 20 percent dry Cantabro loss. The Cantabro loss after MIST was above 30 percent only for Mixture 1. Mixtures 2 and 4, that employed 100 percent of the Matrimar limestone, had the lowest values both dry and after MIST. Mixture 4, the PFC-F with 100 percent Matrimar limestone, had the best performance as compared to the other three mixtures.

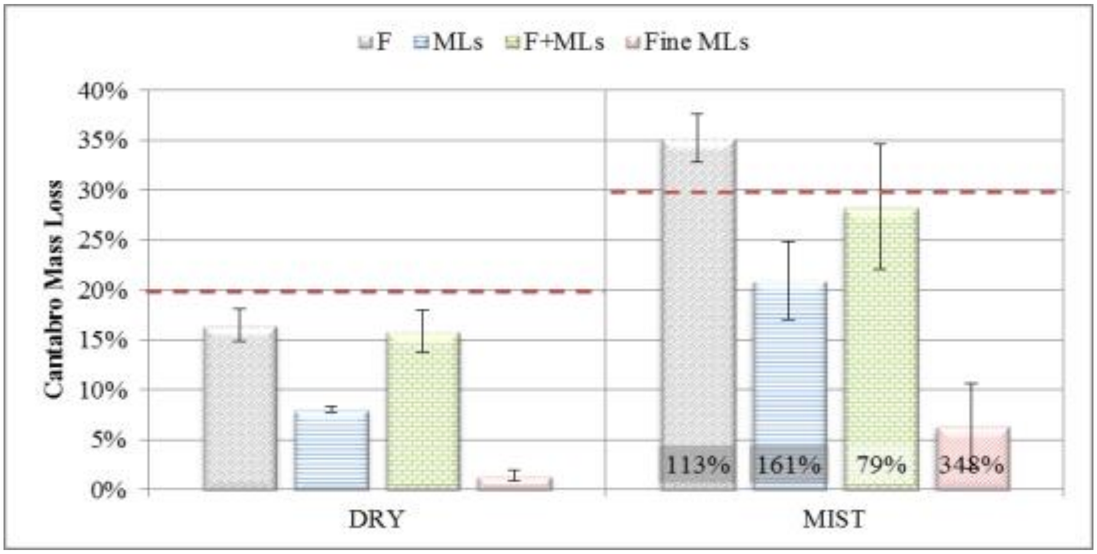


Figure 35. Cantabro Loss for Dry and MIST-Conditioned Specimens.

Hamburg Wheel Tracking Test

HWTT is a common test procedure that TxDOT used to determine mixture susceptibility to rutting and moisture damage. A minimum requirement of 10,000 load cycles to 12.5 mm rut depth is now part of the Special Specification # 3269 for PFC-F.

Figure 36 shows the HWTT results for the four mixtures. In the figure, each bar represents the average of two replicate results. The results indicate that Mixtures 1 and 4 are susceptible to rutting and stripping. The other two mixtures exceeded 10,000 cycles before failure. Mixture 3 had the best performance, lasting 20,000 cycles before failure and showing no signs of stripping. Mixture 2 also had an acceptable performance. Mixture 4, however, demonstrated the worse performance of all four mixtures with less than 2,000 cycles to 12.5 mm rut depth. Visual observation of Mixture 4 after testing showed no clear signs of stripping as shown in Figure 37.

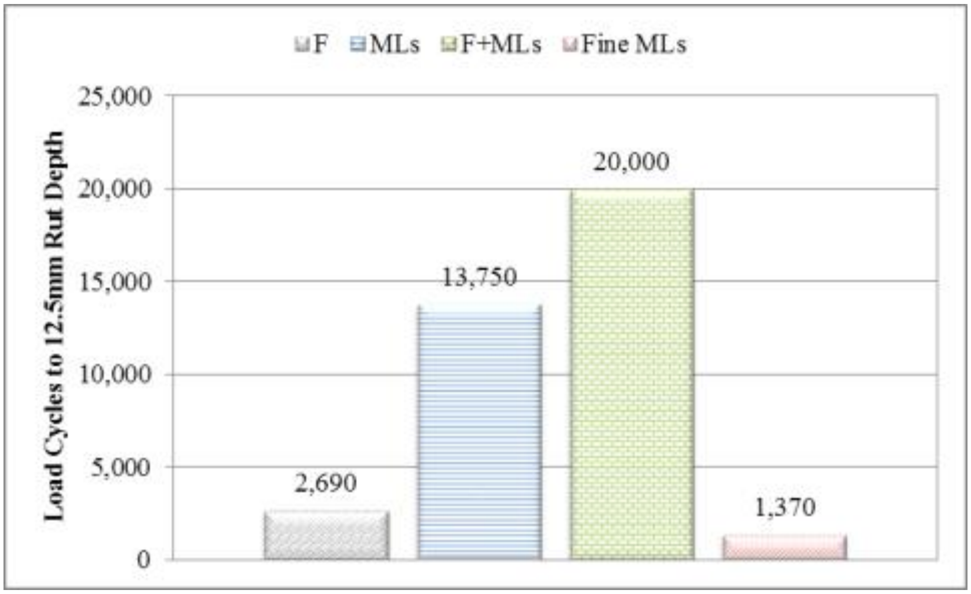


Figure 36. HWTT Number of Load Cycles to Failure and Stripping for the PFC Mixtures.

Figure 37. HWTT Specimen Showing Excessive Rutting and Minimal Stripping.

Indirect Tensile Strength

Figure 38 shows the IDT results. In the figure, each bar represents the average of two (in the case of Mixtures 1 and 3) or three values (in the case of Mixtures 2 and 4). The error bars span ± 1 standard deviation from the average value. The values over the MIST results represent the relative difference between the average dry and average MIST results. Based on an ANOVA with a significance level of 5 percent, the only values that showed a statistical difference are highlighted in gray in Figure 39 (i.e., Mixtures 2 and 4). These correspond to the mixtures with 100 percent Matrimar limestone, both coarse and fine gradation. However, all MIST IDT strength values were within 10 percent of the dry IDT strength values, and therefore the relative differences could be considered practically insignificant.

Overall, most of the IDT strength values for the PFC-C mixtures were acceptable and not considerably affected by the conditioning procedure (MIST values within 10 percent of the dry values).However, the PFC-F mixture (i.e., Mixture 4) showed significantly lower dry IDT strength values (less than 30 psi) compared to the other three mixtures (i.e., Mixtures 1–3).

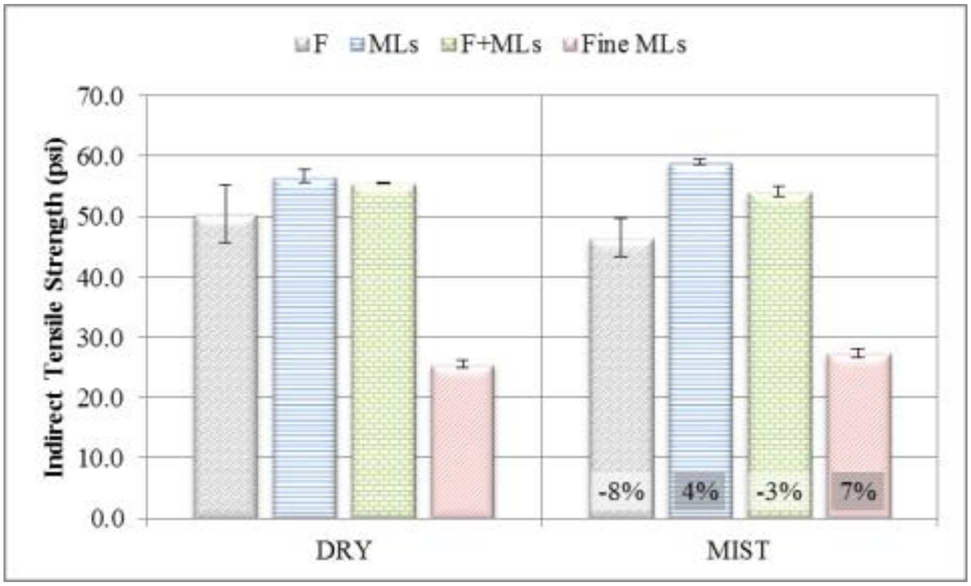


Figure 38. Indirect Tensile Strength Results for Dry and MIST-Conditioned Specimens.

Figure 39 shows the TSR. Usually a TSR value ≥ 80 percent is considered acceptable in terms of moisture susceptibility. The TSR values for all mixtures were above this threshold. As previously noted in the Technical Memorandum for Task 5 and confirmed with these results, the IDT test is not recommended for PFC performance evaluation.

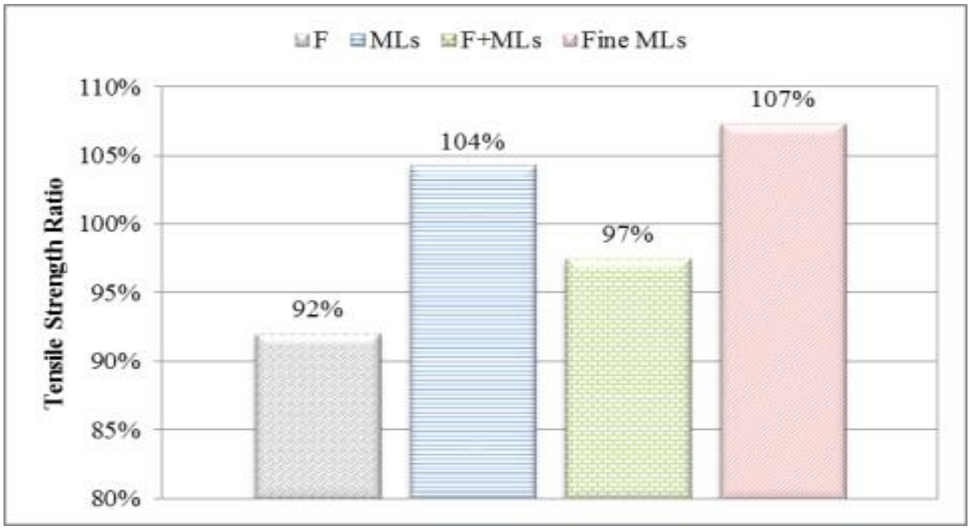


Figure 39. TSR Results.

FINAL RECOMMENDATION TO PHARR DISTRICT

Based on the results presented in this section, the research team recommends that the Pharr District should build PFC test sections with the Matrimar crushed limestone; this is Mixture 3 in Table 2 presented earlier. Using the lab testing results, researchers believe this material will be a better performer than the current gravel mixes that use either the AR or PG 76-22 binder. Currently, the Pharr District has not used the Matrimar crushed limestone in their PFCs.

The AR mix used in the past raveled badly and lasted only 526 passes in the HWTT. Table 7 shows a direct comparison of the lab performance of the gravel versus limestone mixes, this being with a locally available PG 76-22 asphalt. The limestone PFC has better performance in both the Hamburg and wet/dry Cantabro, indicating that it is potentially a better mix and less susceptible to raveling.

Table 7. Superior Lab Performance of Limestone-Based PFC with Pharr District Materials.

Test Parameter	Fordyce 7.0% PG 76-22 Binder	Matrimar 7.1% PG 76-22 Binder
Hamburg Load Cycles to Failure	2,690	13,750
Cantabro Loss (%) Dry	16.5	8.0
Cantabro Loss (%) after Moisture Conditioning	35.2	21.0
IDT (psi)	50.5	56.7

The one requirement that the district must waive to make this happen is the need to use only SAC A materials on major roadways. The gravel is an SAC A and the limestone is an SAB B from the rated source catalog. However, it must be recalled that the Matrimar is one of the best limestone available in Texas; it has an LAA loss of 25 and a soundness value of 3. (The soundness value of the Fordyce gravel is 4 percent.) In TxDOT study 0-5836, the performance of PFCs in Texas was tracked over several years and at least two of the sections were comprised of 100 percent SAC B aggregate (US 59 in Yoakum is 5 years old, and IH 20 in Abilene is 7 years old). These PFCs performed very well in terms of durability and functionality. Their long-term skid resistance, however, was not as good as that of the SAC A PFCs. The Brownwood District recently constructed one of the fine PFCs in 2012 using 100 percent limestone on US 183, and it is also performing well. Note that the limestone used in Yoakum and Abilene was inferior to the Matrimar materials.

If the district wishes to pursue this option but is concerned about long-term skid resistance, TTI would be happy to conduct some laboratory skid measurements with the wheel track polishing shown below in Figure 40. In this test, researchers made 100,000 passes of a loaded wheel under wet conditions over test slabs, and measured the skid resistance periodically with the Dynamic friction tester shown below. Comparative tests could be conducted on the existing gravel and proposed limestone PFCs.

Figure 40. TTI's Lab Polishing and Skid Resistance Measuring Systems.

CHAPTER 4. FIELD MEASUREMENTS OF SPLASH AND SPRAY

INTRODUCTION

In Task 6 of Project 0-6741, the research team developed the following two devices for measuring the amount of splash and spray generated as a vehicle moves over a pavement. These two devices are described in this chapter.

- Splash and Spray catcher (matches and weighs amount of water).
- Automated Video Logging System (captures high-definition images and advanced image processing techniques).

The Splash and Spray system works. It is described in the next section and some sample data are presented. It does quantify the amount of water and spray generated from a roadway, but it has many limitations. After this initial evaluation, the research team decided to focus attention on the automated video logging system. This system has an onboard water supply system, and has the potential to collect data on long projects and identify draining and non-draining areas. Future work should focus on improving the automated system.

SPLASH AND SPRAY CATCHER

This section documents the development and initial testing of the prototype equipment for measuring the amount of splash and spray. This system provides a direct measurement of the amount of water that the tires of the test vehicle picked up and sprayed onto a catch basin. Figure 41 shows the prototype equipment on which the initial tests were conducted.

Figure 41. Prototype Splash and Spray Catcher.

As shown in Figure 41, the splash and spray catcher is mounted at the back of the test vehicle, where it catches the water that the truck's rear tires picked up and sprayed. A metal screen running along the width of the prototype minimizes the water backsplash during testing. The catcher is supported on the black-painted steel frame that is bolted to the bed of the test vehicle. The frame permits the operator to adjust the height of the catcher above the ground. After a test run, water in the catcher was drained into a pan for determination of weight and volume. The vehicle mud guard shown in the picture was removed prior to testing.

There is also a video camera to capture videos of test runs, and a light-emitting diode light bar for illumination. The video frames are tied to distance from the start of the test run using an encoder mounted with the camera and hooked up to the vehicle transmission. As shown in Figure 41, the camera is attached to a wooden frame, which is also bolted to the bed of the test vehicle. The type of camera used for testing is meant for underwater filming, so it is specifically suited for measuring splash and spray.

Initial Testing

Initial tests were conducted along a new test track consisting of PFC and chip seal sections. This test track was constructed for testing inertial profilers on a recent TxDOT implementation project. For the initial tests conducted on the prototype splash and spray catcher, researchers collected measurements on two segments of the PFC test section. Based on observations of water ponding along the PFC section during rain events, the segment located between stations 390 to 410 exhibits a higher tendency to pond water than the other segment located between stations 555 and 575. Thus, the research team wanted to check whether the test data would reflect this difference at these locations.

To wet the test segment, researchers set up the water delivery system shown in Figure 42 along the edge of the adjacent concrete pavement. This sprinkler system consists of two 2-inch diameter by 10-ft long PVC pipes with holes drilled along the length of each pipe. The pipes are connected to a water meter, which in turn is attached to a 50-ft water hose connected to a 6000-gallon water truck. For these initial tests, the research team borrowed a water meter from another TTI division. Unfortunately, the water meter worked only briefly during the day of testing. Researchers observed water leaking from the meter, which probably diminished the flow necessary to make the meter work. As a surrogate for monitoring the volume of water discharged to the pavement, the research team recorded the wetting time for each test.

Researchers turned on the water valve at the truck, and allowed water to run through the pipes and into the test lane. As shown in Figure 42, researchers wetted the test segment over its width. The wetting time took approximately two minutes. The team then made test runs at different times after turning off the water supply, and determined the volume of water collected in the catcher basin from each run. All runs were made at 30 mph.

Figure 42. Test Setup between Stations 390 to 410.

Figure 43 shows the water volumes determined from test runs at three different times on the segment located between stations 390 to 410. As expected, the highest volume of water (about 5.7 liters) was measured close to the time when the water was turned off. At 21 minutes after this event, the water volume was less than the first reading, indicating possible water loss by drainage from the segment. However, the third reading (4.3 liters) is about the same as the second, reflecting the observed water ponding at this location.

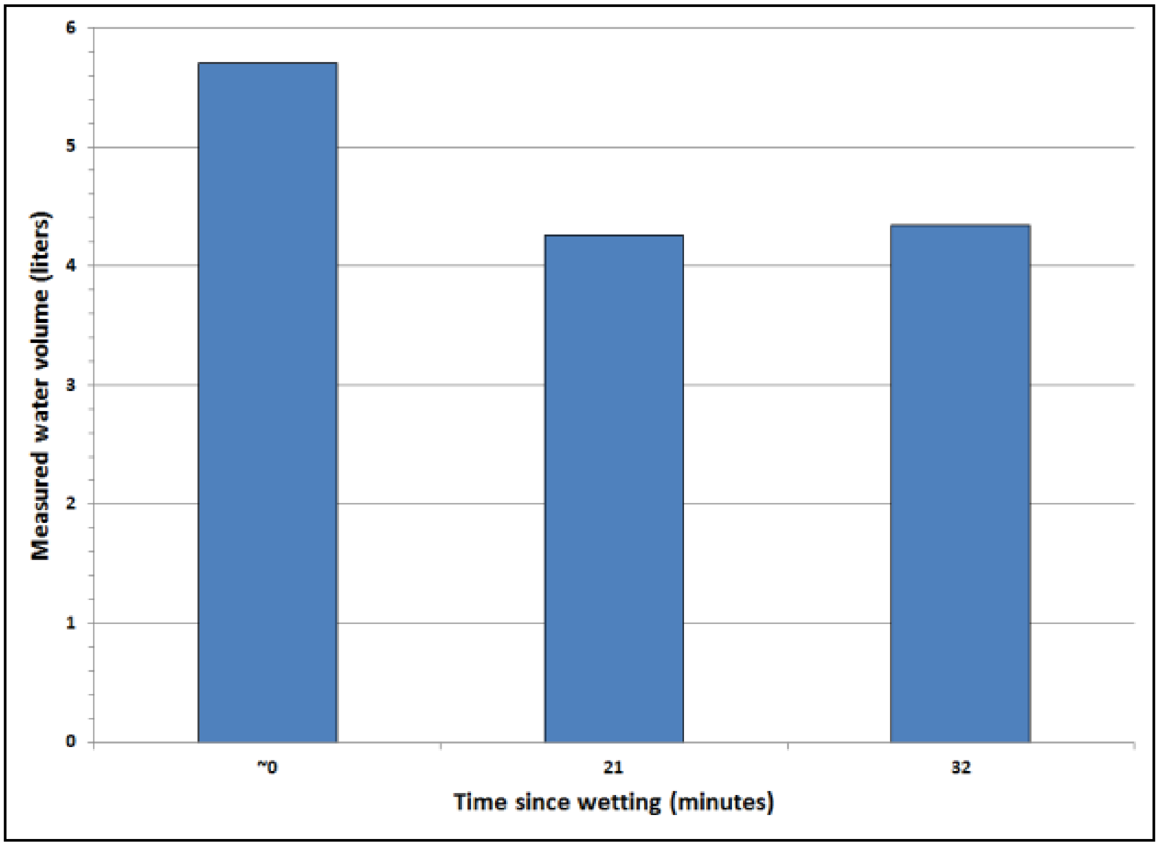


Figure 43. Measured Water Volumes between Stations 390 to 410.

Researchers also conducted a similar test on the PFC segment between stations 555 and 575. The research team moved the water truck along with the other test equipment to this location, and set up the water delivery system similar to the previous test. Figure 44 shows the measured water volumes from the two test runs made at this location. Again, researchers observed that the highest water volume of 2.4 liters was measured close to the time when water was turned off. However, only 0.2 liters of water was collected after the second run, which occurred about 7 minutes from the first test. These results along with those shown earlier in Figure 43 were consistent with the observed difference in water ponding between the two PFC test segments.

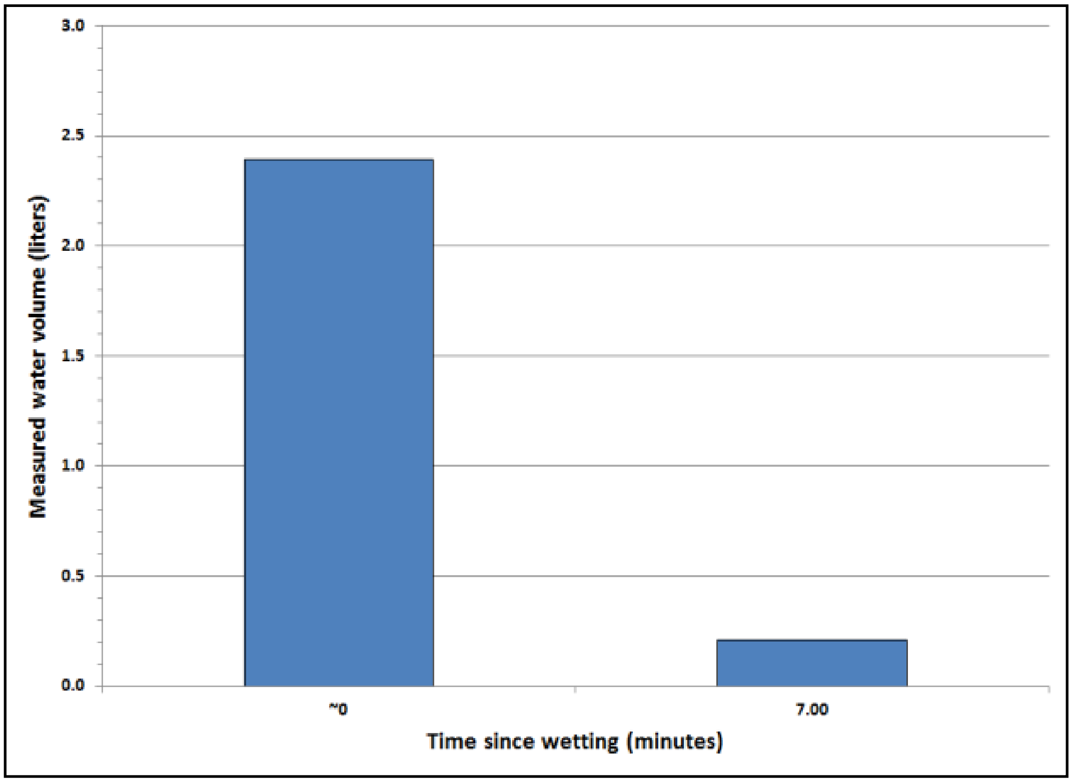


Figure 44. Measured Water Volumes between Stations 555 to 575.

Researchers made a third series of tests on the same PFC segment, but this time they collected measurements along the west wheel path of the PFC segment located between stations 555 and 575. The team set up the water delivery system to sprinkle water along the west wheel path as illustrated in Figure 45. While this setup directed most of the water along the test wheel path, water eventually found its way along the east wheel path, which influenced the measurements. In addition, the east wheel path got wet due to residual water draining from the pipe after researchers turned off the water supply.

To simulate the effect of different surface permeabilities or the length of time allowed for water to permeate through the surface, the test series included runs where the water supply at the test segment was turned off at each of three distance intervals between the test vehicle and the test segment. The farther the test vehicle was from the test location when the water supply was turned off, the more time it took for the vehicle to reach that location. Consequently, water would have more time to permeate through the surface so that less volume is collected from the splash and spray catcher when the vehicle passed the test segment. Conversely, the closer the test vehicle was to the test location when the water supply was turned off, the more standing water would be present on the surface, and the greater volume of water would be collected.

Prior to each run, the driver would park the test vehicle at station 1590 as shown in Figure 45. The driver would stay at that location while other researchers prepared the test segment for the upcoming run. Preparations included wetting the west wheel path until water covered most of that wheel path, and sweeping water away from the east wheel path. Note that any water along the east wheel path was collected onto the spray catcher on any given run.

Figure 45. West Wheel Path Wetted prior to Test Run between Stations 555 and 575.

When the test location was ready, a researcher signaled for the driver to start his test run. Exactly when this signal was given required some timing so as to have about the same wetting time for all test runs. As will be shown shortly, the wetting time ranged from 3.43 to 3.81 minutes with an average of 3.57 minutes and a coefficient of variation of 3.75 percent. Note that differences in wetting times introduce variability in the test measurements. Figure 46 shows the measurements of splash and spray at different times since wetting. The data plotted in this chart are also given in Table 8, where the following information is given:

- Station—the approximate location of the test vehicle when the water supply was turned off. The station gives the distance (in feet) from the south end of the PFC-chip seal test track.
- Wetting time—the duration (in seconds) between the time the water supply was turned on and the time it was turned off. A longer wetting time means more water discharged at the test location for a given run. Researchers used wetting time as a surrogate variable for the amount of water discharged to the test pavement since the water meter was non-functional during the day of testing.
- Time since wetting—the duration (in seconds) between the time the water supply was turned off (about the time the test vehicle passed the given station), and the time the same vehicle passed the test segment. Time since wetting is computed as the ratio of the distance between the given station and the test location over the speed of the test vehicle (30 mph or 44 ft/sec).
- Run—stands for run number.

- Volume—quantity of water collected. At the end of each run, researchers drained the water from the splash and spray catcher into a pan, which was then weighed on a portable scale. This measurement gave the weight of the water and pan. The weight of water collected was then determined by subtracting the weight of the pan from this measurement. Researchers computed the volume of water collected by dividing the weight of water by its unit weight (8.34 lb/gal).

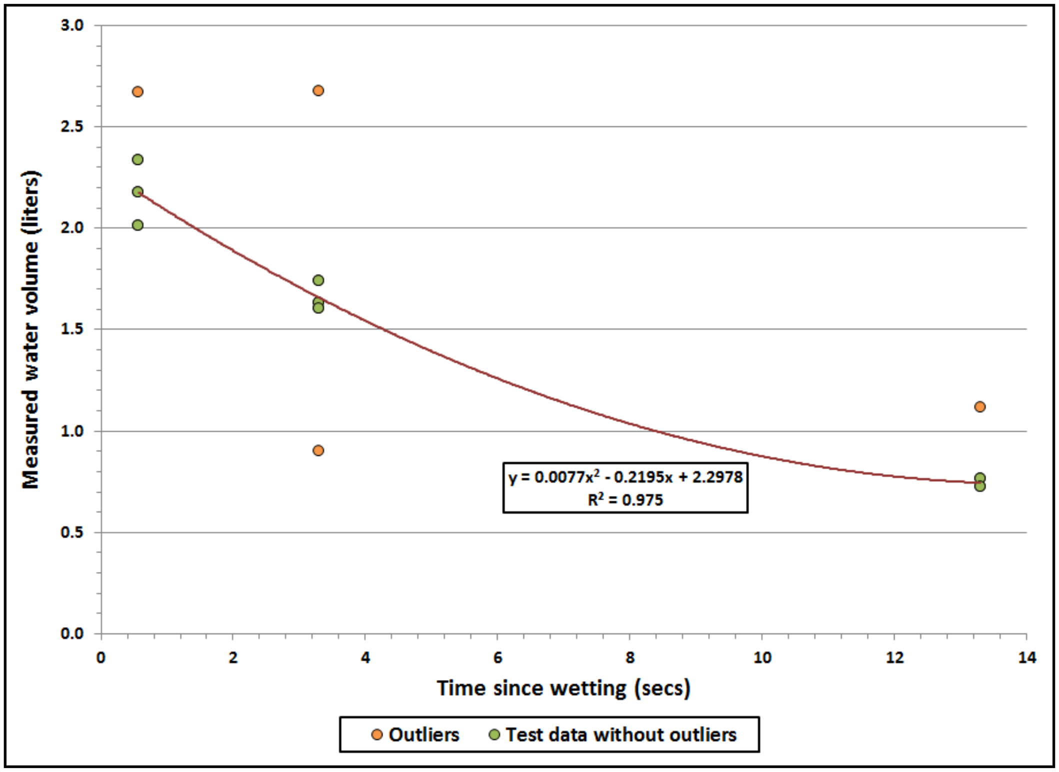


Figure 46. Measured Water Volume vs. Time since Wetting.

Table 8. Splash and Spray Measurement Data on West Wheel Path Section.

Station	Run	Wetting Time (min)	Time Since Wetting (sec)	Volume (liter)[1]
590	1	3.43	0.57	2.337
590	2	3.73	0.57	2.672
590	3	3.47	0.57	2.176
590	4	3.49	0.57	2.014
710	1	3.50	3.30	1.739
710	2	3.49	3.30	2.675
710	3	3.70	3.30	0.902
710	4	3.73	3.30	1.634
710	5	3.53	3.30	1.603
1150	1	3.44	13.30	1.115
1150	2	3.50	13.30	0.763
1150	3	3.81	13.30	0.726

[1] Shaded cells indicate possible outliers.

Figure 46 shows possible outliers in the test measurements, which are identified by the orange dots. Variability in the test measurements come from a number of factors that include the following:

- Variations in the amount of water present along the east wheel path that got collected onto the splash and spray catcher.
- Timing errors that introduce variations in wetting times, as noted previously.
- Variations in the timing of water cutoff that introduce differences in time since wetting between runs. These errors may be further attributed to:
    - Variations in the arrival time of the test vehicle at the given station.
    - Differences in when this event is called to signal the water cutoff.
    - Variations in water cutoff. To explain this, the technician first turned off the water supply by constricting the water hose, after which he turned the water valve off. Constricting the water hose permitted a rapid cutoff. However, this required the technician to hold the constriction while turning the water valve off. There were some instances when the pressure on the hose was momentarily released, allowing water to spray onto the pavement before the valve was completely shut off.
- Variations in drainage of water on the PFC surface.

In spite of the above sources of variability, Figure 46 shows a distinct inverse relationship between the amount of water collected and the time since wetting. This observation agrees with what is to be expected. In addition, for each level of the independent variable, there are repeat measurements (identified by the green dots) that show reasonable agreement. A second-degree polynomial fitted through these points yields an R^2 of 97.5 percent. These observations suggest that the method tested in this task for measuring splash and spray is conceptually sound. However, improvements in the prototype are needed to reduce the effect of factors that affect the measurements, and to render the equipment more suitable for field measurements.

Conclusions and Recommendations for the Catcher-Based System

The system described will catch and quantify the amount of splash and spray generated by any road surface, but it has the following limitations:

- It requires a complete lane closure and a method of wetting the pavement artificially.
- The results are highly dependent on the time between wetting and conducting the test.
- It is slow and cannot be used on a continuous basis.
- The system also picks up much roadway debris (stone, sand, etc.).

Many improvements were recommended for this system; however, the research team felt it was better to focus attention on a more automated setup with an onboard water supply system. The proposed system is described in the following section.

AUTOMATED SPLASH SPRAY VIDEO LOGGING SYSTEM

Figure 47 shows the components and a photo of the developed video logging splash spray system.

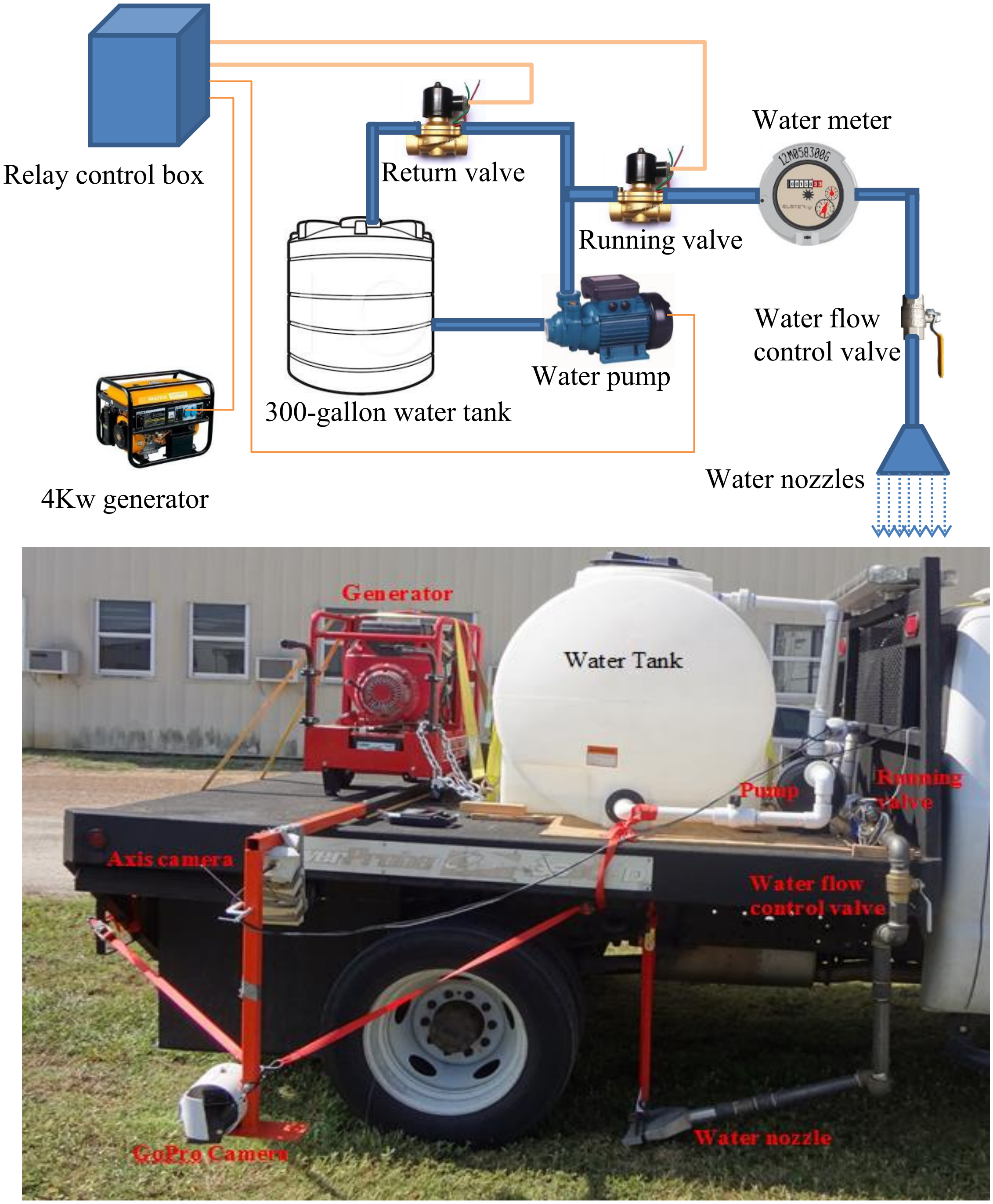


Figure 47. Automated Splash Spray Measuring System Developed in Project 0-6741.

The important components are shown below. Figure 48 shows the water nozzle. This is the same nozzle used on a TxDOT skid truck and it does distribute a uniform flow of water onto the pavement. Figure 49 and Figure 50 present the schematic of the system operation. The blackboard and lighting are added for enhancing the contrast to clearly see the water spray.

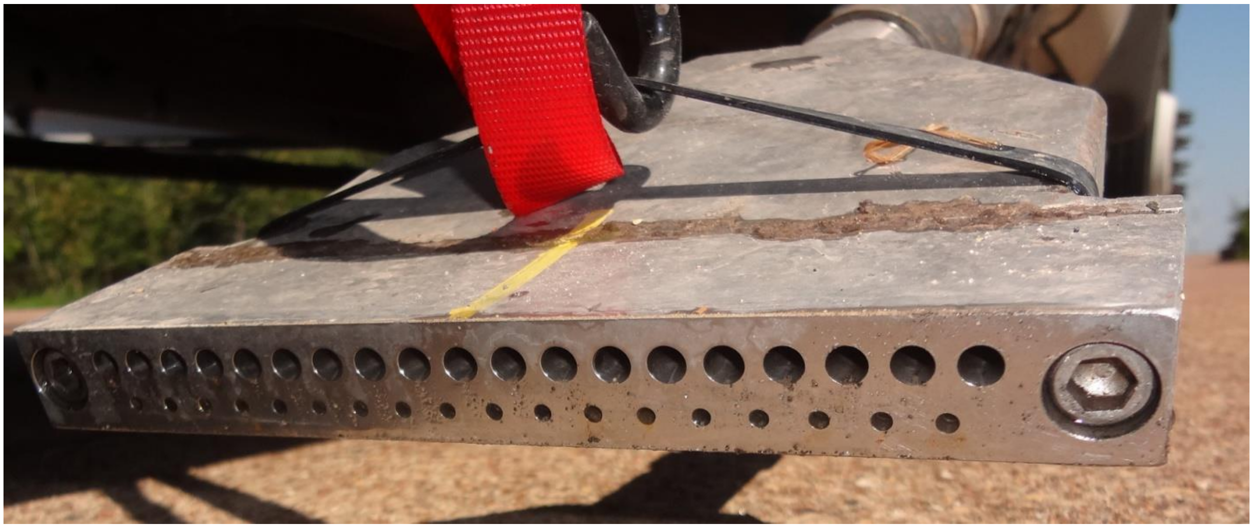


Figure 48. Water Nozzle.

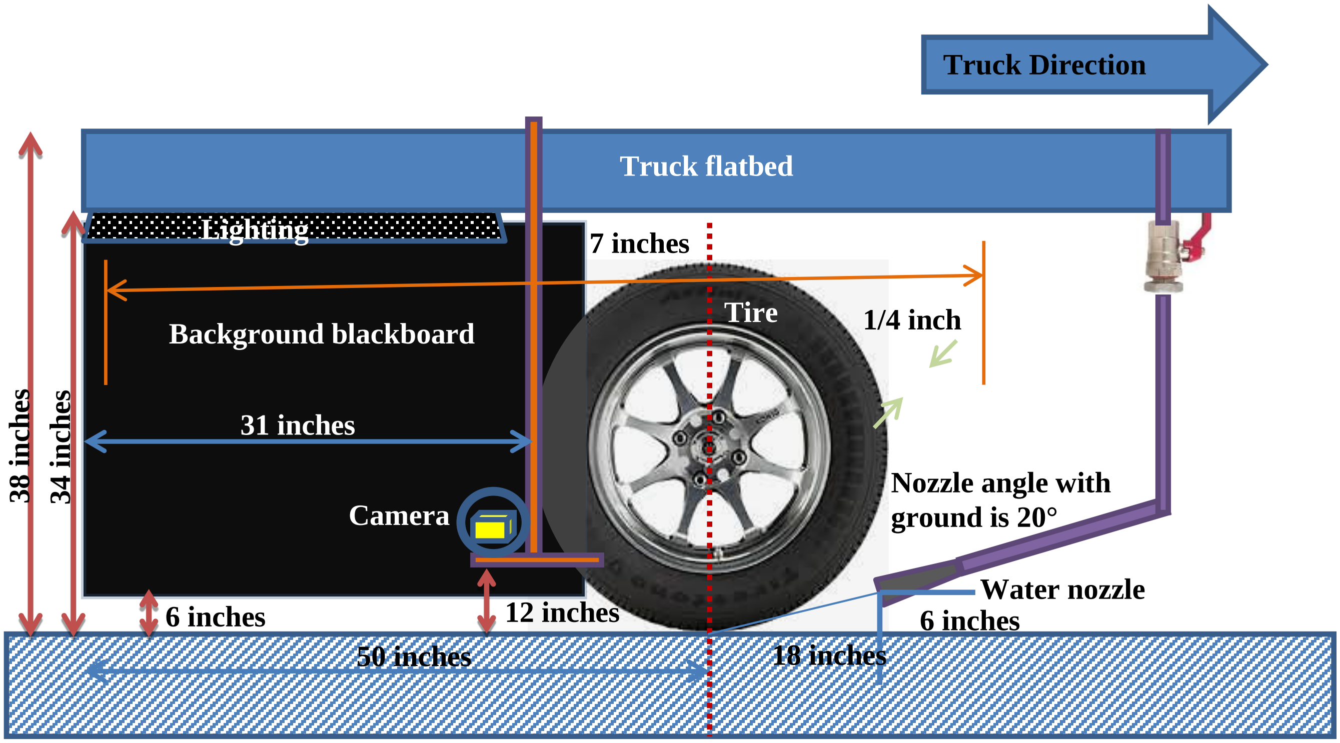


Figure 49. Splash Test Truck Camera Arrangement and Dimension (Side View).

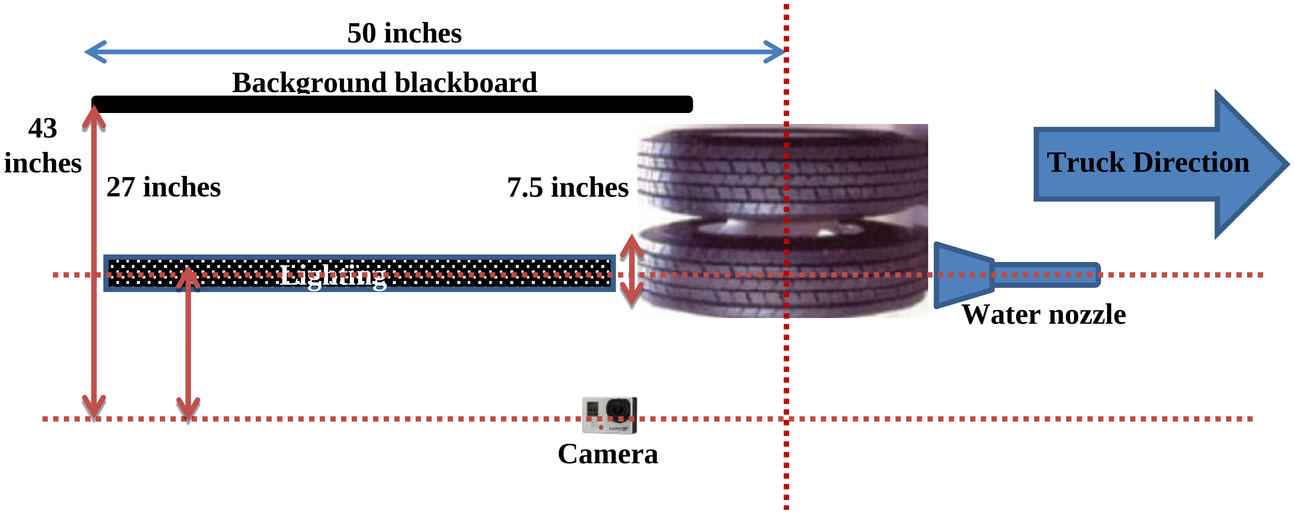


Figure 50. Splash Test Truck Camera Arrangement and Dimension (Top View).

After much trial and error, researchers determined that the optimum location of the camera housing is 27 inches from the center of the tires. The distance from the camera to the blackboard is 43 inches. For this setup, the camera must have a very wide angle to capture an area of 100 inches×40 inches for a distance of 43 inches.

CAMERA AND CAMERA MOUNT

The selection of the optimum camera system and the housing design is critical to the success of this system. The following were major considerations in the selection of the camera:

- Must have a wide angle of view to capture the whole frame of an area measuring 100 inches×43 inches with a distance of 43 inches, which requires that the camera must have at least a horizontal angle of 100 degrees, and a vertical angle of 53 degrees.
- Based on researchers' estimation, the camera must have a shutter speed of 1/5000 second.
- The camera size must be small and light. Big cameras will need extra protection and a major mount effort to reduce unwanted vibration.
- Camera must handle low light conditions and high contrast lighting conditions.
- A large resolution (at least full high definition with a resolution of 1920×1080) and a high frame rate are required. For the 50 mph driving speed, if researchers use 48 frames per second, that means each frame or photo covers a distance of 1.5 ft.
- The camera must have a long distance remote controller. The operator sits inside the vehicle and can fully operate the camera with this item.

Based on the above requirements, the research team selected the GoPro® Hero 3+. The critical features of this camera are:

- The horizontal angle range is 55~142 degrees, and the vertical angle is 28~61 degrees.
- The GoPro Hero3+'s shutter speed's range is ½ to 1/8192 second.
- The camera's size is 2.25×1.5×1.125 inches, and weighs only 4.8 oz.

- The GoPro camera automatically adjusts frame rates according to lighting conditions for enhanced low-light performance.
- The camera offers multiple image size options, with a maximum resolution of 4K (3840×3640). At this resolution, the frame rate is 15 fps, which is too slow for capturing the splash. If the researchers use 1440P (1920×1440), the frame rate can be 48 fps; if they use 1080p (1920×1080), the rate can be 60 fps.
- The GoPro camera uses Wi-Fi™ to fully control the camera within a range of up to 600 ft (or 180 meters) in optimal conditions. This camera also has a smart phone app to serve as a remote controller.

Figure 51 shows the camera on the housing that the research team developed to reduce vibration.

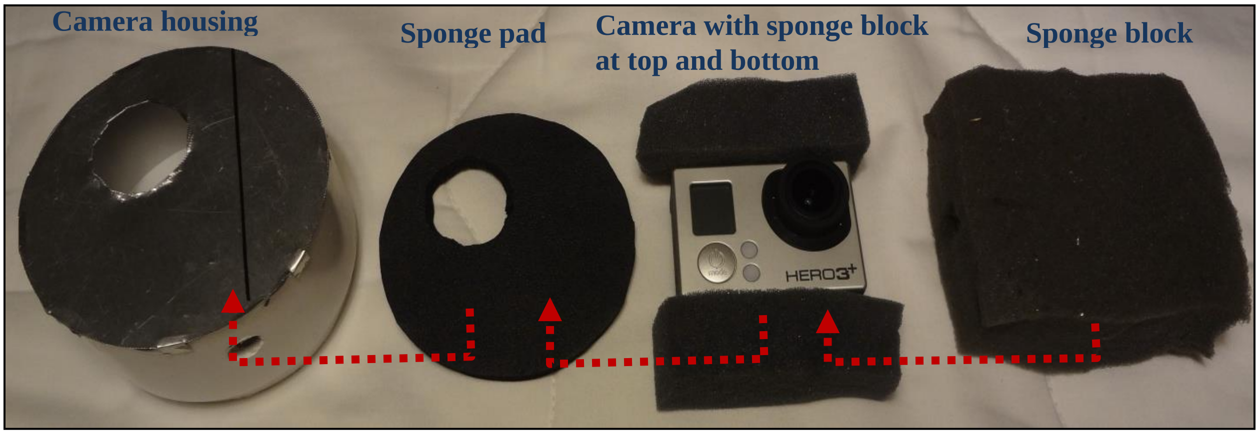


Figure 51. High-Definition GoPro Hero 3+ Camera in Designed Housing.

The next major consideration is how to mount the camera and ensure that the lens does not get completely covered with the water splash generated from the pavement. For that, Dr. Wenting Liu developed an innovative camera housing that funnels air from the movement of the vehicle, past the camera housing to force water away from the camera lens. Figure 52 shows the camera housing. The curved plastic attachment at the rear of the housing directs a stream of air past the camera and forces the water droplets away from the camera lens. Figure 53 shows the final operational unit.

Figure 52. Splash Protect Cover’s Back View (Extra Wing Will Force the Air to Clean the Lens).

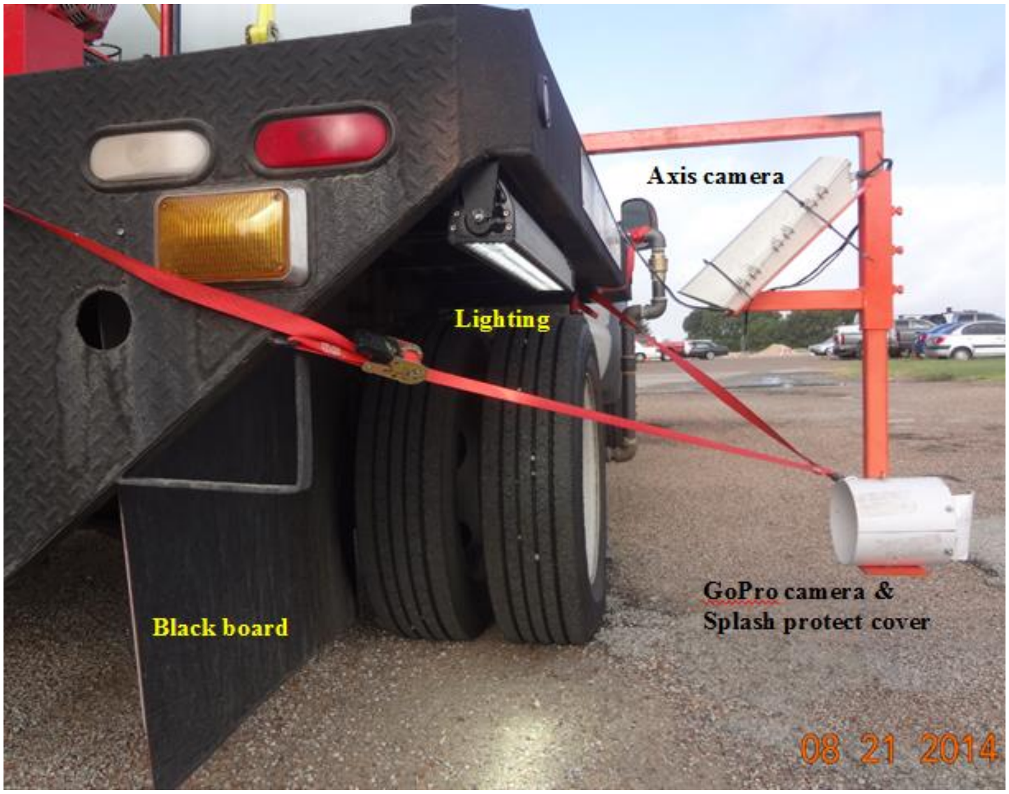


Figure 53. Final Arrangement for the Splash Spray Monitoring System.

SPLASH AND SPRAY DATA ACQUISITION

The next component that the automated system requires is a data acquisition system. The system must have the following capabilities:

- Control the pump and the running valve to start the splash.
- Record test location using a Global Positioning System (GPS) and distance traveled using a Distance Monitoring Instrument (DMI).
- Monitor water flow rate and number of gallons used.
- Capture high-definition images that the data interpretation algorithms will use.

Figure 54 shows the components of the data acquisition system; the data acquisition card's analog input is used to get the flow rate from water meter's voltage output. The distance encoder's voltage output is hooked up to the data acquisition laptop's analog port to get the travel distance.

The two digital output ports are used to control two valves (by relay circuit): one valve is used to control the pump, and another one is used to control turning on the splash.

The Axis® high-definition camera is used to capture the video, and a GPS is hooked up with the computer's COM port to record the GPS information.

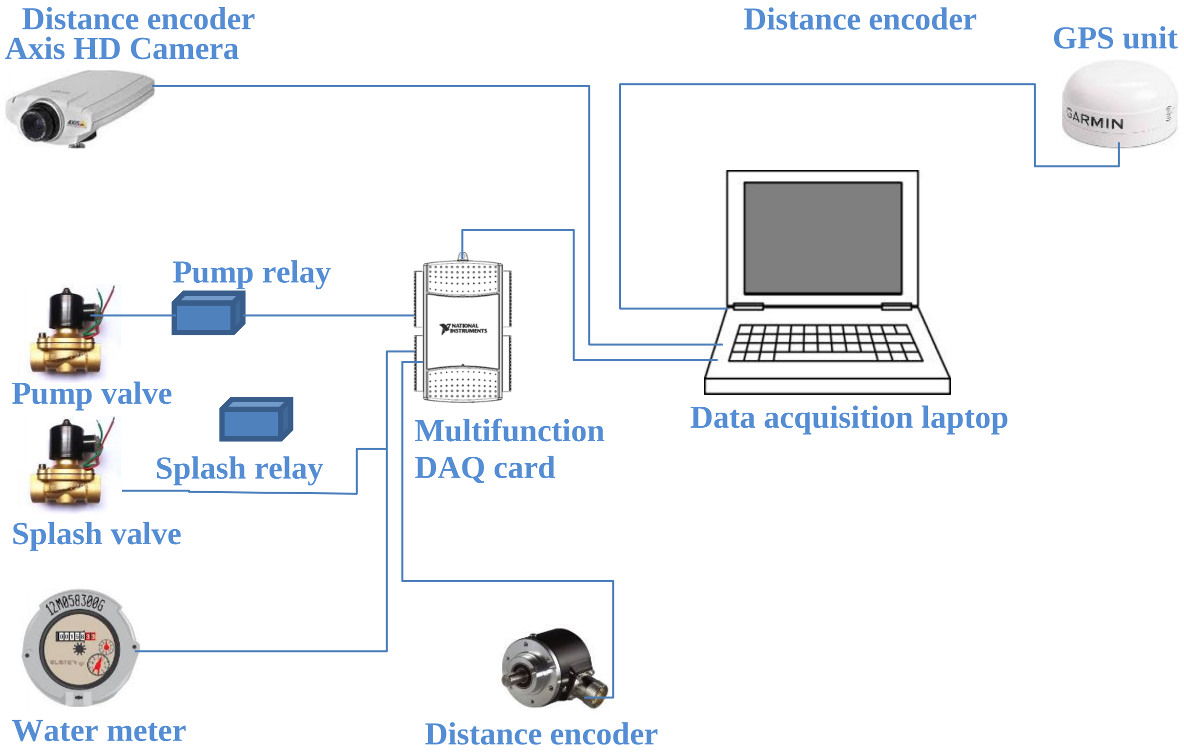


Figure 54. The Splash Spray Data Acquisition System.

The data acquisition components are housed in a box on the bed of the truck as shown in Figure 55. The operator controls the system using a laptop computer while seated in the passenger seat of the truck.

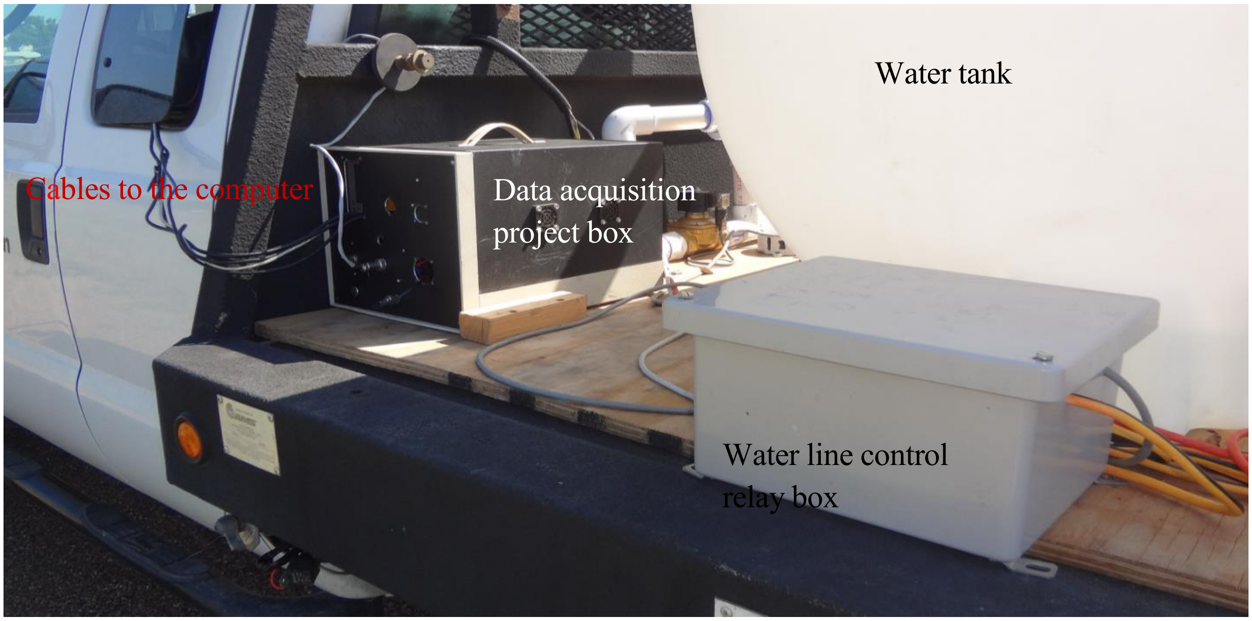


Figure 55. Data Acquisition Project Box and Water Line Control Relay Box.

A dedicated data acquisition software package was written for this application; the main screen from this system is shown in Figure 56. The system was field-tested on PFC projects at TTI's Riverside Campus and in the Bryan District in summer 2014.

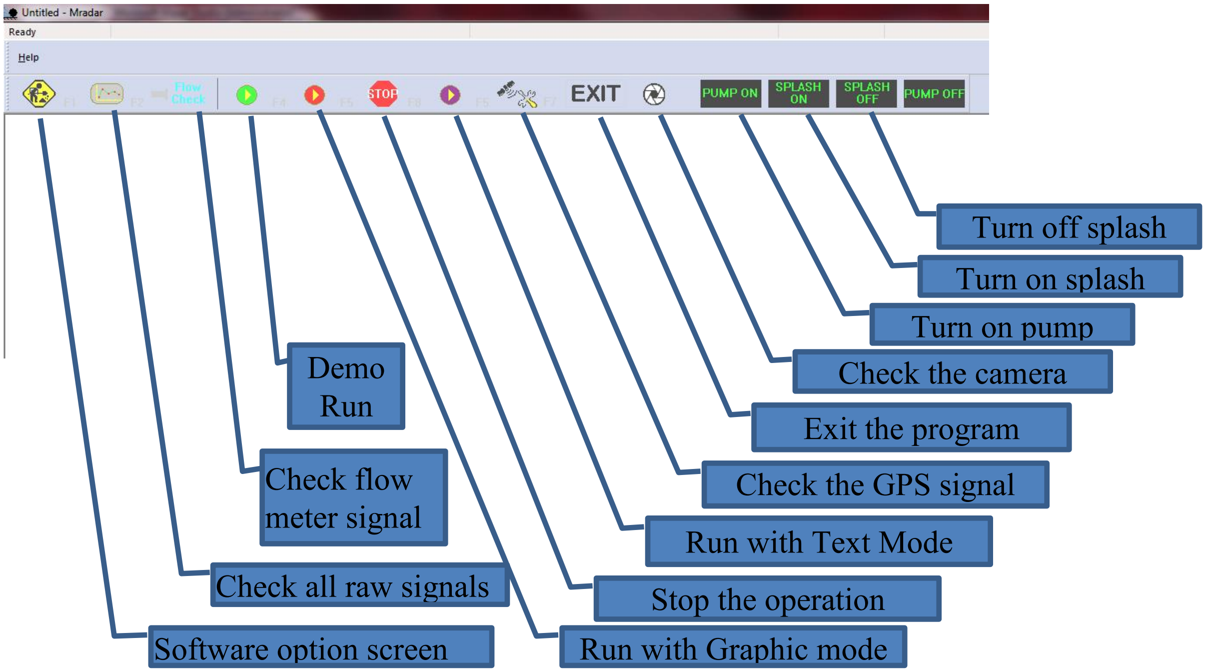


Figure 56. The Interface of the Splash Spray Data Acquisition System.

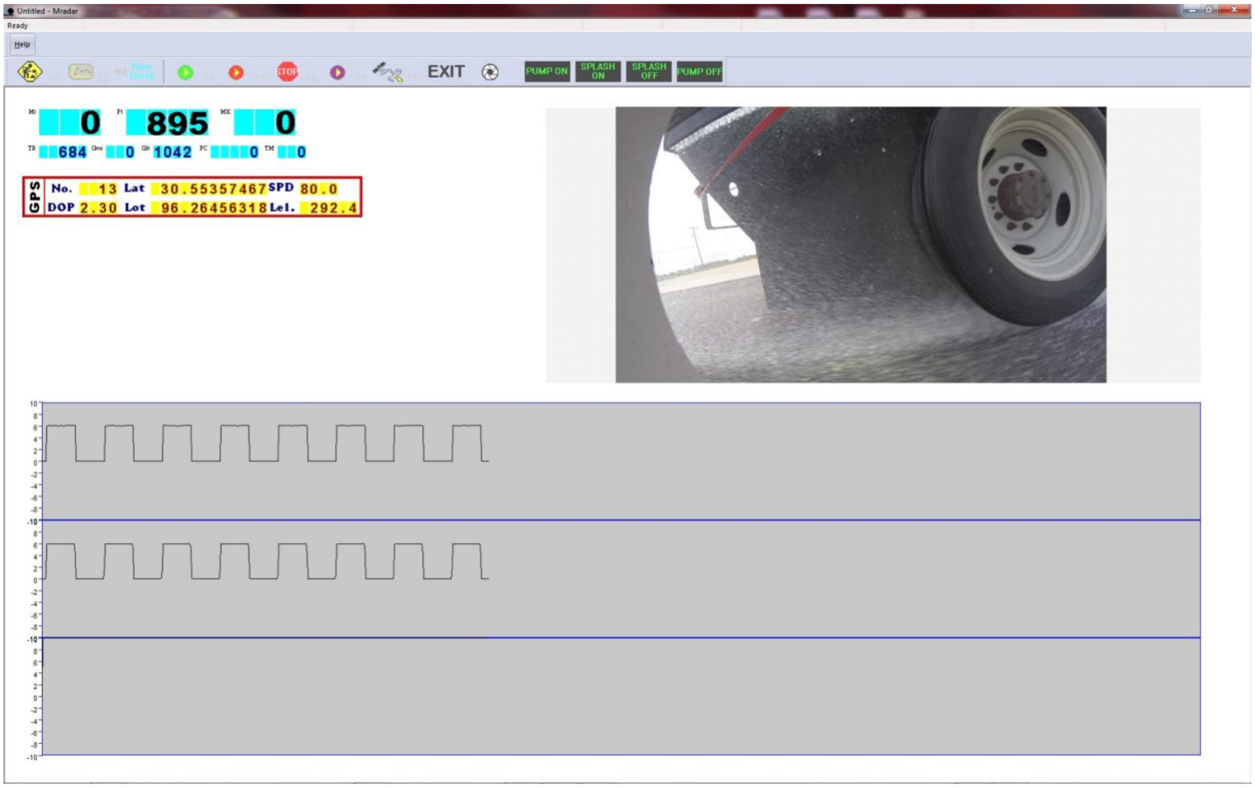
From Figure 56, the F1 button is for setup test options, and the F7, , Flow Check buttons are for checking the GPS, camera, and water flow rate status, respectively. The F2 button is used to check the raw analog signal; most of the time, it is used for debugging the hardware problems. The F4 button is the demo toolbar button to display the images; data are not collected under this option.

The F5 and F5 buttons are used to collect the same data with a user-defined interface. The graphic interface button (F5) is used for the operator to view images while data are being collected to ensure the system is running normally. The text interface button F5 is used for showing DMI and flow rate information in the GoPro video file.

The other four buttons, PUMP ON, SPLASH ON, SPLASH OFF, PUMP OFF, are used to control the pump and valve to start the splash. In the field test, researchers assigned F1 for turning on the splash and F2 for turning off the splash to save water.

The STOP F8 button will stop the data acquisition. The EXIT will exit the program.

Under normal operations, when hitting the F5 button, the operator sees the screen shown in Figure 57. The upper left portion of the figure shows the DMI and GPS information, and the collected image is shown in the upper right section.



Mi 0 Ft 895 MK 0

TR 684 Gmi 0 Gft 1042 PC 0 TM 0

GPS No. 13 Lat 30.55357467 SPD 80.0

DOP 2.30 Lot 96.26456318 Lel. 292.4

Figure 57. Typical Splash Image Observed during Data Collection.

IMAGE DATA PROCESSING

The software used to processing the photos is the NI Vision Builder 2011, which is developed by National Instruments™ for digital photo processing. With this package, the user can focus on different areas of the image (areas marked with green lines in Figure 58) and look for changes in image intensity.

```
Top =32
Mid =32
Bom=106
Tire =32
```

Simulate Acquisition 1 PASS Final31-Go 024.jpg

Simulate Acquisition 2 PASS Final31-Go 041.jpg

Vision Assistant 1 PASS

Vision Assistant 2 PASS

Bottom-int PASS Average Int. = 106.1

Middle_int PASS Average Int. = 32.1

Top-int PASS Average Int. = 32.3

tire-int PASS Average Int. = 31.7

Custom Overlay 1 PASS

Inspection Status PASS

Acquire Image: Acquires an image from the selected camera and image acquisition board.

Acquire Image (1394, GigE, or USB): Acquires an image from the selected IEEE 1394, Gigabit Ethernet, USB, or IP camera.

Read/Write Camera Attributes: Read and write attributes from the selected IEEE 1394, Gigabit Ethernet, or USB camera.

Acquire Image (IEEE 1394): Acquires an image from the selected IEEE 1394 camera.

Simulate Acquisition: Simulates the acquisition of images by reading images from file.

Select Image: Selects a new image to inspect.

Figure 58. National Instruments Image Processing Package Vision Builder 2011.

Each image consists of a number of pixels at the resolution chosen this is 1820×1080, almost 2 million pixels. In the grayscale image, each of these pixels is assigned a number from 0 to 255 based on its brightness, where the value of 0 represents total black and 255 is totally white. The NI software package above allows the user to break the image into a number of monitor areas represented by the green lines. The average intensity is then computed for all of the pixels enclosed in these areas. This is shown in Figure 59 and Figure 60.

Figure 59 shows a typical image from a section at Riverside Campus. The same image as processed by the NI package is shown in Figure 60. First, the user denotes the monitor locations by the green lines. In this case, five areas were marked. The computed image intensity in each of these areas is shown in Figure 60. The bottom areas have a lot of white from the splashes; this has a computed intensity of 112 (on a scale from 0–255). The selection of the monitor areas is user defined and will be reviewed.

Figure 59. Grayscale Image Showing Surface Splash.

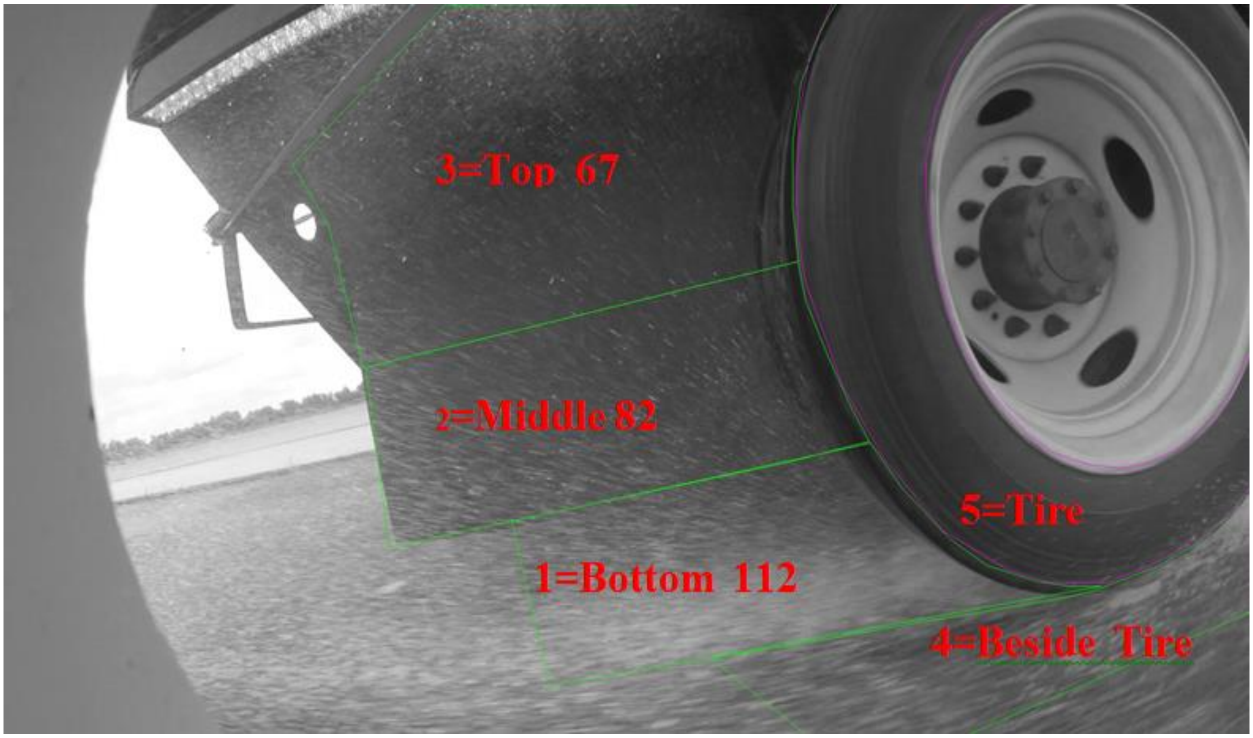


Figure 60. Computed Intensities for Areas Marked behind the Tire.

CONCLUSIONS AND RECOMMENDATIONS

The developers of this system, Dr. Wenting Liu and Gerry Harrison, did an excellent job of overcoming many of the technical challenges in building an operational field system, not least of which was keeping the water from completely covering the lens. To keep the system practical and safe, it was essential to mount the camera as close as possible to the tire being monitored. The camera housing, particularly its wing that funnels air and forces water away from the lens, is one of the major technical innovations.

It is acknowledged that this prototype system works and achieves the objectives set out in Task 6 of Project 0-6741. However, as with any prototype, there is always room for improvement. Based on the initial data collection, researchers listed the following areas that should be reviewed for future implementation efforts:

- Optimal Nozzle Location. It is thought that the current nozzle is too close to the tire and is not giving sufficient time for the true benefit of the PFC to be identified. Future efforts should focus on finding the optimal location for the water nozzle.
- Camera Improvements. The camera currently has an automatic iris adjustment feature that measures long runs where environmental conditions change (dark to bright); this feature will automatically change brightness settings. Future efforts will focus on fixing the camera's iris settings. One other consideration here is to perhaps put the entire system in a curtained-off enclosure.
- Improvements to Lighting. Currently, a lighting system has been installed to illuminate the water droplets thrown from the pavement so as to make their detection easier with the image processing systems. However, the uniformity of this system should be improved, for there are currently some areas that are brighter than the others are.
- Considering the Use of a Bald Tire. The current tire is a RoadMaster RM 170 22570R19.5. It has four deep treads approximately 10 mm wide and 10 mm deep. These deep treads throw streams of water. The system will probably give different results with different tires. Consideration should be given to evaluating the potential of using a bald tire so the influence of tread type and depth is eliminated.
- New Test Vehicle. Funds were not available to purchase the optimal test vehicle for this system, so an F550 truck was borrowed for this work. This was not optimal. Recommendations are under development by the research team as to the optimal vehicle configuration, consideration will be given to have this splash and spray system built into a trailer systems.
- Improved Blackboard. The blackboard size needs to be evaluated. It is important to provide a constant contrast area. However, the current blackboard is not large enough. One problem is that the lower part of the area is the pavement surface and it's color is variable along the highway as is the intensity of light reflected from the surface. This may require the while video capture area to be shrouded so that more uniformity can be achieved. The size of the blackboard, camera location, and the need for a shroud around the systems needs to be fully investigated.
- Water Control Valve. Currently the water control valve is 6 ft from the nozzle; this should be moved closer to the nozzle in future systems to improve the starting and stopping of the water flow.

REFERENCE

1. Vavrik, W.R., and S.H. Carpenter (1998). “Calculating Air Voids at Specified Number of Gyrations in Superpave Gyratory Compactor.” *Transportation Research Record.* No. 1630, Materials and Construction. Transportation Research Board, National Research Council.