Technical Report Documentation Page

1. Report No. FHWA/TX-15/0-6742-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF DESIGN AND CONSTRUCTION ISSUES OF THIN HMA OVERLAYS		5. Report Date Published: April 2015
		6. Performing Organization Code
7. Author(s) Bryan Wilson, Tom Scullion, and Abu Faruk		8. Performing Organization Report No. Report 0-6742-1
9. Performing Organization Name and Address Texas A&M Transportation Institute College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-6742
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483		13. Type of Report and Period Covered Technical Report: September 2012–August 2014
		14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Performance Tests for Thin Asphalt Layers
URL: http://tti.tamu.edu/documents/0-6742-1.pdf

16. Abstract

While the overall implementation of thin HMA overlays in Texas has been successful, some issues need to be addressed: appropriate blending of SAC A and SAC B aggregate to ensure adequate skid resistance; best practices to achieve adequate bonding (surface prep and tack coats); and correct quality assurance test methods to achieve adequate compaction. The purpose of this research, therefore, was to address these concerns through laboratory and field testing. In addition, preliminary work to refine a crack propagation model for thin overlays was performed.

Laboratory friction testing considered samples with two gradation types, four aggregates types, and five levels of aggregate blending. Samples were polished with simulated traffic in the lab and tested with the dynamic friction tester. Results show the terminal polish value for all designs with 100 percent SAC B replacement failed, as had designs with 50 and 75 percent blending of one SAC B+ and one marginal SAC B aggregate. SAC B replacement up to 25 percent was acceptable for all aggregates.

Shear and tensile strength tests were developed to measure interlayer bond strength. A computer model suggested the maximum shear stress at a bonded thin-overlay interface is 120 psi. Bond strength tests were performed on laboratory samples made with two base mix types, two thin overlay types, 5 tack types (including non-tracking tacks), 3 tack rates, simulated milling, and moisture conditioning. Bond strength was most dependent on the mix type being bonded and compaction effort, and less on tack type and tack rate. In the tensile strength tests and half the shear tests, non-tracking tacks had higher strengths than samples using CSS-1H or no tack. No single non-tracking tack was found to have better performance than others. Variable tack rates of CSS-1H were only significant on dense-graded mixes. Low and moderate levels of tack provided the best bond. Milled samples had higher strength than unmilled samples in shear. A tack tracking test was developed to discern different non-tracking times during curing.

Four compaction quality assurance test methods were used on three thin overlay projects. Properties measured were flow time with the current TxDOT permeability test, surface dielectric with high-frequency ground penetrating radar, mean profile depth (MPD) with the circular-track meter, and bulk density from field cores. Correlations of the tests were strong on a project-by-project basis, but generally not good when combining the data sets. Flow Time-MPD, Flow Time-Core Voids, and Surface Dielectric-Core Voids were best correlations overall.

TTI provided support to TxDOT on many new thin overlay demonstration projects, ranging from mix design, performance testing, construction method recommendations, and bonding testing. Hand working of on TOM-B project caused problems with mat thickness and compaction uniformity. Using tack did not influence bond strength except for one fine-permeable friction course in shear testing. Thermal segregation problems were noted on two projects.

Recommendations are contained in the draft specifications, including aggregate blending guidelines, bond strength testing, micro-milling, and minimum and maximum flow times for compaction quality control.

17. Key Words Fine-Graded, Thin Overlay, HMA, Fine DGM, Fine SMA, TOM, Fine PFC, Overlay Test, Permeability, Skid Resistance		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia 22312 http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 218	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EVALUATION OF DESIGN AND CONSTRUCTION ISSUES OF THIN HMA OVERLAYS

by

Bryan Wilson
Associate Research Scientist
Texas A&M Transportation Institute

Tom Scullion
Senior Research Engineer
Texas A&M Transportation Institute

and

Abu Faruk
Research Associate
Texas A&M Transportation Institute

Report 0-6742-1
Project 0-6742
Project Title: Performance Tests for Thin Asphalt Layers

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published: April 2015

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

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. It is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Tom Scullion, P.E. (Texas, #62683). 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.

ACKNOWLEDGMENTS

This project was conducted for TxDOT, and the authors thank TxDOT and FHWA for their support in funding this research. We acknowledge the continuing support of the members of the Project Monitoring Committee, past and present, including Dale Rand, Robert Lee, Ronald Baker, Paul Montgomery, and Paul Norman. We also appreciate the help of Wade Odell as our project manager.

Field evaluations were assisted by Beata Kwater (Houston), Donald Bunch (Houston), Mike Arellano (Austin), Miles Garrison (Atlanta), Brett Haggerty (San Antonio), Rich Burkholder (Durwood Greene), George Jordan (Angel Brothers), and David Fuller (Ramming). Laboratory evaluations were assisted by Harry Bush (Vulcan), Rick Fuentes (Vulcan), Chris Haas (Old Castle), and John Wedgeworth (Capitol Aggregates). The help of several Texas A&M Engineering students was invaluable, namely, Cody Browne, Foster Rigsby, Mayur Yelpale, Sanket Shah, and Jonathan Chiou.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AIMS	Aggregate Imaging System
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CAE	Complete ABAQUS Environment
CAM	Crack Attenuating Mixture
CMHB-F	Coarse-Matrix High-Binder, Type F
COV	Coefficient of Variance
CTM	Circular Track Meter
DFT	Dynamic Friction Tester
DGM	Dense-Graded Mix
FHWA	Federal Highway Administration
GPR	Ground Penetrating Radar
HMA	Hot Mix Asphalt
LTE	Load Transfer Efficiency
MPD	Mean Profile Depth
NMAS	Nominal Maximum Aggregate Size
OGFC	Open-Graded Friction Course
OT	Overlay Test
PFC	Permeable Friction Course
Pecos RTC	Pecos Research Test Center
QC/QA	Quality Control and Quality Assurance
RAP	Reclaimed Asphalt Pavement
RAS	Reclaimed Asphalt Shingles
SAC	Surface Aggregate Classification
SMA	Stone Matrix Asphalt
Bulk SSD	Bulk Saturated Surface-Dry
TOM	Thin Overlay Mix
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
UT mix	Ultra-Thin Mixture
VCA	Voids in the Coarse Aggregate
WFV	Water Flow Value

CHAPTER 1
INTRODUCTION

PROBLEM STATEMENT

The Texas Department of Transportation (TxDOT) is interested in cost-effective surface maintenance mixes for both urban and rural pavements. Traditional hot mix asphalt (HMA) overlays, with lift thicknesses from 1.25 to 2.0 inches, have a long history of successful implementation. Under good circumstances, they can have a service life of 8 to 10 years and extend the overall pavement life. However, with limitations of available funds, there is always a need to explore more economical resurfacing options. Surface treatments, the long-standing economical option, are often discouraged within cities because of problems with chip loss and resulting property damages. They can also be very noisy, which is undesirable when people live and work near freeways.

One solution is thin HMA overlays. These overlay mixes can be laid 1.0 inch or thinner because they use a small nominal maximum aggregate size (No. 4 or 3/8 inch) and use high-quality materials to ensure adequate performance (*1*). They are more economical than traditional overlays and, as an added benefit, mitigate problems with curb/gutter height restrictions. Though still more expensive than surface treatments, these mixes should not have chip-loss problems, are relatively quiet, and when properly designed and constructed may provide the same service life as traditional mixes.

The purpose of agency specifications and testing programs in pavement design/construction is to ensure that the final product has acceptable performance and long-term durability. These objectives can be achieved in a number of ways:

- Raw material controls.
- Detailed design processes.
- Laboratory testing.
- Construction procedure controls.
- Quality assurance testing of the final product.

This research project focuses on the following items for thin overlay designs: material controls of aggregate, construction procedures, and quality assurance.

Shortly before this project was proposed, TxDOT did not have thin overlay options that were implementation-ready state-wide. However, since then, several specifications for thin overlay mixes (TOMs) and other types of thin HMA overlays have been implemented. This process has been fairly smooth, but some questions have arisen, including:

- Appropriate blending of SAC A and SAC B aggregate to ensure adequate skid resistance.
- Best practices to achieve adequate bonding (surface prep and tack coats).
- Correct control methods to achieve adequate compaction.

The purpose of this research, therefore, is to address these concerns through laboratory and field studies of skid resistance, pavement bonding, and compaction quality control.

Scope

This focus of this project is the continued development of thin overlay specifications. The greatest attention was given to fine gap-graded designs (TOMs and fine stone matrix asphalt [SMA]) and fine dense-graded designs (TOM-B and ultra-thin [UT] mix). Some attention was given to fine-permeable friction course (fine-PFC) projects as well.

In addition to general specification refinement, the work scope is summarized as follows:

- Literature review and industry interviews.
- Laboratory evaluation of the effect of aggregate blending on skid resistance.
- Development of bond strength tests.
- Evaluation of tack coat and milling practices on bond strength.
- Computer modeling.
- Laboratory testing.
- Development of a tracking resistance tests.
- Development of a micro-milling specification.
- Evaluation of compaction quality assurance test methods.
- Refinement of a crack propagation model.
- Documentation and support for thin overlay demonstration projects.

DELIVERABLES

This project provides TxDOT with draft test specifications for bond strength testing in shear and tension, draft construction specifications for micro-milling, and revised specifications of Item 342 (Thin Surface Mixtures). The document *Thin Overlay Guidelines: Project Selection, Design, and Construction*, was also prepared as a go-to aid for district engineers and contractors.

OUTLINE

This report contains eight chapters:

- Chapter 1 describes the problem statement, project scope, and deliverables.
- Chapter 2 gives background information for thin HMA overlay designs and results of TxDOT interviews.
- Chapter 3 presents the laboratory testing of aggregate blending on skid resistance.
- Chapter 4 covers several topics related to tack coat and milling practices, and thin overlay bond strength testing.
- Chapter 5 presents the evaluation of different compaction quality assurance tests.
- Chapter 6 describes initial data collection to refine a crack propagation model.
- Chapter 7 documents several thin overlay demonstration projects.
- Chapter 8 summarizes the research, findings, and offers recommendations.

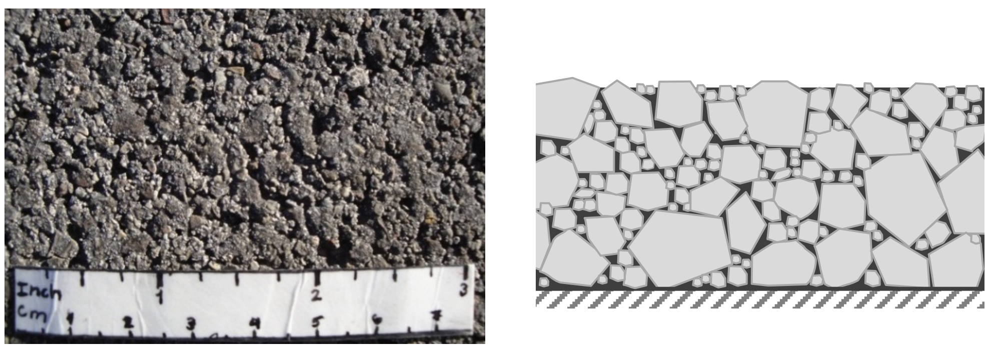
CHAPTER 2
LITERATURE REVIEW AND INTERVIEWS

OVERVIEW

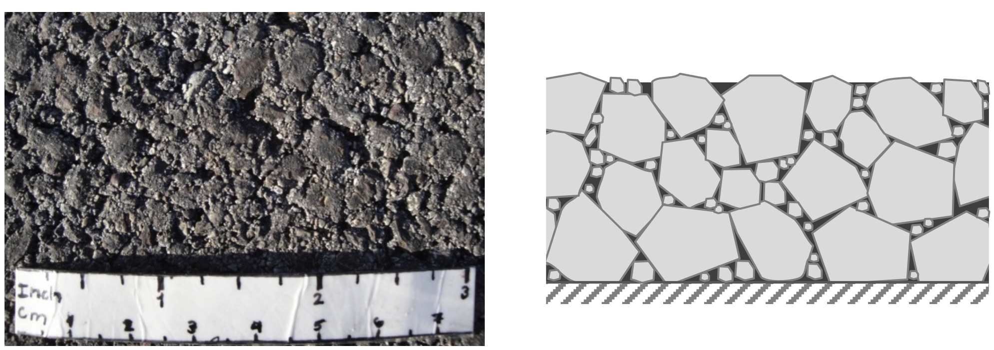
This chapter reports the findings of a literature review of laboratory design and construction practices of thin overlays. These findings were compared to current practices in Texas. The researchers also surveyed TxDOT districts about their perceptions of thin overlay performance. The survey results help identify deficiencies of the current specifications, and identify misconceptions that districts may have with the mixes.

THIN OVERLAY TYPES

The definition of a thin overlay, for the purpose of this project, is any HMA surface mix laid 1.0 inch or thinner. Three categories of thin overlays, illustrated in Figure 2.1, are dense-graded, gap-graded, and open-graded mixes. This section discusses function and project selection, and materials and mix design information for these three thin overlay categories.

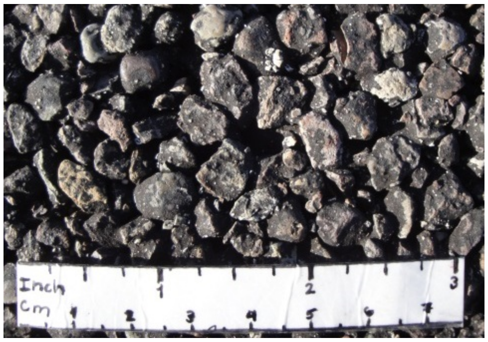


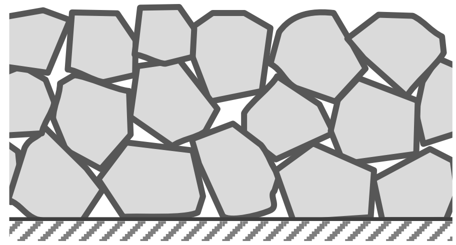
(a)



(b)

Figure 2.1. Surface and Cross Section of Thin Overlays: a) Dense-Graded, b) Gap-Graded, and c) Open-Graded.





(c)

Figure 2.1. Surface and Cross Section of Thin Overlays: a) Dense-Graded, b) Gap-Graded, and c) Open-Graded. (cont.)

Function and Project Selection

A general description of each mix type is given, including function and the appropriate candidate pavement application. Agencies that have related specifications are also mentioned.

Dense-Graded

Dense-graded mixes for thin overlays have a nominal maximum aggregate size (NMAS) of either 9.5 or 4.75 mm, where most of the aggregate passes either the 3/8-inch or No. 4 sieve, respectively. The coarser mixes can be laid as thin as 0.75 inch and the finer mixes as thin as 0.5 inch. Because smaller aggregate sizes were used, these mixes often have higher asphalt contents than other dense-graded mixes; the minimum recommended asphalt content is around 6.5 percent. During construction, they are easy to hand work and compact. The resulting surface is very smooth, thus minimizing vehicle vibrations, a significant source of interior vehicle noise (*2*).

Thin dense-graded mixes are ideally suited for pavement maintenance applications, but can also be used in new construction. For maintenance purposes, they can correct raveling, rejuvenate weathered surfaces, seal against further oxidation, and restore micro-texture on polished sections. Candidate pavements should have no structural deficiencies like fatigue cracking or active rutting problems. Minor rutting (< 0.25 inch) may be allowable, but larger surface irregularities should first be corrected with a leveling course or milling. These binder-rich mixes should not be applied to flushed pavements. Their application on high-speed roads is often discouraged since the surface macro-texture is minimal and could lead to skid problems in wet weather (*3*). Others prohibit their use on high-volume roads to mitigate potential rutting problems.

Several state and federal agencies have specifications for thin dense-graded mixes. Some of these are listed as follows:

- Texas–Fine-graded crack attenuating mix (CAM) (SS 3246) when used on the surface.
  Ultra-thin (UT) mixture (Item 347).
- Ohio–Smoothseal Type D (ODOT Item 424).
- Georgia–9.5 mm Superpave Type I (Section 828.2.03, supplemental specification).
  4.75 mm fine-graded mix (Section 828.2.04).
- Maryland–9.5 mm, fine-graded mix (Section 904.04).
  4.75 mm mix (Section 904.04).
- Virginia–Thin HMA Concrete Overlay (Special Provision SU210000A).
  4.75 mm surface mix (SM-4.75) (Special Provision 315U00).
- Florida–Type SP (Superpave)-9.5 (Section 334).
- National Center for Asphalt Technology (NCAT)–4.75 mm Superpave design (*4, 5*).
- California–No. 4 HMA Type A (Section 39).

Gap-Graded

Like the previously discussed dense-graded mixes, gap-graded mixes for thin overlays can have a NMAS of either 9.5 or 4.75 mm, which are laid as thin as 0.75 and possibly 0.5 inch. These gap-graded mixes are commonly referred to as stone matrix asphalt and were originally developed in Germany as "Splittmastixasphalt." SMA mixtures are more durable than traditional dense-graded mixes due to a high binder content and a strong coarse aggregate skeleton or matrix. The space created within the matrix is filled with asphalt-rich mastic. SMA mixes are, therefore, rut resistant yet still flexible and impermeable. However, these mixes have a harsh gradation and can be difficult to compact. The resulting surface often has more texture than dense-graded mixes, but this is still not considered a highly textured surface. The tire-pavement noise should be lower than for standard SMA options (*6, 7*).

Thin gap-graded mixes can correct low- to moderate-severity cracking, low- to moderate-severity raveling, and low-severity rutting. They can correct polished surface problems but should not be applied to flushed pavements. Candidate pavements should have no structural deficiencies like fatigue cracking or active rutting problems. Minor rutting (< 0.25 inch) may be allowable, but larger surface irregularities should first be corrected with a leveling course or milling. These mixes are similar to the dense-graded mixes, and some agencies prohibit placing these on higher speed roads.

A few of the gap-graded mix specifications for thin overlay applications are as follows:

- Texas–Stone-matrix asphalt, Type F (SMA-F) (Item 346).
  Thin overlay mix (TOM) (Item 347).
- Maryland–Gap graded stone matrix asphalt (GGSMA), 9.5 mm (Section 904.05).

- Virginia–9.5 mm stone matrix asphalt (SMA-9.5) (Section 248, SS 24805).
- NCAT–9.5 mm SMA (*8, 9*).
  4.75 mm SMA (*7*).

Open-Graded

Open-graded mixes for thin overlays use a uniformly graded aggregate with a NMAS of 9.5 mm (material passes the 3/8 inch sieve but is retained on the No. 4 sieve). They also use a small portion of fibers to prevent draindown of the binder. The result is a stone-on-stone contact mix with an open structure. These mixes have very good surface drainage, greatly reducing splash-and-spray, and risks of hydroplaning. The mix also provides good nighttime visibility. It can be laid as thin as 0.75 inch. In the case of a bonded PFC, the mix is laid immediately after a generous tack coat application through a spray paver.

As with the other mixes mentioned, this product works well in maintenance applications. It can correct low-severity cracking, low-severity rutting, and restore skid resistance. It is a particularly good option for flushed pavements since the open aggregate skeleton allows expansion of the excessive binder.

Examples of open-graded mix specifications are as follows:

- Texas–Permeable friction course (PFC), Type F (PFC-F) (Item 342).
  Thin-bonded PFC (SS 3127).
- Virginia–9.5 mm PFC (PFC-9.5) (Special provision, may be discontinued) (*10*).
- New Mexico–Open-graded friction course (OGFC) (Section 403).
- Georgia–9.5 mm OGFC (Section 828.2.01).
- California–3/8-inch OGFC (Section 39).

Materials and Mix Design

General materials and mix design specifications are discussed here, while more details are found in Appendix A.

Most of the previously mentioned specifications have detailed material requirements. Aggregates must be durable, provide good skid resistance, resist polishing, etc., as the following performance indicators specify:

- LA abrasion loss.
- Soundness from magnesium/sodium sulfate or freeze-thaw cycling.
- Percentage of fractured faces.
- Percentage of flat and elongated aggregates.
- Percentage of deleterious materials.

- Fine aggregate angularity.
- Sand equivalency.
- Linear shrinkage.
- Aggregate absorption.

On the other hand, Ohio Smooth-seal and New Mexico OGFC have very few material requirements.

Most of these specifications allow recycled materials. When incorporated, a different binder grade is often specified to account for the stiffening effect of reclaimed asphalt pavement and shingles (RAP and RAS). The previously recommended TTI specifications prohibit the use of RAP or RAS, but these materials are being incorporated to some degree. Binder requirements vary with each agency. Georgia and Virginia allow lower grade binders (PG 67-22 and PG 64-22, respectively) in their dense-graded mixes, with the assumption that the mixes will not be used for high-traffic roads. On the other hand, Texas, TTI, and Ohio recommend PG 76-22 to ensure the thin layer can perform under critical conditions. For gap- and open-graded mixes, agencies specify PG 70-22 or PG 76-22 binder. Warm mix additives are permitted in designs in Texas and Virginia. Other agencies do not explicitly allow or prohibit warm mix additives.

Of the dense-graded mixes studied, all but Ohio Smoothseal are designed with the Superpave design method or a variation thereof. Ohio Smoothseal is designed with the Marshall method. Most designs have a target density of 96 percent, though the Georgia 4.75 mm mix has a density range of 93 to 96 percent. Voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), voids in the total mix (VTM), and fines-to-binder ratio requirements vary slightly among the agencies. For gap-graded mixes, all mixes generally adhere to the Superpave method. Virginia and Maryland also incorporate volumetric measurements to ensure coarse aggregate interlock where the percent voids in the coarse aggregate (VCA) of the compacted mix (VCA_{design}) should be less than the VCA in a dry-rodded condition (VCA_{DRC}). Design densities are between 96 and 97 percent. The Texas SMA and TOM mixes can be designed with either the Superpave compactor or the Texas gyratory compactor. Agencies specify between 50 to 100 gyratory cycles. The open-graded mixes are designed differently from agency to agency. Texas designs these similarly to the Superpave method within a range of acceptable air voids (72–76) followed by performance testing. Others base the design off the draindown test or hypothetical binder thickness. All agencies require a draindown test to select the fiber content.

CONSTRUCTION PRACTICES

The other focus of this research project is to evaluate thin overlay construction practices. This section reviews the following categories of practices employed by state agencies:

- Surface preparation.
- Compaction.
- Quality assurance testing.

Surface Preparation

When the existing surface is excessively uneven or distressed, agencies frequently recommend milling prior to the new overlay. Milling can mitigate reflective cracking by removing spalled crack edges that cause uneven stress distributions in the new overlay. For these thin overlays, special consideration should be given to a new process called micro-milling. A micro-milling drum has more teeth spaced closer together, and produces a finer texture. Since these overlays are so thin, the texture of traditional milling can be too uneven, and interfere with construction. Traditionally, milled surfaces can present particular challenges for open-graded overlays due to bonding difficulty and water getting trapped in the milled texture (*11*). Georgia has a micro-milling specification requiring a ridge-to-valley depth of 1/16th inch and a center-to-center spacing of 0.2 inch. A micro-milling specification was also drafted for this project.

As part of preparing the surface, a tack coat is often recommended to ensure a good bond between the surface (existing or milled) and the new overlay. The maximum application rate for *residual* asphalt is generally 0.05 gal/yd^2 and can be as little as 0.01 gal/yd^2. This depends on the condition of the existing surface (texture and exposed binder), and the nature of the new overlay. For example, a new or bleeding surface would require less tack, and applications of open-graded mixes generally require more tack. The maximum allowable tack rate in Texas is 0.08 gal/yd^2 of residual asphalt. A list of tack coat rates for 20 states is given in Appendix A (*12*). Within the allowable range, agencies permit the contractor to select the optimal rate in the field. Georgia provides more guidance for acceptable ranges depending on the surface condition and overlay type. Applying excessive tack can cause shear slippage and bleeding.

When applying tack coats, the spray system should be checked prior to construction. The spray nozzles should be unclogged, and oriented correctly to produce either double or triple coverage of spray. Adjusting the height of the spray bar can assist in this. Another method for applying tack is with a paver-mounted spray bar. This equipment applies the tack immediately before laying the asphalt, eliminating issues of contaminating the tack coat. Alternatively, a tracking-resistant tack could be used. In all cases, the surface should first be cleaned prior to the tack, especially if the surface was milled. These considerations are not included in the Texas thin overlay specifications.

The State of Virginia goes a step further by testing the final bond strength at the tack interface. These procedures will be discussed further in the Quality Control and Quality Assurance (QC/QA) section. Virginia has also adopted “trackless tack,” as the standard during the normal paving season.

Compaction

Mix compaction is an essential factor affecting long-term performance of HMA. Guidance, therefore, is often given to contractors for pavement and mix temperatures, number and types of rollers, roller settings, and roller patterns. Appendix A contains a summary of such guidelines from several state agencies.

The minimum allowable pavement temperature in most agencies is between 50 and 60 °F. Most agencies specify the minimum mat temperature at the start of compaction (anywhere between 225 to 300 °F), and the temperature at which compaction is not allowed (140 to 160 °F). Virginia has the most detailed specifications, suggesting different asphalt temperatures for different mix types, binder types, and omitting temperature requirements when using a warm mix additive. On the other hand, Texas provides very little guidance in their latest specifications. Texas suggest a minimum pavement temperature, a final mix temperature when all but light rolling should stop, and describe how to guard against thermal segregation. Texas specifications have no guidance for minimum asphalt temperature for break-down compaction. This property is very important for thin overlays since the thin mat cools very quickly. In particular, thin gap-graded mixes are difficult to compact at cooler temperatures.

In most cases, only double steel wheel rollers are permitted during breakdown, intermediate, and finish rolling. The only exception is the new Texas specification for SMA-F that permits pneumatic rollers if material pick-up does not occur. Pneumatic rollers can leave surface irregularities in the mat, which, for thin lifts, might not be corrected with finish rolling. Maryland, California, and Virginia require multiple rollers to be on site, with a minimum weight of 10 tons. In many cases, the operators are prohibited from using a vibratory mode, especially for open-graded mixes. Virginia allows vibration on its gap-graded mix, but only if set to a low amplitude and high frequency. The Texas TOM and UT mix specification takes this same approach.

Lastly, open-graded mixes are most often specified by the laydown rate rather than the compacted thickness, and range from 55 to 90 lb/yd^2.

Quality Control and Quality Assurance

Quality control and quality assurance are important aspects of pavement construction. Quality control is the monitoring of materials and procedures during construction, while quality assurance is the final evaluation of the completed project. Different material properties are measured for acceptance/rejection decisions, or for assigning bonuses/penalties to the final payment.

During construction, mix gradation, asphalt content, theoretical maximum density, and other volumetric measurements are monitored. Both the state and the contractor usually test these properties; a third-party referee is involved if needed. The engineer may request other tests (drain down, rutting susceptibility, moisture susceptibility, aggregate soundness, etc.) if the need arises.

Density is most often measured with coring and directly measuring the bulk density, and/or non-destructive density gauge testing (*13*). Unfortunately, these methods have severe limitations when considered for thin overlays. Most states do not specify density requirements because of the difficulties encountered (*14*). The lift can be too thin to feasibly extract, trim, and reliably measure density. Nuclear and non-nuclear gauges are not recommended because the probing depth of such devices is greater than the lift thickness of these treatments. Even "thin lift gauges" are not suitable for thicknesses less than 1.75 inches, because the area of influence will include the underlying layer (*15*). Maryland, however, specifies using a test control strip and a thin-lift nuclear gauge for establishing rolling patterns. Virginia and Georgia forgo density testing of any kind, and accept compaction based on lift thickness and material yields. Virginia uses this method for materials placed less than 110 lb/yd^2/inch-thick, and Georgia for materials less than 90 lb/yd^2.

In the recent TxDOT specifications for TOM and UT mix, the department recognized the limitations of traditional density testing and adopted an alternative method. The Permeability of Water Flow of Hot Mix Asphalt test is normally used to ensure drainage in open-graded mixes, requiring a defined volume of water to drain through a small area in no more than 20 seconds. It has been repurposed now to ensure *again*st permeability in TOMs and UT mixes by requiring a *minimum* flow time of 60 seconds. (This minimum has since been increased to 300 seconds.) However, this flow time was chosen somewhat arbitrarily, is not correlated to density, and is subject to debate. Furthermore, there is no maximum recommended flow time, which may permit problems with over-compaction and loss of macrotexture.

Other tests that may be suitable for testing thin HMA overlay density are the rolling density meter (high-frequency radar) and a circular track meter (laser-based macrotexture measurement system). The radar system can rapidly make full-coverage measurements. The circular track meter (CTM) can make reliable spot measurements.

One final quality assurance test is the bond strength between the overlay and existing surface. Virginia allows the engineer to core the road and confirm the functionality of the tack coat through tensile and shear strength tests. The average shear strength of three cores must meet or exceed 100 psi, with no single core having a shear strength less than 50 psi on milled surfaces. For non-milled surfaces, the average must meet or exceed 50 psi, with no samples less than 30 psi. For tensile strength on milled surfaces, the minimum acceptable average strength is 40 psi (none less than 20 psi). And for non-milled surfaces, the average minimum tensile strength is 30 psi (none less than 20 psi) (*16*).

THIN OVERLAY EXPERIENCE IN TEXAS (SURVEY RESULTS)

A survey on the experience of TxDOT with thin overlays was sent to the director of construction or director of maintenance at each district. The results are summarized in this section and the complete survey is contained in Appendix B. For reference, the results were collected the end of 2012. Since then, more districts have constructed thin overlays. For the survey as a whole, the response rate was 88 percent (22 out of 25 districts). The response rate of individual questions was between 52 and 88 percent.

Figure 2.2 presents the extent of district experience with thin overlay mixes constructed less than 1-inch thick. Districts had the most experience with dense-graded mixes (over 50 percent), and around 35 percent of districts had experience with gap-graded and open-graded thin mixes. Many respondents noted that "experience" constituted just one or two projects.

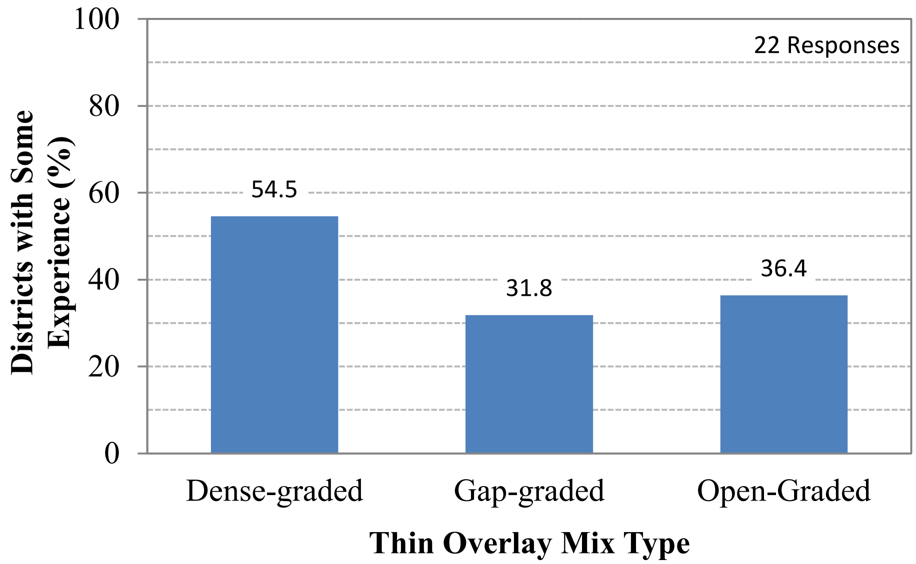


Figure 2.2. District Experience with Thin Overlays.

The next few figures illustrate the perceived advantages and disadvantages of each mix type. Overlay properties are ordered vertically from most advantageous to least advantageous, with the advantageous perception on the right in blue. The corresponding disadvantageous perception is on the left in red. Properties suggested in the survey address structural performance (cracking, rutting, etc.), functionality (skid resistance, noise, etc.), and logistics/economics (constructability, cost, etc.).

According to Figure 2.3, districts perceive thin dense-graded mixes as follows:

- Low cost.
- Quiet (noise reduction).
- Meet curb-gutter requirements.

- Easy constructability.
- Crack resistant.
- Resistant to moisture damage.

The greatest deterrents to using these mixes are lack of experience, rutting resistance, and problems with wet weather (skid and visibility). Those that are marked "Other" referred to shearing failures and excessively low densities. The property that was neither advantageous nor disadvantageous was "Long-term cost." This is either because districts feel it has an average long-term benefit, or they simply do not have the experience to make a strong case either way. They do recognize, however, that the initial cost can be much lower than alternative options like a traditional HMA overlay or microsurfacing.

Figure 2.4 presents the perceptions on gap-graded mixes. In this case, the advantageous properties were associated with:

- Structural performance (cracking, rutting, and moisture damage resistance).
- Functional performance (skid resistance and noise reduction).
- Long-term cost.
- Meet curb-gutter restraints.

Many also felt initial cost to be beneficial, but nearly just as many felt it was a disadvantage. Disadvantages were also lack of experience and then constructability.

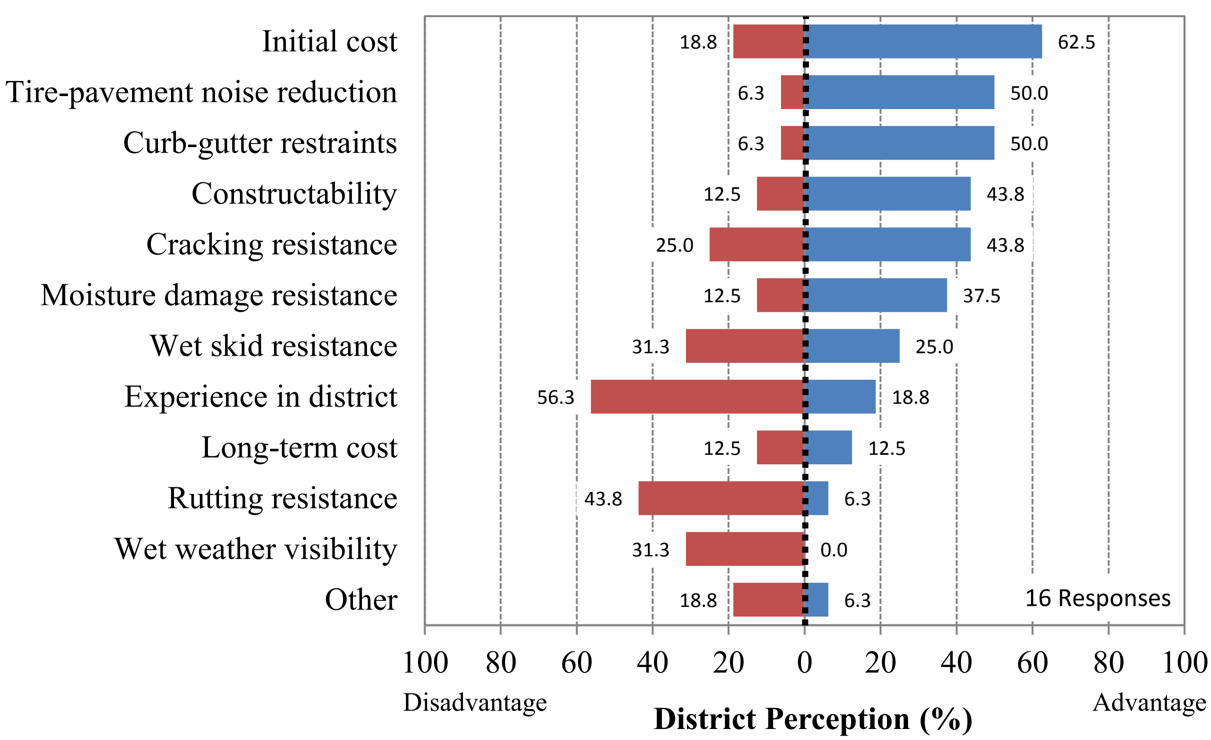


Figure 2.3. Perceived Advantages and Disadvantages of Thin Dense-Graded Mixes.

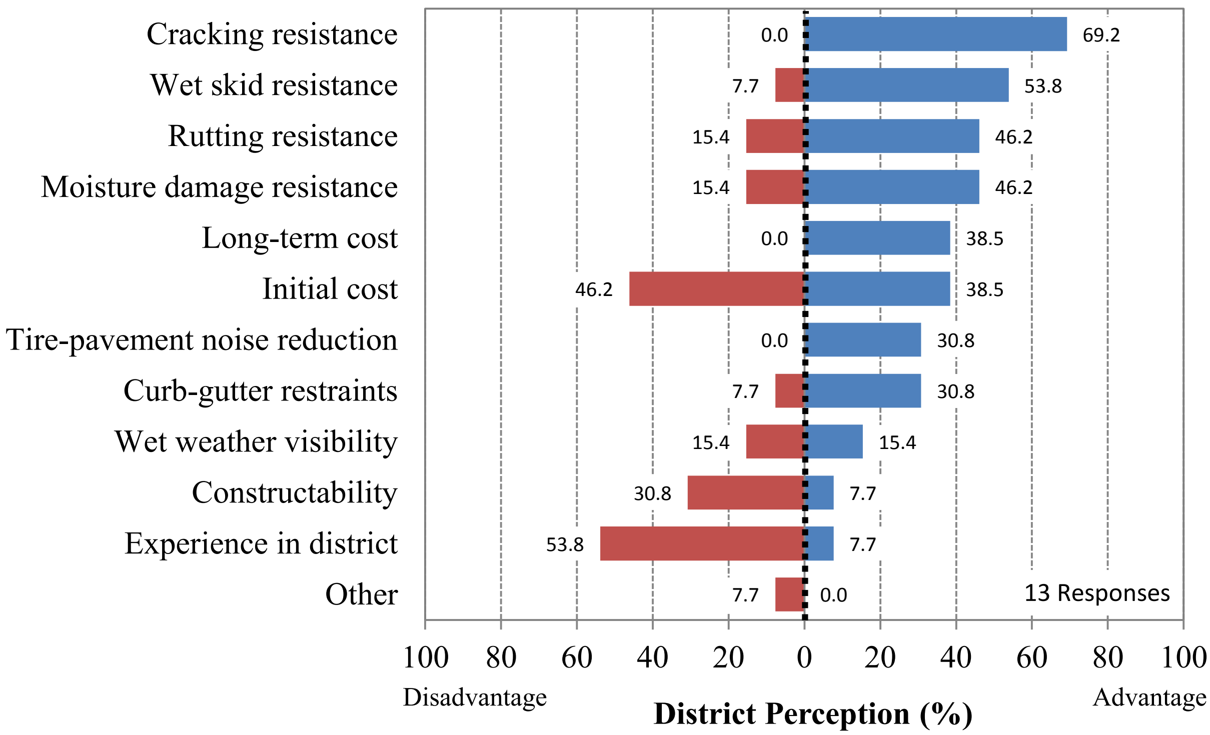


Figure 2.4. Perceived Advantages and Disadvantages of Thin Gap-Graded Mixes.

Since experience with the mix is so low, it is likely that perceptions of the mix are based more on traditional SMA properties. For example, traditional SMA is binder rich, and thus more expensive up front; but since this is a thin-lift mix, it should be less expensive than other comparable options. Based on the researchers' recent experience, thin gap-graded mixes can actually be less expensive than thin dense-graded options because of lower asphalt content (6.8 versus 7.4 percent on average) (*17*). Districts perceive these as having good skid resistance. From the perspective of macrotexture, however, these thin mixes have little to no advantage compared to dense mixes.

Figure 2.5 shows the district perceptions of open-graded thin overlays. Districts were very clear on the following advantages:

- Wet weather visibility and skid resistance.
- Noise reduction.
- Constructability.
- Cracking resistance.
- Curb-gutter restraints.
- Rutting resistance.

As is true with traditional PFC, the advantages are primarily with functionality and less with structural performance.

The disadvantages were:

- Lack of experience.
- Freeze-thaw durability.
- Raveling.
- Maintenance (last three listed under "Other").

As with the previous mixes discussed, perceptions of cost were polarized. More districts felt initial costs were a disadvantage and opinions on long-term cost were split. This again is likely a result of districts not having much experience with the mixes.

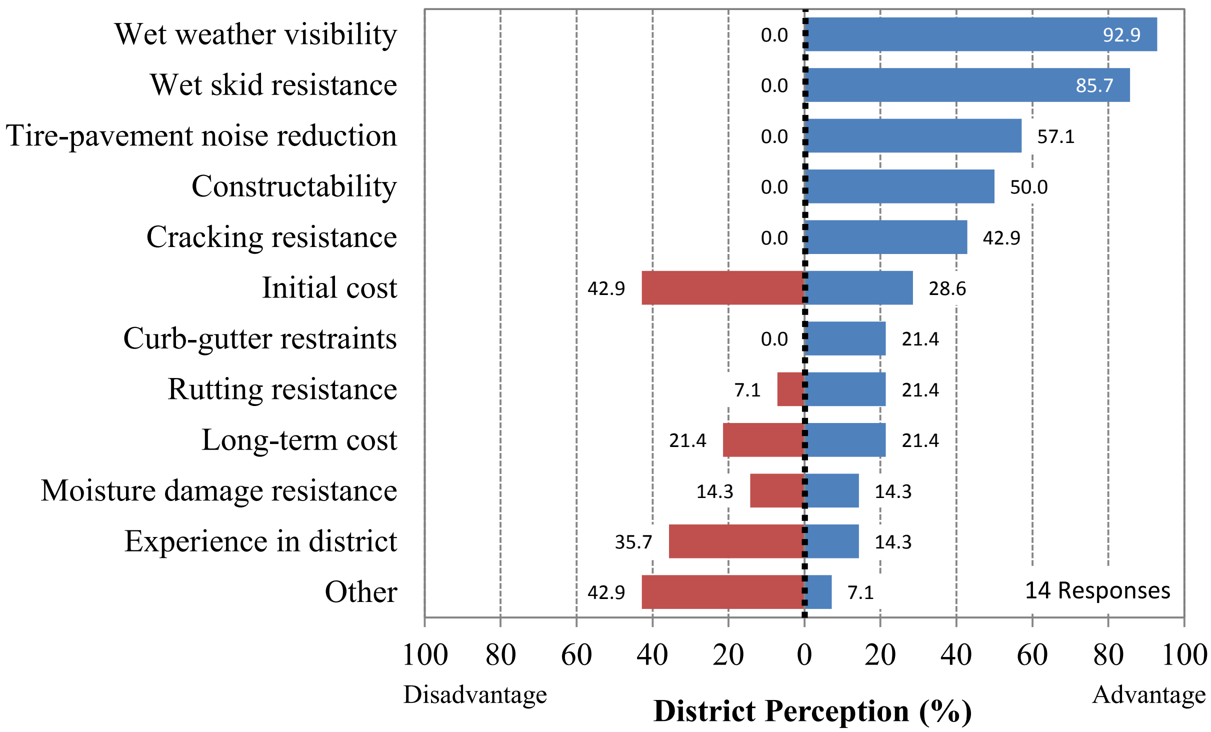


Figure 2.5. Perceived Advantages and Disadvantages of Thin Open-Graded Mixes.

The respondents were then asked to describe design and construction issues they have encountered with each mix. Table 2.1 summarizes the responses. A number of these comments deal with difficulty getting acceptable material qualities and gradations.

Table 2.1. Thin Overlay Design and Construction Issues.

Mix Type	Designs and Construction Issues	
Dense-Graded	• Achieving cross slope • Over-asphalted mixes • Availability of materials • Quality of local aggregates	• Meeting gradation requirements • Aggregate crushing practices of suppliers • Plant control
Gap-Graded	• Difficult to design • Material handling in the laboratory • Distresses from lack of compaction • Requires good tack coat	• Rutted over a bleeding underseal • Inconsistant results with HWTT and field density
Open-Graded	• Works well with bleeding surface • Quality and compatibility of local aggregates	• Limited to full-sun pavement sections (freeze-thaw)

The districts were then asked how they expected thin overlay use to change in the future. Over 80 percent of the districts expect an increasing use (see Figure 2.6). The SMA-F and PFC-F specifications are new to TxDOT, and this survey suggests that most districts should at least plan to try these mixes out, if not adopt them as a significant part of their maintenance operations.

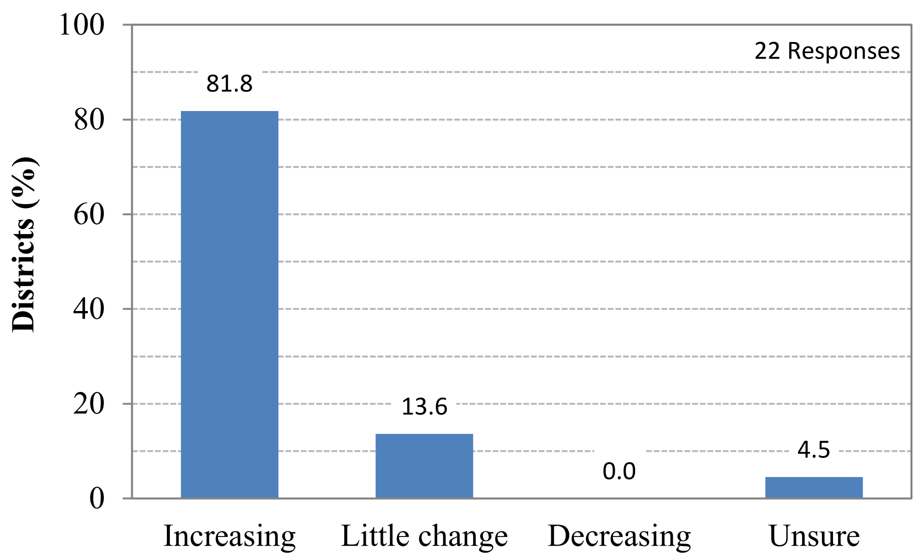


Figure 2.6. Predicted Future Use of Thin Overlays.

The respondents were also asked if they knew of any thin overlay projects in their districts that were performing poorly or performing well. Four dense-graded projects and one open-graded project were performing poorly. In contrast, there were six dense-graded projects, 13 gap-graded projects, and five open-graded projects performing well.

SUMMARY

Researchers reviewed the literature and several agency specifications for thin overlays. In particular, they focused on laboratory design and construction practices. They also surveyed TxDOT districts concerning their perceptions of thin overlay performance.

The following are the key findings from the literature and information search:

Materials/Mix Design

- The Austin District's UT Mix is a No. 4 (4.75 mm) dense-graded mix that other agencies have successfully developed. The district should continue to experiment with this.
- Texas has stricter coarse aggregate LA abrasion criteria. Unless it is too restrictive, this should benefit Texas.
- Texas and Virginia specifically allow using warm mix additives. This relatively new technology is expected to increase workability of the thin overlays.
- Maryland and Virginia check for aggregate interlock on their gap-graded mixes by evaluating the VCA in the dry rodded condition and in the mix design. This and other aggregate packing metrics may ensure better designed gap-graded mixes.

Construction Procedures

- All agencies state that milling should be done to correct surface problems, but only Georgia has provided a specification for micro-milling.
- The recommended tack rates in Texas are much higher than the other agencies. Most specify a rate producing a residual asphalt content of 0.01–0.05 gal/yd^2. Texas specifies a rate of 0.03–0.08 gal/yd^2 of residual asphalt.
- Texas gives no recommendations for the minimum mix temperature for compaction, while most agencies do. This can be a critical factor for compacting thin layers that cool quickly.
- The current wording in TxDOT's SMA specification (Item 346) allows pneumatic tire rollers to compact SMA-F. This should be changed for thin overlay applications.

- TXDOT is the only agency that uses the water flow test to ensure impermeability of SMA-F. Though the effectiveness of this test is uncertain, using it is not a bad idea.
- Virginia has tensile and shear strength criteria for cores to ensure adequate bond strength. This is a concept worth looking into.

The key results from the district survey are as follows:

- About 50 percent of districts have experience with thin dense-graded overlays, and around 35 percent with gap- and open-graded overlays. In many cases, however, this experience consists of just one or two projects.
- For all mix types, districts noted that a lack of experience was a major disadvantage to implementing thin overlays.
- For dense- and open-graded mix types, districts were split nearly 50:50 as to whether the mixes had good or poor long-term performance. This is an important topic that must be researched and communicated to districts.
- Districts perceived thin dense-graded mixes to have low initial costs while gap- and open-graded mixes were less economical. In many cases, this could be just the opposite since dense-graded mixes have higher binder contents. This perception needs to be corrected.
- Districts seem to assume that the same properties of mixes they are familiar with will be the same in these thinner versions. This is usually acceptable, but for thin gap-graded mixes, the skid resistance will likely be similar to that of thin dense-graded mixes.
- The prominent design issue mentioned was obtaining materials with the appropriate qualities and gradations.
- Over 80 percent of the districts expect to increase their use of thin overlays if, for nothing else, to experiment with the new specifications.
- Districts reported very few projects with poor performance and several with good performance.

CHAPTER 3
EVALUATION OF AGGREGATE BLENDING ON SKID RESISTANCE

OVERVIEW

With the increased application of thin overlays, there is more demand for quality SAC A materials. In most locations around the state, however, SAC A is not locally available and needs to be imported over long distances. In one case where it is available, the materials are being depleted faster than they can be produced. Therefore, there is growing pressure on districts to blend lower quality SAC B materials into their designs.

This chapter reports the findings of laboratory skid resistance testing in which the researchers explore the following topics:

- General evaluation of thin overlay skid resistance (macro- and micro-texture).
- Maximum amount of SAC B aggregate blending that still results in acceptable long-term skid resistance.
- Comparison of polished friction properties of different SAC B aggregates.

PROCEDURES

Laboratory Testing

Skid resistance, measured in terms of the coefficient of friction and surface macrotexture, was evaluated on two thin overlay types, using different aggregate types and different blending percentages. Samples were polished in the lab to replicate long-term polishing under traffic.

Materials

Table 3.1 shows the aggregate materials used in this study, and source ratings. Aggregate A is a SAC A native trap rock (basalt). Two of the SAC B aggregates were dolomitic-limestone. Some refer to these aggregates as SAC B+; they are soluble in acid, but can have high resistance to abrasion and polishing. The other two SAC B aggregates were calcitic-limestone. In all mixes, a dry limestone screening was used as a filler to make the mixes workable.

The baseline reference samples for friction were made using 100 percent Aggregate A for the coarse fraction. From there, the researchers replaced the A aggregate with the different SAC B aggregates. Coarse aggregate replacement occurred at 25, 50, 75, and then 100 percent. Two types of mixes were designed: a TOM and a TOM Type B. For the TOM, coarse aggregate was considered material retained on the No. 4 sieve; for the TOM-B, the definition was changed to material retained on the No. 8 sieve because this type of mix has very little No. 4 aggregate.

Table 3.1. Aggregate Properties.

Property		Name: A	B1	B2	B3	B4
Agg. Type		Trap Rock	Dol. Limestone	Dol. Limestone	Calc. Limestone	Calc. Limestone
Surf. Agg. Classification		A	B (B+)	B (B+)	B	B
Source Rating	LA Abrasion	14	29	23	25	31
	Soundness (Mg)	8	7	6	14	17
	MicroDeval	13	11	8	15	23

To single out the effect of aggregate type on friction, all mix gradations of a given mix type were kept constant. In some instances, this required engineering the existing aggregate gradations to fit the specific gradation curve. The researchers separated the aggregate onto specific sieve sizes, and recombined the rock in controlled proportions. The team did not allow the samples to vary by more than 1.5 percent from the target gradations shown in Figure 3.1.

In all designs, the research team used an unwashed limestone screening as fine aggregate, and the asphalt was PG 76-22.

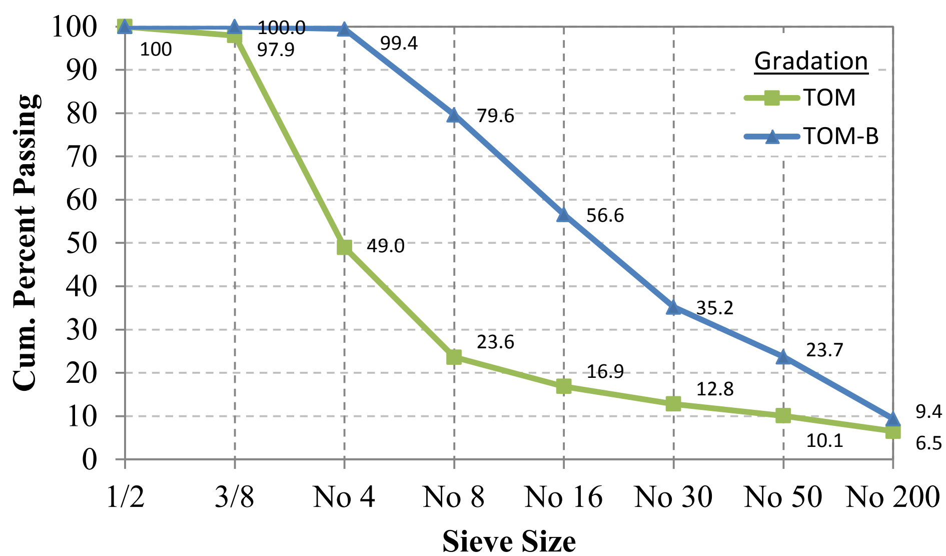


Figure 3.1. Target Gradation Curves.

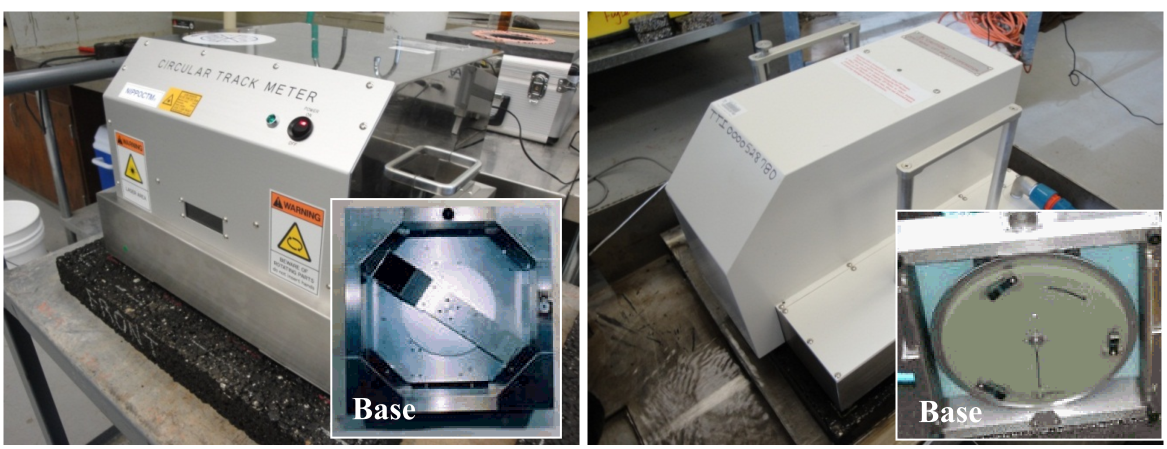
Skid/Polishing Resistance Test

Skid and polishing resistance are designed into the mix through aggregate quality requirements and gradation requirements. Another approach to meet this objective is to measure the friction and texture properties of compacted laboratory samples before and after simulated traffic.

In this approach, the researchers molded the slab specimens with a PMW Linear Compactor (see Figure 3.2), then evaluated the skid resistance in terms of coefficient of friction and texture depth.

Figure 3.2. PMW Linear Compactor for Molding Slabs.

The research team measured texture depth with a circular-track meter (see Figure 3.3a). The portable device uses a laser scanner to measure the texture depth along a 280 mm (11-inch) diameter circular track. The measurements are then used to calculate the mean profile depth (MPD). The wet coefficient of friction is measured with a dynamic friction tester (DFT) (see Figure 3.3b). A circular disk equipped with three calibrated skid pads is freely rotated up to 90 km/h (55 mph), and is then lowered onto a wet surface and allowed to slow until it stops. During deceleration, the resistance force is measured and used to calculate the friction coefficient at different speeds.



(a) Circular Track Meter **(b) Dynamic Friction Tester**

Figure 3.3. Testing Equipment.

After initial testing, the slabs are placed in a three-wheel polisher (see Figure 3.4), that NCAT developed to simulate traffic wear. The device runs three load-bearing tires over a slab in a constant turning motion. Water is applied to the surface to simulate wet conditions, and to wash away abraded particles and prevent overheating. Testing with the DFT was conducted before polishing, then after 2,000; 30,000; and 100,000 cycles. CTM testing was done before polishing and after 100,000 cycles. MPD values at 2,000 and 30,000 cycles were estimated from previously identified correlation models.

(a) **(b)**

Figure 3.4. Slab Polishing: a) Three-Wheel Polisher and b) Polished Slab.

Aggregate Imaging System and Skid Prediction Model

Previously at TTI, Masad et al. worked on a method for predicting long-term skid resistance based on aggregate properties before and after polishing, not based on a replicated mixture (*18*). The technique uses the aggregate imaging system (AIMS) (Figure 3.5), which photographs the silhouette and near-field high-resolution images of individual aggregates (Figure 3.6) to characterize their shape, angularity, and surface texture. The AIMS device removes user error and bias, and automates several steps of aggregate characterization.

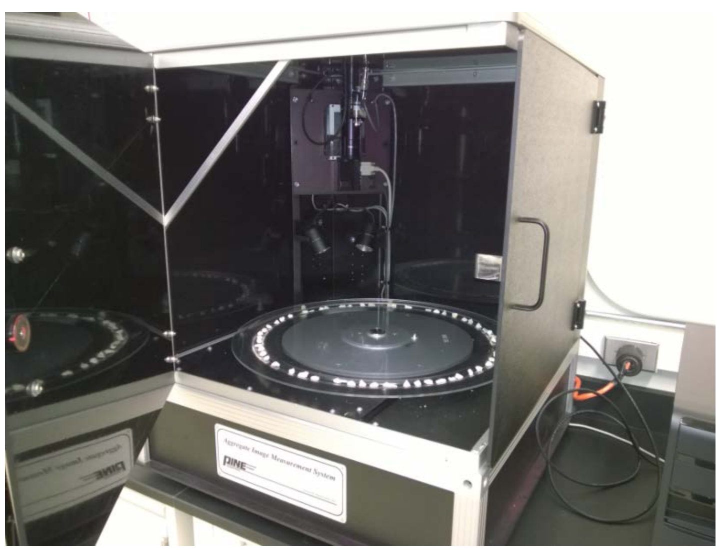
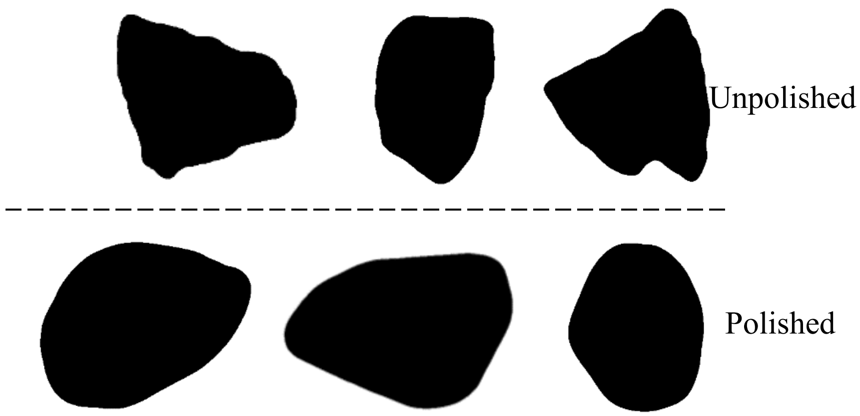
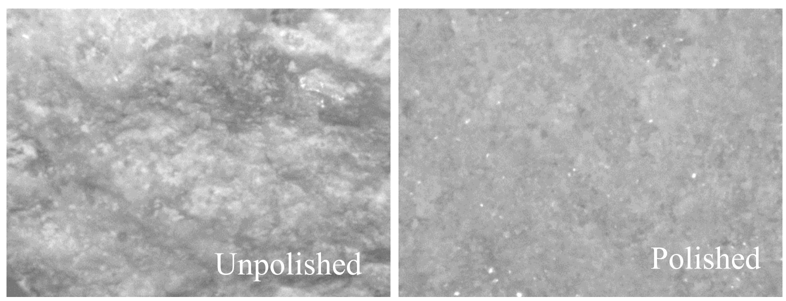


Figure 3.5. Aggregate Imaging System (AIMS).



(a)



(b)

Figure 3.6. Aggregate before and after Micro-deval: a) Shape/Angularity and b) Texture.

The coarse fraction of each aggregate type (retained on No. 4 sieve) was washed, dried, and then conditioned in the micro-deval for 1,000 cycles, according to Tex-461-A. The weight retained on the No. 16 sieve before and after micro-deval was used to calculate the percent loss. Aggregates before and after micro-deval were processed with the AIMS device. Per instructions, measurements were made separately for aggregates retained on the 3/8-inch and the No. 4 sieves. No materials were retained on the larger sieves.

Statistical Analysis

The DFT results were analyzed with analyses of variance (ANOVA). Table 3.2 summarizes the dependent variable and explanatory variables. The optimal models met the following criteria:

- Maximize the adjusted R^2 value.
- Significant factors have a p-value ≤ 0.05.
- Other factors must have a p-value ≤ 0.20.
- Avoid explanatory variables with high inter-correlation.
- Main factors of interactions must be included.
- Components of the model should be reasonable theoretically.

Table 3.2. Inputs for ANOVA.

Dependent Variable	Explanatory Variables*	Variable Type	Values
μ at 20 km/h	Gradation type	Class	Fine, Coarse
	% SAC B	Class	0, 25, 50, 75, 100
	Agg. Type	Class	A, B1, B2, B3, B4
	Cycles	Class	2K, 30K, 100K
	Mean Profile Depth	Quantitative	-
	Avg Angularity Before	Quantitative	-
	Avg. Angularity After	Quantitative	-
	Avg. Texture Before	Quantitative	-
	Avg. Texture After	Quantitative	-

* Two-way and limited 3-way interactions were also investigated

Three models were identified: one for all the data together, then two for the TOM and TOM-B data separately.

Post-hoc tests were conducted to identify significant differences among factor variables. The least square means (a type of statistical average) were compared with Tukey's Standard honest significant difference (HSD) tests.

RESULTS

Figure 3.7 gives an example of the data obtained from this study, showing the effect of slab polishing on a TOM with different replacement percentages of aggregate B1. The thick black line represents 100 percent trap rock, and each line below is the incremental replacement of the trap rock with B1. The shaded area below $\mu = 0.3$ is what the researchers suggest as a rejection criterion. From past experience, the researchers noted that designs with low-quality SAC B aggregates have a polished friction coefficient below this value. However, this criterion is based on general observations and needs to be verified with field correlation testing. In addition, this value does not account for the effect of macrotexture.

The figure shows that polishing decreases friction, and the higher the SAC B aggregate substitution there is, the lower the friction. For some samples, the trend was not as clear. In addition, different aggregates had different rates of friction loss.

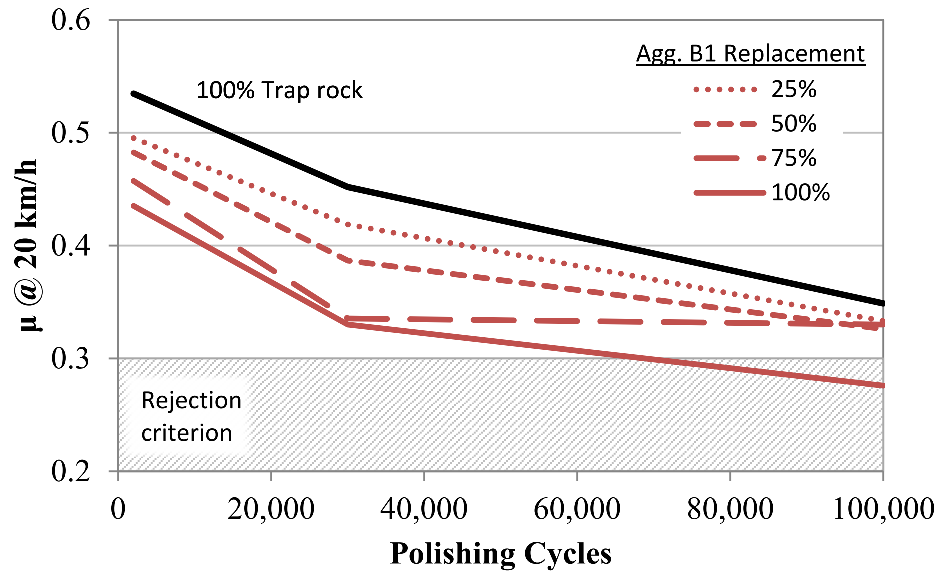


Figure 3.7. Polishing Resistance of a TOM Slab with B1 Aggregate Substitution.

Figure 3.8 show the macrotexture readings before and after polishing for both mix types. Based on statistical *t*-tests, macrotexture was significantly different between mix types (~1.0 mm for TOM versus ~0.60 mm for TOM-B), and polishing reduced the texture of TOMs. Polishing did not significantly reduce or increase texture on TOM-B designs.

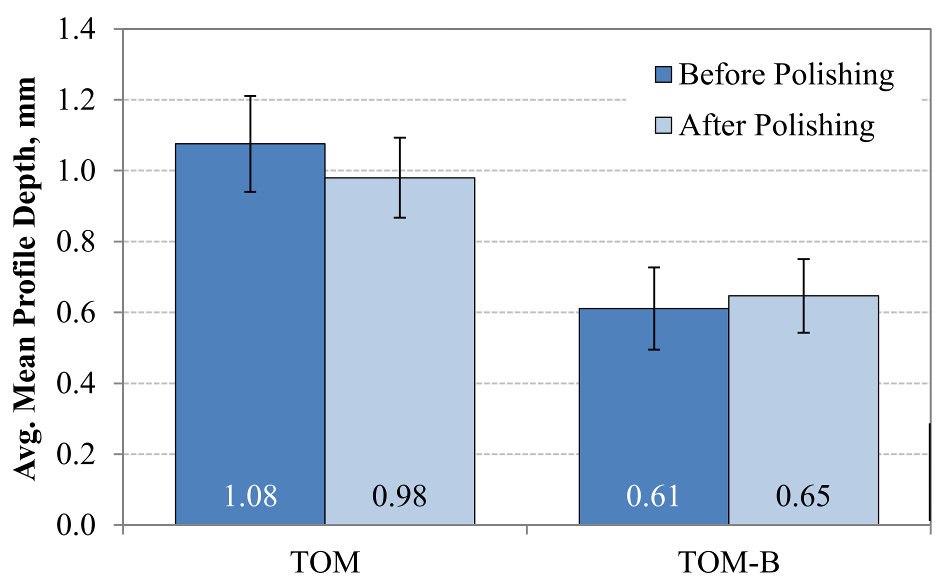


Figure 3.8. Macrotexture before and after Polishing.

Table 3.3 presents the AIMS results. The trap rock maintained Moderate values for angularity and texture after polishing. Angularity of aggregates B1, B2, and B3 dropped to Low after polishing. All replacement aggregates had Low texture before and after polishing.

Table 3.3. AIMS Results.

Property	Name									
	A		B1		B2		B3		B4	
Avg. Angularity										
Before polishing	3049	Mod	2856	Mod	3036	Mod	2814	Mod	2940	Mod
After polishing	2203	Mod	1977	Low	2385	Mod	1500	Low	1798	Low
Avg. Texture										
Before polishing	443	Mod	96	Low	178	Low	159	Low	127	Low
After polishing	400	Mod	74	Low	86	Low	80	Low	73	Low

Table 3.4 summarizes the statistical model results. All models had R^2 values greater than 0.90, and had the main factors of *Cycles, % SAC B,* and *SAC B Agg. Type*. The "All Data" and "TOM-B" models had a significant three-way interaction among these main factors, meaning that for a given substitution percentage, and a given degree of polishing, some SAC B aggregate would perform better or worse than other SAC B aggregates. The "All Data" model also included a *Mean Profile Depth* factor, to account for a difference between the TOM and TOM-B designs. The TOM Model was slightly stronger without the three-way interaction, only considering two-way interactions instead.

One observation about the models is that the friction coefficient, μ, *decreases* as macrotexture *increases*. This has been observed in other studies as well. It may be attributed to the fact that more texture results in less contact between the slider and the surface.

Factors that were not part of the models were AIMs measurements and associated interactions. This is not to say the values were poor predictors of performance; they were not as significant as grouping aggregates as individual classes rather than by these measured properties.

Table 3.4. ANOVA Results (Models to Predict μ at 20 Km/H).

Factor	p-Value		
	All Data Model	TOM Model	TOM-B Model
Cycles	1.9E-86	9.1E-32	8.7E-52
% SAC B	1.5E-36	1.2E-23	1.3E-26
SAC B Agg. Type	9.6E-07	0.008	1.2E-10
Mean Profile Depth	3.6E-27	0.165	-
Cycles * % SAC B	-	0.001	-
Cycles * SAC B Agg. Type	-	1.2E-06	-
% SAC B * SAC B Agg. Type	-	0.005	-
Cycles * % SAC B * SAC B Agg. Type	1.5E-05	-	6.6E-15
R^2	0.903	0.931	0.966

Table 3.5 through Table 3.7 summarize the comparisons of DFT values from the All Data Model three-way interaction. Each table represents a certain level of polishing (2000, 30,000, and 100,000 cycles). These can be interpreted as the friction value for a thin overlay a month after construction, after a few years, and eventual terminal friction value. The values are ordered from highest friction to lowest friction, and the statistical grouping is given. Values that share a common group letter are not statistically different. The rejection criterion of 0.30 is also included in the comparisons, and any value in the same group, or lower, is considered failed.

For reference, the smooth-tire skid number can be approximated as $SN_S = (100 * \mu) - 10$, though this is not a hard-and-fast rule.

Table 3.5. Statistical Results of All Data Models at 2,000 Cycles.

Factor		DFT,20 Average*	Grouping**							
2K Cycles										
SAC B %	Agg. Type									
0	A	0.544	A							
25	B2	0.528	A	B						
25	B3	0.522	A	B						
50	B3	0.509		B	C					
50	B1	0.502		B	C	D				
25	B4	0.500		B	C	D				
25	B1	0.498		B	C	D				
50	B4	0.491		B	C	D	E			
75	B1	0.488			C	D	E			
75	B4	0.481			C	D	E	F		
50	B2	0.477			C	D	E	F		
75	B2	0.476				D	E	F		
75	B3	0.456					E	F	G	
100	B2	0.454					E	F	G	
100	B1	0.447						F	G	
100	B4	0.443						F	G	
100	B3	0.430							G	
Rejection Criteria		**0.30**								**H**

* Least square mean **Tukey's HSD

At 2,000 cycles, no designs are failing. Designs with 25 percent replacement of B2 and B3 aggregate are statistically the same as the 100 percent SAC A design. Friction drops from 0.54 to 0.45, and lower with 100 percent SAC B replacement. Between these values, there is considerable overlap of performance ranking, and no SAC B aggregate performed statistically better than another at the same level of replacement.

Increasing to 30,000 cycles shows more difference among the designs. Two aggregates at 25 percent replacement (B3 and B1) were grouped with the trap rock design. Aggregate B1 had higher friction at 100 percent replacement than all other SAC B aggregates. These other three designs (100 percent B2, B3, and B4) were not statistically different from the rejection criteria. If applied on a real project, these are expected to have poor skid resistance after a few years of service. Other than B1, there is no clear indication that one of the remaining SAC B aggregates performs better than the rest after 30,000 cycles.

Table 3.6. Statistical Results of All Data Models at 30,000 Cycles.

Factor		DFT,20 Average*	Grouping							
30K Cycles										
SAC B %	Agg. Type									
0	A	0.483	A							
25	B3	0.456	A	B						
25	B1	0.455	A	B						
25	B2	0.435		B	C					
25	B4	0.411			C	D				
50	B1	0.405			C	D				
75	B1	0.403			C	D				
50	B4	0.393				D	E			
50	B3	0.381				D	E			
100	B1	0.366					E	F		
75	B3	0.363					E	F		
50	B2	0.345						F	G	
75	B2	0.339						F	G	
75	B4	0.335						F	G	
100	B2	0.323							G	**H**
100	B4	0.322							G	**H**
100	B3	0.320							G	**H**
Rejection Criteria		**0.30**								**H**

* Least square mean **Tukey's HSD

After 100,000 cycles, several more designs had rejected friction values, including designs with 50 and 75 percent replacement. No designs at 25 percent replacement were rejected. Rejected designs include all with 100 percent replacement, and the B2 and B3 designs with 50 and 75 percent replacement. B2 is a “SAC B+.” On the upper end, with 25 percent replacement, B4 and B3 design were similar to the 100 percent SAC A design. Both of these aggregates are regular SAC B aggregates, and would not classify as “SAC B+.” Among these results, it seems there is an issue with several 75 percent replacement designs having higher performance than their 50 percent replacement counterparts. From a statistical perspective, however, these results are actually no different, suggesting that in the long term, there is little or no difference in performance between 50 and 75 percent aggregate replacement.

Table 3.7. Statistical Results of All Data Models at 100,000 Cycles.

Factor		DFT,20 Average*	Grouping							
100K Cycles										
SAC B %	Agg. Type									
0	A	0.402	A							
25	B4	0.401	A	B						
25	B3	0.390	A	B	C					
25	B1	0.361		B	C	D				
75	B1	0.361			C	D				
75	B4	0.346				D	E			
25	B2	0.345				D	E			
50	B1	0.342				D	E			
50	B4	0.342				D	E			
50	B3	0.323					E	**F**		
75	B2	0.320					E	**F**		
100	B4	0.320					E	**F**	**G**	
50	B2	0.317					E	**F**	**G**	
75	B3	0.313					E	**F**	**G**	
100	B1	0.311					E	**F**	**G**	
Rejection Criteria		**0.30**						**F**	**G**	
100	B3	0.282							**G**	**H**
100	B2	0.253								**H**

* Least square mean **Tukey’s HSD

SUMMARY

Skid resistance, measured in terms of the coefficient of friction and surface macrotexture, was evaluated on two thin overlay types, using different aggregate types and different blending percentages. Samples were polished in the lab to replicate long-term polishing under traffic.

The key results are as follows:

- TOMs can have good long-term skid resistance with 100 percent trap rock (friction coefficient around 0.4 and macro texture around 1.0 mm).
- Friction decreases with more polishing, higher SAC B aggregate replacement, and higher macrotexture.
- At all levels of polishing, only the design with 25 percent replacement of aggregate B3 was statistically the same as the 100 percent trap rock design.
- After 30,000 cycles (a few years of traffic), designs with 100 percent replacement with B2, B3, and B4 were considered failed ($\mu<0.3$).
- After 100,000 cycles (terminal polish value), all designs with 100 percent replacement had failed, as had designs with 50 and 75 percent replacement of B2 and B3, respectively.
- A 25 percent replacement was acceptable for all SAC B aggregates, and a 50 percent and 75 percent replacement was acceptable for B1 and B4, respectively.
- The poorest performing SAC B aggregates were B2 and B3. In contrast, B2 had the *highest* ratings in texture and angularity after polishing of the SAC Bs, and had the lowest measurements for LA abrasion, micro-deval, and soundness in the rated source catalog.
- Correlations among AIMS results and DFT results are currently inconclusive.
- Macrotexture was higher for the TOM (MPD ~1.0 mm) than the TOM-B (~0.6 mm).
- Polishing decreased the macrotexture of TOM designs, and had no significant effect on TOM-B macrotexture.

.

CHAPTER 4
EVALUATION OF TACK COAT AND MILLING PRACTICES ON BOND STRENGTH

OVERVIEW

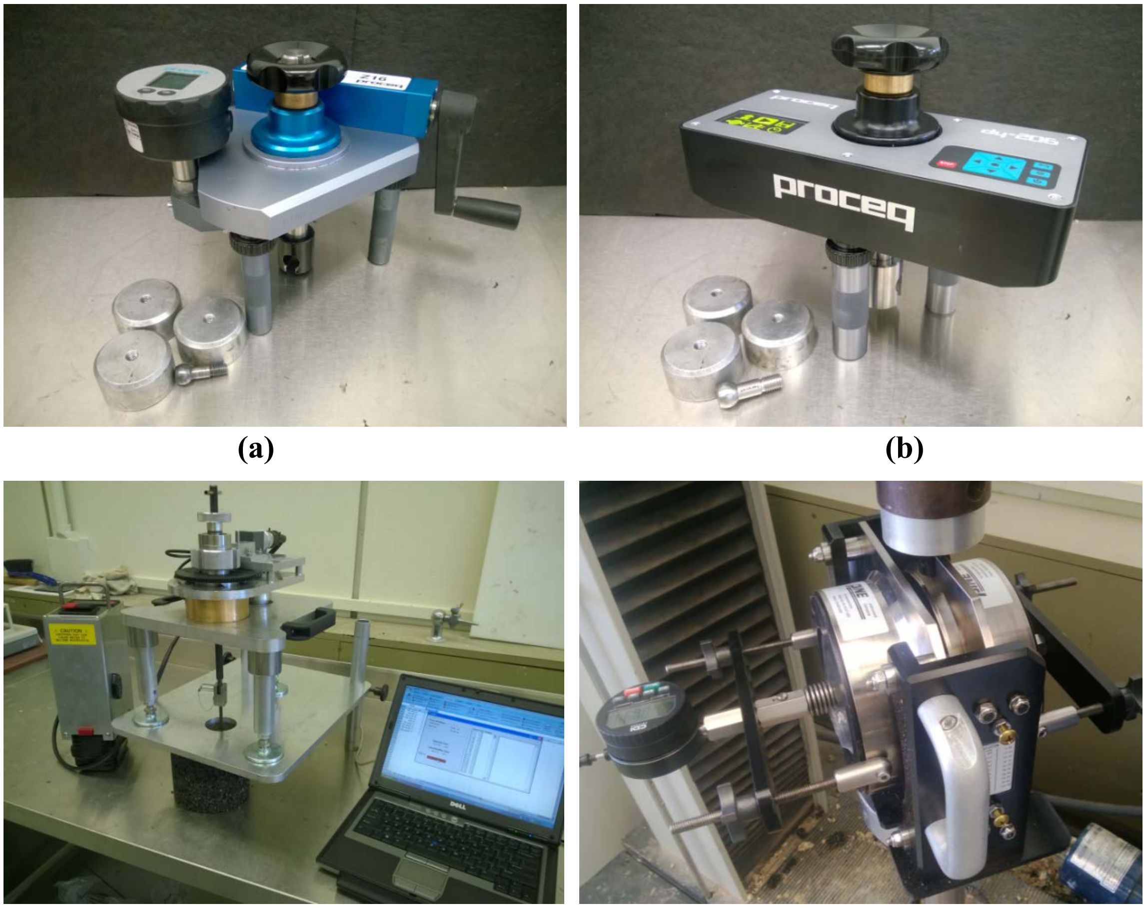
The performance of a thin overlay is largely dependent on the quality of its bond to the underlying layer. Tack coats are placed between pavement layers to improve bonding, but the effectiveness of these coats can vary significantly based on construction and material factors. The optimal rate is a function of existing surface texture, overlay mix gradation, and effective binder contents of the layers. To ensure the optimal rate has been achieved requires some method for testing bond strength.

This chapter reports on the evaluation of the following topics:

- Development of bond strength tests.
- Investigation of a bond strength criterion.
- Evaluation of tack coat and milling practices on bond strength.
- Development of tracking resistance tests for tack materials.
- Development of a micro-milling specification.

DEVELOPMENT OF BOND STRENGTH TESTS

The researchers evaluated four bond strength test devices. Three were direct tension tests and one was a direct shear test (see Figure 4.1). The three tension tests were each compared directly in preliminary testing, and draft test procedures were written. Draft test procedures were also written for the shear device, and comparisons of the shear test to one of the tension tests was done later in this study.



(a) (b) (c) (d)

Figure 4.1. Bond Strength Test Device: a) DynaZ Pull-Off Tester, b) DY-206 Pull-Off Tester, c) Road Science™ Bond Strength Tester, and d) PINE Interlayer Shear Strength Apparatus.

Comparing Tensile Strength Devices

The purpose of the comparative strength testing was to identify the most repeatable tensile-strength device and better understand the best pull rate and other test parameters. Researchers made 6-inch-diameter bonded samples with a Superpave gyratory compactor, and used a TOM for both lifts. The bottom was compacted with 20 gyrations. A non-tracking tack was heated to 170 °F and applied with a brush to the sample surface. The sample and tack were allowed to cure for at least 30 minutes at 140 °F, then the top lift was compacted on top. Table 4.1 shows the test matrix for preliminary tension tests.

Table 4.1. Preliminary Tension Test Matrix.

<table>
<tr><th>Surface Mix Gyrations</th><th>Test Device</th><th>Test Speed</th><th>Test Temp</th></tr>
<tr><td rowspan="4">10</td><td rowspan="3">DY 206</td><td>30 psi/s</td><td rowspan="8">72</td></tr>
<tr><td>5 psi/s</td></tr>
<tr><td>15 psi/s</td></tr>
<tr><td>Road Science</td><td>0.5 mm/min</td></tr>
<tr><td rowspan="10">20</td><td rowspan="3">DynaZ</td><td>0.5 mm/min</td></tr>
<tr><td>5.0 mm/min</td></tr>
<tr><td>0.5 in/min</td></tr>
<tr><td rowspan="5">DY 206</td><td rowspan="3">5 psi/s</td></tr>
<tr><td>40</td></tr>
<tr><td rowspan="2">72</td></tr>
<tr><td rowspan="2">30 psi/s</td></tr>
<tr><td>40</td></tr>
<tr><td rowspan="2">Road Science</td><td rowspan="2">0.5 mm/min</td><td>72</td></tr>
<tr><td>40</td></tr>
</table>

ANOVAs were performed on the resulting data to identify which test and test methods produced the lowest variability.

Table 4.2 through Table 4.4 show the results where bolded values are statistically significant. The first shows that the device type factor was not a significant predictor of bond strength. The only influential factors were the pull rate, sample temperature, compaction effort of the upper mix, and a pull rate*temperature interaction.

The next table shows results from comparing the coefficients of variance (COVs) based on device type and pull rate. This analysis suggests that there is no statistical difference in test precision for a given device or device-pull rate combination. Though not statistically significant, the researchers did note that the COV for faster pull rates was slightly higher.

The last analysis was done to consider the argument that a slower pull rate would favor sample failure at the bond interface. Though more data should be collected to better address this question, the results in Table 4.4 show that testing at the lowest rate (0.5 mm/min) resulted in failures in locations other than the bond about 60 percent of the time. At 5.0 mm/min, non-interface failures occurred 33 percent of the time, and then 66 percent of the time at 12.5 mm/min. There is no statistical backing that one test rate favors failure at the interface over another.

While any of the devices are capable of measuring with reasonable precision, the DY 206 is the most convenient device to use. The pull rate is automated and data are stored automatically, including information about the bond failure modes. The device is highly portable and has accompanying easy-to-use data analysis software. In comparison, the DynaZ device is not automated (manual hand crank) and more prone to operator error, and the Road Science device is large, heavy, and complicated to operate.

Table 4.2. ANOVA Results for Tensile Strength.

Effect	*p*-Value
Device	0.947
Pull Rate	**1.66E-09**
Temperature	**2.62E-17**
Compaction Effort	**0.041**
Compaction Effort*Rate	0.329
Rate*Temperature	**1.05E-07**

Table 4.3. ANOVA Results for Coefficient of Variance among Devices and Pull Rates.

Effect	*p*-Value
Device	0.165
Device*Pull Rate	0.258

Table 4.4. Results of Failure Mode vs. Pull Rate.

		Frequency of Failure Mode, %			
Device	Pull Rate	Pull Stub/ Glue	Within Upper Lift	Bond Interface	Within Bottom Lift
Road Science and DynaZ	0.5 mm/min	33.3	6.7	40.0	20.0
DynaZ	5.0 mm/min	0.0	0.0	66.7	33.3
DynaZ	12.5 mm/min	33.3	0.0	33.3	33.3
DY-206	5psi/s	16.7	38.9	38.9	5.6
	30psi/s	33.3	25.0	41.7	0.0

Developing Draft Specifications

Two draft specifications for bond strength testing were prepared: one for shear testing and another for tensile strength testing. The tensile strength test considered testing with either the DY 206 or DynaZ devices. Specifications are contained in Appendix E.

INVESTIGATION OF A BOND STRENGTH CRITERION

In this subtask, the researchers used computational modeling and shear stress-strain analysis of a bonded HMA layer to predict the maximum expected shear stress at the bond interface under a stopping/turning vehicle. The research team did this with a 3D Finite element (FE) model that used the Abaqus software.

The Abaqus Software

ABAQUS is a suite of finite element analysis modules used for stress, heat transfer, and other types of analysis in mechanical, structural, civil, and related engineering applications. The ABAQUS system consists of several modules, and the key modules for mechanical purposes are ABAQUS/Standard (general purpose finite element module) and ABAQUS/Explicit (dynamic finite element module). The software package Complete ABAQUS Environment (CAE) was used as a framework for modeling, managing, and analyzing the ABAQUS models visually. Figure 4.2 shows the main user interface screen for the ABAQUS/CAE software.

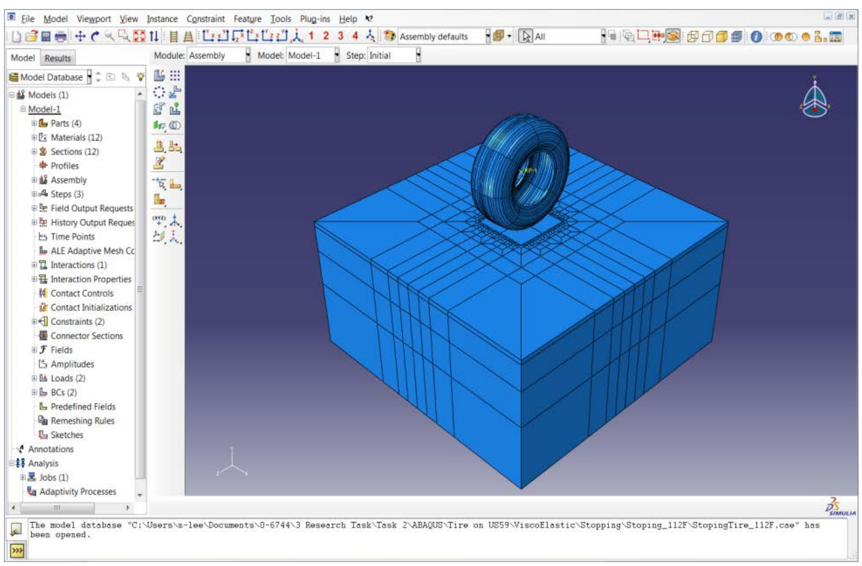
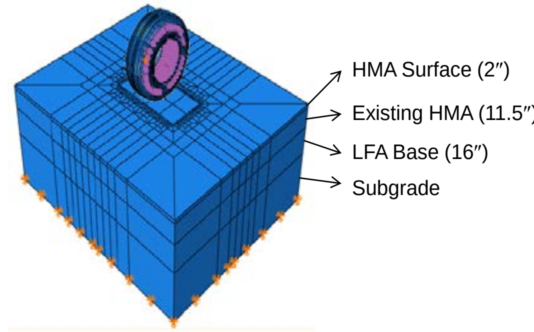


Figure 4.2. ABACUS/CAE Main Screen-User Interface.

Pavement Structure

For the 3-D FE viscoelastic modeling, the US 59 Highway in the Atlanta District—a test section in Study 0-6658, with known material properties and climatic data—was used as the reference PVMNT structure (see Figure 4.3).



Layer#	Thickness (Inches)	Layer Material	Year Constructed
7	2.0	Type D (PG 64-22 with 20% RAP)	2011
3-6	~11.5	Existing HMA	-
1-2	~16.0	LFA Base (8″ + 8″ = 16″)	-
0	∞	Compacted Subgrade Soil	-

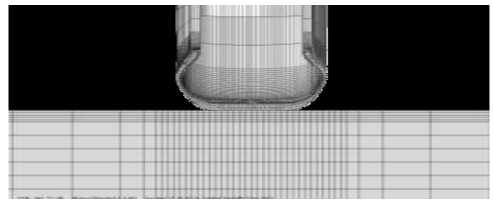


Figure 4.3. US 59 Pavement Structure and Abaqus 3-D Modeling.

Table 4.5 shows the layer thickness and HMA modulus values used for the modeling. The following equation was used to correct the HMA back-calculated modulus to 77 °F (*19*):

$$E_{77^o F} = \left(T^{2.81}/200000\right) \times E_{FWD} \qquad \text{(Equation 1)}$$

Where:

$E_{77°F}$ = Corrected HMA modulus to 77 °F in ksi
E_{FWD} = Back-calculated falling-weight deflectometer (FWD) modulus in ksi without any temperature corrections
T = Pavement temperature in °F during the FWD test that was measured at 1-inch depth.

Table 4.5. Pavement Structure and Moduli Values.

Layer	Thickness (in.)	Layer Modulus (ksi)
HMA Overlay (Type D)	2.0	423.3
Existing HMA	11.5	423.3
LFA Base	16.0	129.8
Subgrade	-	44.0

In this preliminary study, the HMA surface layer was modeled as an isotropic viscoelastic medium and the rest of layers, i.e., the existing HMA, the base, and the subgrade, were modeled as an elastic medium. For simulating traffic loading on the pavement, a tire was modeled inclusive of the rubber, steel wires, and threads.

However, note that for a better representation of the material properties of the PVMNT, viscoplastic and damage properties of both the overlay and the existing HMA need to be considered. In addition, the non-linear anisotropic behavior of the base and subgrade layers must be properly modeled. Nonetheless, the simplified material characteristics assumed in this study gives an initial insight on the stress-strain responses of the PVMNT structure, and serves as an initial step toward a more detailed sensitivity evaluation study.

Material Properties

The time and temperature dependent behavior of the HMA is captured in the Abaqus through modeling the viscoelastic properties of and is represented by the following equations:

$$s = \int_{-\infty}^{t} 2G(t-\tau)\frac{de}{d\tau}d\tau \quad \text{(Equation 2)}$$

$$p = \int_{-\infty}^{t} K(t-\tau)\frac{d(tr[\varepsilon])}{d\tau}d\tau \quad \text{(Equation 3)}$$

Where:

s and e = Deviatoric stress and strain respectively.

p and $tr[\varepsilon]$ = Volumetric stress and trace of volumetric strain respectively.

t = Relaxation time.

K and G, in Equations 2 and 3, are the bulk and shear moduli of the HMA respectively and are calculated from the dynamic modulus test data of the HMA. However, the frequency-dependent dynamic modulus data need to be converted to the moduli values in the time domain using the Prony series as described in Equations 4 and 5:

$$G(t) = G_o\left[1-\sum_{i=1}^{n} G_i\left(1-e^{-t/\tau_t}\right)\right] \quad \text{(Equation 4)}$$

$$K(t) = K_o\left[1-\sum_{i=1}^{n} K_i\left(1-e^{-t/\tau_t}\right)\right] \quad \text{(Equation 5)}$$

Where:

G_o and K_o = Instantaneous shear and elastic moduli, respectively.

G_i, K_i, and τ_i = Prony series parameters.

Linear elastic behavior is assumed for existing HMA, granular base, and subgrade.

Modeling the Interlayer Bond Strength Variation

To ensure the accurate computational modeling of the effect of interlayer bonding on PVMNT structure behavior, it is imperative that the interfacial properties (interfacial strength, interfacial energy, etc.) of the PVMNT materials (HMA) are accurately defined in the FE model. However, due to the complicated nature of the tests required to measure these interfacial HMA properties, the researchers had to seek alternative techniques to simulate the interlayer bond strength variation.

In this preliminary study, the interlayer bond strength between the HMA overlay and the existing HMA was controlled by introducing a very thin (1 mm) layer of linear elastic material between these two layers. The elastic properties (modulus, E) of this thin interlayer were varied to simulate the bonding between the HMA overlay and the existing HMA. To achieve full bonding, the modulus of the interlayer was kept the same as that of the HMA layers (423.3 ksi), whereas an interlayer modulus value of 211.7 ksi (50 percent of HMA modulus) was used to simulate 50 percent bond strength, and so on. Table 4.6 lists the bond strength levels that were considered in this study and the corresponding interlayer modulus values used.

Table 4.6. Interlayer Modulus.

Inter-Layer Bonding	Interlayer Modulus (ksi)
100%	423.3
75%	317.5
50%	211.7

Results and Analysis

The PVMNT structure was developed using the material properties described above. The PVMNT structure was subjected to a single tire with vertical static loading of 9 kips. The tire inflation pressure was 100 psi. Figure 4.4 presents a typical model response.

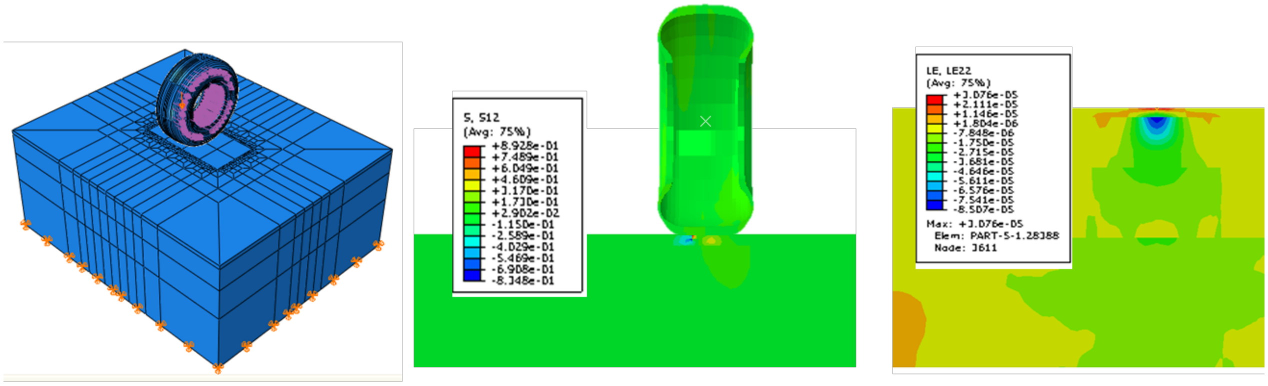


Figure 4.4. Model Assembly and Typical Shear Stress Strain Responses (100 Percent Bonding).

To study the effect of the bond strength on the shear stress at the interface, the researchers calculated the shear stress distributions across the depth of the PVMNT from the model outputs (see Figure 4.5).

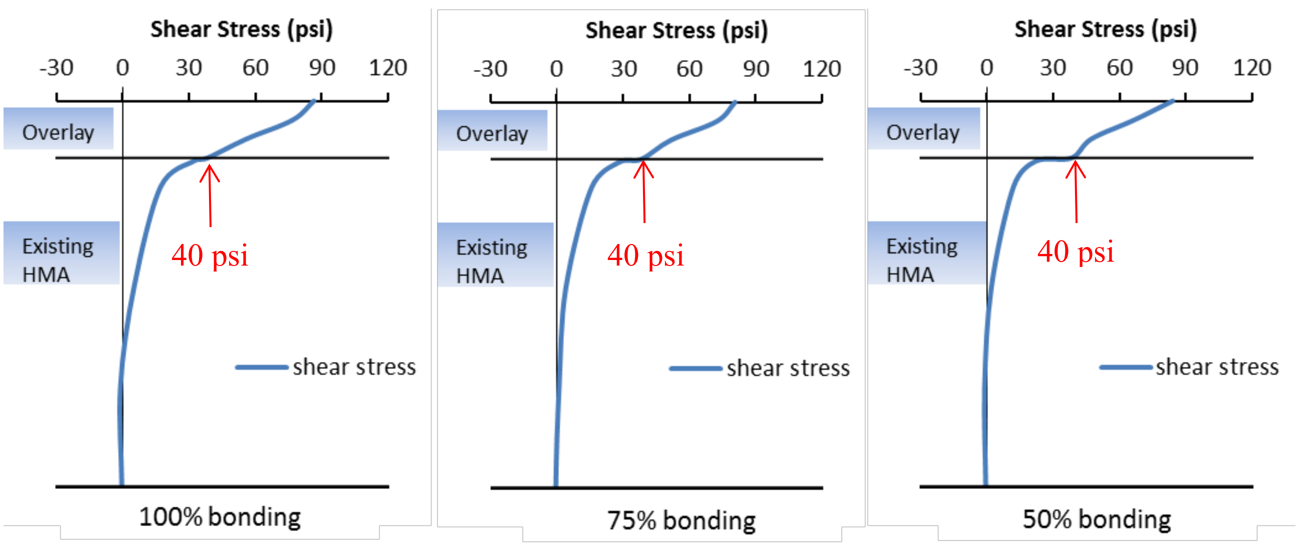


Figure 4.5. Shear Stress Distribution across the PVMNT Depth with Varying Bond Strength.

The maximum shear stress in all three cases remains the same, approximately 40 psi. It is evident that the interlayer bond strength affects the shear stress transfer at the interface of the existing HMA and the overlay. At lower bond strengths (weaker interlayer bonding), the shear stress is less effectively transferred, and thus there is a higher chance of debonding between the layers. However, this effect becomes more prominent when a tilted tire is used for loading instead of a vertically loaded tire.

A tire inclined at an angle of 5° is used to simulate the effect of turning traffic in conjuncture with the varying bond strengths. Figure 4.6 and Figure 4.7 present the results.

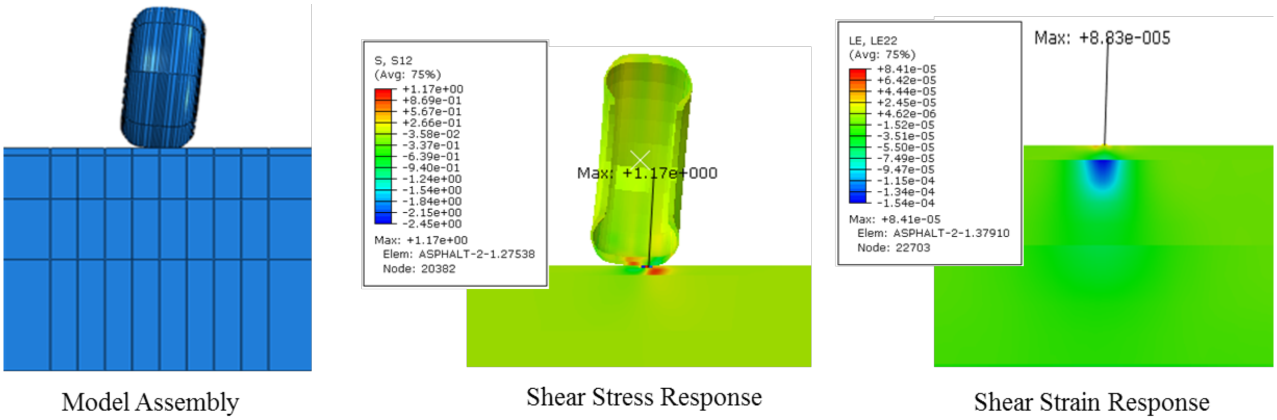


Figure 4.6. Model Assembly and Typical Shear Stress Strain Responses for Tilted Tire (5°).

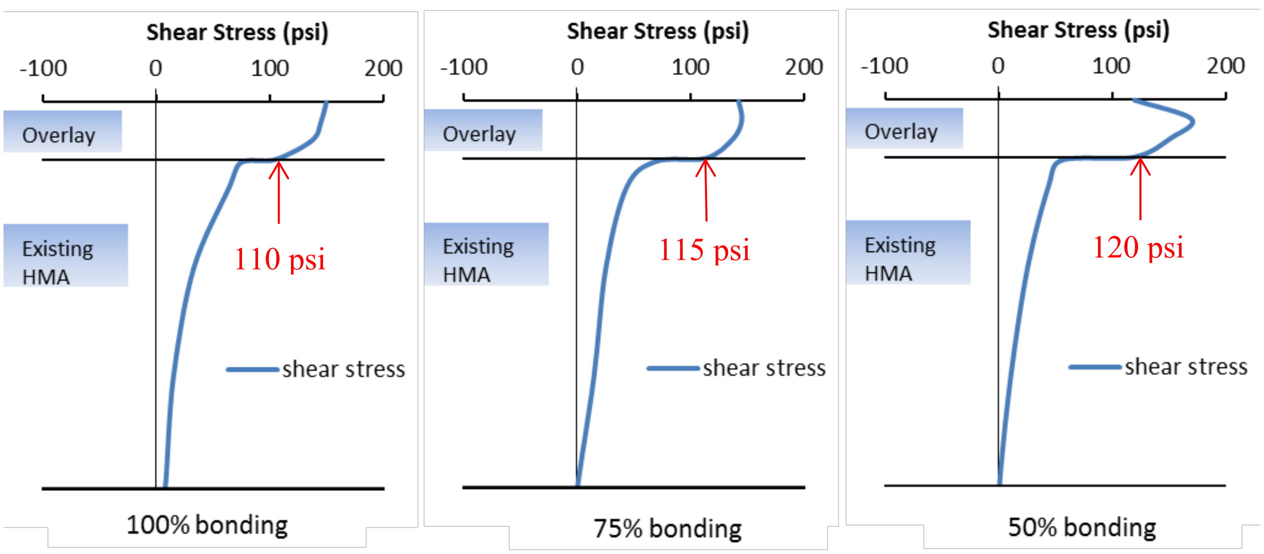


Figure 4.7. Shear Stress Distribution across the PVMNT Depth for Tilted Tire (5°).

From the above figures, it is evident the bond strength plays a more significant role in terms of shear stress transfer across the HMA layers when the tire loading is inclined. An overlay with a poorer bond is subject to higher internal loads and may be prone to premature failure from shoving or cracking.

At this point, the researchers do not consider these results sufficient for formulating a bond strength criteria. This would require validation from the field. But the values identified here (40 psi and 120 psi) are in line with other research findings and specifications: 100 psi (*16*), 87 to 100 psi (*20*), and 40 psi (*21*).

EVALUATION OF TACK COAT AND MILLING PRACTICES ON BOND STRENGTH

The objectives of this subtask are:

- Compare and correlate the tension strength and bond strength tests.
- Evaluate the effect of different tack types and tack rates on bond strength.
- Evaluate the effect of simulated moisture damage on bond strength.
- Compare the effects of different surface textures (dense-graded, open-graded, and milled) and different thin mix gradations on bond strength.

Table 4.7 gives the overall test matrix for this subtask. All sample types were tested with both the shear test and the tension test. This is a fraction factorial design, where more emphasis is placed on testing with a standard tack type (CSS-1H) and using dense-graded Type C HMA. The effects of milling and sample conditioning were a small part of the study.

Table 4.7. Bond Strength Test Matrix.

Base Mix	Surface Mix	Milled	Tack Type	Tack Rate	Conditioning
PFC	PFC-F	N	None	-	N
			CSS-1H	H	
				L	
				M	
	TOM		None	-	
			CSS-1H	H	
				L	
			NT-1	M	
			NT-2		
			NT-3		
			NT-4		
Type C	PFC-F	N	None	-	N
					Y
			CSS-1H	H	N
				L	
				M	
					Y
			B		N
					Y
		Y	None	-	N
			CSS-1H	H	
				L	
				M	
	TOM	N	None	-	N
					Y
			CSS-1H	H	N
				L	
				M	
					Y
			NT-1		N
					Y
			NT-2		N
			NT-3		
			NT-4		
		Y	None	-	N
			CSS-1H	H	
				L	
				M	

Materials

Five tacks were evaluated:

- CSS-1H.
- eTac, now labeled eTac-H, by Ergon.
- FastSet by Western Emulsions.
- Trackless Tack™ by Calumet.
- UltraFuse™ by Blacklidge Emulsions.

CSS-1H is a typical cationic slow-set emulsion used for tack coats. Most of the laboratory testing focuses on this tack, looking at different rates and surface preparation practices. The last four tacks are all marketed as non-tracking tacks. eTac, FastSet, and Trackless Tack are emulsions with a hard-pen base binder. They break relatively quickly and resist tracking. UltraFuse is a hot-applied hard-pen binder that sets up in seconds. In this report, the researchers have anonymized the non-tracking tacks by randomly assigning the designation Non-Tracking (NT)-1 through 4.

Four different HMA types were used in sample preparation:

- Dense-graded Type C.
- PFC.
- TOM.
- PFC Type F (PFC-F).

Plant mix from a Type C and PFC project were used as base slabs, representative of the existing surface. TOM and a PFC-F plant mix were used for the thin overlay.

Procedures

Substrate slabs were compacted in a PMW Linear Compactor (Figure 3.2). These 20 × 20 × 2-inch slabs were used to represent an existing HMA surface. Researchers chose a low target void of 4 percent for the Type C slab to avoid bond strength test failures in the substrate. The PFC target voids was 80. Lower voids in this mix would cause aggregate crushing.

Two of the Type C slabs were given a simulated milled texture using an asphalt scarifier (see Figure 4.8). The average mean-texture depth of the milled surface was a little over 1.0 mm.

Four tack coat types/tack rates could be applied to each slab (see Figure 3.4). For *moderate* tack rates, the researchers followed manufacturers' recommendations. The slabs were preheated to 60 °C (140 °F), then the emulsion tack was applied at 80 °C (175 °F) and Ultrafuse as 163 °C (325 °F) using paint brush, and then the tack coat was allowed to cure for 30 to 60 minutes at 60 °C (140 °F).

The slab was returned to the linear slab compactor where an overlay mix was spread over the tack coat and compacted to 1.25 inches thick to the target void content (92 percent for TOM and 78 percent for PFC-F). Applying a thinner lift of HMA was not possible because of the difficulty in evenly distributing the loose mix. The bonded slabs were allowed to cure at room temperature for at least 30 days.

Figure 4.8. Applying Simulated Milled Texture.

Figure 4.9. Tack Application.

From each slab quadrant, the researchers cored three 4-inch-diameter samples for the shear test and three 2-inch-diameter partial-depth cores for pull-off testing. They placed the moisture-conditioned samples in the InstroTek Moisture Induced Stress Tester (MIST) for 1,000 cycles at 40 psi. All samples were air dried for at least 24 hrs before testing.

Shear testing was performed with the PINE Interlayer Bond Strength Device at a strain rate of 0.5 inch/min. and the tension test with the Proceq DynaZ Pull-Off Tester at a strain rate of 0.5 inch/min (Figure 4.1). The newer pull-off device was not used because TTI evaluated and acquired this device after substantially completing this set of testing.

Statistical Analysis

The research team analyzed the results using various statistical methods, including non-linear regression, *t* Tests, and ANOVAs. In all cases, statistical significance between sample populations was defined with a *p*-value less than 0.05 (95 percent confidence).

At first, a general ANOVA was performed on all the data to identify the most influential variables (main effects). The variables included those intentionally part of the test matrix (slab type, tack type, tack rate, etc.). What could not be observed was the variability associated with each slab sample, which may be a confounding variable.

After the preliminary analysis, five specific comparisons were made (see Table 4.8). Most of these looked at a subset of the data since this project used a fractional factorial test design. In the "Shear test versus tension test" comparison, a non-linear regression model was found between the results from the two tests. Also, the coefficients of variance were compared to see if one test had higher precision or not. ANOVAs were used to compare performance among all the tack types at a moderate application rate, and then with different tack rate and milling practices with CSS-1H. A *t*-test was done to look at the effect of moisture conditioning on CSS-1H samples.

For all but the first comparison, the analyses were performed separately on each base-overlay combination, since the Type C and TOM mixes were significantly stronger than PFC and PFC-F.

Table 4.8. Summary of Statistical Analyses.

		Indepenent Variables						
Comparison	**Dependent Variables**	Test Type	Tack Type	Tack Rate	Milled Surface	Moisture Conditioned	Base-Overlay Combination	**Statistical Test**
Shear Test vs Tension Test	Coefficient of Variance	Avg Shear Strength Avg Tensile Stength	All	All	Yes No	Yes No	All	Non-linear regression *t* Test
Tack Type	Shear Strength Tensile Strength	-	All	Moderate None	No	No	TypeC-TOM PFC-TOM	ANOVA Tukeys HSD
Tack Rate and Milling	Shear Strength Tensile Strength	-	CSS-1H	All	Yes No	No	TypeC-TOM TypeC-PFC-F PFC-TOM PFC-PFC-F	ANOVA Tukey's HSD
Moisture Conditioning	Shear Strength Tensile Strength	-	CSS-1H	Moderate None	No	Yes No	TypeC-TOM TypeC-PFC-F	*t* Test

Results

Table 4.9 shows the ANOVA results on all the data, with only the main effects considered. The following variables were significant at this high-level view:

- Base-Overlay combination.
- Milling.
- Tack type for shear tests.
- Tack rate for tension tests.

The most significant of these was the base-overlay combination. Variability was expected, and can be accounted for by grouping later analyses according to specific base-overlay slab combinations. What is not shown, however, is that there may be significant variation from sample to sample, not caused by these factors, but rather by the sample preparation method, in which four sample types were cut from a single prepared slab. From these data, it is difficult, if not impossible, to isolate the effect of the controlled variables (tack type, tack rate, slab type, etc.) from the uncontrolled variability of compacting one slab from another. Some preliminary study in the project also suggests that density variability within a slab can result in very different tensile and shear strengths. Another main effect was the slab type (Type C versus PFC versus TOM, versus PFC-F).

Table 4.9. General Main Effects from All Data.

	***p*- Value**	
Factor	Shear	Tension
Condition	0.170	0.771
Rate	0.793	**0.022**
Tack Type	**0.026**	0.156
Milling	**1.7E-07**	**2.2E-04**
Base-Overlay	**1.1E-16**	**1.7E-14**

Understanding that the slab sample preparation method may confound the data, the researchers performed more focused statistical analyses. Table 4.10 summarizes the significant and insignificant effects in each comparison. These results are discussed in the following subsections.

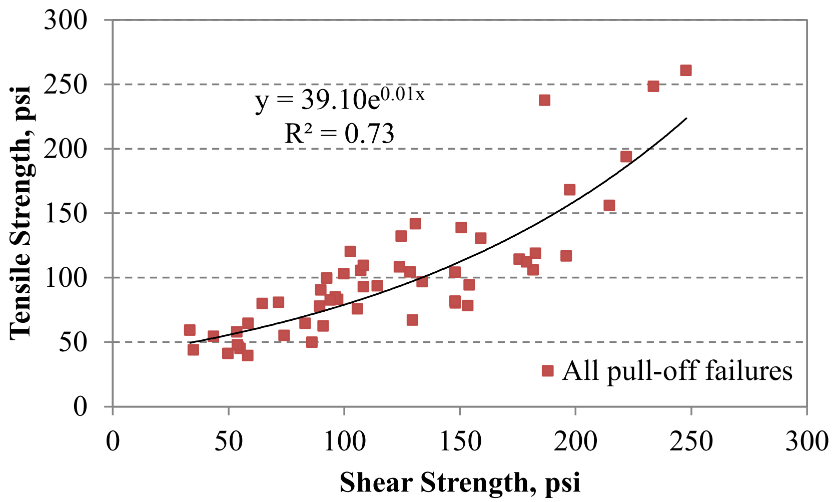
Table 4.10. Statistical Results Summary.

Test	Dependent Variable	Group	Factor	*p*- Value
Shear Test vs Tension Test	Coefficients of Variance	-	-	0.394
Tack Type	Shear Strength	Type C-TOM	**Tack type**	**1.5E-06**
		PFC-TOM	**Tack type**	**4.9E-04**
	Tensile Strength	Type C-TOM	**Tack type**	**0.015**
		PFC-TOM	**Tack type**	**0.022**
Tack Rate and Milling	Shear Strength	Type C-TOM	**Rate**	**2.4E-04**
			Milling	**2.4E-12**
			Rate*Milling	0.420
		Type C-PFPC-F	Rate	0.626
			Milling	**2.1E-04**
			Rate*Milling	**0.015**
		PFC-TOM	Rate	0.931
		PFC-PFC-F	Rate	0.630
	Tensile Strength	Type C-TOM	**Rate**	**0.010**
			Milling	**0.001**
			Rate*Milling	0.546
		Type C-PFPC-F	**Rate**	**0.020**
			Milling	0.997
			Rate*Milling	**0.011**
		PFC-TOM	Rate	0.349
		PFC-PFC-F	Rate	0.242
Moisture Conditioning	Shear Strength	Type C-TOM	Conditioning	0.534
		Type C-PFC-F	Conditioning	0.518
	Tensile Strength	Type C-TOM	Conditioning	0.525
		Type C-PFC-F	Conditioning	0.105

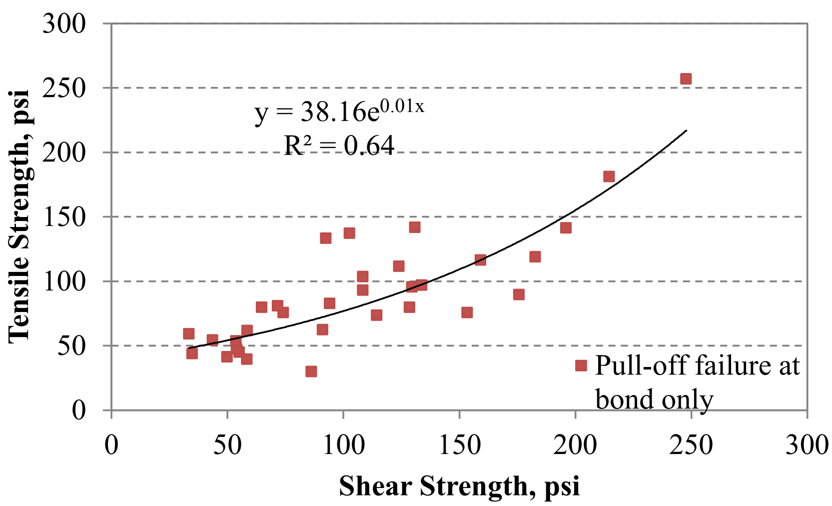
Shear Test versus Tension Test

The *t*-test comparing the coefficients of variance from the shear and tension test were found to be statistically the same. In fact, the averages were nearly identical. What this suggests is that either test could be used without any loss or benefit from the perspective of precision.

Figure 4.10 shows the regression equation used to compare the shear test results to the tension test. When using all available tensile strength data, regardless of failure mode, the R^2-value is 0.73. Looking only at tests failing at the bond interface reduces the R^2-value to 0.64. This suggests that results from a sample failing in a location other than the bond interface may still be considered acceptable. All the following analyses considered all available tensile strength results, not just those failing at the bond.



(a)



(b)

Figure 4.10. Regression Comparing the Shear Test to the Tension Test: a) All Samples and b) Samples Failing at the Bond.

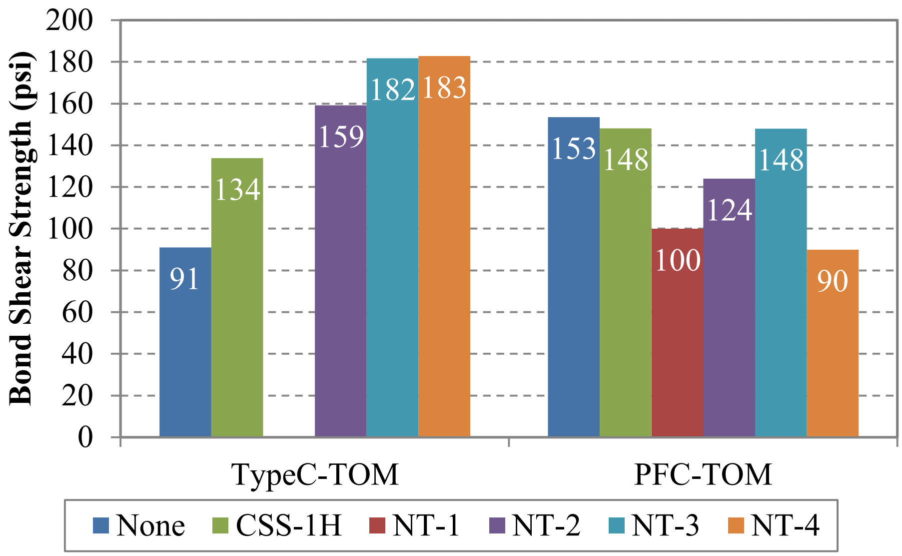
Tack Type

Table 4.10 shows that tack type was a significant factor in all comparisons. This means that at least one tack type was found to be statistically different than another tack (or "None"). Table 4.11 shows the average strengths and statistical groupings, and Figure 4.11 gives the associated plots. There is little consistency found among all the comparisons. Three of the four samples without tack, "None," and samples with CSS-1H had the lowest strengths. However, the trend is surprisingly reversed in the PFC-TOM sample. The ordering of non-tracking tacks 1 through 4 is not consistent. In tensile strength testing, no strength difference was found among the non-tracking tacks, and in many cases the performance of non-tracking tack was no different than CSS-1H.

On the other hand, most of the strengths observed in the lab were very high, and likely higher than what would be observed in the field.

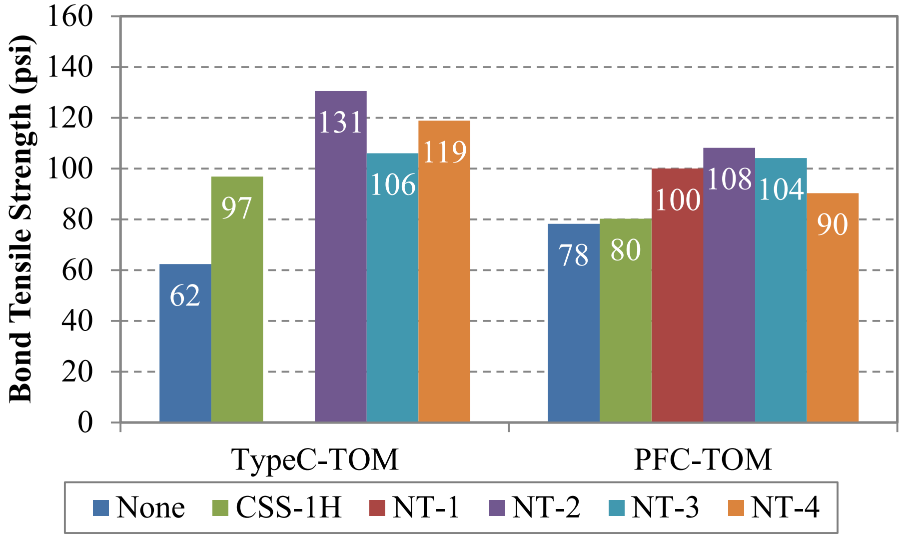
Table 4.11. Statistical Results for Tack Type Comparisons.

Shear Test										
Type C-TOM					**PFC-TOM**					
Tack	Average Strength, psi	Tukey Ranking			Tack	Average Strength, psi	Tukey Ranking			
NT-4	182.8	A			None	153.5	A			
NT-3	181.7	A			CSS-1H	148.1	A	B		
NT-2	159.1	A	B		NT-3	148.0	A	B		
CSS-1H	133.8		B		NT-2	124.0	A	B	C	
None	91.0			C	NT-1	100.0			C	
					NT-4	90.0			C	
Tensile Test										
Type C-TOM					**PFC-TOM**					
Tack	Average Strength, psi	Tukey Ranking			Tack	Average Strength, psi	Tukey Ranking			
NT-2	130.5	A			NT-2	108.2	A			
NT-4	118.8	A	B		NT-3	107.1	A	B		
NT-3	106.0	A	B		NT-1	102.9	A	B		
CSS-1H	96.8	A	B		NT-4	90.3	A	B		
None	62.4		B		CSS-1H	80.3	A	B		
					None	78.2		B		



(a)

Figure 4.11. Strength Results by Tack Type: a) Shear Test and b) Tensile Test.



(b)

Figure 4.11. Strength Results by Tack Type: a) Shear Test and b) Tensile Test. (cont.)

Tack Rate and Milling

Table 4.10 shows that tack rate was significant only for the Type C base slabs and not for the PFC slabs. This may be because the coarser and porous texture of the PFC nullified the effect of increasing the tack rate. The scenario may have been different if the PFC slabs were old and closed up from many years of traffic.

The results from the statistically significant comparisons are given in Table 4.12 and further in Figure 4.12. For the shear test, the moderate application of CSS-1H had the highest bond strength between Type C and TOM (174 psi). All other rates were statistically lower and undistinguishable. In the tensile strength test, the low CSS-1H rate gave the highest strength when bonding both TOM and PFC-F to Type C (144 and 72 psi). In all cases, samples with no tack had the lowest average strengths.

Performance on milled samples was statistically higher than un-milled samples (see Table 4.13 and Figure 4.13). This may be caused by better bonding to the exposed aggregate, better bonding with increased surface texture, or both. In the shear test, bond strength increased for both the Type C-TOM and the Type C-PFC-F slabs (197 psi and 79 psi, respectively). The tensile strength test only saw an increase for the Type C-TOM slab (138 psi). If the increased bond is caused by the surface texture, it may be that the shear result is more affected by milling than the tension test because the shearing mechanisms is required to overcome the aggregate interlock at the bond.

Some tack rate-milling interactions were identified as significant. However, due to the high variability and unpredictability already noted in these results, interpreting these interaction effects is discouraged.

Table 4.12. Statistical Results for Tack Rate Comparison.

Shear Test			
Type C-TOM			
Tack Rate	Average Strength, psi	Tukey Ranking	
Moderate	182.8	A	
Low	181.7		B
High	159.1		B
None	133.8		B

Tensile Test							
Type C-TOM				**PFC-TOM**			
Tack Rate	Average Strength, psi	Tukey Ranking		Tack Rate	Average Strength, psi	Tukey Ranking	
Low	130.5	A		Low	108.2	A	
Moderate	118.8	A	B	High	107.1	A	B
High	106.0	A	B	Moderat	102.9		B
None	96.8		B	None	90.3		B

Table 4.13. Statistical Results for Milling Comparison.

Shear Test		
Average Strength, psi		
Milled	Type C-TOM	Type C-PFC-F
Y	197.0	79
N	105.0	50

Tensile Test	
Average Strength, psi	
Milled	Type C-TOM
Y	138.0
N	95.0

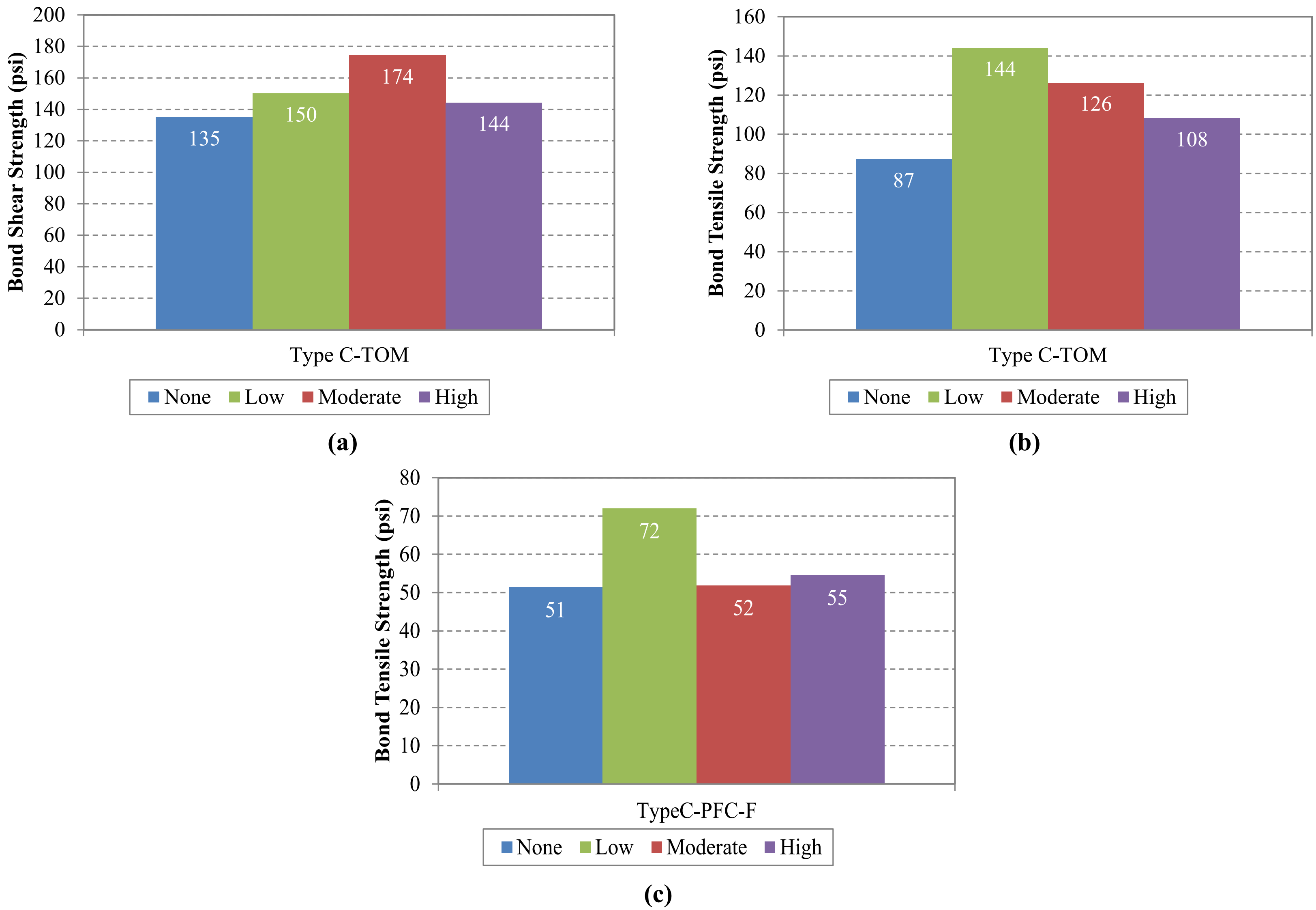
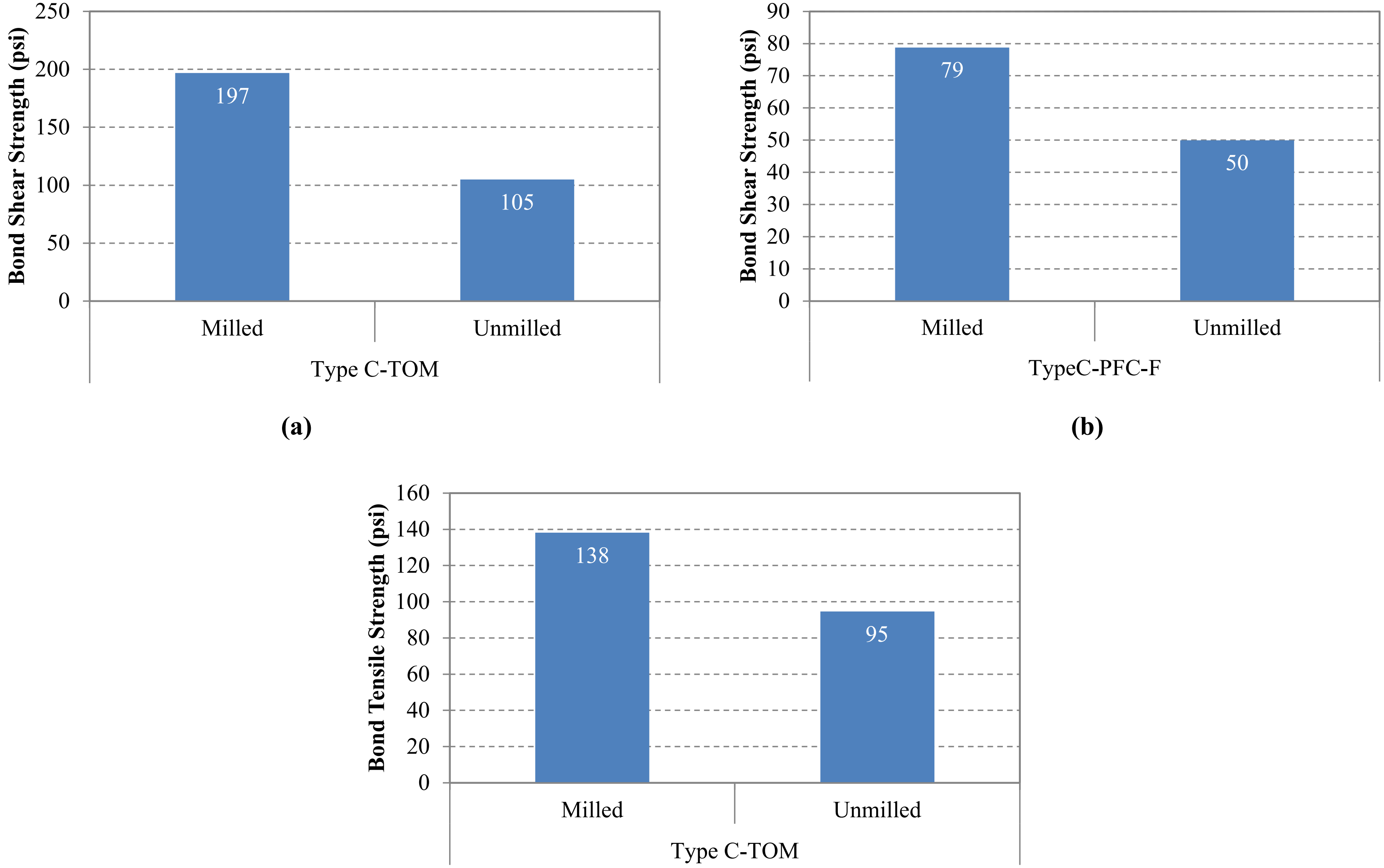


Figure 4.12. Strength Results vs. Tack Rate: a) Shear Test on Type C-TOM, b) Tensile Test on Type C-TOM, and c) Tensile Test on Type C-PFC-F.



(a) (b) (c)

Figure 4.13. Strength Results by Milling: a) Shear Test on Type C-TOM, b) Shear Test on Type C-PFC-F, and c) Tensile Test on Type C-TOM.

DEVELOPMENT OF A TRACKING RESISTANCE TEST

The chemical company, BASF, had previously developed a tracking resistance test similar to ASTM D711-10 (Standard Test Method for No-Pick-Up Time of Traffic Paint). The time it takes a thin film sample to break and lose its tackiness is measured by rolling a heavy wheel with rubber gaskets over the sample and across a piece of paper. In this test, the researchers used the procedures from the BASF company to test different tack materials.

Materials

The same five tack materials were evaluated in this study as in the bond strength study, namely:

- CSS-1H.
- eTac, now eTac-H, by Ergon.
- FastSet by Western Emulsions.
- Trackless Tack^{TM} by Calumet.
- UltraFuse^{TM} by Blacklidge Emulsions.

Procedures

The researchers prepared tack coat samples by spreading tack 15 mils thick with a thin film applicator over asphalt paper. They glued the paper to a wooden board to aid in handling, and confirmed film thickness with a thin film thickness gage. The sample was placed in an oven at 40°C (104°F) to cure. Every 15 minutes, the researchers rolled a 10-lb roller, equipped with heated square-cut rubber gaskets, across the sample and over white poster board (see Figure 4.14).

Tack tracking at each test interval was ranked according to the scale shown in Table 4.14. This rating was done in intervals of 1 inch along the run, so a given tack track could have multiple track rankings. The overall tracking percentage was calculated using a weighted average of tracking severity (Equation 6) and then graphed versus time.

$$Tracking\% = \frac{\sum L_s * MF_s}{L_{Total}} \qquad \text{(Equation 6)}$$

Where

L = length
MF = Multiplication factor
S = Severity

Figure 4.14. Tack Tracking BASF Roller Test.

Table 4.14. Tack Tracking Rating Scale.

Rating	Multiplication Factor	Example
Heavy	1.0	
Mod-Heavy	0.75	
Moderate	0.5	
Light	0.25	
None	0	

Results

Figure 4.15 shows the results of the tracking test. The non-tracking tacks all showed less tracking than CSS-1H. NT-3 had no tracking at all. NT 1 and 4 had less than 30 percent tracking after 15 minutes, and less than 10 percent tracking after 30 minutes. NT 2 had a considerable amount of tracking after 15 minutes, but about 15 percent tracking after 30 minutes. All tacks, including CSS-1H, had essentially no tracking after 45 minutes.

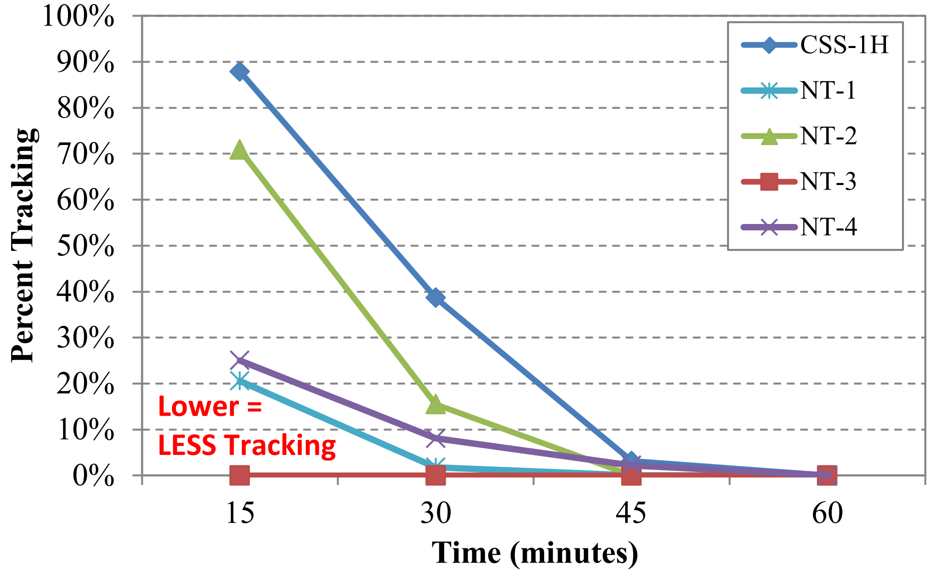


Figure 4.15. BASF Tack Tracking vs. Time.

DEVELOPMENT OF A MICRO-MILLING SPECIFICATION

For this task, the researchers also drafted a recommended micro-milling specification. This is contained in the Appendix E.

SUMMARY

The key results are as follows:

Preliminary Tensile Strength Testing

- In the preliminary study, no one tensile strength device had better performance than another.
- The most influential test parameters in the preliminary study were pull rate and temperature.

Bond Strength Criteria

- Computer models showed higher concentrations of shear stress in the overlay for poorly bonded samples.
- The shear stress at the interface for the lowest slip condition was 40 psi under normal traffic conditions and 120 psi for critical turning/breaking/accelerating conditions.

Effect of Surface Preparation and Tack Coat Practices on Bond Strength

- The tensile and shear strength tests had good correlation with an R^2 value of 0.73. The precision of each test was statistically the same, with an average COV around 15 percent.
- The tensile and shear strength of bonded samples is largely dependent on the type of mix being bonded and the compaction effort, and less on the tack type and tack rate.
- In the tensile strength tests and half the shear tests, non-tracking tacks had higher performance than samples using CSS-1H or with no tack.
- No single non-tracking tack was found to have considerably better performance than the others.
- The tack rate of CSS-1H was significant only when applied on dense-graded mixes, not over PFC, and was most notable in the tensile strength test. Low and moderate levels of tack provided the best bond. Using no tack produced the lowest bond.
- Milled samples had higher strength than unmilled samples, most notably in the shear test.
- Moisture conditioning did not significantly affect the results.

Tracking Resistance Testing

- The BASF roller test was able to discern different non-tracking times among the tacks tested.
- Non-tracking tacks exhibited a range of non-tracking times and different degrees of tracking. Time to less than 10 percent tracking ranged from less than 15 minutes to 45 minutes. Standard CSS-1H had the most tracking overall.

CHAPTER 5
EVALUATION OF COMPACTION AND QUALITY ASSURANCE PRACTICES

OVERVIEW

Achieving adequate compaction in HMA largely governs HMA performance (*22*). Reducing the layer air voids seals the layer against moisture and oxidation, and enhances the structural integrity. The compaction process is particularly critical for thin lifts because the mat behind the screed is prone to rapid cooling. The most common QC/QA techniques for compaction density are 1) coring and directly measuring the bulk density, and 2) non-destructive density gauge testing (*13*). Unfortunately, these methods have severe limitations in thin lift applications. Other methods and technologies may be of use to monitor thin lift density.

This chapter describes field testing of four methods for compaction quality assurance on three thin overlay projects. The following topics were explored:

- Reliability of the current permeability test for density quality assurance of TOMs.
- Investigation into other field density tests.
- Recommended upper and lower limits of density for TOMs.

PROCEDURES

Compaction on three TOM projects was evaluated with four properties: permeability, surface dielectric from ground penetrating radar (GPR), macrotexture from a CTM, and bulk saturated surface-dry (SSD) voids from field cores.

Test Projects

The projects evaluated represent a range of unique thin overlay mix designs, as detailed in Table 5.1. The designs on FM 1887 and US 59 were both TOMs, gap-graded mixes with a NMAS of 9.5 mm. FM 1887 was compacted to 1.0 inches, and US 59 to between 1.0 and 1.25 inches. The RM 12 mix was a UT mixture, also gap-graded, with a NMAS of 4.75 mm. This was compacted to 0.5 mm thick. Each mix was designed with a different coarse aggregate (limestone, sandstone, and granite), different asphalt contents (6.7 and 7.5 percent) and different asphalt grades (PG 70-22 and 76-22).

During construction, the rolling pattern was adjusted to create three sections having low, moderate, and high levels of compaction. This allowed the researchers to assess a wide range of densities with each test method.

Table 5.1. Mix Design Information.

Project	Mix Type	Thickness, in.	Coarse Agg.	Cummulative % Passing 1/2	3/8	No. 4	No. 8	No. 16	No. 30	No. 50	No. 200	Asphalt Content (%)	Grade	Theo. Max SG	Design Density
FM1887	TOM	1	Limestone	100	92.4	45.1	24.2	12.7	10.1	7.8	5.5	6.7	70-22	2.474	97.5
RM 12	UT Mix	0.5	Sandstone	100	99.9	93.9	58.1	35.7	25.1	18.6	11.8	7.3	76-22	2.348	97.5
US 59	TOM	1	Granite	100	94.5	43.3	23	15.5	12.2	10.1	6.6	6.7	76-22	2.440	97.5

Density Testing

After compaction, a rolling density meter, equipped with a 2 GHz GPR, was used to measure the surface dielectric in and between the wheel paths every 0.1 ft (Figure 5.1a). The researchers noted locations with relatively low, moderate, and high dielectric values. Several of these and some randomly selected locations were identified for further testing. This process provided the researchers with test locations having a wide range of mat densities. The team returned to the test locations with the GPR and made focused dielectric readings.

Mean profile depth measurements were made at each location in general accordance with ASTM E2157 (Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter). Three measurements were made: directly above the rolling density meter measurement and offset a few inches to either side (Figure 5.1b).

The water flow was measured using to Tex-246-F (Figure 5.1c). The test was run a minimum of 5 minutes. If terminated early, before draining the specified 10 inches, the elapsed time and current water head were recorded and the expected total flow time was calculated using Equations 7 and 8. The first equation is based on the fluid theory for falling head systems, and the second empirically corrects for overestimations from the first test.

$$t_2 = t_1 \times \frac{ln(h_0/h_2)}{ln(h_0/h_1)}$$ (Equation 7)

$$t_{Corrected} = \frac{t_2 + CF * t_1}{1 + CF}$$ (Equation 8)

Where:

t_2 = Expected flow time at the end of the test, min.
t_1 = Time of measurement and early test termination, min.
h_0 = Water head at the start of the test, 14.5 inch.
h_1 = Water head measurement at early test termination, in.
h_2 = Water head at the end of the test, 4.5 inch.
$t_{Corrected}$ = Expected flow time, corrected for assumption errors, min.
CF = Correction factor from empirical testing, 0.2.

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

Figure 5.1. Field Tests: a) Rolling Density Meter (Dielectric), b) Water Flow (Flow Time), and c) Circular Track Meter.

After testing, the researchers took 6-inch diameter cores at nearly all test locations and brought these back to the lab. Three cores were not obtained because of an equipment malfunction. Lift thickness was noted and cores were trimmed as needed, leaving as much of the overlay intact as possible. Bulk-specific gravity was measured in the lab according to ASTM D2726 (Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures).

Statistical Analysis

The results from the three field tests and from the core voids were compared with non-linear regression analyses in SAS. Each regression model used the power function in Equation 9.

$$y = ax^b \qquad \text{(Equation 9)}$$

Where:

y = Dependent variable.
x = Independent (prediction) variable.
a and b = Constants

Preliminary data analysis showed that data trends were most pronounced on a project level. Therefore, the test result comparisons were done on a project-by-project basis. A total of 18 analyses were performed. A few data points were excluded from the analyses: two flow measurements with no discernable drain down, and a void measurement from a core that was trimmed very thin.

Goodness of fit was determined with a calculated *prediction strength index*, a value between 0 and 1.0, comparable to R^2. The index is an average of R^2 and the standard error of the regression as it relates to the desired measurement resolution. The calculations are shown in Equations 10 and 11. A *good* regression was defined as having a prediction strength index from 0.6 to 0.8, and a *very good* regression had a value greater than 0.8.

$$Prediction\ Strength\ Index = \frac{R^2 + CumNormDist(Z)}{2} \qquad \text{(Equation 10)}$$

$$Z = \frac{Sig.\,Measurement\ Resolution}{RMSE} * 0.6 \qquad \text{(Equation 11)}$$

Where:

CumNormDist( ) = Converts a Z-score to its representative cumulative percent.
Z = Z-score based on the ratio of the significant measurement resolution
RMSE = Root mean squared error.

RESULTS

Regression

Table 5.2 summarizes the regressions analysis results. The results are organized by the test comparison (ex. flow time versus mean texture depth), then by project. Results include the optimized model parameters, the prediction strength index by project, and then the average prediction strength index by test comparison. The *good* and *very good* prediction comparisons are further illustrated in Figure 5.2 (field tests) and Figure 5.3 (field tests versus core voids).

Table 5.2. Regression Analysis Results.

Test Comparison			Regression Results			
			Parameter values		Pred. Strength Index	
x	y	Project	a	b	Individual	Average
Flow	MTD	**FM 1887**	**1.08**	**-0.142**	**0.83**	0.74
		RM 12	0.585	-0.125	0.71	
		US 59	1.19	-0.111	0.69	
Flow	Dielectric	**FM 1887**	**5.18**	**0.037**	**0.90**	0.64
		RM 12	3.72	0.065	0.68	
		US 59	5.04	0.044	0.35	
Dielectric	MTD	**FM 1887**	**253.5**	**-3.33**	**0.88**	0.66
		RM 12	8.48	-2.03	0.70	
		US 59	6.021	-1.054	0.38	
Flow	Voids	**FM 1887**	**12.6**	**-0.195**	**0.85**	0.73
		RM 12	17.7	-0.252	0.54	
		US 59	1.2E+01	-0.092	0.80	
MTD	Voids	**FM 1887**	**11.1**	**1.17**	**0.73**	0.63
		RM 12	35.9	1.57	0.55	
		US 59	10.1	1.07	0.61	
Dielecric	Voids	**FM 1887**	**23044**	**-4.59**	**0.82**	0.69
		RM 12	3706	-4.04	0.74	
		US 59	47.1	-0.883	0.53	

(shaded)	Good --- 0.6 $\leq$ prediction strength index $<$ 0.8
Bold	Very good --- 0.8 $\leq$ prediction strength index

$$y = ax^b$$

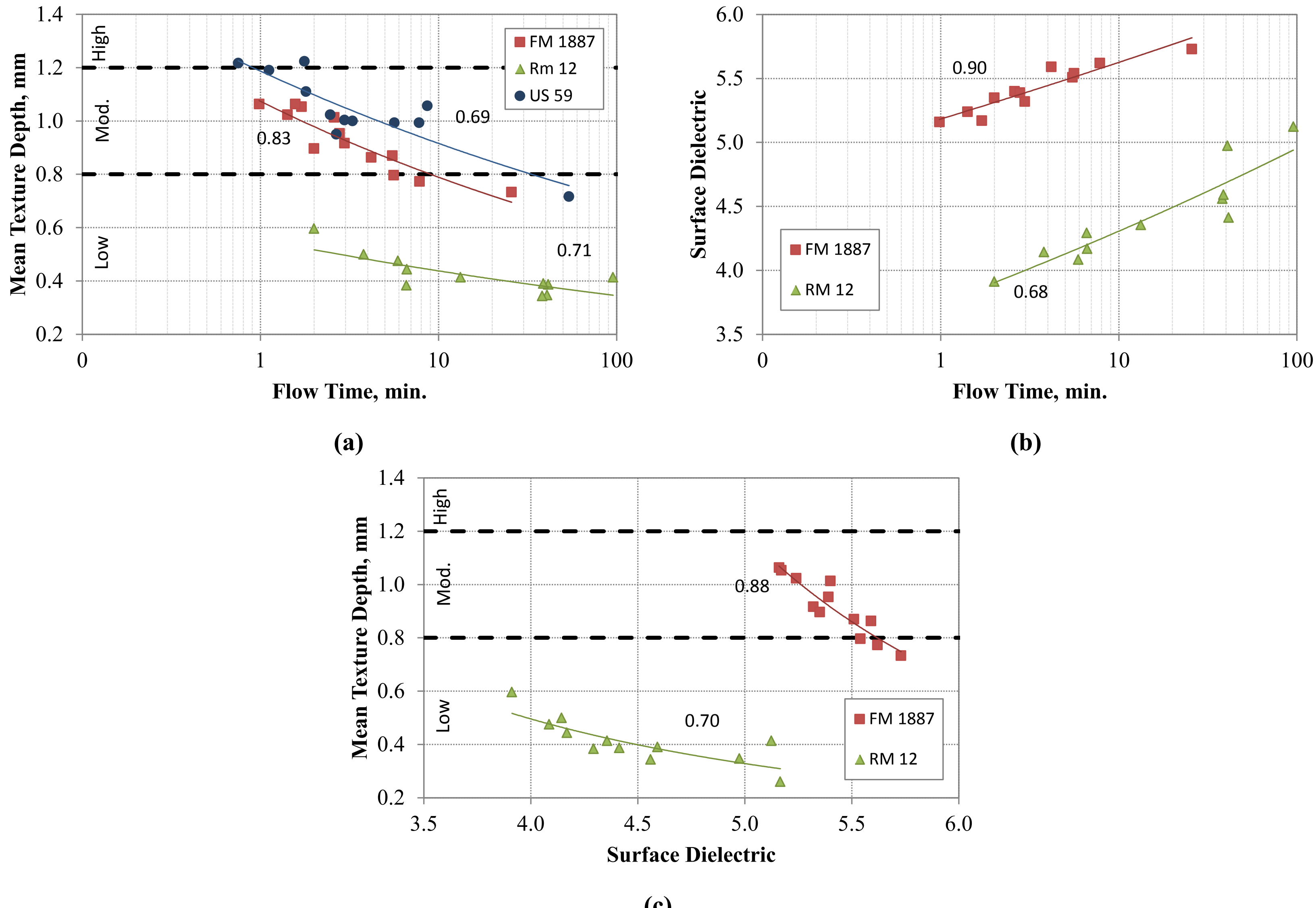
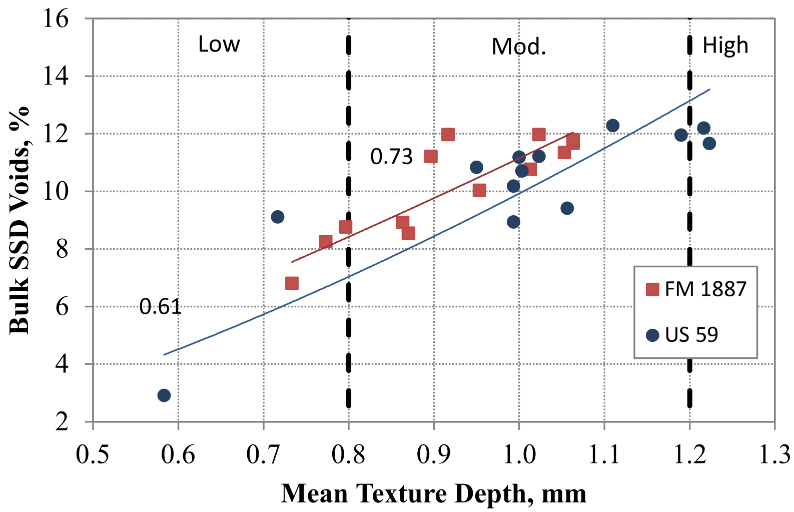
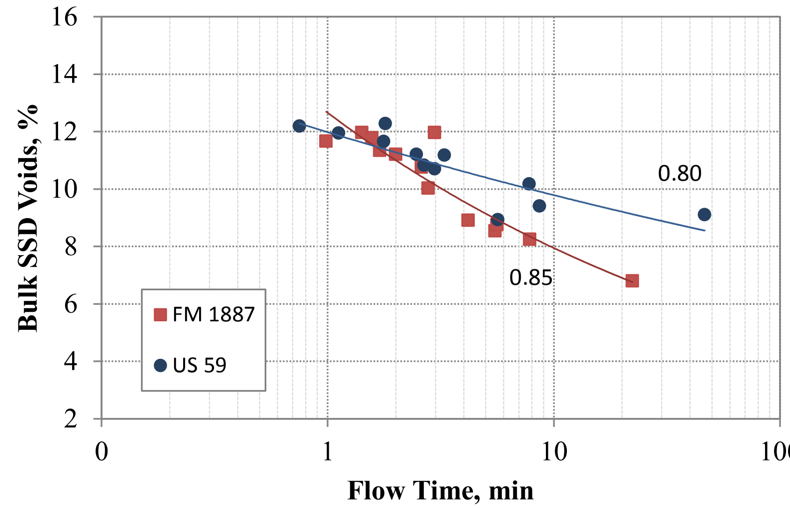


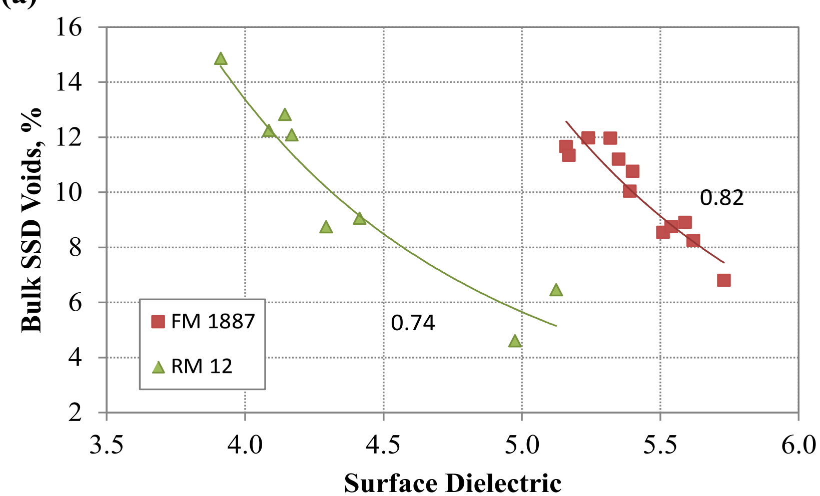
Figure 5.2. Comparisons of Field Test Results by Project: a) Flow Time-MTD, b) Flow Time-Dielectric, and c) Dielectric-MTD.



(a)



(b)



(c)

Figure 5.3. Comparisons of Field Test Results to Core Bulk SSD Voids: a) MTD, b) Flow Time, and c) Dielectric.

Thirteen out of the 18 regressions were rated *good* or *very good*. All tests correlated well with each other on at least two projects, and all had at least one *very good* correlation. The Flow Time-MTD comparison had *good* and *very good* correlations on all projects. The average prediction strength index on each test comparison reveals that the overall strongest test comparisons were Flow Time-MTD, Flow Time-Core Voids, and Surface Dielectric-Core Voids. These had an overall average prediction strength of 0.74, 0.73, and 0.69, respectively. The Flow Time and the Surface Dielectric measurements, therefore, may be best suited to measure mat density. Flow Time is also closely related to surface macrotexture.

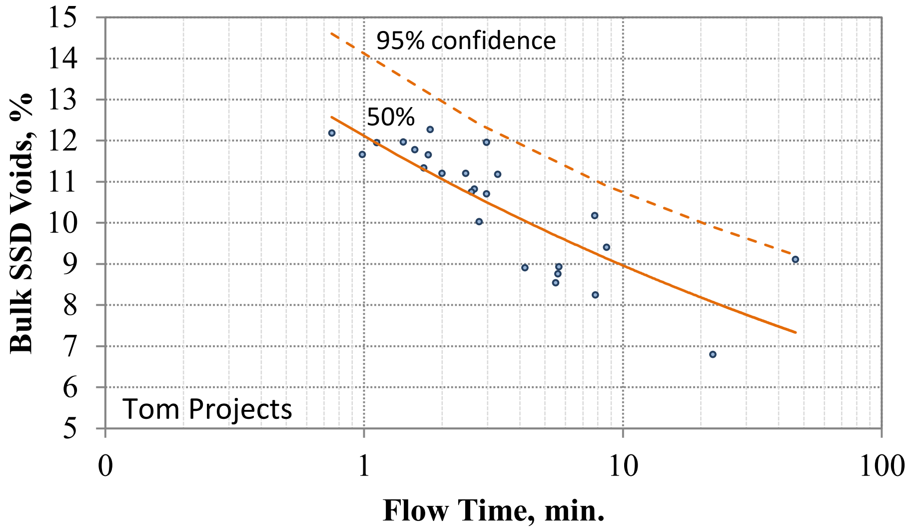
Correlations were all *very good* on the FM 1887 TOM project, the strongest of which was Flow Time-Surface Dielectric (0.90). The project with the poorest correlations was US 59, where the weakest comparisons were with Surface Dielectric. At the time of testing, the researchers noted unusual readings, but were unable to troubleshoot the test equipment. Whether the issue can be explained by a failure of the test equipment is unknown. Results from the RM 12 UT mix project correlated well on half the comparisons. The three weak correlations all involved core void measurements, which is not surprising considering this project was placed at 0.5-inches thick and then cores required trimming as well, pushing the limits of the bulk voids measurement method.

Core voids were in the general range of 7 to 15 percent, with most voids around 10 percent. TOM and UT mix are known for being difficult to compact which could explain the high air void content. The mixes are also fine, which traditionally have higher voids.

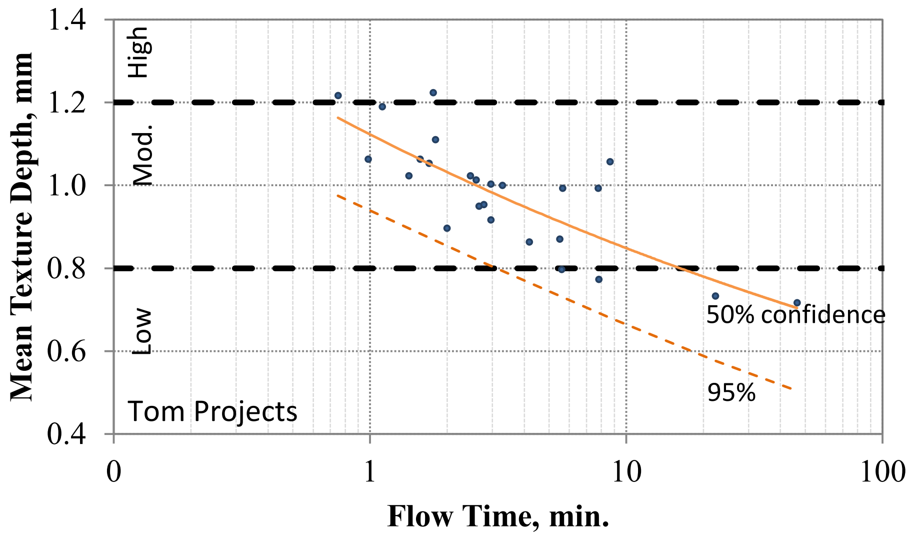
Pass-Fail Criteria

The next step was to define the pass-fail flow time criteria. The current TxDOT TOM specification requires a flow time greater than 60 seconds. Figure 5.4a shows the Flow Time-Core Voids regression for the two TOM projects combined. The upper 95 percent confidence prediction interval is also plotted. If the target compaction voids were 7 percent, at 50 percent confidence, the flow time would be over 1 hour, and at 95 percent confidence would be considerably higher. In practice, the test would only be run a few minutes, then predicted total time calculated with Equations 4 and 5.

Figure 5.4b shows the Flow Time-MTD regression with the additional 95 percent prediction interval. Though not specifically defined, a general division from moderate to low macrotexture is an MTD of 0.8 mm. The regression equations from this study suggest that a flow time of 2 minutes will ensure with 95 percent confidence that macrotexture is greater than 0.8 mm. This is likely too conservative and may present problems with reaching adequate density. Six minutes may be more appropriate, giving a confidence of about 80 percent. Projects with a lower speed limit or non-critical section may be OK with an even higher flow time of 10 minutes. Not shown here, the RM 12 UT mix had a macrotexture between 0.6 and 0.3 mm. Given the finer nature of the mix, achieving a macrotexture in the moderate range will not be possible; therefore UT mix should only be placed on lower speed or non-critical sections.



(a)



(b)

Figure 5.4. Average and 95 Percent Prediction Intervals Based on Flow Time: a) Voids and b)MTD.

Full-Coverage Density Mapping

One benefit of the rolling density meter is it allows for the creation of full-coverage density maps. The operator walks the mat collecting dielectric readings, and these can be converted to predicted density once a correlation has been established. Figure 5.5 is a density map for a portion of a section of RM 12, and the map shows considerable variability. The inner wheel path achieved better compaction than the outer wheel path. This can be explained if the roller compacted the inner half first while the mat was hot, and then the outer half after it cooled.

However, there is also a low-density anomaly between the wheel paths. This kind of variation is important to acknowledge. When performing spot measurements with the water flow test, the test operator should be aware that testing one location to another could yield very different results, even within close proximity. The operator should observe the lay-down procedures, noting actions like the screed stopping, transitions to new batches of mix, hand working, starting and stopping locations of the rollers, roller overlap, etc. Selection of the test location and interpretation of the results should consider these factors. Another option would be increasing the frequency of randomly selected test locations.

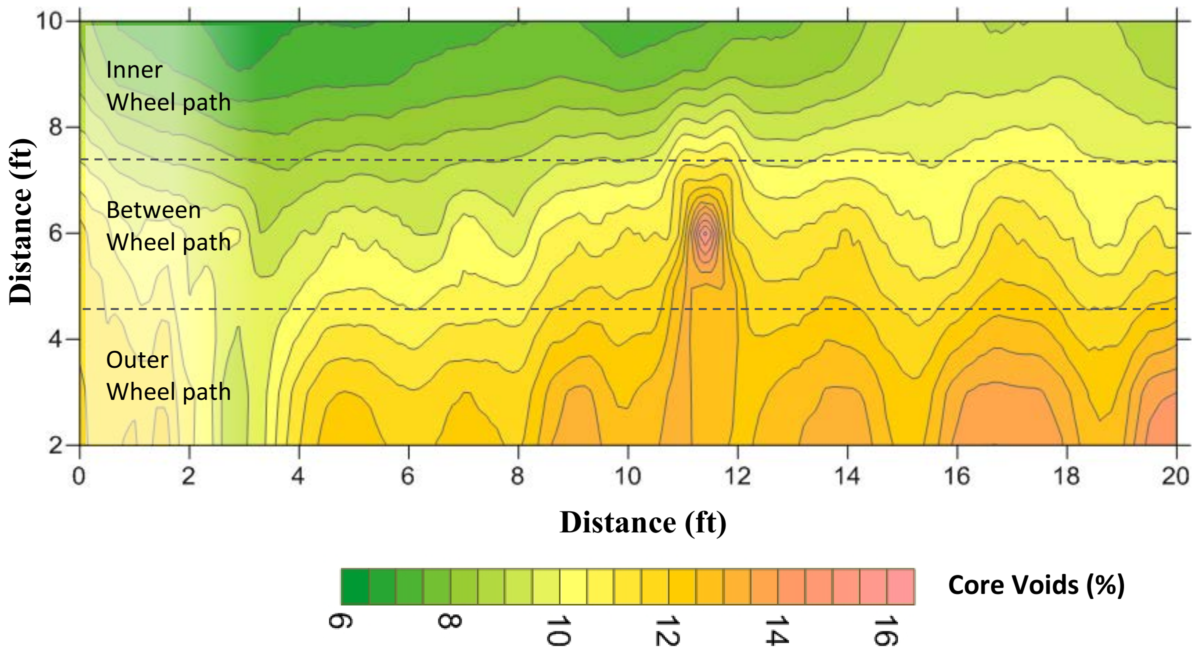


Figure 5.5. RM 12 Density Map from Surface Dielectric.

SUMMARY

The objective of this research was to assess the TxDOT water flow test, rolling density meter, CTM, and traditional core testing for measuring thin HMA overlay density. These four test methods were used on three thin overlay projects, and correlations among the tests were analyzed. When applicable, the researchers identified lower and upper limits of test values to achieve adequate density while avoiding over-densification (loss of macrotexture).

The key results are as follows:

- Correlations of the tests were strong on a project-by-project basis, but generally not good when combining the data sets.
- Flow Time-MTD, Flow Time-Core Voids, and Surface Dielectric-Core Voids were best overall, with average prediction strengths of 0.74, 0.73, and 0.69, respectively.

CHAPTER 6
REFINEMENT OF THE TX-CRACK-PRO CRACK PROPAGATION MODEL

OVERVIEW

The overlay test (OT) is currently included in all thin overlay specifications to minimize reflection cracking issues. However, observations have been made of cracking on thin mixes sooner than expected, despite passing the OT requirement. Examples of such problems are:

- A CAM in the Paris District over a cement-treated base.
- A CAM in the Bryan District under similar circumstances.
- A Coarse-Matrix High-Binder Type F (CMHB-F) in the Austin District.

One shortcoming of current OT cycle requirements is that site-specific variables (traffic, climate, pavement structure, distress condition) are not accounted for. Therefore, a given mix that passes the OT criteria could perform well in one location, but exhibit premature failure in another.

Dr. Zhou et al. developed a model for predicting the rate of cracking in a new overlay in TxDOT Project 0-5123, and Dr. Lytton in NCHRP 669 (*23, 24*). The model has been incorporated into a software package called *TxCrackPro* (Texas Overlay Crack Propagation). With this software, the pavement engineer can predict the rate of reflection cracking based on input parameters for traffic conditions, climate conditions, the existing pavement structure, and the surface condition. The final results are a plot of the percent of cracks reflecting through the overlay versus time. Though the model has successfully predicted cracking rates on some projects, the model still has much to be improved upon.

The purpose of this task was to establish new pavement test sections that can be used to further calibrate the TxCrackPro model specifically for thin overlays. Nearly all thin overlay projects recently constructed during this project were placed on intact HMA pavements with minimal cracking. Districts are not interested in placing these thin mixes over jointed concrete or significantly distressed pavement. It was, therefore, not possible to assess crack propagation through thin these mixes to the extent originally proposed. To fulfill the project objectives, the researchers evaluated two previously constructed thin overlay projects (each composed of several mix design types), established one new thin overlay test section including a Type D HMA control section, and identified two upcoming thin overlay projects for evaluation.

SITE DESCRIPTIONS

Data on four overlay projects were evaluated in this research. These included two existing projects with nine different mix designs, and one new project with two mix designs. Two upcoming projects were also identified that can be similarly evaluated if funding can be identified. Table 6.1 summarizes these projects. They represent a wide range of climatic and traffic properties.

For most of the sites, the researchers:

- Measured base and subgrade properties with falling-weight deflectometer.
- Conducted a distress survey and record location, type, and severities of existing cracks.
- Measured the load-transfer efficiency (LTE) across transverse cracks and concrete joints.

Falling weight data and distress surveys were not available for the Pecos RTC sites; however, pictures of the existing site were collected and detailed surveys of the surrounding area were completed. The condition of Pumphrey Drive and Hempstead Road were evaluated on a regular basis, but the Pecos RTC sites were only evaluated once after 2.5 years.

Table 6.1. Projects for the Crack Propogation Model Study.

Street	City	Date Constructed	Overlay Mix Type	Existing Structure/Condition	Traffic	Climate
Existing						
Pumphrey Drive	Fort Worth	Summer 2007	Type F with crumb rubber Type F with Latex Type F with crumb rubber and no tack coat	Jointed concrete	Moderate	Wet-Moderate Freeze
Pecos RTC		Spring 2011	Two Fine PFCs Two Fine SMAs Two CAMs	Block cracked and fatigued HMA	None	Dry-Moderate Freeze
New						
Hempstead Road	Houston	Fall 2013	1-inch TOM over 1-inch Type D 2-inch Type D	HMA with reflection cracking over jointed concrete. Some fatigue cracking.	Low	Wet-Low Freeze
Future						
Wurzbach Pkwy	San Antonio	-	TBD	Block cracked HMA	High	Dry-Low Freeze
US 59-FR	Houston	-	TOM w/ Underseal	Jointed concrete	Moderate -High	Wet-Low Freeze

TESTING

Hempstead Road, Houston

This project is located on Hempstead Road in Houston, and was part of a larger Type D overlay project. While most of the project received a 2-inch Type D overlay, a smaller section had a 1-inch Type D lift followed by a 1-inch TOM. These two sections are shown in Figure 6.1 and the typical section in Figure 6.2. The specific area tested was the westbound inside lane that had a uniform substructure of full-width jointed concrete overlain with 8 inches of asphalt. GPR testing confirmed this substructure.

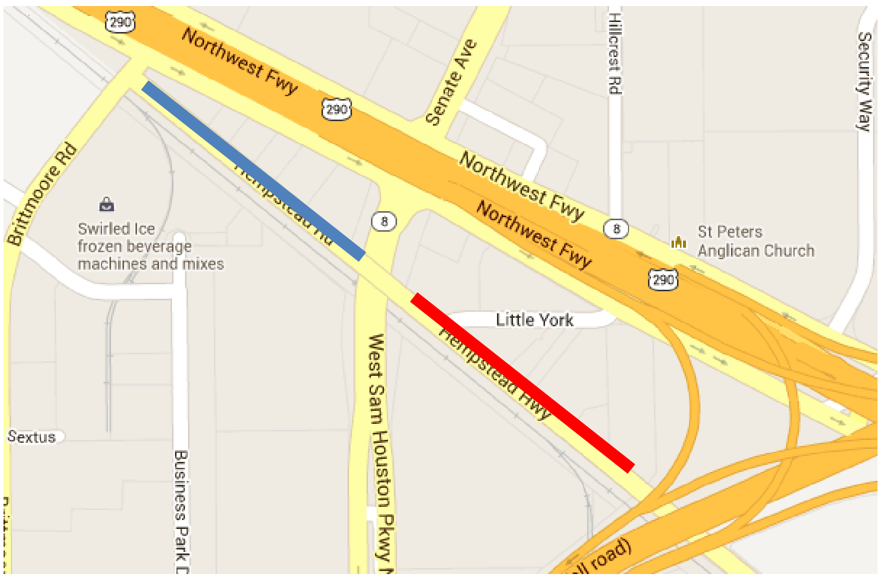


Figure 6.1. Test Section Location.

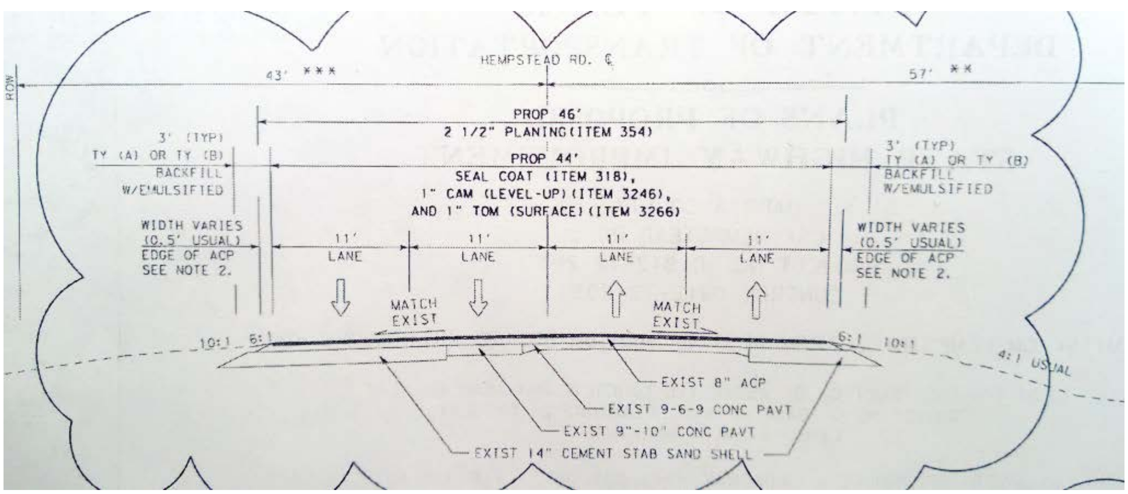


Figure 6.2. Typical Section.

The existing surface had a number of distresses: moderate-high severity reflective transverse cracking (not evenly spaced), low-moderate severity fatigue cracking, and reflective longitudinal cracking. The condition was fully documented with distress mapping, marking the location and severity of each crack. The surface was also milled, better exposing cracks but also leaving an undesirable scabbed surface. The effect of scabbing may confound the results if it causes premature cracking. The researchers used an FWD to measure the load-transfer efficiency across several transverse cracks (Figure 6.4). Measurements were made in September, a warm month, which means crack widths are smaller and will lead to higher LTE.

Figure 6.3. Prepared Surface.

Figure 6.4. Load Transfer Testing with an FWD.

Construction took place in October and November 2013. An underseal was placed prior to paving to protect the existing surface and promote better bonding. Placement of the Type D mix (both the 2-inch test section and the 1-inch level-up lift) was not documented. The following notes are all for construction of the TOM. The air temperature was cool and there was a strong breeze. The conditions were not ideal for construction, but not prohibitive either. The TOM rolling pattern was two vibratory passes and two oscillating passes. Type D and TOM plant mix samples were collected for laboratory testing. The Type D overlay samples lasted 0 cycles in the overlay tester, and TOM samples lasted an average of 435 cycles.

Figure 6.5. Final TOM Surface.

The estimated ESALs in a 20-yr period in the inside lane were estimated as 0.2 million using Equation 12:

$$ESALs = AADT * \%T * T_f * D * L * 365 * 20 \quad \text{(Equation 12)}$$

Where:

$ESALs$ = equivalent single axle loads per day.
$AADT$ = annual average daily traffic (~10,000).
$\%T$ = percentage of truck traffic (~15%).
T_f = truck factor, or average ESALs per truck (~0.21 for urban principal arterial).
D = directional distribution factor (0.5).
L = lane distribution factor (~0.2).

Field and laboratory properties were input into the TxCrackPro software to predict the rate of reflection cracking in both sections. The current model allows prediction of only one distress type at a time. The model also does not allow prediction of an existing HMA layer over jointed concrete. This structure was instead modeled as HMA over a very stiff stabilized base. Also, for the Type D mix, the overlay cycles parameter was set to 1, rather than 0, since 0 cycles results in immediate failure.

After one winter, the site was revisited to check for reflective cracking. At the time, no cracking was observed in either the 2-inch Type D or the Type D/TOM sections. The researchers then visited the site six months later. Still, no distress was visible. Until cracking is present, the comparison of TxCrackPro predictions to actual performance is limited.

Pumphrey Drive, Fort Worth

This project was initially placed in conjunction with research project 5-5123, *Implementation of Thin Lift Type F HMAC Mix Design*. The researchers placed several 1.0- and 1.5-inch Type F mixes over a jointed concrete pavement in the Fort Worth District. Each design had slight alterations with the binder type (PG 64-22 only, with 3 percent modified SBR latex, and with 7 percent crumb rubber). Figure 6.6 shows the section location and layouts.

The existing condition was generally acceptable in the main lanes, aside from some longitudinal cracking and settlement distresses. The ramp section had issues with spalling joints. Problem locations were repaired full-depth before overlay construction.

The project was constructed in July and August 2007; the researchers followed the typical pavement surface preparatory practices. The pavement surface was swept and tack coated prior to the HMA placement. One section, noted in the figure, was not tacked. During paving, the pavement and air temperatures were 106°F and 78°F, respectively, and rising. The overlay mat thickness for the north half of the project was 1.5 inches, and 1.0 inches for the south half where traffic volumes are lower. Two steel rollers, an 18-ton and 5-ton, were used in static mode on the southbound outside lane. The 18-ton roller was used for the mix breakdown in two to four passes, and the 5-ton roller used as the finishing roller at two to three passes. Rolling compaction in vibration mode was conducted only at the joints.

To accelerate the compaction operation, two 18-ton steel rollers placed two passes each on all the other lanes for both the crumb rubber and SBR latex mixes. One of the 18-ton breakdown rollers generally followed just behind the paver. No density measurements were conducted; only the 1-inch mat thickness was monitored.

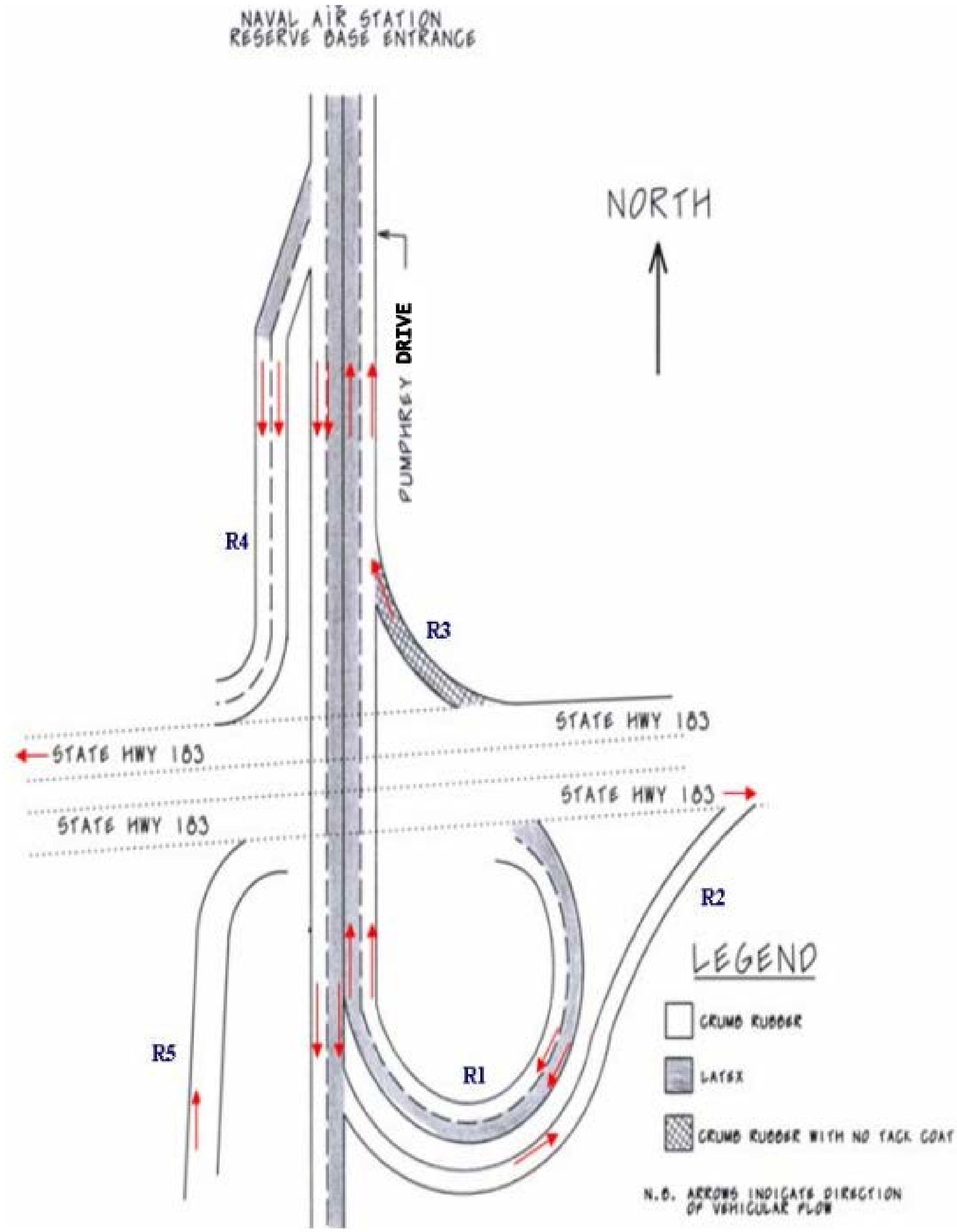


Figure 6.6. Pumphrey Drive Layout.

Reflection cracking on this project has been monitored over the past 7 years every 6 months. In this project, the research team visited the site once again to collect updated reflection cracking data. They observed the pavement condition above each underlying concrete joint, and designated these as either "cracked" or "not cracked." The data collected were added to the existing data set.

Pecos RTC

The entry road and northern portion of the circular test track were used for the thin overlay sections (Figure 6.7). The following thin overlays were designed and constructed on these sections using two different material sources, and three gradation types (dense, gap, and open-graded):

- Hoban-CAM.
- Hoban-Fine SMA.
- Hoban-Fine PFC.
- Eastland-CAM.
- Eastland-Fine SMA.
- Eastland-Fine PFC.

Figure 6.8 shows the test section layout. Section lengths measured from 560 to 1420 ft.

Figure 6.7. Project Location on Testing Facilities.

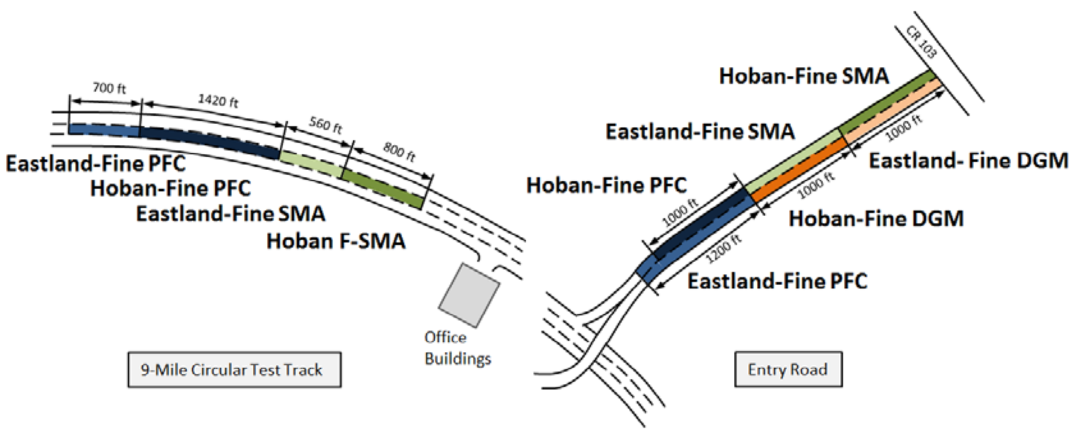


Figure 6.8. Section Layout.

The existing pavement structure of the entry road consisted of a thin 1-inch overlay on 9 to 15 inches of base. The circular track structure is 5 inches of HMA on 12 inches of base. The HMA here may consist of an older 3-inch layer with 2 inches of newer asphalt on top. Cracking in the test track extends to the bottom of the asphalt. Both sections were subject to very low traffic.

Both pavement surfaces are heavily distressed. The entry road has extensive fatigue cracking. The middle lane of the test track, in the area of the thin overlays, has block cracking and fatigue cracking around the construction joints (see Figure 6.9).

Table 6.2 summarizes the mix designs. Hoban mixes used rhyolite gravel from the Hoban for the coarse aggregate and a limestone screening from Turner. The Eastland mixes used Eastland limestone for both the coarse and fine portions. All mixes used Alon PG 76-22 asphalt binder. Additional 0.3 percent fibers were used in the PFC and SMA mixes. All mixes passed the Hamburg test. The CAMs passed the overlay test very well. The fine SMAs did not pass the overlay test at 6.5 percent, which is why the recommended asphalt content was so much higher. The fine PFCs passed the overlay test.

(a) Entry Road **(b) Test Track**

Figure 6.9. Surface Distress.

The thin overlays were constructed at the end of April in 2011. The fatigued pavement was left unrepaired and unsealed. A tack coat was applied beneath each overlay. No significant complications occurred during construction. Limited measurements with a nuclear density gauge were made on the two fine SMA mixes but not on any of the other sections. The Hoban-Fine SMA section on the entry road was compacted to an average 92.7 percent maximum density. The same mix on the test track was at 88.5 percent density. The Eastland-Fine SMA section on the test track was at 94.3 percent density. In all cases, much lower densities were observed within the first 200 ft of paving.

Table 6.2. Mix Composition.

Mix Type	Aggregate Composition	Aggregate Quarry	Asphalt	Other	Hamburg Rut Depth (mm)	Hamburg Cycles	Overlay (cycles)
CAM							
Hoban	65% Gr 6 35% Scrn	Hoban Turner	8.8%	-	5.5	20,000	2,855
Eastland	30% Gr 5 70% Man sand	Eastland Eastland	8.1%	-	10.4	20,000	1,028
Fine SMA							
Hoban	60% Gr 6 40% Scrn	Hoban Turner	7.0%	0.3% fibers	2.3*	20,000*	27*
Eastland	60% Gr 6 40% Man Sand	Eastland Eastland	7.2%	0.3% fibers	3.9*	20,000*	156*
Fine PFC							
Hoban	100% Gr 5	Hoban	6.5%	0.3% fibers	8.1	10,000	635
Eastland	100% Gr 6	Eastland	6.5%	0.3% fibers	6.3	10,000	640

* Tested at 6.5%

One water flow measurement was made on the Hoban-Fine PFC and was less than 9 seconds, passing the maximum 20-second requirement. The Eastland-Fine PFC, on the other hand, initially had an average water flow value (WFV) of 33 seconds. The roller pattern was then lowered to two passes, and the average WFV was 23 seconds.

The overlay performance was evaluated three times since construction, but it was assessed visually only once after 2.5 years (August 2013). Table 6.3 summarizes the surface distress. On the entry road, the conditions of each mix were very good except the Eastland CAM. There was minimal transverse cracking in the Hoban-CAM, but extensive transverse and random cracking in the Eastland-CAM (see Figure 6.10). Most of the transverse cracks were starting along the pavement edge, and the random cracking was between the wheel paths. The researchers are still considering why the asphalt-rich CAM performed so much poorer than the other mixes. On the circular track, all sections are showing signs of reflective cracking. These are predominantly transverse cracks and are more prominent in the fine PFC sections (see Figure 6.11). The preexisting distress in the circular track was either more severe or more active than on the entry road.

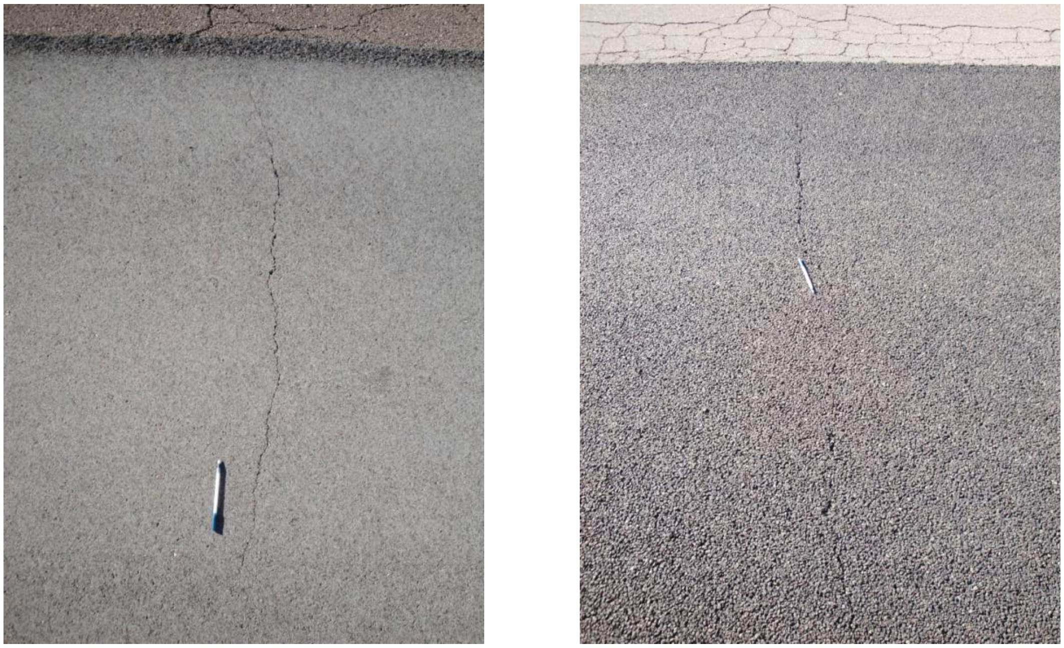
Table 6.3. Distress Summary for Thin Overlays.

Mix Type	Entry Road				Circular Track			
	Transverse Cracking		Random Cracking	Long. Cracking	Transverse Cracking		Random Cracking	Long. Cracking
	Length (ft)	Count	Area (ft^2)	Count	Length (ft)	Count	Area (ft^2)	Count
Hoban								
CAM	0.3	0.2	0.0	0.0	-	-	-	-
Fine SMA	0.0	0.0	0.0	0.0	5.6	2.0	0.0	0.2
Fine PFC	0.0	0.0	0.0	0.0	9.6	3.7	0.0	0.1
Eastland								
CAM	12.5	8.1	25.0	0.0	-	-	-	-
Fine SMA	0.0	0	0	0.0	9.3	2.7	0.0	0.2
Fine PFC	0.0	0	0	0.0	9.1	4.0	0.0	0.1

Values represent distress per 100 linear feet or pavement (1,200 ft^2)
All distress severities were low

(a) (b)

Figure 6.10. Eastland-CAM on the Entry Road: a) Transverse Cracking Near Edge and b) Random Cracking between Wheel Paths.



(a) **(b)**

Figure 6.11. Transverse Cracking in Circular Test Track Sections: a) Eastland-Fine SMA and b) Hoban-Fine PFC

Wurzbach Parkway, San Antonio

Wurzbach Parkway in San Antonio was identified as a candidate project for calibrating the TxCrackPro model. The parkway is an urban principal arterial with an AADT above 20,000. In many sections of the project, the existing surface asphalt has low to moderate severity block cracking, with block spacing between 5 and 15 ft, and crack widths between 1/8 and 1/2-inch (Figure 6.12). While this type of distress may suggest that a more substantive maintenance treatment be selected, coring at these cracks revealed that the cracks were isolated to the top-most HMA layer (Figure 6.13). The surface was micro-milled to remove existing roughness.

This project has unique attributes that set it apart from the other projects in the study. This is the only HMA pavement with surface-layer block cracking on a high-severity traffic road. The project is scheduled for construction next year (2015). If funding is available, the crack propagation behavior on this project will be assessed.

Figure 6.12. Low- to Moderate-Severity Block Cracking on Wurzbach Parkway.

Figure 6.13. Cracking Isolated in the Top HMA Layer.

ANALYSIS

The TxCrackPro software predicts crack propagation through HMA overlays. This model was run for Hempstead Road, Pecos RTC, and also for Pumphrey Drive. The reliability of the Pecos RTC predictions is particularly questionable because of a large number of assumptions made.

Figure 6.14 shows the predicted cracking rates for the sections on Hempstead Road. The Type-D-TOM and the Type D sections had the same predicted cracking rates. Cracking rates were slightly different (though essentially identical) for existing longitudinal, transverse, and fatigue distress. The sections are expected to have 50 percent reflection cracking after just under three years. After 12 months in service, no distress was seen on the surface.

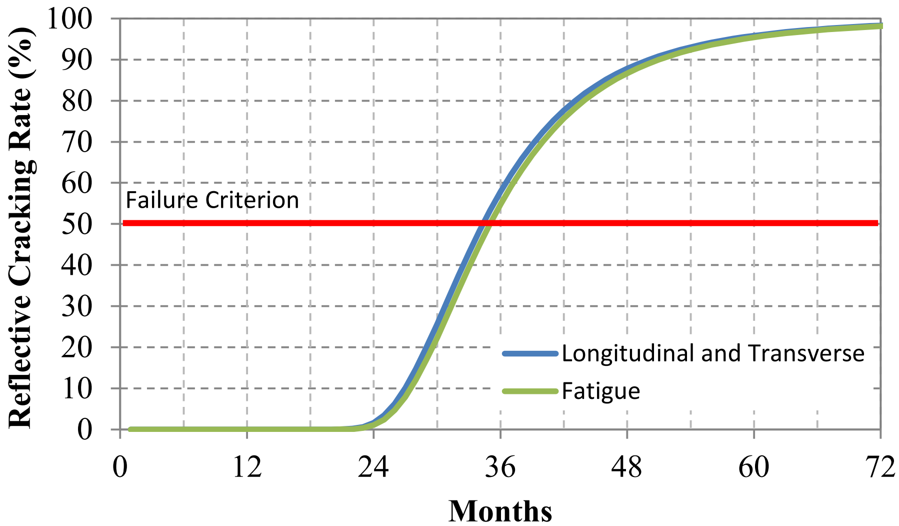


Figure 6.14. Predicted Reflective Cracking on Hempstead Road.

The Pecos RTC results are summarized in Figure 6.15. Only the CAM projects could be modeled with some degree of accuracy (SMA values were for mix designs with 0.5 percent less asphalt [a significant difference] and the models did not have a default option for PFC layer types.) The model predicts that both CAMs will not crack within a 15 years. This is likely caused by the high overlay test cycles (1,000+) and essentially no traffic. Much of the distress at the Pecos RTC is thermal in nature and should be captured by the climate models. As mentioned previously, the Eastland-CAM already has signs of transverse and random cracking. The Hoban-CAM does not. Both SMAs and PFCs on the entry road are intact. The PFCs and SMAs on the circular track are all beginning to have reflective transverse cracking. This project may underline some key deficiencies of the TxCrackPro model. Further study should be made to determine actual material properties rather than accepting default values.

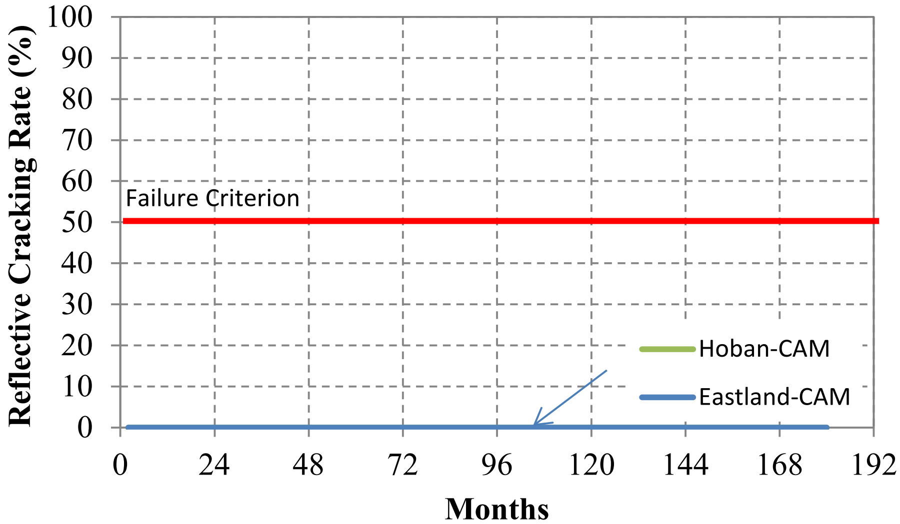
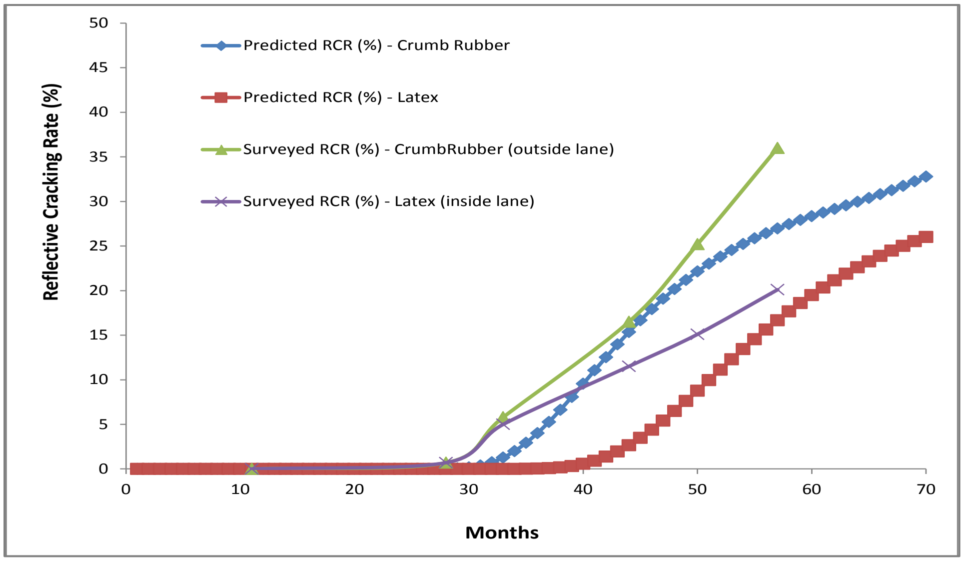
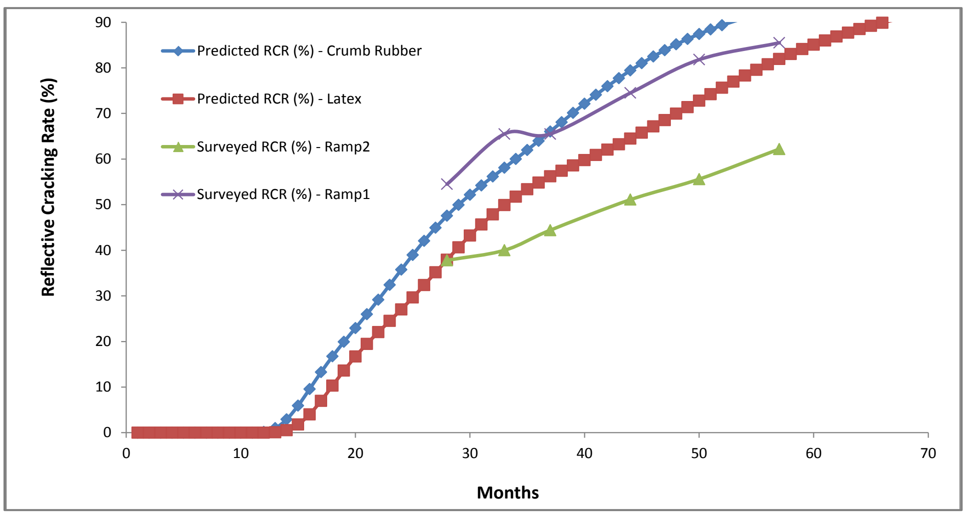


Figure 6.15. Predicted Reflective Cracking at the Pecos RTC Entry Road.

Figure 6.16 shows the predicted and actual crack propagation rates for Pumphrey Drive. These graphs show data through spring 2014. The first chart shows data from the straight main road sections. The TxCrackPro model correctly predicted that the crumb rubber mix would crack sooner than the latex mix. For both mixes, the actual cracking rates were higher than predicted. The model suggests cracking will start to taper off, but actual readings to date do not show this same trend. The second graph shows results from the ramps, which were in much worse condition. The crumb rubber mix, “Ramp 2,” had much less cracking than predicted. While the model predicted 100 percent cracking, the actual measurements showed 60 percent cracking. The latex mix, “Ramp 1,” cracked a little more than predicted, though the general predictions are accurate.



(a)



(b)

Figure 6.16. Predicted and Actual Cracking Results on Pumphrey Drive: a) Main Road and b) Ramps.

SUMMARY

At this time, few conclusions can be drawn about the validity of the TxCrackPro model and nature of crack propagation through thin lifts. Hempstead Road has not been in service long enough to observe reflection cracking. The data we have for Pecos RTC projects are insufficient, resulting many input assumptions. The resulting models vary greatly under-predicted cracking. Finally, the Pumphrey Drive results were collected and added to the existing prediction curves, which continue to have reasonable correlations.

Hempstead Road will continue to be monitored. Another thin overlay over block cracking on Wurzbach Parkway in San Antonio could also be investigated.

CHAPTER 7
DEMONSTRATION PROJECTS

OVERVIEW

Throughout the research project, TTI provided support to TxDOT on many of their new thin overlay demonstration projects. The support took different forms, such as:

- Mix design.
- Preliminary mix performance testing.
- Guidance on construction techniques.
- Establishment of rolling patterns.
- Mix and compaction quality assurance testing.
- Interlayer bonding performance.

This chapter and appendix material summarize demonstration projects of one PFC-F, four TOMs, and two TOM-B/UT mixes, including mix design, construction notes, and performance data.

PROJECT DESCRIPTION

Table 7.1 and Table 7.2 summarize the locations and existing conditions on each of the seven demonstration projects. Many projects were constructed immediately over aged chip seals. The US 59-TOM was placed over continuously reinforced concrete with an intermediary hot rubber seal and CAM. The FM 1887-TOM and Hempstead-TOM were also placed on new construction. Traffic on most of these projects was low, but the US 59-TOM was applied on an urban interstate with an annual average daily traffic (AADT) count of 248,000.

Table 7.1. Demonstration Project Locations.

Mix Type	Location			
	District	City	Route	Description
Fine PFC and TOM	San Antonio	San Antonio	Lp 1604, FR	From Nacogdoches Rd south to turnaround and exit ramps
TOM	Houston	Near Hempstead	FM 1887	From FM 359 to FM 3346
TOM	Houston	Houston	US 59	Between Beltway 8 and Lp 610. Focus area near 610.
TOM	Houston	Houston	Hempstead Rd	Between Perimeter Pk Dr. and Senate Ave. bridge.
UT Mix	Austin	Wimberly	RM 12	Runs through town and north.
TOM-B	Atlanta	Atlanta	FM 251 and FM 785	1,500 ft along FM 251 and the intersection

Table 7.2. Demonstration Project Existing Conditions.

Project	Existing Condition: Pavement	Existing Condition: Traffic
Lp 1604-Fine PFC/TOM	Aged chip seal. Slight flushing in wheel paths and light raveling outside of wheel paths.	Moderate (on-ramp) Low (turnaround)
FM 1887-TOM	New Type D smoothing course.	Low (690 AADT)
US 59-TOM	New CAM and hot rubber seal over continually reinforced concrete	Very high (248,000 AADT)
Hempstead-TOM	New 1-inch Type D and underseal over distressed HMA (milled) and jointed concrete.	Low
RM 12-UT Mix	Aged chip seal. Some longitudinal cracking in the wheel paths.	Low (5,800 AADT)
Atlanta-TOM-B	Aged chip seal. Heavy raveling at school accesses and intersection.	Low (2,400 AADT) Turning buses

OVERLAY DESIGN AND CONSTRUCTION

Table 7.3 summarizes the mix designs for each project. Aggregate sources include trap rock, dolomitic limestone, granite, sandstone, and gravel. All projects used SAC A aggregate and PG 76-22 binder, except the FM 1887 job. This was a SAC B design for a non-critical rural FM road. All designs passed the necessary laboratory tests, but some designs were more difficult to achieve. The Hempstead Road project, for example, went through several iterations before adequately passing the Hamburg test.

Table 7.4 summarizes construction information, including dates, surface preparation, lift thickness, and rolling pattern. Overall, construction went smoothly. After a small amount of trial-and-error, a satisfactory rolling pattern was established meeting flow time requirements. One issue was encountered on the Atlanta-UT Mix when hand work caused an uneven mat thickness, leading to spots of over- and under-compaction. Strong winds and falling temperatures were also a concern on the Hempstead-TOM, but the contractor was still able to achieve adequate compaction.

ADDITIONAL TESTING

Following construction, bond strength testing was performed on the Lp-1604 projects and on the Atlanta-UT mix. On the FM 1887-TOM, US 59-TOM, and RM 12-UT mix density testing and IR profiling to measure mat thermal segregation was also performed on FM 1887 and RM 12. Table 7.5 summarizes the results.

Table 7.3. Summary of Project Mix Designs.

Mix Name	Percent Passing (%)							Coarse Agg Type		Asphalt		HWTT		Overlay, Cycles
	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 200	Type	Source	PG	%	Cycles	Depth	
Fine PFC														
Lp 1604, FR	93.6	37.5	3.1	1.5	1.3	1.1	1	Trap rock	Knippa	76-22	7	10,000	11.6	-
TOM														
FM 1887	92.4	45.1	24.2	12.7	10.1	7.8	5.5	Dolomite	Burnet	70-22	6.7	15,000	4.82	1,000+
US 59	94.5	43.3	23	15.5	12.2	10.1	6.6	Granite	Jone Mill	76-22	6.7	20,000	2.7	1,000+
Lp 1604, FR	97.6	41.4	22	17.1	13.9	11.2	7.6	Trap rock	Knippa	76-22	6.2	20,000	6.3	1,000+
Hempstead Rd	100	46.7	25	18.2	14.4	11.7	7.7	Sandstone	Delta	76-22	6.8	20,000	9.6	~500
TOM-B / UT Mix														
RM 12	99.9	93.9	58.1	35.7	25.1	18.6	11.8	Sandstone	Delta	76-22	7.3	20,000	10.5	893
Atlanta	100	85	54.1	36.7	25.7	18.1	6.4	Gravel	Little River	76-22	6.6	20,000	2.53	785

Table 7.4. Construction Notes.

Mix Name	Construction Date	Surface Preparation	Lift Thickness, in.	Rolling Pattern	Other Notes
Fine PFC					
Lp 1604, FR	Aug-13	E-Tac, residual rate of 0.02 gal/sy	1.0	3 slow static passes	-
TOM					
FM 1887	May/June 2013	None (placed over new Type D)	1.0	Variable for test sections	Avg MPD - 0.93 mm
US 59	Jul-14	None (placed over new CAM)	1.25	Tandem rollers. 2 vibratory, 1 finish. Other patterns for test sections.	Avg. MPD ~ 1.0 mm Flow time ~ 2:30 min.
Lp 1604, FR	Aug-13	E-Tac, residual rate of 0.02 gal/sy	1.0	3 vibratory, 1 static (2 tandem rollers)	Avg MPD-0.71mm No water flow
Hempstead Rd	Oct/Nov 2013	Light tack coat. Placed over new Type D.	1.0	2 static, 2 oscillate	Strong wind and falling temperatures Flow time - 1:45
TOM-B / UT Mix					
RM 12	Jul-14	0.02 residual tack rate.	0.6	1 vibratory, 2 static, 1 finish Other patterns for test sections	MPD - 0.4 mm ~ 6 minutes flow time.
Atlanta	Jun-14	Calumet Trackless Tack, residual rate of 0.04 gal/sq.	0.5	Vibratory on screed, one static roller (unknown passes)	Foamed asphalt. Initial problems with handworking. Flow time - 8 min.

Table 7.5. Additional Test Results.

Test Type and Project		Results			Comments
Tensile Strength		No tack (psi)	Tack (psi)	Failure location	
Lp-1604	FPFC	23	23	Within the overlay mix	No strength difference with or without tack
	TOM	31	31	Tack interface	
Atlanta-TOM-B	Non-Raveled	97	91	Within overlay and chip from seal	High strength. No difference with or without tack, or with or without raveling.
	Raveled	96	101	Within the overlay mix	
Shear Strength		No tack (psi)	Tack (psi)	Failure location	
Lp-1604	FPFC	32	58	Tack interface	FPFC with tack significantly stronger.
	TOM	92-105	75-100	Tack interface and chip from seal	No strength difference with or without tack
		Estimated voids (%)			
Density Distribution		Average	St. Dev.		
FM 1887-TOM		10.8	1.9		Values taken from GPR-core voids correlation. Core void readings from thin lifts may be inaccurate.
RM 12-UT Mix		12.9	1.9		
US 59-TOM		10.1	0.6		
Thermal Segregation		Moderate (%)	Severe (%)		
FM 1887-TOM		77.0	5.0		Collected with IR scanner.
RM 12-UT Mix		12.9	28.0		

For most bond strength measurements made, the tack coat rate did not affect the final strength, and neither did the variable surface condition of the Atlanta project. Shear strength on Lp 1604 was lower than the peak shear strength modeled in Chapter 4. At this time, the correct bond strength criterion is unknown. The literature suggests a lower criterion of 100 psi. Estimated densities, measured first with GRP and correlated to field cores, were all high. This may be a result of measuring voids on such thin lifts. Finally, segregation was overall more prevalent on FM 1887, but more severe locations were identified on RM 12.

SUMMARY

TTI provided support to TxDOT on many of their new thin overlay demonstration projects. The support took different forms, including:

- Mix design.
- Preliminary mix performance testing.
- Guidance on construction techniques.
- Establishing rolling patterns.
- Mix and compaction quality assurance testing.
- Interlayer bonding performance.

Researchers documented one PFC-F, four TOMs, and two TOM-B/UT mix projects. The key results are as follows:

- All projects were successfully designed and constructed (though the Hempstead-TOM was more difficult to design).
- Hand-working of the Atlanta-TOM-B project caused problems with mat thickness and compaction uniformity.
- The texture depth of TOM projects was between 0.93 to 1.0 mm. The RM 12-UT Mix had a texture depth of just 0.6 mm.
- The actual residual tack rate on some of these projects was much lower than the target (~0.02 versus 0.05 gal/yd^2).
- The presence of tack did not affect bond strength except for the PFC-F in shear testing, in which tack increased the strength.
- Correlated voids were higher than expected, but may be inaccurate due to measuring voids on thin lifts.
- Thermal segregation is an issue when laying these thin mixes. One project had 77 percent moderately segregated areas, and another had 28 percent severe segregation.

CHAPTER 8
CONCLUSION

REPORT SUMMARY

While the implementation of thin HMA overlays in TxDOT has been fairly smooth, some issues have arisen. These include:

- Questions about the appropriate blending of SAC A and SAC B aggregate to ensure adequate skid resistance.
- Best practices to achieve adequate bonding (surface prep and tack coats).
- Correct quality assurance test methods to achieve adequate compaction.

The purpose of this research, therefore, was to address these concerns through laboratory and field studies. In addition, preliminary work to refine a crack propagation model for thin overlays was performed. The project deliverables are draft specifications for bond strength testing, micromilling, updated thin overlay specifications, and the document *Thin Overlay Guidelines: Project Selection, Design, and Construction*.

FINDINGS

Following is a comprehensive list of key findings from each chapter.

Chapter 2: Literature Review and Interviews:

Materials/Mix Design

- The Austin District's UT Mix is a No. 4 (4.75 mm) dense-graded mix that other agencies have successfully developed. The district should continue to experiment with this.
- Texas has stricter coarse aggregate LA abrasion criteria. Unless it is too restrictive, this should benefit Texas.
- Texas and Virginia specifically allow using warm mix additives. This relatively new technology is expected to increase workability of the thin overlays.
- Maryland and Virginia check for aggregate interlock on their gap-graded mixes by evaluating the VCA in the dry rodded condition and in the mix design. This and other aggregate packing metrics may ensure better designed gap-graded mixes.

Construction Procedures

- All agencies state that milling should be done to correct surface problems, but only Georgia has provided a specification for micro-milling.

- The recommended tack rates in Texas are much higher than the other agencies. Most specify a rate producing a residual asphalt content of 0.01–0.05 gal/yd^2. Texas specifies a rate of 0.03–0.08 gal/yd^2 of residual asphalt.
- Texas gives no recommendations for the minimum mix temperature for compaction, while most agencies do. This can be a critical factor for compacting thin layers that cool quickly.
- The current wording in TxDOT's SMA specification (Item 346) allows pneumatic tire rollers to compact SMA-F. This should be changed for thin overlay applications.
- TXDOT is the only agency that uses the water flow test to ensure impermeability of SMA-F. Though the effectiveness of this test is uncertain, using it is not a bad idea.
- Virginia has tensile and shear strength criteria for cores to ensure adequate bond strength. This is a concept worth looking into.

District Survey

- About 50 percent of districts have experience with thin dense-graded overlays, and around 35 percent with gap- and open-graded overlays. In many cases, however, this experience consists of just one or two projects.
- For all mix types, districts noted that a lack of experience was a major disadvantage to implementing thin overlays.
- For dense- and open-graded mix types, districts were split nearly 50:50 as to whether the mixes had good or poor long-term performance. This is an important topic that must be researched and communicated to districts.
- Districts perceived thin dense-graded mixes to have low initial costs while gap- and open-graded mixes were less economical. In many cases, this could be just the opposite since dense-graded mixes have higher binder contents. This perception needs to be corrected.
- Districts seem to assume that the same properties of mixes they are familiar with will be the same in these thinner versions. This is usually acceptable, but for thin gap-graded mixes, the skid resistance will likely be similar to that of thin dense-graded mixes.
- The prominent design issue mentioned was obtaining materials with the appropriate qualities and gradations.
- Over 80 percent of the districts expect to increase their use of thin overlays if, for nothing else, to experiment with the new specifications.
- Districts reported very few projects with poor performance and several with good performance.

Chapter 3: Evaluation of Aggregate Blending on Skid Resistance

- TOMs can have good long-term skid resistance with 100 percent trap rock (friction coefficient around 0.4 and macro texture around 1.0 mm).

- Friction decreases with more polishing, higher SAC B aggregate replacement, and higher macrotexture.
- At all levels of polishing, only the design with 25 percent replacement of aggregate B3 was statistically the same as the 100 percent trap rock design.
- After 30,000 cycles (a few years of traffic), designs with 100 percent replacement with B2, B3, and B4 were considered failed ($\mu<0.3$).
- After 100,000 cycles (terminal polish value), all designs with 100 percent replacement had failed, as had designs with 50 and 75 percent replacement of B2 and B3, respectively.
- A 25 percent replacement was acceptable for all SAC B aggregates, and a 50 percent and 75 percent replacement was acceptable for B1 and B4, respectively.
- The poorest performing SAC B aggregates were B2 and B3. In contrast, B2 had the *highest* ratings in texture and angularity after polishing of the SAC Bs, and had the lowest measurements for LA abrasion, micro-deval, and soundness in the rated source catalog.
- Correlations among AIMS results and DFT results are currently inconclusive.
- Macrotexture was higher for the TOM (MPD ~1.0 mm) than the TOM-B (~0.6 mm).
- Polishing decreased the macrotexture of TOM designs, and had no significant effect on TOM-B macrotexture.

Chapter 4: Evaluation of Tack Coat and Milling Practices on Bond Strength

Preliminary Tensile Strength Testing

- In the preliminary study, no one tensile strength device had better performance than another.
- The most influential test parameters in the preliminary study were pull rate and temperature.

Bond Strength Criteria

- Computer models showed higher concentrations of shear stress in the overlay for poorly bonded samples.
- The shear stress at the interface for the lowest slip condition was 40 psi under normal traffic conditions and 120 psi for critical turning/breaking/accelerating conditions.

Effect of Surface Preparation and Tack Coat Practices on Bond Strength

- The tensile and shear strength tests had good correlation with an R^2 value of 0.73. The precision of each test was statistically the same, with an average COV around 15 percent.
- The tensile and shear strength of bonded samples is largely dependent on the type of mix being bonded and the compaction effort, and less on the tack type and tack rate.

- In the tensile strength tests and half the shear tests, non-tracking tacks had higher performance than samples using CSS-1H or with no tack.
- No single non-tracking tack was found to have considerably better performance than the others.
- The tack rate of CSS-1H was significant only when applied on dense-graded mixes, not over PFC, and was most notable in the tensile strength test. Low and moderate levels of tack provided the best bond. Using no tack produced the lowest bond.
- Milled samples had higher strength than unmilled samples, most notably in the shear test.
- Moisture conditioning did not significantly affect the results.

Tracking Resistance Testing

- The BASF roller test was able to discern different non-tracking times among the tacks tested.
- Non-tracking tacks exhibited a range of non-tracking times and different degrees of tracking. Time to less than 10 percent tracking ranged from less than 15 minutes to 45 minutes. Standard CSS-1H had the most tracking overall.

Chapter 5: Evaluation of Compaction and Quality Assurance Methods

- Correlations of the tests were strong on a project-by-project basis, but generally not good when combining the data sets.
- Flow Time-MTD, Flow Time-Core Voids, and Surface Dielectric-Core Voids were best overall, with average prediction strengths of 0.74, 0.73, and 0.69, respectively.

Chapter 6: Refinement of the TxCrackPro Crack Propagation Model

- One older overlay project indicates reasonable correlation with the existing cracking model, while cracking on a more recent project was greatly under predicted.
- No significant findings are available from the newest projects at this time.

Chapter 7: Demonstration Projects

- All projects were successfully designed and constructed (though the Hempstead-TOM was more difficult to design).
- Hand-working of the Atlanta-TOM-B project caused problems with mat thickness and compaction uniformity.
- The texture depth of TOM projects was between 0.93 to 1.0 mm. The RM 12-UT Mix had a texture depth of just 0.6 mm.
- The actual residual tack rate on some of these projects was much lower than the target (~0.02 versus 0.05 gal/yd^2).

- The presence of tack did not affect bond strength except for the PFC-F in shear testing, in which tack increased the strength.
- Correlated voids were higher than expected, but may be inaccurate due to measuring voids on thin lifts.
- Thermal segregation is an issue when laying these thin mixes. One project had 77 percent moderately segregated areas, and another had 28 percent severe segregation.

RECOMMENDATIONS

Based on the research findings, the researchers recommend the following:

Skid Resistance

- Promote mix designs with 100 percent trap rock and 25 percent SAC B replacement as having acceptable long-term skid resistance. Blending of some SAC B aggregates can be done successfully up to 50 and possibly 75 percent, and still maintain acceptable friction.
- Use TOM for higher speed, more critical sections (adequate macrotexture). TOM-B and UT Mix should be adequate for lower speeds and non-critical sections.
- Consider using the laboratory polishing/friction test set up to evaluate blended-aggregate thin overlays.
- Consider a terminal friction value of 0.3, or higher, as the minimum criteria for a thin overlay in high-speed traffic scenarios.

Bond Strength and Tack Coat Testing, and Surface Preparation

- Adopt the DY-206 and Pine Interlayer Shear Tester for bond strength testing on an as-need basis (Appendix E).
- Exact bond strength criteria have not yet been established, but may be around 100 psi for shear testing and 40 psi for tension testing.
- Adopt the BASF test, or similar, as a routine method to measure tracking resistance of non-tracking tacks.
- Use the draft micro-milling specification as needed (Appendix E).

Compaction Quality Assurance

- Continue to use the flow test as a surrogate measure of density on thin overlays.
    - Minimum flow times were not determined from this research, but, as per existing specifications, suggested as 150 seconds for TOM and 300 seconds for UT mix.
    - Maximum flow time (TOM): 6 minutes for high-speed/critical sections; 10 minutes for lower-speed non-critical sections.
    - Maximum flow time (UT mix): None.

- Use the extrapolation equations developed for flow time in Chapter 5 when the test is running slowly and eventual flow time is desired.
- Employ the rolling density meter on the project-level when full-coverage density measurements are desired.

Some recommendations have been incorporated into the draft thin overlay specification (see Appendix H).

Future research topics are as follows:

- The relationship of laboratory friction and field skid resistance.
- The relationship of aggregate properties (LA Abrasion, micro-deval, soundness, AIMS angularity, and AIMS texture) to the friction coefficient.
- The effect of pavement surface and material properties on bond strength, especially in the field.
- Failure criteria for bond strength.
- Criterion to define non-tracking tack.

REFERENCES

1. Newcomb, D. E. *Thin Asphalt Overlays for Pavement Preservation.* Information Series, 135, National Asphalt Pavement Association, Lanham, MD, July 2009.

2. Sandberg, U. and J. A. Ejsmont. *Tyre/Road Noise Reference Book*. INFORMEX, Kisa, Sweden, 2002.

3. Walubita, L. and T. Scullion. *Thin HMA Overlays in Texas: Mix Design and Laboratory Material Property Characterization.* Report 0-5598-1, Texas Transportation Institute, Texas A&M University System, College Station, TX, January 2008.

4. Cooley Jr., L. A., R. S. James, and M. S. Buchanan. *Development of Mix Design Criteria for 4.75 mm Superpave Mixes – Final Report.* Report 02-04, National Center for Asphalt Technology, Auburn University, Auburn, AL, February 2002.

5. West, R. C., M. A. Heitzman, D. M. Rausch, and G. Julian. *Laboratory Refinement and Field Validation of 4.75 mm Superpave Designed Asphalt Mixtures, Volume 1: Final Report.* Report 11-01, National Center for Asphalt Technology, Auburn University, Auburn, AL, March 2011.

6. Croteau, J.-M. and N. Hanasoge. Fine-Graded Stone Mastic Asphalt – Pavement Rehabilitation of Bloomington Road (York Region Road 40). In *Proceedings, 2006 Annual Conference of the Transportation Association of Canada*, Charlottetown, Prince Edward Island, Canada, 2006. http://www.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2006/docs/s016/croteau.pdf. Accessed October 8, 2012.

7. Xie, H., L. A. Cooley, and M. H. Huner. *4.75 mm NMAS Stone Matrix Asphalt (SMA) Mixtures.* Report 03-05, National Center for Asphalt Technology, Auburn, AL, December 2003.

8. Cooley Jr., L. A. and E. R. Brown. *Potential of Using Stone Matrix Asphalt (SMA) for Thin Overlays.* Report 03-01, National Center for Asphalt Technology, Auburn University, Auburn, AL, April 2003.

9. Brown, E. R., R. B. Mallick, J. E. Haddock, and J. Bukowski. *Performance of Stone Matrix Asphalt (SMA) Mixtures in the United States.* Report No. 97-1, National Center for Asphalt Technology, Auburn University, Auburn, AL, January 1997.

10. *Special Provision for Porous Friction Course*. Virginia Department of Transportation, October 2008.

11. Lai, J. S., M. Bruce, D. M. Jared, P. Y. Wu, and S. Hines. Georgia's Evaluation of Surface Texture, Interface Characteristics, and Smoothness Profile of Micromilled Surface. In *Proceedings, Transportation Research Board 88th Annual Meeting*, Washington D.C., January 2009. http://trid.trb.org/view.aspx?id=881403.

12. Virginia Department of Transportation. *Tack Coat Survey*, Pavement Interactive. http://www.pavementinteractive.org/wp-content/uploads/2008/06/TackCoatSurvey1.pdf. Accessed December 19, 2012.

13. Choubane, B., P. B. Upshaw, G. A. Sholar, G. C. Page, and J. A. Musselman. *Nuclear Density Readings and Core Densitities: A Comparative Study.* Report FL/DOT/SMO/98-418, Florida Department of Transportation, Gainseville, FL, July 1998.

14. Heitzman, M. A. and E. R. Brown. *Thin HMA Overlays for Pavement Preservation and Low Volume Asphalt Roads.* Report 13-05, National Center for Asphalt Technology, Auburn University, Auburn, AL, May 2013.

15. Williams, S. G. *Non-Nuclear Methods for HMA Density Measurements.* Department of Civil Engineering, Univeristy of Arkansas, Fayetteville, AR, June 2008.

16. McGhee, K. K. and T. M. Clark. *Bond Expectations for Milled Surfaces and Typical Tack Coat Materials Used in Virginia.* Report 09-R21, Virginia Transportation Research Council, Charlottesville, VA, June 2009.

17. Wilson, B. T., T. Scullion , and C. Estakhri. *Design and Construction Recommendations for Thin Overlays in Texas.* Report 0-6615-1, Texas A&M Transportation Institute, College Station, TX, September 2013.

18. Masad, E., A. Rezaei, A. Chowdhury, and J. P. Harris. *Predicting Asphalt Mixture Skid Resistance Based on Aggregate Characteristics.* Report 0-5627-1, Texas Transportation Institute, Texas A&M University System, College Station, TX, August 2009.

19. Walubita, L., G. Das, E. Espinoza, J. Oh, T. Scullion , S.-I. Lee, J. L. Garibay, S. Nazarian, and I. Adballah. *Texas Flexible Pavements and Overlays: Year 1 Report - Test Sections, Data Collection, Analyses, and Data Storage System.* Report 0-6658-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 2012.

20. Tran, N. H., R. Willis, and G. Julian. *Refinement of the Bond Srength Procedure and Investigation of a Specification.* Report 12-04, National Center for Asphalt Technology, Auburn University, Auburn, AL, June 2012.

21. Mohammad, L. N., M. A. Elseifi, A. Bae, N. Patel, J. Button, and J. A. Scherocman. *Optimization of Tack Coat for HMA Placement.* NCHRP Report 712, National Cooperative Highway Research Program, Washington, D.C., 2012.

22. Vivar, E. d. P. and J. E. Haddock. *HMA Pavement Performance and Durability.* FHWA/IN/JTRP-2005/14, Purdue University, Lafayette, IN, April 2006.

23. Zhou, F. and T. Scullion *Mix Design, Construction, and Performance of a Thin HMA Overlay on Pumphrey Drive, Fort Worth Texas.* Report 5-5123-01-2, Texas Transportation Institute, Texas A&M University System, College Station, TX, December 2008.

24. Lytton, R. L., F. L. Tsai, S.-I. Lee, R. Luo, S. Hu, and F. Zhou. *Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays.* NCHRP Report 669, National Cooperative Highway Research Program, Washington, D.C., 2010.

APPENDIX A
THIN HMA OVERLAY SPECIFICATION DETAILS

Table A.1. Material Specifications for Dense-Graded Mixes.

Property	Dense-Graded Mix Type: Texas CAM	Ohio Smooth-seal (B)	NCAT (4.75 mm)	Georgia (4.75 mm)	Georgia (9.5 mm SP)	Maryland (9.5 mm, fine-graded)	Maryland (4.75 mm)	Virginia (Thin HMA	Virginia (SM-4.75)	California No. 4 HMA Type A
Coarse Aggregate										
Aggregate Class	TxDOT SAC A[1]	-	-	GDOT Class A	See plans	-	-	-	-	-
Deleterious Materials	See specs	-		See specs	See specs	See specs	See specs	See specs	See specs	See specs
LA Abrasion, % loss, max	30	-	45	40	40, 55[11]	45	45	40	40	45
Soundness (Type), %, max	(Magnesium) 20	-		(Magnesium) 15	(Magnesium) 15	(Sodium) 12	(Sodium) 12	(Magnesium) 15[2]	(Magnesium) 15[2]	-
Fractured Faces, %, min										
1 face	-	-	-	85[3]	85[3]	-	-	-	80	90
2 faces	95[3]	-	-	-	-	-	-	-	85	75
Flat Elongated, %, max										
3:1	-	-	-	20	-	10	10	25	-	-
5:1	10	-	10	10	10	-	-	10	30	10
Other	-	-	-	No alluvial gravel	No alluvial gravel	Angularity, Absorption Polish Value ≥ 5	Angularity, Absorption Polish Value ≥ 5	Absorption	-	-
Fine Aggregate										
Linear Shrinkage, %, max	3	-	-	-	-	Non plastic	Non plastic	-	-	-
Aggregate Angularity, min	-	-	40-45[8]	-	-	-	-	45	40	-
Other	-	-	-	.estrict local san	estrict local san	-	-	Soundness	Soundness	-
Combined Aggregate[4]										
Sand Equivalent, %, min	45	-	40-50[8]	28 or 40[10]	28 or 40[10]	Report	Report	50	40	-
Other Materials										
Asphalt grade	See plans	PG 76-22[5]	Note 7	PG 67-22[9]	PG 76-22	-	-	70-28	64-22 to 76-22	See Specs
Recycled agg., %, max	0	10	-	Allowed	Allowed	20% RAP[6], 5% RAS	20% RAP[6], 5% RAS	None	Allowed	15%
Lime, %	1.0	1.0-1.5	-	1 min.	1 min.	-	-	1	1	-
Other	WMA allowed	10% Silica, no antistrip	-	-	-	-	-	-	-	Crumb rubber

1. Can blend with quality SAC B
2. 6 freeze-thaw cycle testing as well
3. Only applies to crushed gravel
4. Aggregates, without mineral filler, RAP, or additives
5. Minimum asphalt grade.
6. May go higher if passes dynamic modulus test
7. Based on traffic and climate conditions
8. Based on traffic conditions
9. Unless polymer modifier required
10. Depends on agg. type
11. Depends on class of coarse aggregate

'-' Not specified

Table A.2. Material Specifications for Gap-Graded Mixes.

Property	Gap-Graded Mix Type				
	Texas SMA-F	Texas TOM	Maryland (9.5 mm)	Virginia (SMA-9.5)	NCAT (9.5 mm)
Coarse Aggregate					
Aggregate Class	TxDOT SAC A[1]	TxDOT SAC A	-	-	-
Deleterious Materials	See specs	See specs	See specs	-	See specs
LA Abrasion, % loss, max	30	35	30	40	30
Sulfate Soundness (Type), %, max	(Magnesium) 20	(Magnesium) 20	(Sodium) 12	(Magnesium) 15	(Magnesium) 20
2 Fractured Faces, %, min					
1 face	-	-	-	100	100
2 faces	95[2]	100[2]	-	90	90
Flat Elongated, %, max					
3:1	-	-	20	20	20
5:1	10	10	5	5	5
Other	-	-	Polish Value > 8	Absorption	Absorption
Fine Aggregate					
Linear Shrinkage, %, max	3	3	-	-	-
Aggregate Angularity, min	-	-	-	45	45
Other	-	-	-	Soundness, Liquid Limit < 25	-
Combined Aggregate[3]					
Sand Equivalent, %, min	45	45	-	-	-
Other Materials					
Asphalt grade	PG 76	70-22, 76-22	-	70-22 or 76-22	-
Recycled agg., %, max	20 (15 RAP, 5 RAS)	None	20 (RAP), No RAS	20%	-
Fibers, %	0.2-0.5	-	0.2-0.4	0.3 min	Allowed
Lime, %, max	1	1	1-1.5	1	-
Other	-	WMA allowed	-	-	-

1. Can blend with quality SAC B
2. Only applies to crushed gravel
3. Aggregates, without mineral filler, RAP, or additives

'-' Not specified

Table A.3. Material Specifications for Open-Graded Mixes.

Property	Open-Graded Mix Type					
	Texas PFC-F	Texas TBPFC	Virginia PFC-9.5	New Mexico OGFC	California 3/8-inch OGFC	Georgia 9.5mm OGFC
Coarse Aggregate						
Aggregate Class	TxDOT SAC A[1]	See plans	-	Note 4	-	GDOT Class A
Deleterious Materials	See specs	See specs	-	-	-	See specs
LA Abrasion, % loss, max	30	30	40	-	40	40
Soundness (Type), %, max	(Magnesium) 20	(Magnesium) 20	(Magnesium) 15	-	-	(Magnesium) 15
2 Fractured Faces, %, min						
1 face	-	-	100	-	90	85[3]
2 faces	95[3]	95[3]	90	75	75	-
Flat Elongated, %, max						
3:1	-	-	25	-	-	20
5:1	10	10	10	-	10	-
Other	-	-	Absorption	-	-	No alluvial gravel
Combined Aggregate[3]						
Sand Equivalent, %, min	NA	NA	45	-	-	-
Other Materials						
Asphalt grade	PG 76	PG 76	70-28	70-28+,	See spec	76-22
Recycled agg., %, max	None	None	None	-	None	-
Fibers, %, max	0.2-0.5	0.2-0.5	0.3		?	0.2-0.4
Lime, %, max	1	1-2	1	Allowed	Allowed	1
Other	WMA allowed	Rubber allowed	-		Rubber allowed	

1. Can blend with quality SAC B
2. Only applies to crushed gravel
3. Aggregates, without mineral filler, RAP, or additives
4. NM Aggregate Index < 20

NA - Not applicable
'-' Not specified

Table A.4. Gradations for Dense-Graded Mixes.

Sieve Size	Dense-Graded Mix Type									
	Texas CAM	Ohio Smooth-seal (B)	NCAT (4.75 mm)	Georgia (4.75 mm)	Georgia (9.5 mm SP)	Maryland (9.5 mm, fine-graded)	Maryland (4.75 mm)	(Thin HMA Overlay)	Virginia (SM-4.75)	California No. 4 HMA Type A
	Percent Passing (%)									
1/2 in.	100	100	100	100	100		100	100	100	100
3/8 in.	98-100	95-100	95-100	90-100	90-100		100	85-100	95-100	100
No. 4	70-90	85-95	90-100	75-95	65-85		80-100	25-40	90-100	94-100
No. 8	40-65	53-63	-	60-65	48-55		36-76	19-32	-	72-77
No. 16	20-45	37-47	30-54	-	-		-	15-23	30-55	-
No. 30	10-30	25-35	-	-	-		-	10-18	-	37-43
No. 50	10-20	9-19	-	20-50	-		-	8-13	-	-
No. 200	2-10	3-8	6-12	4-12	5-7		2-12	4-7	6-13	2-12

'-' Not specified

Table A.5. Gradations for Gap-Graded Mixes.

Sieve Size	Gap-Graded Mix Type				
	Texas SMA-F	Texas TOM	Maryland (9.5 mm)	Virginia (SMA-9.5)	NCAT (9.5 mm)
	Percent Passing (%)				
1/2 in.	100	100	100	90-100	100
3/8 in.	70-90	85-100	75-90	70-85	90-100
No. 4	30-50	40-60	30-50	25-40	26-60
No. 8	20-30	17-27	20-30	15-25	20-28
No. 16	8-30	5-27	-	-	13-21
No. 30	8-30	5-27	-	-	12-18
No. 50	8-30	5-27	-	-	12-15
No. 200	8-14	5-9	8-13	9-11	8-10

'-' Not specified

Table A.6. Gradations for Open-Graded Mixes.

	Open-Graded Mix Type					
	Texas PFC-F	Texas TBPFC	Virginia PFC-9.5	New Mexico OGFC	California 3/8-inch OGFC	Georgia 9.5mm OGFC
Sieve Size	Percent Passing (%)					
1/2 in.	100	100	100	100	100	100
3/8 in.	95-100	80-100	85-100	90-100	90-10	85-100
No. 4	20-55	35-60	20-40	25-55	29-36	20-40
No. 8	0-15	1-20	5-10	0-12	7-18	5-10
No. 16	0-12	1-10	-	-	-	-
No. 30	0-8	-	-	0-8[1]	0-10	-
No. 50	0-8	-	-	-	-	-
No. 200	0-4	1-4	2-4	0-4[1]	0-3	2-4

'-' Not specified
1. For sieves No. 10 and No. 40

Table A.7. Specified/Average Tack Coat Rates (*12*).

State	Rate (%)	Residual/Diluted
Colorado	0.05	Residual
Georgia	0.06-0.08 (open-graded)	NS
Idaho	0.05	NS
Illinois	0.05-0.1	NS
Iowa	0.02-0.05	Residual
Kentucky	0.05	Residual
Maine	0.025	Residual
Maryland	0.01-0.05	Residual
Mississippi	0.05-0.1	NS
Missouri	0.02 -0.1	NS
Nebraska	0.1-0.2	NS
New Hampshire	0.02-0.05	NS
Nevada	0.07	NS
Ohio	100% cover	-
Oregon	0.2-0.5	NS
South Carolina	0.05-0.15	Diluted
South Dakota	0.05	NS
Texas	0.04-0.10	Residual
Utah	95% cover	-
Virginia	0.05-0.10	Diluted
	Additional shear and tensile strength requirements	

NS - Not specified

Table A.8. Laydown and Compaction Procedures.

State	Temperatures	Roller Configuration
Maryland	• Dense-graded: Min of 225°F at placement. • Gap-graded: Finish compaction before 240°F.	• Gap-graded: 3 static steel-wheel rollers, 10-12 tons each, Stay within 500 ft of paver, No vibration, Maintain speed of 1 to 3 mph. No pneumatic rollers.
California	• All thin lifts: Min pavement temp of 55°F, Min air temp of 50°F. • Dense-graded: 1st breakdown coverage before 240°F, Finish breakdown and intermediate compaction by 180°F, Finish all before 140°F. • Open-graded w/ modified binder: 1st coverage before 240°F, Finish all before 180°F.	• Dense-graded: Three rollers and roller operators on site, No vibration. • Open-graded: Tandem steel wheel rollers, At least 2 or 3 rollers depending on production level, No vibration.
Texas	• All mixes: Use thermal profile to monitor temperature, Min pavement temp of 50°F with Pave-IR system or 70°F without. Only light finish rolling below 160°F.	• Gap-graded: Pnumatic rollers allowed if material pick-up does not occur. TTI suggests tandem steelwheel rollers. For TOM, no pnumatic rollers and limit vibration to low amplitude/high frequency. • Open-graded: Steel wheel roller, No vibration, No pneumatic rollers
Virginia	• Dense-graded: Min. pavement temp of 50°F, Min. asphalt temp 290°F, 2 passes before 185°F, Complete breakdown in 8 minutes (2 rollers) or 15 min (1 roller). • Gap-graded: Min. pavement temp of 50°F or 40°F with warm mix, Min mix temp of 300°F for PG 70-22 and as specified by supplier for PG 76-22, For warm mix no minimum mix temp specified. • Open-graded: Min. pavement temp of 50°F, 4 roller passes before 180°F.	• Dense-graded: Two steel double drum rollers, Min 10 tons each. • Gap-graded: Min 3 rollers available for compaction and/or finishing, Min 10 tons each, Use vibration with caution with no more than 3 passes, Use highest frequency and lowest amplitude. Pre-paving meeting if you have never laid SMA. • Open-graded: Two steel wheel rollers, Min. 10 tons each, No vibration.
Georgia	• All thin lifts: Min air temp of 55°F.	• No pneumatic tires on OGFC, PEM, SMA.
Ohio	• Smoothseal: Min pavement temp of 60°F, Min mix temp of 300°F when arriving on site.	• NA

APPENDIX B
SURVEY AND SURVEY RESULTS

Survey Purpose

Many TxDOT districts are looking to implement the newest generation of thin HMA overlays. The performance and economic benefit of these layers are promising, but there are still a few design and construction issues we need to work out. These issues are being addressed by TTI in TxDOT research project 0-6742: Evaluation of Performance Tests and Construction Procedures for Thin Overlays.

In this brief survey, you will describe your district's experience with thin HMA overlays and inform TTI of any thin overlay projects, performing both well and poorly, to be used in future evaluations.

Contact Information

Tom Scullion (Research Supervisor)
Program Manager: Flexible Pavements
t-scullion@tamu.edu
(979) 845-7511

Bryan Wilson (Pricipal Investigator)
Assoc. Research Scientist, TTI
b-wilson@ttimail.tamu.edu
(979) 458-7989

Overview

18 questions total in 8 sections :

- Respondent info and definitions
- Thin dense-graded mixes
- Thin gap-graded mixes
- Thin open-graded mixes
- Projects with poor performance
- Projects with good performance
- Projects for surface preparation study
- Future use of thin overlays

* Respondent Information

District name	
Respondent name	
TxDOT position	
Phone number	
E-mail	

* *Please review the following before proceding*

Definitions

Thin HMA Overlay: Any hot-mix asphalt surface layer compacted to a thickness of 1.0 inches or less.

Thin Dense-Graded Mix

- CAM (SS 3165), *as a surface layer*
- Dense-graded HMA-Type F (Item 340)

Thin Gap-Graded Mixes

- SMA-F (Item 346, Type F)
- TOM (SS 3239)

Thin Open-Graded Mixes

- PFC-F (Item 342, Type F)
- TBPFC (SS 3127)

CAM	Crack attenuating mix
SMA-F	Stone matrix asphalt, Type F
TOM	Thin Overlay Mix
PFC-F	Permeable friction course, Type F
TBPFC	Thin-bonded permeable friction course

May also be a similar one-time use or special specification.
For the purpose of this project, if any of the previously mentioned mixes is constructed thicker than 1.0 inches, it is not considered a thin HMA overlay.

☐ I have reviewed the definitions

* Do you have experience with thin dense-graded mixes in your district?
(e.g. CAM as surface mix, dense-graded Type F)

- ○ Yes
- ○ No
- ○ Not sure

In your opinion, what are the ADVANTAGES of thin dense-graded HMA overlays?
(e.g. CAM as surface mix, dense-graded Type F)

- ☐ Initial cost
- ☐ Long-term cost
- ☐ Experience in district
- ☐ Constructability
- ☐ Rutting resistance
- ☐ Cracking resistance
- ☐ Wet skid resistance
- ☐ Moisture damage resistance
- ☐ Wet weather visibility
- ☐ Tire-pavement noise
- ☐ Curb-gutter restraints
- ☐ Other ________

? If you are unsure, mark "Other" and write "No answer."

In your opinion, what are the DISADVANTAGES of thin dense-graded HMA overlays?
(e.g. CAM as surface mix, dense-graded Type F)

- ☐ Initial cost
- ☐ Long-term cost
- ☐ Little/no experience in district
- ☐ Constructability
- ☐ Rutting resistance
- ☐ Cracking resistance
- ☐ Wet skid resistance
- ☐ Moisture damage resistance
- ☐ Wet weather visibility
- ☐ Tire-pavement noise
- ☐ Curb-gutter restraints
- ☐ Other ________

? If you are unsure, mark "Other" and write "No answer."

Please describe any design or construction issues you are aware of with thin dense-graded HMA overlays.
(e.g. CAM as a surface mix, dense-graded Type F)

* Do you have experience with thin gap-graded mixes in your district?
(e.g. SMA-F, TOM)

- ○ Yes
- ○ No
- ○ Not sure

In your opinion, what are the ADVANTAGES of thin gap-graded HMA overlays?
(e.g. SMA-F, TOM)

- ☐ Initial cost
- ☐ Long-term cost
- ☐ Experience in district
- ☐ Constructability
- ☐ Rutting resistance
- ☐ Cracking resistance
- ☐ Wet skid resistance
- ☐ Moisture damage resistance
- ☐ Wet weather visibility
- ☐ Tire-pavement noise
- ☐ Curb-gutter restraints
- ☐ Other ________

? If you are unsure, mark "Other" and write "No answer."

In your opinion, what are the DISADVANTAGES of thin gap-graded HMA overlays?
(e.g. SMA-F, TOM)

- ☐ Initial cost
- ☐ Long-term cost
- ☐ Little/no experience in district
- ☐ Constructability
- ☐ Rutting resistance
- ☐ Cracking resistance
- ☐ Wet skid resistance
- ☐ Moisture damage resistance
- ☐ Wet weather visibility
- ☐ Tire-pavement noise
- ☐ Curb-gutter restraints
- ☐ Other ________

? If you are unsure, mark "Other" and write "No answer."

Please describe any design or construction issues you are aware of with thin gap-graded HMA overlays.
(e.g. SMA-F, TOM)

* Do you have experience with thin open-graded mixes in your district? (e.g. PFC-F, TBPFC)

- Yes
- No
- Not sure

In your opinion, what are the ADVANTAGES of thin open-graded HMA overlays? (e.g. PFC-F, TBPFC)

- Initial cost
- Long-term cost
- Experience in district
- Constructability
- Rutting resistance
- Cracking resistance
- Wet skid resistance
- Moisture damage resistance
- Wet weather visibility
- Tire-pavement noise
- Curb-gutter restraints
- Other ____

If you are unsure, mark "Other" and write "No answer."

In your opinion, what are the DISADVANTAGES of thin open-graded HMA overlays? (e.g. PFC-F, TBPFC)

- Initial cost
- Long-term cost
- Little/no experience in district
- Constructability
- Rutting resistance
- Cracking resistance
- Wet skid resistance
- Moisture damage resistance
- Wet weather visibility
- Tire-pavement noise
- Curb-gutter restraints
- Other ____

If you are unsure, mark "Other" and write "No answer."

Please describe any design or construction issues you are aware of with thin open-graded HMA overlays. (e.g. PFC-F, TBPFC)

* How do you see the use of thin HMA overlays in your District changing in the future?

- Increasing use
- Little change in use
- Decreasing use
- I'm not sure

Table B.1. Thin Dense-Graded HMA Overlays.

District	Experience	Advantages OR Disadvantages: Initial cost	Long-term cost	Experience in district	Constructability	Rutting resistance	Cracking resistance	Wet skid resistance	Moisture damage resistance	Wet weather visibility	Tire-pavement noise reduction	Curb-gutter restraints	Other	Design or construction issues
Abilene	No	-	-	DA	-	-	A	DA	A	DA	-	-		
Amarillo	Yes	A	-	A	A	DA	DA	A	DA	-	A	A		
Atlanta	Yes	A	A	A	DA	DA	-	DA	-	-	-	A	DA: Low permeability	Cross slope, Too much asphalt, Plant control, Availability of materials
Austin	Yes	A	DA	DA	A	DA	A	-	A	-	A	DA	DA: Shear failure	
Beaumont	No	A	-	DA	-	-	-	-	-	-	-	A		
Brownwood	No	-	-	-	-	-	-	-	-	-	-	-		
Bryan	Yes	DA	-	-	A	-	DA	DA	A	DA	-	A		
Childress	Yes	A	-	-	A	DA	A	-	A	-	A	-		
Corpus Christi	No	-	-	-	-	-	-	-	-	-	-	-		
El Paso	No	-	-	-	-	-	-	-	-	-	-	-		
Fort Worth	Yes	-	-	DA	A	DA	A	A	-	-	-	-	A: Research purposes	
Houston	Yes	-	-	-	-	-	-	-	-	-	-	-		
Laredo	Yes	DA	-	-	DA	DA	-	-	DA	-	A	-	DA: Blistering	
Lubbock	No	-	-	-	-	-	DA	DA	-	DA	A	-		
Lufkin	Yes	A	-	A	A	-	A	-	-	DA	DA	A		
Odessa	No	-	-	DA	-	DA	-	-	-	-	-	-		
Paris	Yes	A	-	DA	-	-	A	-	A	-	A	A		Contractors in our district tend to have problems meeting the gradation requirements with CAM.
Pharr	No	A	A	DA	-	A	A	A	A	-	A	-		We predominantly use TY D and TY B hot mix. We have merely explored the possibility of utilizing CAM mixes in our District. We have had an E.I.T. perform research by designing a CAM mix as per Item 3131 to see if our local aggregate would meet all criteria. Preliminary results indicated that our local gravel sources can meet this spec.
Tyler	Yes	A	-	DA	-	-	-	A	-	DA	-	A		
Waco	Not sure	-	-	-	-	-	-	-	-	-	-	-		
Wichita Falls	Yes	A	DA	-	A	-	DA	DA	-	-	A	A		
Yoakum	No	-	-	-	-	-	-	-	-	-	-	-		

Table B.2. Thin Gap-Graded HMA Overlays.

		Advantages OR Disadvantages												
District	Experience	Initial cost	Long-term cost	Experience in district	Constructability	Rutting resistance	Cracking resistance	Wet skid resistance	Moisture damage resistance	Wet weather visibility	Tire-pavement noise reduction	Curb-gutter restraints	Other	Design or construction issues
Abilene	No	DA	A	-	-	-	A	-	A	DA	-	-		
Amarillo	No	A	-	-	DA	-	-	-	-	-	-	-		Pain to design, mix and clean up
Atlanta	Yes	DA	A	DA	DA	A	-	A	A	-	-	-		Materials availabilty, Plant control
Austin	Yes	A	A	A	DA	A	A	A	A	A	A	DA	DA: Flushing/bleedin g	Issues with rutting due to underseals bleeding. Distress due to a lack of compaction due to applying the mix too thick.
Beaumont	No	-	-	-	-	-	-	-	-	-	-	-		
Brownwood	No	-	-	-	-	-	-	-	-	-	-	-		
Bryan	Yes	DA	A	DA	A	A	A	A	A	A	A	A		
Childress	No	-	-	-	-	-	-	-	-	-	-	-		
Corpus Christi	No	-	-	-	-	-	-	-	-	-	-	-		
El Paso	Yes	DA	-	DA	-	A	A	-	-	-	-	-		
Fort Worth	No	-	-	-	-	-	-	-	-	-	-	-		
Houston	No	-	-	-	-	-	-	-	-	-	-	-		
Laredo	Yes	A	-	-	DA	DA	A	-	DA	-	-	-		SMA-F had inconsistency on Hamburgs and field density.
Lubbock	Yes	-	-	-	-	A	A	A	-	-	-	-		Needs a good tack coat.
Lufkin	No	A	-	-	-	-	-	-	-	DA	-	-		
Odessa	No	-	-	-	-	-	-	-	-	-	-	-		
Paris	Yes	A	-	DA	-	-	A	A	A	-	-	A		
Pharr	No	DA	-	DA	-	A	A	A	A	-	A	-		
Tyler	No	-	-	DA	-	-	-	A	-	-	-	A		
Waco	No	-	-	-	-	-	-	-	-	-	-	-		
Wichita Falls	No	DA	A	DA	-	-	A	-	-	-	A	A		
Yoakum	No	-	-	-	-	-	-	-	-	-	-	-		

Table B.3. Thin Open-Graded HMA Overlays.

District	Experience	Advantages OR Disadvantages: Initial cost	Long-term cost	Experience in district	Constructability	Rutting resistance	Cracking resistance	Wet skid resistance	Moisture damage resistance	Wet weather visibility	Tire-pavement noise reduction	Curb-gutter restraints	Other	Design or construction issues
Abilene	No	DA	A	-	A	-	A	A	-	A	A	-	DA: Early Freeze	
Amarillo	No	-	-	-	A	A	A	A	A	A	A	-	DA: First to freeze, last to thaw	
Atlanta	No	-	-	-	-	-	-	-	-	-	-	-		
Austin	No	-	-	-	-	-	-	-	-	-	-	-		
Beaumont	No	-	-	-	-	-	-	-	-	-	-	-		
Brownwood	Yes	-	-	DA	-	A	A	A	A	A	-	-		On our project we just laid it the width of the lanes to address a bleeding rough road. There was a slight drop off 3/4" on the shldr edge.
Bryan	Yes	A	-	DA	A	-	-	-	-	A	A	-		
Childress	Yes	A	-	-	A	-	A	A	-	-	A	-		
Corpus Christi	No	-	-	-	-	-	-	-	-	-	-	-		
El Paso	No	-	-	-	-	-	-	-	-	-	-	-		
Fort Worth	Yes	-	DA	A	A	-	-	A	DA	A	-	-	A: Ride on the bridgesDA: First to freeze, last to thaw	Good for full sun sections of roadway but not for any areas susceptible to any kind of shade within this District due to the freeze-thaw episodes we experience.
Houston	Yes	DA	DA	-	-	DA	-	A	-	A	A	-		
Laredo	No	DA	-	-	-	-	-	-	-	A	-	-		
Lubbock	Yes	A	-	-	-	-	-	A	-	A	A	-	DA: shelling at intersections	
Lufkin	Yes	A	-	A	A	-	-	A	DA	A	-	A		
Odessa	Yes	-	A	-	-	-	-	A	-	A	-	-	DA: Long term maintenance	
Paris	No	-	-	-	-	-	-	-	-	-	-	-		May be issues with local aggregate sources not meeting requirements.
Pharr	No	DA	DA	DA	A	-	A	A	-	A	A	-	DA: Raveling problems with Rubber PFC.	Gravel sources not compatible with rubber
Tyler	No	-	-	DA	-	-	-	A	-	A	-	A		
Waco	No	-	-	-	-	-	-	-	-	-	-	-		
Wichita Falls	No	DA	A	DA	-	A	A	A	-	A	A	A		
Yoakum	No	-	-	-	-	-	-	-	-	-	-	-		

Table B.4. Future Thin Overlay Use.

District	How do you see the use of thin HMA overlays in your District changing in the future?			
	Decreasing use	Little change in use	Increasing use	I'm not sure
Abilene			x	
Amarillo		x		
Atlanta			x	
Austin			x	
Beaumont			x	
Brownwood			x	
Bryan			x	
Childress			x	
Corupus Christi			x	
El Paso			x	
Fort Worth			x	
Houston				x
Laredo			x	
Lubbock			x	
Lufkin			x	
Odessa			x	
Paris			x	
Pharr		x		
Tyler			x	
Waco		x		
Wichita Falls			x	
Yoakum			x	

APPENDIX C
FRICTION TEST DATA

Table C.1. Friction Test Data.

Slab #	Sample	Gradation type	% SAC B	Aggregate	Cycles	DFT,20	MPD	Avg Angularity Before	Avg Angularity After	Avg Texture Before	Avg Texture After
1	1	Fine	0	A	2	0.520	0.647	3049	2203	443	400
1	2	Fine	0	A	2	0.530	0.647	3049	2203	443	400
1	3	Fine	0	A	2	0.526	0.647	3049	2203	443	400
2	1	Fine	25	B1	2	0.532	0.564	3001	2147	356	318
2	2	Fine	25	B1	2	0.524	0.564	3001	2147	356	318
2	3	Fine	25	B1	2	0.498	0.564	3001	2147	356	318
3	1	Fine	50	B1	2	0.546	0.578	2953	2090	269	237
3	2	Fine	50	B1	2	0.576	0.578	2953	2090	269	237
3	3	Fine	50	B1	2	0.542	0.578	2953	2090	269	237
4	1	Fine	75	B1	2	0.518	0.667	2904	2033	182	155
4	2	Fine	75	B1	2	0.514	0.667	2904	2033	182	155
4	3	Fine	75	B1	2	0.472	0.667	2904	2033	182	155
5	1	Fine	100	B1	2	0.500	0.581	2856	1977	96	74
5	2	Fine	100	B1	2	0.468	0.581	2856	1977	96	74
5	3	Fine	100	B1	2	0.464	0.581	2856	1977	96	74
6	1	Fine	25	B2	2	0.570	0.768	3045	2249	377	321
6	2	Fine	25	B2	2	0.550	0.768	3045	2249	377	321
6	3	Fine	25	B2	2	0.540	0.768	3045	2249	377	321
7	1	Fine	50	B2	2	0.526	0.392	3042	2294	311	243
7	2	Fine	50	B2	2	0.516	0.392	3042	2294	311	243
7	3	Fine	50	B2	2	0.494	0.392	3042	2294	311	243
9	1	Fine	100	B2	2	0.500	0.547	3036	2385	178	86
9	2	Fine	100	B2	2	0.468	0.547	3036	2385	178	86
9	3	Fine	100	B2	2	0.462	0.547	3036	2385	178	86
8	1	Fine	75	B2	2	0.522	0.486	3039	2340	244	164
8	2	Fine	75	B2	2	0.500	0.486	3039	2340	244	164
8	3	Fine	75	B2	2	0.490	0.486	3039	2340	244	164
10	1	Fine	25	B3	2	0.540	0.576	2990	2027	372	320
10	2	Fine	25	B3	2	0.530	0.576	2990	2027	372	320
10	3	Fine	25	B3	2	0.520	0.576	2990	2027	372	320
11	1	Fine	50	B3	2	0.560	0.503	2931	1851	301	240
11	2	Fine	50	B3	2	0.544	0.503	2931	1851	301	240
11	3	Fine	50	B3	2	0.506	0.503	2931	1851	301	240
12	1	Fine	75	B3	2	0.466	0.598	2873	1675	230	160
12	2	Fine	75	B3	2	0.450	0.598	2873	1675	230	160
12	3	Fine	75	B3	2	0.440	0.598	2873	1675	230	160
13	1	Fine	100	B3	2	0.500	0.431	2814	1500	159	80
13	2	Fine	100	B3	2	0.472	0.431	2814	1500	159	80
13	3	Fine	100	B3	2	0.446	0.431	2814	1500	159	80
14	1	Coarse	0	A	2	0.580	1.155	3049	2203	443	400
14	2	Coarse	0	A	2	0.512	1.155	3049	2203	443	400
14	3	Coarse	0	A	2	0.512	1.155	3049	2203	443	400
15	1	Coarse	25	B3	2	0.526	1.092	2990	2027	372	320
15	2	Coarse	25	B3	2	0.456	1.092	2990	2027	372	320
15	3	Coarse	25	B3	2	0.528	1.092	2990	2027	372	320
16	1	Coarse	50	B3	2	0.524	0.948	2931	1851	301	240
16	2	Coarse	50	B3	2	0.502	0.948	2931	1851	301	240
16	3	Coarse	50	B3	2	0.476	0.948	2931	1851	301	240
17	1	Coarse	75	B3	2	0.482	0.938	2873	1675	230	160
17	2	Coarse	75	B3	2	0.472	0.938	2873	1675	230	160
17	3	Coarse	75	B3	2	0.450	0.938	2873	1675	230	160
18	1	Coarse	100	B3	2	0.464	0.775	2814	1500	159	80
18	2	Coarse	100	B3	2	0.420	0.775	2814	1500	159	80
18	3	Coarse	100	B3	2	0.434	0.775	2814	1500	159	80
19	1	Coarse	25	B1	2	0.510	0.895	3001	2147	356	318
19	2	Coarse	25	B1	2	0.480	0.895	3001	2147	356	318
19	3	Coarse	25	B1	2	0.496	0.895	3001	2147	356	318
20	1	Coarse	50	B1	2	0.486	0.765	2953	2090	269	237
20	2	Coarse	50	B1	2	0.486	0.765	2953	2090	269	237
20	3	Coarse	50	B1	2	0.476	0.765	2953	2090	269	237
21	1	Coarse	75	B1	2	0.468	1.052	2904	2033	182	155
21	2	Coarse	75	B1	2	0.464	1.052	2904	2033	182	155
21	3	Coarse	75	B1	2	0.440	1.052	2904	2033	182	155
22	1	Coarse	100	B1	2	0.460	0.875	2856	1977	96	74
22	2	Coarse	100	B1	2	0.444	0.875	2856	1977	96	74
22	3	Coarse	100	B1	2	0.402	0.875	2856	1977	96	74
23	1	Coarse	25	B2	2	0.500	0.965	3045	2249	377	321
23	2	Coarse	25	B2	2	0.484	0.965	3045	2249	377	321
23	3	Coarse	25	B2	2	0.464	0.965	3045	2249	377	321

Table C.1. Friction Test Data (cont.).

Slab #	Sample	Gradation type	% SAC B	Aggregate	Cycles	DFT,20	MPD	Avg Angularity Before	Avg Angularity After	Avg Texture Before	Avg Texture After
24	1	Coarse	50	B2	2	0.508	0.867	3042	2294	311	243
24	2	Coarse	50	B2	2	0.502	0.867	3042	2294	311	243
24	3	Coarse	50	B2	2	0.450	0.867	3042	2294	311	243
25	1	Coarse	75	B2	2	0.490	0.942	3039	2340	244	164
25	2	Coarse	75	B2	2	0.470	0.942	3039	2340	244	164
25	3	Coarse	75	B2	2	0.450	0.942	3039	2340	244	164
26	1	Coarse	100	B2	2	0.510	0.716	3036	2385	178	86
26	2	Coarse	100	B2	2	0.476	0.716	3036	2385	178	86
26	3	Coarse	100	B2	2	0.442	0.716	3036	2385	178	86
27	1	Coarse	25	B4	2	0.464	0.956	3021	2102	364	318
27	2	Coarse	25	B4	2	0.500	0.956	3021	2102	364	318
27	3	Coarse	25	B4	2	0.472	0.956	3021	2102	364	318
28	1	Coarse	50	B4	2	0.516	0.772	2994	2001	285	236
28	2	Coarse	50	B4	2	0.484	0.772	2994	2001	285	236
28	3	Coarse	50	B4	2	0.482	0.772	2994	2001	285	236
29	1	Coarse	75	B4	2	0.502	0.856	2967	1899	206	155
29	2	Coarse	75	B4	2	0.466	0.856	2967	1899	206	155
29	3	Coarse	75	B4	2	0.450	0.856	2967	1899	206	155
30	1	Coarse	100	B4	2	0.446	0.919	2940	1798	127	73
30	2	Coarse	100	B4	2	0.422	0.919	2940	1798	127	73
30	3	Coarse	100	B4	2	0.410	0.919	2940	1798	127	73
1	1	Fine	0	A	30	0.490	0.733	3049	2203	443	400
1	2	Fine	0	A	30	0.480	0.733	3049	2203	443	400
1	3	Fine	0	A	30	0.482	0.733	3049	2203	443	400
2	1	Fine	25	B1	30	0.502	0.602	3001	2147	356	318
2	2	Fine	25	B1	30	0.506	0.602	3001	2147	356	318
2	3	Fine	25	B1	30	0.492	0.602	3001	2147	356	318
3	1	Fine	50	B1	30	0.436	0.635	2953	2090	269	237
3	2	Fine	50	B1	30	0.448	0.635	2953	2090	269	237
3	3	Fine	50	B1	30	0.442	0.635	2953	2090	269	237
4	1	Fine	75	B1	30	0.428	0.726	2904	2033	182	155
4	2	Fine	75	B1	30	0.468	0.726	2904	2033	182	155
4	3	Fine	75	B1	30	0.438	0.726	2904	2033	182	155
5	1	Fine	100	B1	30	0.436	0.627	2856	1977	96	74
5	2	Fine	100	B1	30	0.396	0.627	2856	1977	96	74
5	3	Fine	100	B1	30	0.408	0.627	2856	1977	96	74
6	1	Fine	25	B2	30	0.446	0.809	3045	2249	377	321
6	2	Fine	25	B2	30	0.446	0.809	3045	2249	377	321
6	3	Fine	25	B2	30	0.430	0.809	3045	2249	377	321
7	1	Fine	50	B2	30	0.388	0.463	3042	2294	311	243
7	2	Fine	50	B2	30	0.358	0.463	3042	2294	311	243
7	3	Fine	50	B2	30	0.368	0.463	3042	2294	311	243
9	1	Fine	100	B2	30	0.326	0.593	3036	2385	178	86
9	2	Fine	100	B2	30	0.328	0.593	3036	2385	178	86
9	3	Fine	100	B2	30	0.308	0.593	3036	2385	178	86
8	1	Fine	75	B2	30	0.362	0.589	3039	2340	244	164
8	2	Fine	75	B2	30	0.330	0.589	3039	2340	244	164
8	3	Fine	75	B2	30	0.350	0.589	3039	2340	244	164
10	1	Fine	25	B3	30	0.490	0.656	2990	2027	372	320
10	2	Fine	25	B3	30	0.506	0.656	2990	2027	372	320
10	3	Fine	25	B3	30	0.474	0.656	2990	2027	372	320
11	1	Fine	50	B3	30	0.414	0.574	2931	1851	301	240
11	2	Fine	50	B3	30	0.422	0.574	2931	1851	301	240
11	3	Fine	50	B3	30	0.418	0.574	2931	1851	301	240
12	1	Fine	75	B3	30	0.434	0.595	2873	1675	230	160
12	2	Fine	75	B3	30	0.436	0.595	2873	1675	230	160
12	3	Fine	75	B3	30	0.416	0.595	2873	1675	230	160
13	1	Fine	100	B3	30	0.420	0.608	2814	1500	159	80
13	2	Fine	100	B3	30	0.368	0.608	2814	1500	159	80
13	3	Fine	100	B3	30	0.394	0.608	2814	1500	159	80
14	1	Coarse	0	A	30	0.456	1.086	3049	2203	443	400
14	2	Coarse	0	A	30	0.450	1.086	3049	2203	443	400
14	3	Coarse	0	A	30	0.450	1.086	3049	2203	443	400
15	1	Coarse	25	B3	30	0.410	1.071	2990	2027	372	320
15	2	Coarse	25	B3	30	0.400	1.071	2990	2027	372	320
15	3	Coarse	25	B3	30	0.400	1.071	2990	2027	372	320
16	1	Coarse	50	B3	30	0.360	0.932	2931	1851	301	240
16	2	Coarse	50	B3	30	0.330	0.932	2931	1851	301	240

Table C.1. Friction Test Data (cont.).

Slab #	Sample	Gradation type	% SAC B	Aggregate	Cycles	DFT,20	MPD	Avg Angularity Before	Avg Angularity After	Avg Texture Before	Avg Texture After
16	3	Coarse	50	B3	30	0.378	0.932	2931	1851	301	240
17	1	Coarse	75	B3	30	0.330	0.881	2873	1675	230	160
17	2	Coarse	75	B3	30	0.310	0.881	2873	1675	230	160
17	3	Coarse	75	B3	30	0.300	0.881	2873	1675	230	160
18	1	Coarse	100	B3	30	0.260	0.779	2814	1500	159	80
18	2	Coarse	100	B3	30	0.290	0.779	2814	1500	159	80
18	3	Coarse	100	B3	30	0.272	0.779	2814	1500	159	80
19	1	Coarse	25	B1	30	0.432	0.928	3001	2147	356	318
19	2	Coarse	25	B1	30	0.410	0.928	3001	2147	356	318
19	3	Coarse	25	B1	30	0.414	0.928	3001	2147	356	318
20	1	Coarse	50	B1	30	0.400	0.824	2953	2090	269	237
20	2	Coarse	50	B1	30	0.374	0.824	2953	2090	269	237
20	3	Coarse	50	B1	30	0.386	0.824	2953	2090	269	237
21	1	Coarse	75	B1	30	0.354	1.056	2904	2033	182	155
21	2	Coarse	75	B1	30	0.328	1.056	2904	2033	182	155
21	3	Coarse	75	B1	30	0.324	1.056	2904	2033	182	155
22	1	Coarse	100	B1	30	0.330	0.876	2856	1977	96	74
22	2	Coarse	100	B1	30	0.352	0.876	2856	1977	96	74
22	3	Coarse	100	B1	30	0.308	0.876	2856	1977	96	74
23	1	Coarse	25	B2	30	0.418	0.895	3045	2249	377	321
23	2	Coarse	25	B2	30	0.408	0.895	3045	2249	377	321
23	3	Coarse	25	B2	30	0.416	0.895	3045	2249	377	321
24	1	Coarse	50	B2	30	0.380	0.812	3042	2294	311	243
24	2	Coarse	50	B2	30	0.368	0.812	3042	2294	311	243
24	3	Coarse	50	B2	30	0.336	0.812	3042	2294	311	243
25	1	Coarse	75	B2	30	0.344	0.948	3039	2340	244	164
25	2	Coarse	75	B2	30	0.330	0.948	3039	2340	244	164
25	3	Coarse	75	B2	30	0.340	0.948	3039	2340	244	164
26	1	Coarse	100	B2	30	0.360	0.777	3036	2385	178	86
26	2	Coarse	100	B2	30	0.358	0.777	3036	2385	178	86
26	3	Coarse	100	B2	30	0.346	0.777	3036	2385	178	86
27	1	Coarse	25	B4	30	0.400	0.975	3021	2102	364	318
27	2	Coarse	25	B4	30	0.390	0.975	3021	2102	364	318
27	3	Coarse	25	B4	30	0.370	0.975	3021	2102	364	318
28	1	Coarse	50	B4	30	0.382	0.806	2994	2001	285	236
28	2	Coarse	50	B4	30	0.330	0.806	2994	2001	285	236
28	3	Coarse	50	B4	30	0.464	0.806	2994	2001	285	236
29	1	Coarse	75	B4	30	0.340	0.929	2967	1899	206	155
29	2	Coarse	75	B4	30	0.310	0.929	2967	1899	206	155
29	3	Coarse	75	B4	30	0.300	0.929	2967	1899	206	155
30	1	Coarse	100	B4	30	0.332	0.931	2940	1798	127	73
30	2	Coarse	100	B4	30	0.272	0.931	2940	1798	127	73
30	3	Coarse	100	B4	30	0.308	0.931	2940	1798	127	73
1	1	Fine	0	A	100	0.410	0.770	3049	2203	443	400
1	2	Fine	0	A	100	0.400	0.770	3049	2203	443	400
1	3	Fine	0	A	100	0.406	0.770	3049	2203	443	400
2	1	Fine	25	B1	100	0.384	0.610	3001	2147	356	318
2	2	Fine	25	B1	100	0.406	0.610	3001	2147	356	318
2	3	Fine	25	B1	100	0.370	0.610	3001	2147	356	318
3	1	Fine	50	B1	100	0.362	0.650	2953	2090	269	237
3	2	Fine	50	B1	100	0.390	0.650	2953	2090	269	237
3	3	Fine	50	B1	100	0.350	0.650	2953	2090	269	237
4	1	Fine	75	B1	100	0.346	0.760	2904	2033	182	155
4	2	Fine	75	B1	100	0.366	0.760	2904	2033	182	155
4	3	Fine	75	B1	100	0.334	0.760	2904	2033	182	155
5	1	Fine	100	B1	100	0.376	0.640	2856	1977	96	74
5	2	Fine	100	B1	100	0.326	0.640	2856	1977	96	74
5	3	Fine	100	B1	100	0.340	0.640	2856	1977	96	74
6	1	Fine	25	B2	100	0.362	0.860	3045	2249	377	321
6	2	Fine	25	B2	100	0.358	0.860	3045	2249	377	321
6	3	Fine	25	B2	100	0.346	0.860	3045	2249	377	321
7	1	Fine	50	B2	100	0.382	0.443	3042	2294	311	243
7	2	Fine	50	B2	100	0.420	0.443	3042	2294	311	243
7	3	Fine	50	B2	100	0.408	0.443	3042	2294	311	243
9	1	Fine	100	B2	100	0.290	0.600	3036	2385	178	86
9	2	Fine	100	B2	100	0.288	0.600	3036	2385	178	86
9	3	Fine	100	B2	100	0.262	0.600	3036	2385	178	86
8	1	Fine	75	B2	100	0.364	0.597	3039	2340	244	164
8	2	Fine	75	B2	100	0.358	0.597	3039	2340	244	164

Table C.1. Friction Test Data (cont.).

Slab #	Sample	Gradation type	% SAC B	Aggregate	Cycles	DFT,20	MPD	Avg Angularity Before	Avg Angularity After	Avg Texture Before	Avg Texture After
8	3	Fine	75	B2	100	0.364	0.597	3039	2340	244	164
10	1	Fine	25	B3	100	0.414	0.677	2990	2027	372	320
10	2	Fine	25	B3	100	0.406	0.677	2990	2027	372	320
10	3	Fine	25	B3	100	0.420	0.677	2990	2027	372	320
11	1	Fine	50	B3	100	0.310	0.578	2931	1851	301	240
11	2	Fine	50	B3	100	0.360	0.578	2931	1851	301	240
11	3	Fine	50	B3	100	0.326	0.578	2931	1851	301	240
12	1	Fine	75	B3	100	0.390	0.600	2873	1675	230	160
12	2	Fine	75	B3	100	0.378	0.600	2873	1675	230	160
12	3	Fine	75	B3	100	0.352	0.600	2873	1675	230	160
13	1	Fine	100	B3	100	0.292	0.623	2814	1500	159	80
13	2	Fine	100	B3	100	0.314	0.623	2814	1500	159	80
13	3	Fine	100	B3	100	0.324	0.623	2814	1500	159	80
14	1	Coarse	0	A	100	0.364	1.187	3049	2203	443	400
14	2	Coarse	0	A	100	0.372	1.187	3049	2203	443	400
14	3	Coarse	0	A	100	0.310	1.187	3049	2203	443	400
15	1	Coarse	25	B3	100	0.330	1.170	2990	2027	372	320
15	2	Coarse	25	B3	100	0.350	1.170	2990	2027	372	320
15	3	Coarse	25	B3	100	0.316	1.170	2990	2027	372	320
16	1	Coarse	50	B3	100	0.290	1.003	2931	1851	301	240
16	2	Coarse	50	B3	100	0.322	1.003	2931	1851	301	240
16	3	Coarse	50	B3	100	0.334	1.003	2931	1851	301	240
17	1	Coarse	75	B3	100	0.262	0.940	2873	1675	230	160
17	2	Coarse	75	B3	100	0.266	0.940	2873	1675	230	160
17	3	Coarse	75	B3	100	0.250	0.940	2873	1675	230	160
18	1	Coarse	100	B3	100	0.270	0.820	2814	1500	159	80
18	2	Coarse	100	B3	100	0.260	0.820	2814	1500	159	80
18	3	Coarse	100	B3	100	0.292	0.820	2814	1500	159	80
19	1	Coarse	25	B1	100	0.318	1.000	3001	2147	356	318
19	2	Coarse	25	B1	100	0.336	1.000	3001	2147	356	318
19	3	Coarse	25	B1	100	0.346	1.000	3001	2147	356	318
20	1	Coarse	50	B1	100	0.340	0.877	2953	2090	269	237
20	2	Coarse	50	B1	100	0.300	0.877	2953	2090	269	237
20	3	Coarse	50	B1	100	0.338	0.877	2953	2090	269	237
21	1	Coarse	75	B1	100	0.318	1.153	2904	2033	182	155
21	2	Coarse	75	B1	100	0.334	1.153	2904	2033	182	155
21	3	Coarse	75	B1	100	0.338	1.153	2904	2033	182	155
22	1	Coarse	100	B1	100	0.270	0.937	2856	1977	96	74
22	2	Coarse	100	B1	100	0.288	0.937	2856	1977	96	74
22	3	Coarse	100	B1	100	0.270	0.937	2856	1977	96	74
23	1	Coarse	25	B2	100	0.326	0.957	3045	2249	377	321
23	2	Coarse	25	B2	100	0.280	0.957	3045	2249	377	321
23	3	Coarse	25	B2	100	0.304	0.957	3045	2249	377	321
24	1	Coarse	50	B2	100	0.272	0.857	3042	2294	311	243
24	2	Coarse	50	B2	100	0.270	0.857	3042	2294	311	243
24	3	Coarse	50	B2	100	0.268	0.857	3042	2294	311	243
25	1	Coarse	75	B2	100	0.278	1.023	3039	2340	244	164
25	2	Coarse	75	B2	100	0.270	1.023	3039	2340	244	164
25	3	Coarse	75	B2	100	0.276	1.023	3039	2340	244	164
26	1	Coarse	100	B2	100	0.260	0.820	3036	2385	178	86
26	2	Coarse	100	B2	100	0.246	0.820	3036	2385	178	86
26	3	Coarse	100	B2	100	0.240	0.820	3036	2385	178	86
27	1	Coarse	25	B4	100	0.330	1.057	3021	2102	364	318
27	2	Coarse	25	B4	100	0.402	1.057	3021	2102	364	318
27	3	Coarse	25	B4	100	0.366	1.057	3021	2102	364	318
28	1	Coarse	50	B4	100	0.334	0.853	2994	2001	285	236
28	2	Coarse	50	B4	100	0.350	0.853	2994	2001	285	236
28	3	Coarse	50	B4	100	0.318	0.853	2994	2001	285	236
29	1	Coarse	75	B4	100	0.326	1.003	2967	1899	206	155
29	2	Coarse	75	B4	100	0.344	1.003	2967	1899	206	155
29	3	Coarse	75	B4	100	0.282	1.003	2967	1899	206	155
30	1	Coarse	100	B4	100	0.288	1.003	2940	1798	127	73
30	2	Coarse	100	B4	100	0.292	1.003	2940	1798	127	73
30	3	Coarse	100	B4	100	0.294	1.003	2940	1798	127	73

APPENDIX D
BOND STRENGTH AND TACK TRACKING TEST DATA

Table D.1. Preliminary Tensile Strength Test Comparison Data.

Sample	Reading	CompEffort	Device	Speed	Temp	Strength, psi	Stub/ Epoxy	Top Mix	Interface	Bottom Mix
1	1	Low	DY206	30psi/s	72	99	10	90	0	0
1	2	Low	DY206	30psi/s	72	94	0	0	100	0
1	3	Low	DY206	30psi/s	72	100	0	0	100	0
2	1	Low	DY206	30psi/s	72	101	100	0	0	0
2	2	Low	DY206	30psi/s	72	78	0	100	0	0
2	3	Low	DY206	30psi/s	72	100	0	100	0	0
3	1	Low	DY206	5psi/s	72	121	10	90	0	0
3	2	Low	DY206	5psi/s	72	111	0	0	90	10
3	3	Low	DY206	5psi/s	72	105	0	100	0	0
4	1	Low	DY206	5psi/s	72	105	0	100	0	0
4	2	Low	DY206	5psi/s	72	101	10	90	0	0
4	3	Low	DY206	5psi/s	72	105	0	100	0	0
5	1	Low	DY206	15psi/s	72	107	0	0	100	0
5	2	Low	DY206	15psi/s	72	108	0	0	100	0
5	3	Low	DY206	15psi/s	72	112	0	100	0	0
6	1	Low	RS	.5mm/min	72	49.5	100	0	0	0
6	2	Low	RS	.5mm/min	72	56.1	100	0	0	0
6	3	Low	RS	.5mm/min	72	47.2	100	0	0	0
7	1	High	DynaZ	.5mm/min	72	57.4	0	100	0	0
7	2	High	DynaZ	.5mm/min	72	59.1	0	0	100	0
7	3	High	DynaZ	.5mm/min	72	59.1	0	0	100	0
8	1	High	DynaZ	5mm/min	72	124.0	0	0	25	75
8	2	High	DynaZ	5mm/min	72	124.0	0	0	100	0
8	3	High	DynaZ	5mm/min	72	135.5	0	0	100	0
9	1	High	DynaZ	12.5mm/min	72	145.0	0	0	100	0
9	2	High	DynaZ	12.5mm/min	72	131.6	100	0	0	0
9	3	High	DynaZ	12.5mm/min	72	156.5	0	0	25	75
10	1	High	DY206	5psi/s	72	116	0	100	0	0
10	2	High	DY206	5psi/s	72	113	0	100	0	0
10	3	High	DY206	5psi/s	72	118	0	0	100	0
11	1	High	DY206	5psi/s	72	111	0	0	100	0
11	2	High	DY206	5psi/s	72	115	0	0	100	0
11	3	High	DY206	5psi/s	72	111	0	0	100	0
12	1	High	DY206	5psi/s	40	117	100	0	0	0
12	2	High	DY206	5psi/s	40	179	100	0	0	0
12	3	High	DY206	5psi/s	40	157	100	0	0	0
13	1	High	DY206	5psi/s	72	136	0	0	100	0
13	2	High	DY206	5psi/s	72	127	0	0	0	100
13	3	High	DY206	5psi/s	72	119	0	0	70	30
14	1	High	DY206	30psi/s	72	117	0	0	100	0
14	2	High	DY206	30psi/s	72	115	0	0	100	0
14	3	High	DY206	30psi/s	72	128	0	0	100	0
15	1	High	DY206	30psi/s	40	198	100	0	0	0
15	2	High	DY206	30psi/s	40	293	100	0	0	0
15	3	High	DY206	30psi/s	40	299	100	0	0	0
16	1	High	RS	.5mm/min	72	61.0	0	0	0	100
16	2	High	RS	.5mm/min	72	51.2	0	0	100	0
16	3	High	RS	.5mm/min	72	62.3	0	0	100	0
17	1	High	RS	.5mm/min	72	67.3	0	0	0	100
17	2	High	RS	.5mm/min	72	57.4	0	0	0	100
17	3	High	RS	.5mm/min	72	56.4	0	0	100	0
18	1	High	RS	.5mm/min	40	192.3	100	0	0	0
18	2	High	RS	.5mm/min	40	159.4	100	0	0	0
18	3	High	RS	.5mm/min	40	162.7	0	0	100	0

Table D.2. Bond Strength Test Data.

Slab	Quarter	Base	Overlay	Milled	Tack	Rate	Condition	Shear Max	Tension Max	Mode
1	2	Type C	TOM	N	CSS-1H	M	Y	94.6	73.5	C
1	2	Type C	TOM	N	CSS-1H	M	Y	97.1	119.4	A
1	2	Type C	TOM	N	CSS-1H	M	Y	151.6	87.5	A
1	3	Type C	TOM	N	ARA-1P	M	Y	79.8	65.7	C
1	3	Type C	TOM	N	ARA-1P	M	Y	64.2	93.4	C
1	3	Type C	TOM	N	ARA-1P	M	Y	71.2	83.4	C
1	4	Type C	TOM	N	None	N	Y	123.3	48.9	C
1	4	Type C	TOM	N	None	N	Y	70.3	101.6	C
1	4	Type C	TOM	N	None	N	Y	88.8	97.5	C
2	1	Type C	PFC-F	N	ARA-1P	M	N	56.2	41.7	C
2	1	Type C	PFC-F	N	ARA-1P	M	N	49.1	38.0	C
2	1	Type C	PFC-F	N	ARA-1P	M	N	44.4	43.8	C
2	2	Type C	PFC-F	N	CSS-1H	M	Y	29.9	43.8	B/C
2	2	Type C	PFC-F	N	CSS-1H	M	Y	44.6	43.8	C
2	2	Type C	PFC-F	N	CSS-1H	M	Y	30.1		-
2	3	Type C	PFC-F	N	ARA-1P	M	Y	38.3	47.9	C
2	3	Type C	PFC-F	N	ARA-1P	M	Y	45.9	61.6	C
2	3	Type C	PFC-F	N	ARA-1P	M	Y	46.5	53.7	C
2	4	Type C	PFC-F	N	None	N	Y	40.6	43.8	C
2	4	Type C	PFC-F	N	None	N	Y	98.5	29.8	C
2	4	Type C	PFC-F	N	None	N	Y	26.2	61.6	C
3	1	PFC	PFC-F	N	CSS-1H	M	N	99.6	69.8	B/C
3	1	PFC	PFC-F	N	CSS-1H	M	N	99.3	77.6	B
3	1	PFC	PFC-F	N	CSS-1H	M	N	69.7	85.5	B
3	2	PFC	PFC-F	N	None	N	N	77.9	59.8	B/C
3	2	PFC	PFC-F	N	None	N	N	85.7	73.5	B
3	2	PFC	PFC-F	N	None	N	N	86.0	59.8	B
3	3	PFC	PFC-F	N	CSS-1H	H	N	98.1	77.6	B/C
3	3	PFC	PFC-F	N	CSS-1H	H	N	97.8	91.7	D
3	3	PFC	PFC-F	N	CSS-1H	H	N	96.1	79.7	B/C
3	4	PFC	PFC-F	N	CSS-1H	L	N	91.1	63.6	D
3	4	PFC	PFC-F	N	CSS-1H	L	N	75.5	93.4	B/C
3	4	PFC	PFC-F	N	CSS-1H	L	N	151.0	69.8	B/C
4	1	PFC	TOM	N	CSS-1H	M	N	142.4	83.4	D
4	1	PFC	TOM	N	CSS-1H	M	N	155.8	77.6	D
4	1	PFC	TOM	N	CSS-1H	M	N	146.2	79.7	D
4	2	PFC	TOM	N	None	N	N	181.7	83.4	A
4	2	PFC	TOM	N	None	N	N	136.1	83.4	C
4	2	PFC	TOM	N	None	N	N	142.7	67.7	C
4	3	PFC	TOM	N	CSS-1H	H	N	153.5	87.5	A
4	3	PFC	TOM	N	CSS-1H	H	N	143.5	87.5	A
4	3	PFC	TOM	N	CSS-1H	H	N	146.8	69.8	A
4	4	PFC	TOM	N	CSS-1H	L	N	161.0	75.6	A
4	4	PFC	TOM	N	CSS-1H	L	N	165.3	97.5	B
4	4	PFC	TOM	N	CSS-1H	L	N	136.0	109.4	B
5	1	PFC	TOM	N	ARA-1P	M	N	128.9	87.5	C
5	1	PFC	TOM	N	ARA-1P	M	N	88.6	117.3	C
5	1	PFC	TOM	N	ARA-1P	M	N	107.6	73.8	C
5	2	PFC	TOM	N	NT-2	M	N	132.3	109.4	D
5	2	PFC	TOM	N	NT-2	M	N	110.7	111.5	C
5	2	PFC	TOM	N	NT-2	M	N	128.9	103.6	D
5	3	PFC	TOM	N	NT-3	M	N	137.7	95.4	D
5	3	PFC	TOM	N	NT-3	M	N	156.4	99.5	D
5	3	PFC	TOM	N	NT-3	M	N	149.8	117.3	D
5	4	PFC	TOM	N	NT-4	M	N	96.9	91.7	B
5	4	PFC	TOM	N	NT-4	M	N	70.6	81.7	B/C
5	4	PFC	TOM	N	NT-4	M	N	102.3	97.5	B
6	1	Type C	PFC-F	N	None	N	N	47.4	49.6	C
6	1	Type C	PFC-F	N	None	N	N	57.6	47.9	C
6	1	Type C	PFC-F	N	None	N	N	57.0	45.8	C

Table D.2. Bond Strength Test Data (cont.).

Slab	Quarter	Base	Overlay	Milled	Tack	Rate	Condition	Shear Max	Tension Max	Mode
6	2	Type C	PFC-F	N	CSS-1H	M	N	59.1	57.8	C
6	2	Type C	PFC-F	N	CSS-1H	M	N	64.2	65.7	C
6	2	Type C	PFC-F	N	CSS-1H	M	N	52.6	69.8	B
6	3	Type C	PFC-F	N	CSS-1H	H	N	56.5	49.6	C
6	3	Type C	PFC-F	N	CSS-1H	H	N	52.7	57.8	C
6	3	Type C	PFC-F	N	CSS-1H	H	N	51.8	65.7	B/C
6	4	Type C	PFC-F	N	CSS-1H	L	N	47.7	55.7	C
6	4	Type C	PFC-F	N	CSS-1H	L	N	25.3	63.6	C
6	4	Type C	PFC-F	N	CSS-1H	L	N	27.1	57.8	C
7	1	Type C	PFC-F	Y	CSS-1H	H	N	87.7	29.8	C
7	1	Type C	PFC-F	Y	CSS-1H	H	N	89.0	69.8	B
7	1	Type C	PFC-F	Y	CSS-1H	H	N	81.9		
7	2	Type C	PFC-F	Y	CSS-1H	L	N	94.5	81.7	B
7	2	Type C	PFC-F	Y	CSS-1H	L	N	105.8	77.6	B
7	2	Type C	PFC-F	Y	CSS-1H	L	N	88.4	95.4	B
7	3	Type C	PFC-F	Y	CSS-1H	M	N	80.4	46.2	C
7	3	Type C	PFC-F	Y	CSS-1H	M	N	48.8	35.9	C
7	3	Type C	PFC-F	Y	CSS-1H	M	N	46.1	35.9	C
7	4	Type C	PFC-F	Y	None	N	N	109.0	39.7	B
7	4	Type C	PFC-F	Y	None	N	N	44.0	49.6	B
7	4	Type C	PFC-F	Y	None	N	N	69.6	75.6	C
8	1	Type C	TOM	N	None	N	N	82.3	65.7	C
8	1	Type C	TOM	N	None	N	N	100.7	65.7	C
8	1	Type C	TOM	N	None	N	N	90.1	55.7	C
8	2	Type C	TOM	N	CSS-1H	H	N	93.8	133.4	C
8	2	Type C	TOM	N	CSS-1H	H	N	81.5	79.7	B
8	2	Type C	TOM	N	CSS-1H	H	N	102.1	85.5	B/C
8	3	Type C	TOM	N	CSS-1H	L	N	121.3	97.5	B
8	3	Type C	TOM	N	CSS-1H	L	N	107.2	125.5	B/C
8	3	Type C	TOM	N	CSS-1H	L	N	79.8	137.1	C
8	4	Type C	TOM	N	CSS-1H	M	N	130.6	87.5	C
8	4	Type C	TOM	N	CSS-1H	M	N	141.1	97.5	C
8	4	Type C	TOM	N	CSS-1H	M	N	129.8	105.3	C
9	1	Type C	TOM	N	ARA-1P	M	N	120.6	93.4	C
9	1	Type C	TOM	N	ARA-1P	M	N	144.7	161.1	C
9	1	Type C	TOM	N	ARA-1P	M	N	127.3	171.0	C
9	2	Type C	TOM	N	NT-2	M	N	152.5	115.2	C
9	2	Type C	TOM	N	NT-2	M	N	149.3	117.3	C
9	2	Type C	TOM	N	NT-2	M	N	175.5	159.0	B
9	3	Type C	TOM	N	NT-3	M	N	178.5	115.2	B
9	3	Type C	TOM	N	NT-3	M	N	194.3	83.4	B
9	3	Type C	TOM	N	NT-3	M	N	172.4	119.4	B
9	4	Type C	TOM	N	NT-4	M	N	178.8	121.4	C
9	4	Type C	TOM	N	NT-4	M	N	193.0	101.6	C
9	4	Type C	TOM	N	NT-4	M	N	176.4	133.4	C
10	1	Type C	TOM	Y	CSS-1H	M	N	209.7	192.9	C
10	1	Type C	TOM	Y	CSS-1H	M	N	218.0	169.3	C
10	1	Type C	TOM	Y	CSS-1H	M	N	216.2	105.3	B
10	2	Type C	TOM	Y	None	N	N	181.3	93.4	A
10	2	Type C	TOM	Y	None	N	N	172.4	133.4	A
10	2	Type C	TOM	Y	None	N	N	183.0	109.4	A
10	3	Type C	TOM	Y	CSS-1H	H	N	200.5	123.5	B/C
10	3	Type C	TOM	Y	CSS-1H	H	N	196.4	141.2	C
10	3	Type C	TOM	Y	CSS-1H	H	N	191.1	85.5	A
10	4	Type C	TOM	Y	CSS-1H	L	N	207.6	155.9	A
10	4	Type C	TOM	Y	CSS-1H	L	N	175.0	149.1	B
10	4	Type C	TOM	Y	CSS-1H	L	N	210.1	199.0	B/C
12	1	PFC	TOM	N	NT-1	M	N	100.7	103.6	D
12	1	PFC	TOM	N	NT-1	M	N	91.8	103.6	D
12	1	PFC	TOM	N	NT-1	M	N	107.4	101.6	D

APPENDIX E
BOND STRENGTH TEST AND MICRO-MILLING SPECIFICATIONS

DRAFT Test Procedure for

TENSILE BOND STRENGTH PULL-OFF TEST

TxDOT Designation: Tex-XXX-X

Draft Date: July 2014

1. SCOPE

1.1. Use this test to determine the tensile strength between two bonded pavement layers. Specimens are most often cores from the field, but bonded laboratory and in situ field specimens may also be tested.

1.2. This test may also determine tensile strength of a uniform layer.

1.3. The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1 *Pull-Off Tester*–a small portable tensile strength test device capable of pulling at a constant displacement rate and/or constant load rate. The device stands over a prepared sample, attaching to a glued disk, and applies a tensile load until failure.

A device in the Proceq DY-2 series is recommended. The older Proceq DynaZ may also be considered.

NOTE: For testing bituminous samples, the device should have a low force working range to produce meaningful results.

2.1.1. Proceq DY 206 (recommended)–an automated, battery-powered, pull-off tester, with a working range of 0.6–6 kN (135–1349 lbf). The device applies a constant loading rate (ex. N/sec) until failure. Data like load vs time, maximum load, failure mode, and test metadata are stored digitally and are retrievable through a built-in interface or a USB connection to a computer. The loading rate and test-end criteria can be preset.

2.1.2. Proceq Dyna Z6–a manually operated pull-off tester with a working range of 0.6-6 kN (135–1349 lbf). The device applies a constant strain rate (ex. 5 mm/minute) when the user rotates a crank at a constant rate. The current and maximum loads are displayed on a digital manometer. Model variations and adapters may be available to digitally collect test data and automate the loading process. *This device is no longer manufactured.*

Figure 1. Proceq DY-2 (Left) and DynaZ (Right) Pull-Off Testers.

2.1.3. Both devices include one aluminum test disk (50 mm-diameter, 25 mm-thick aluminum, with a threaded hole), and a threaded draw bolt. More test disks may be purchased from the manufacturer.

2.2. *Core Drill and 50 mm (2-inch)-Diameter Core Barrel*: to prepare the sample for testing.

2.3. *Reaction* Plates–to facilitate testing of triplicate samples on a 6-inch diameter core or gyratory sample. Provides a solid, uniform, reaction surface for pull-off tester legs to stand on during the test. Custom fabrication.

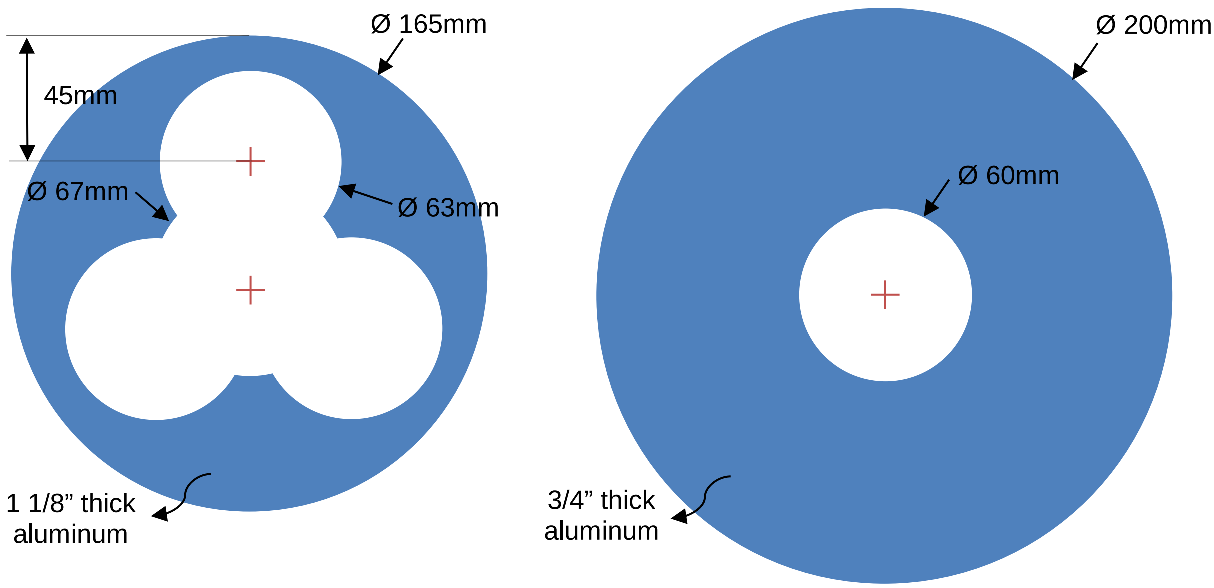


Figure 2. Reaction Plates.

2.4. *Draw Bolt Extender/Adapter*–used to extend the reach of the draw bolt when using the reaction plates. Custom fabrication.

Figure 3. Draw Bolt Extender.

3. MATERIALS

3.1. *High-Strength Adhesive*–Two-Part Epoxy, with a minimum 24-hr. tensile strength of 4.1 MPa (600 psi)

3.2. *Uniformly Fine-Graded Sand (*optional)–used for sample preparation when encountering problems with disk not adhering to the specimen.

4. SPECIMENS

4.1. *Core Specimens*–Specimen diameter must be 6 ± 0.1 in. (150 ± 2 mm). Material below the bond interface in question should be 2 inches or thicker. There is no specific density requirement for core specimens.

4.2. *Laboratory-Molded Specimen*–6-inch diameter bonded specimen, consisting of a substrate, tack, and overlay.

4.2.1. Prepare or obtain a 6-inch substrate specimen. Prepared specimens should generally conform to Tex-241-F, with a diameter of 6 in. (150 mm) and height of at least 2 in. (50 mm). The density may be adjusted as necessary to meet the purpose of the test. A 6-inch core specimen from the field may also be used as a substrate. The core should be trimmed to at least 2 inches (50 mm) thick.

NOTE: To ensure a laboratory prepared substrate sample will fit back into the mold in 4.2.4, consider heating the mold in this step to a temperature 25 F below the compaction temperature.

4.2.2. Preheat substrate to 140 °F (60 °C) to simulate summer daytime construction conditions.

4.2.3. Apply tack to the surface at the specified rate and cure.

4.2.3.1. Place sample on a scale and zero the reading. Brush pre-heated tack to the sample surface until scale reading matches calculated tack rate by weight. Cure the sample and tack for 45 minutes at 140 °F (60 °C).

4.2.3.2. Pour tack calculated tack weight into a 6-inch diameter silicon mold and cure at 140 °F (60 °C) for at least 30 minutes. To transfer the tack from the mold to the sample, invert the sample onto the tack and remove the sample. Allow to cure for 15 more minutes in the oven.

4.2.4. Place substrate sample with tack into a heated gyratory mold and immediately compact another HMA layer in general accordance with Tex-241-F. Lift thickness and density should be adjusted to meet the purpose of the test.

NOTE: To ensure a laboratory substrate sample fits back into the mold, consider heating the mold to a temperature 50 °F above the mold temperature in 4.2.1.

5. PROCEDURE

5.1. *Specimen Preparation:*

5.1.1. Drill three, partial-depth, 50 mm (2-inch)-diameter core holes equally spaced on the specimen surface. The core depth must extend at least 1-inch past the bond interface in question and no closer than 0.5 inches to the bottom of the specimen. Core holes should be at least 0.25 inches from the specimen edge.

5.1.2. Rinse the specimens, and dry using one of the following methods:

- Air dry to remove excess moisture, then use a vacuum device to complete drying.

- Oven dry at 40 °C (104 °F) to constraint weight.

5.1.3. Use epoxy adhesive to glue steel disks to the top of each partial-depth core and cure per manufacturer's instructions (generally 8+ hrs).

5.1.3.1. Ensure disks are clean. Abrading the disk surface with a wire brush may help ensure a good bond.

5.1.3.2. Care should be taken to prevent excess epoxy from dripping into the core holes. If this is an issue, use paper to line the outer wall of the core hole, then pour the sand in the gap between paper and the core. Brush away sand left on the surface.

5.1.3.3. If the disk-epoxy bond often fails, and the problem is not related to disk cleanliness or inadequate epoxy mixing, the user may use the previous method to apply epoxy below the disk and partially up the side of the disk.

5.2. *Testing:*

5.2.1. Place the reactions plates over the sample. The bottom plate should be in full contact with the specimen and plates should not interfere with the test disk or epoxy.

Figure 4. Prepared Sample with Reaction Plates.

5.2.2. Attach extender and draw bolt to a disk.

5.2.3. Position the pull-off tester over the disk and engage the coupler with the draw bolt.

5.2.4. Follow measurement procedures included with the device.

- Recommended loading rate for DY-2 family devices is 5 psi/second for bituminous materials.
- Recommended strain rate for DynaZ family devices is 5 mm/minute for bituminous materials. This most nearly correlates to 1 rotation per second.

NOTE: A metronome must be used to assist in maintaining the correct pull rate with the DynaZ family devices.

5.2.4.1. For the DynaZ, to calculate the manual rotation rate for different strain rates, use the formula below:

$$Rate_{rotation} = Rate_{strain}/0.081$$

$Rate_{rotation}$ = Manual crank rotation rate, rotations/minute

$Rate_{strain}$ = Test strain rate, mm/minute

5.2.5. Record the maximum load and percentage of failure in the following locations (to the nearest 10 percent):

- (A) In the upper-most layer.
- (A/B) at the interface between the upper layer following layer.
- (B) In the second layer.
- Etc. for additional layers.
- (E) is used for failure at the epoxy interface. In the DY-2 devices, this is not an option, so (C/D) may be used instead. This result is generally considered invalid, and should be discarded and re-tested if possible.

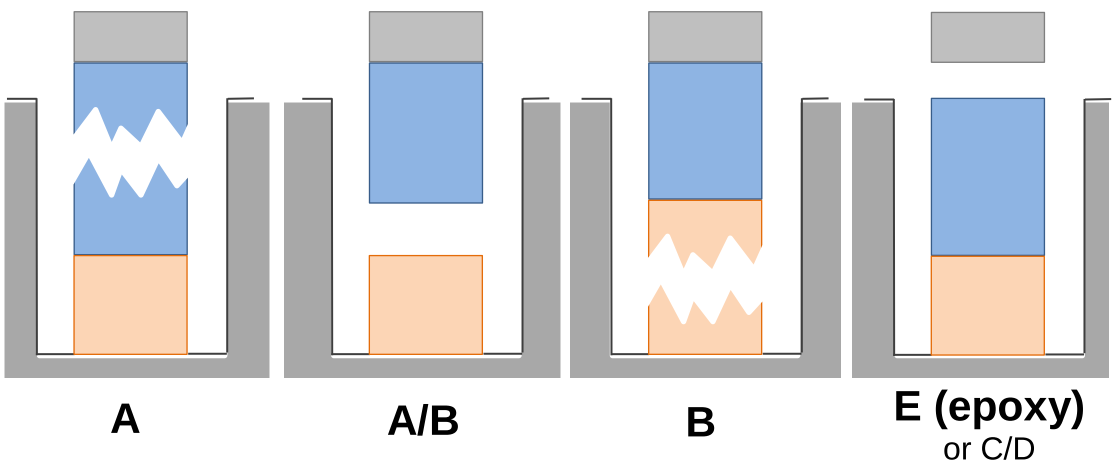


Figure 5. Failure Modes.

5.2.6. Measure the diameter of the failed core three times and average.

5.2.7. Calculate the maximum tensile stress as follows:

$$\sigma_{Max} = 4 * F_{Max}/(\pi D^2)$$

σ_{Max} = Maximum tensile strength, psi
F_{Max} = Maximum tensile load, lbs.
D = Average core diameter, inches

6. REPORT

6.1. Report the following for each specimen

- Average maximum tensile strength
- COV (percent)
- Failure modes for individual samples

DRAFT Test Procedure for

SHEAR BOND STRENGTH TEST

TxDOT Designation: Tex-XXX-X

Draft Date: August 2014

1. SCOPE

1.1. Use this test to determine the shear strength between two bonded pavement layers. Specimens are most often cores from the field, but bonded laboratory specimens may also be tested.

1.2. This test may also determine the shear strength of a uniform layer.

1.3. The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. APPARATUS

2.1. *Interlayer shear strength apparatus* - Holds a cylindrical core horizontally beneath a loading frame, and consists of two parts:1) a ridged sleeve to hold one side of the specimen and provide a reaction force; and 2) a sliding sleeve holding the other side of the specimen and moves perpendicular to the core's vertical axis, producing the shear load.

2.1.1. The device should accommodate 6-inch and 4-inch-diameter cores with the use of a reducer sleeve.

2.1.2. The gap between the sliding and reaction halves should be 1/4-in., and optionally adjust to accommodate larger gaps.

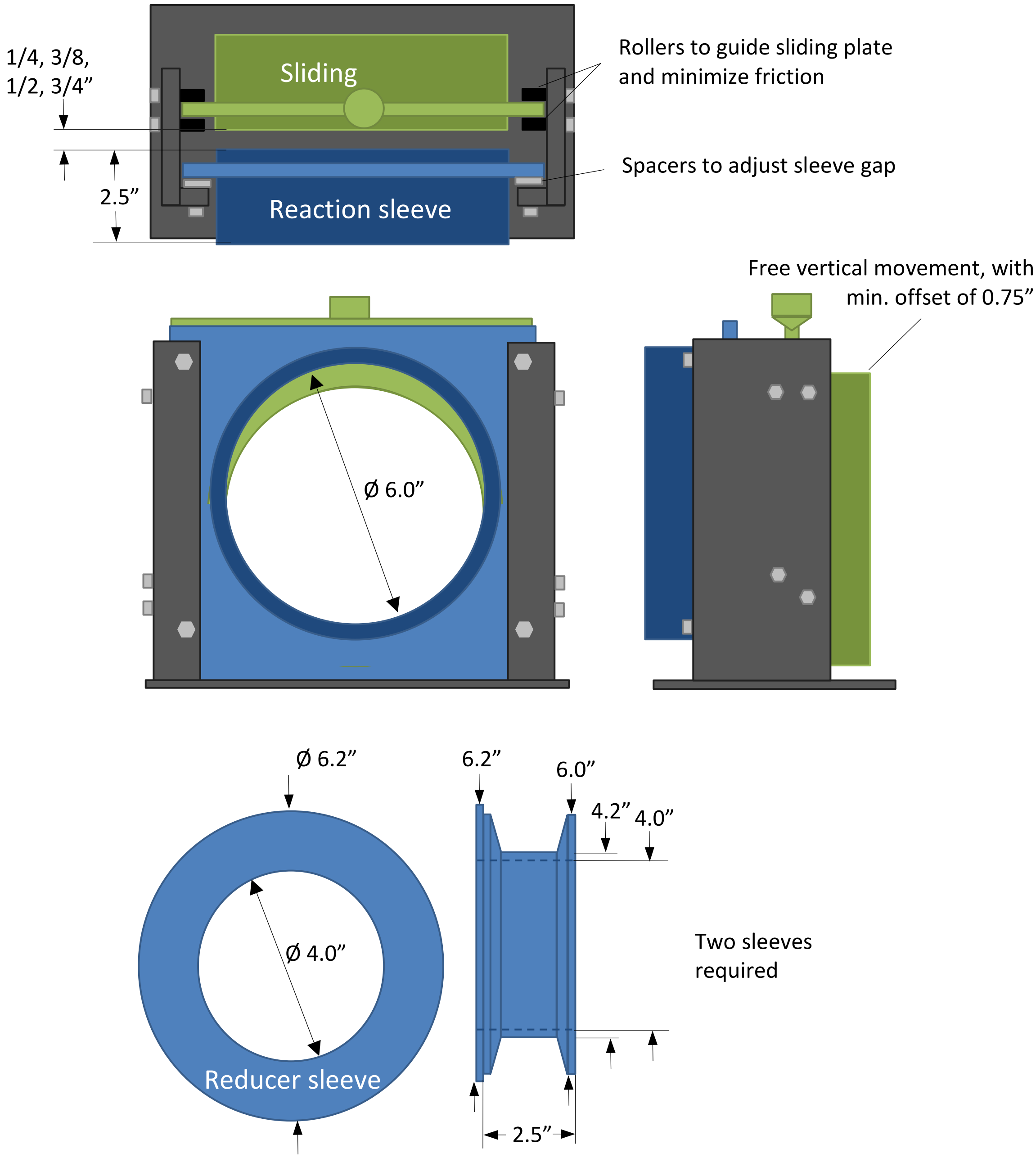


Figure E6. Interlayer Shear Strength Apparatus and Reducer Sleeve.

2.2. *Loading Frame* – Must apply a uniform vertical displacement rate of 0.5 in. (12.5 mm)/minute.

2.3. *Core Drill and 4-inch Core Barrel* – Used to reduce the diameter of core specimens when testing layer thicknesses less than 1.5 in. (38 mm).

3. SPECIMENS

3.1. Measurements on three specimens constitute a single test.

3.2. *Core Specimens* — Specimen diameter must be 6 ± 0.1 in. (150 ± 2 mm) or 4 ± 0.1 in. (100 ± 2mm). The smaller core size must be used for specimens with layer thicknesses less than 1.25 in. (32 mm). There is no specific density requirement.

3.2.1. Mark the direction of traffic on the surface prior to coring.

3.2.2. Carefully remove the core as to minimize stress bond and surrounding layers. Make a note if the core debonds at the interface in question.

3.2.3. Trim cores so the thickness between the bond and specimen end is between no more than 3 in.

3.2.4. Allow specimens to fully dry after coring and trimming.

3.3. *Laboratory-Molded Specimen*–4-inch diameter bonded specimen, consisting of a substrate, tack, and overlay.

3.3.1. Prepare or obtain a 4 or 6-inch substrate specimen with a height of 2 in. (50 mm). Prepared specimens should generally conform to Tex-241-F. The density may be adjusted as necessary to meet the purpose of the test. A core specimen from the field may also be used as a substrate.

NOTE: To ensure a laboratory prepared substrate sample will fit back into the mold in 3.3.4, consider heating the mold in this step to a temperature 25 °F below the compaction temperature.

3.3.2. Preheat substrate to 140 °F (60 °C) to simulate summer daytime construction conditions.

3.3.3. Apply tack to the surface at the specified rate using one of the following methods and cure.

3.3.3.1. Place sample on a scale and zero the reading. Brush pre-heated tack to the sample surface until scale reading matches calculated tack rate by weight. Cure the sample and tack for 45 minutes at 140 °F (60 °C).

3.3.3.2. Pour calculated tack weight into a 6- or 4-inch diameter silicon mold and cure at 140 °F (60 °C) for at least 30 minutes. To transfer the tack from the mold to the sample, invert the sample onto the tack and remove the sample. Allow to cure for 15 more minutes at 140 °F (60 °C).

3.3.4. Place substrate sample with tack into a heated mold and immediately compact another layer in general accordance with Tex-241-F. Lift thickness and density should be adjusted to meet the purpose of the test.

NOTE: To ensure a laboratory substrate sample fits back into the mold, consider heating the mold to a temperature 50 °F above the mold temperature in 3.3.1.

3.4. For specimens with emulsion tack, allow adequate time for tack to cure.

3.5. Measure the specimen diameter three times to the nearest 0.03 in. (1 mm) and average.

4. PROCEDURE

4.1. *Testing:*

4.1.1. Slide the specimen into the shearing apparatus and position the interface in question in the center of the gap. Orient the specimen so the direction of traffic from field cores is vertical. Use the 4-in. diameter sleeve when necessary.

NOTE: If the sample is excessively loose, wrap layers of masking tape around the sample near the interface. To aid in locating the bond, clearly mark the bond before placing it in the apparatus.

4.1.2. Position the apparatus in the loading frame and carefully bring the loading frame head in contact with the top of the shear apparatus. Apply a 10 lb seating load.

4.1.3. Apply the shearing load at a constant rate of displacement of 0.2 in. (5 mm) /minute and record the maximum load before failure.

4.1.4. Calculate the maximum shear strength using the following equation:

$$Shear_{max} = 4 * F_{Max}/(\pi D^2)$$

$Shear_{max}$ = Maximum shear strength, psi

F_{Max} = Maximum load, lbs.

D = Average specimen diameter, in.

4.1.5. Note the location of the failure (at the bond interface, or in the adjacent layers).

5. REPORT

5.1. Report the following for each specimen

- Maximum shear strength for individual specimens
- Note samples that fail at a location other than the bond
- Average shear strength and standard deviation of the three specimens.

ITEM XXX

MICRO-MILLING DRAFT SPECIFICATION

XXX.1. Description. Micro-mill existing asphalt concrete pavements. In comparison to Item 354, Planing and Texturing Pavement, this Item produces a smoother texture with tighter tolerances. This Item is particularly applicable for milling prior to a thin overlay, which is less than 1.25 inches thick.

XXX.2. Equipment.

A. **Micro-milling equipment.** Use micro-milling machines that meet the following criteria:

1. **Machine.**
   - Size and shape to allow traffic safe passage through areas adjacent to the work.
   - Self-propelled with sufficient power, traction, and stability to maintain an accurate depth of cut and slope.
   - Can cut in 1 continuous operation: 3/4 in. of asphalt concrete pavement.
   - Dual longitudinal controls capable of operating on both sides automatically from any longitudinal grade reference, which includes string line, ski, mobile string line, or matching shoe.
   - Transverse controls with an automatic system to control cross slope at a given rate.
   - Integral loading and reclaiming devices to allow cutting, removal, and discharge of the material into a truck in one operation, with side, rear, or front discharge capabilities;
   - Furnished with a lighting system for night work, as necessary.
   - Devices to control dust created by cutting action.
2. **Cutting Mandrill.**
   - Minimum 6-ft cutting width except for work areas less than 6-ft wide.
   - Carbide or equivalent tipped cutting teeth.
   - Maximum 5/16 in. lateral spacing of cutting teeth.
   - Capable of removing pavement to an accuracy of 1/16 and producing the texture described in XXX.4.

B. Sweeper. *Unless otherwise approved, use a street sweeper to remove cuttings and debris from the milled pavement. Equip the sweeper with a water tank, dust control spray assembly, both a pick-up and a gutter broom, and a debris hopper.*

XXX.3. Construction.

A. Grade Reference. When required, place grade reference points at maximum intervals of 50 ft in accordance with Item 5, “Control of the Word.” Use the control points to set the grade reference. Support the grade reference so the maximum deflection does not exceed 1/16 in. between supports.

B. Micro-milling. Prior to commencement of the work, construct a test section that is 500 ft in length to demonstrate compliance with the transverse pattern, texture depth, and cross slope requirements (see XXX.4). Compliance must be approved by the Engineer. If any of these requirements are not met, stop milling operation and take corrective action with approval by the Engineer. Construct another 500-ft test section in a different area than the initial section using the approved corrective action. The second test section is subject to the same requirements, and continued micro-milling is prohibited until an acceptable test section is obtained.

Micro-mill the designated areas and depths specified in the plans, including bridge decks, shoulders, and ramps, as required. The final transverse pattern, texture depth, cross slope, and vertical tolerance should also conform to the requirements in XXX.4. Remove and replace any section that does not comply.

Remove dust, residue, and loose milled material from the micro-milled surface. Until removal is complete, do not allow traffic on the milled surface and do not overlay with asphalt concrete.

C. Edge Treatments*.* Bevel back the longitudinal vertical edges greater than 2 in. deep produced by the removal process and left exposed to traffic. Bevel the vertical edges back at least 3 in. for each 2 in. of material removed. Use an attached mold board or other approved method.

Taper the transverse edges 10 ft to avoid creating a traffic hazard and to produce a smooth surface when removing material at ramp areas and ends of milled sections.

For transverse vertical edges such at bridge approach slabs, drainage structures, and utility appurtenances greater than 1/2 in., protect the edges with a temporary asphalt concrete tie-in (paper joint). Place the temporary tie-in at a taper rate of at least 6:1, horizontal to vertical distance. Do not micro-mill bridge joints. Damage due to micro-milling will be repaired at the Contractor’s expense and to the satisfaction of the Engineer.

D. Salvaged Materials. The Department will retain ownership of planed materials unless otherwise shown on the plans. Stockpile salvaged materials at locations shown on the plans. Prepare the stockpile site by removing vegetation and trash and by providing proper drainage. Keep salvaged material free from contamination during its removal, transportation, and storage. Place different types or qualities of salvaged asphalt paving material into separate stockpiles. Dispose of unsalvageable material in accordance with applicable federal, state, and local regulations.

XXX.4. Acceptance. The micro-milled surface must have a uniform finish free from gouges and ridges, and the width of cut should not vary more than 1/8 in.

The surface should have a transverse pattern of 0.2 in. or smaller, center to center of each strike area. The mean-texture/profile depth (MTD/MPD) will be measured with the sand patch test or a circular-track meter (CTM). The average MTD/MPD in each measured section should be between 0.03 and 0.08 in., and no section should exceed 0.10 in. In the preliminary test section, the Engineer will select 5 random locations for these measurements, unless the surface appears non-uniform, in which case 10 random locations will be selected. During routine construction, the Engineer will randomly select the test locations.

An alternative option to MTD/MPD, is the ridge-to-valley depth (RVD), defined as the difference between the lowest and highest point in a specified base length. The average RVD should be between 0.06 and 0.10 in., and no section should exceed 0.12 in. These measurements could be made with a CTM, single-point laser profiler, or a wide-laser profiler. The base length should be 4 in.

A constant cross slope between pavement edges in each lane must be maintained, as shown on the Plans or directed by the Engineer. This will provide positive drainage to prevent water accumulation on the micro-milled pavement. The cross slope must be uniform with no depressions or slope misalignments greater than 1/4 in. per 12 ft exit when the slope is tested with a straightedge placed perpendicular to the center line.

The pavement surface should not vary by more than 1/8 in. per 10 ft in the longitudinal direction. This will be evaluated with a 10-ft straightedge placed parallel to the centerline at random locations selected by the Engineer. Deviations will be measured from the top of the texture.

XXX.5. Measurement. This Item will be measured by the square yard of surface area for each pavement type including asphalt concrete pavement, concrete pavement, and bridge decks. Measurement will be based on the depth shown for each bid item, within the limits shown on the plans, regardless of the number of passes required. Only 1 bid item for each pavement type will apply to any 1 location.

XXX.6. Payment. The work performed and materials furnished in accordance with this Item and measured as provided under “Measurement” will be paid for at the unit price bid for “Micro-Milling Asphalt Concrete Pavement,” or “Micro-Milling Concrete Pavement,” or “Micro-Milling Bridge Decks.”

This price is full compensation for removing all material to the depth shown; loading, hauling, and unloading; stockpiling or disposing of material; sweeping; tapering and sloping longitudinal or transverse joints; and equipment, labor, tools, and incidentals. Demonstration work to receive approval for use of equipment will not be paid for unless work is performed in accordance with the Contract and is accepted.

APPENDIX F
DENSITY TEST DATA

Table F.1 Density Data from Field Tests.

Project	Mix	Location	MTD_avg	Flow_time	Dielectric	Voids_SSD
US 59	TOM	1	1.19	1.1	4.70	11.95
US 59	TOM	2	1.00	3.0	4.80	10.71
US 59	TOM	3	1.22	1.8	5.10	11.65
US 59	TOM	4	1.00	3.3	5.10	11.18
US 59	TOM	5	1.22	0.8	5.00	12.19
US 59	TOM	6	1.02	2.5	5.90	11.21
US 59	TOM	7	1.11	1.8	5.10	12.28
US 59	TOM	8	0.95	2.7	5.50	10.83
US 59	TOM	9	0.72	46.4	5.80	9.11
US 59	TOM	10	1.06	8.7	5.40	9.41
US 59	TOM	11	0.99	5.7	5.70	8.93
US 59	TOM	11b	0.58			2.91
US 59	TOM	12	0.99	7.8	5.80	10.18
FM 1887	TOM	1	1.06	1.0	5.16	11.67
FM 1887	TOM	2	1.05	1.7	5.17	11.34
FM 1887	TOM	3	0.92	3.0	5.32	11.96
FM 1887	TOM	4	1.02	1.4	5.24	11.97
FM 1887	TOM	5	0.90	2.0	5.35	11.20
FM 1887	TOM	6	1.01	2.6	5.40	10.76
FM 1887	TOM	7	0.95	2.8	5.39	10.03
FM 1887	TOM	8	0.87	5.5	5.51	8.54
FM 1887	TOM	9	0.86	4.2	5.59	8.91
FM 1887	TOM	10	0.77	7.8	5.62	8.25
FM 1887	TOM	11	0.73	22.3	5.73	6.80
FM 1887	TOM	12	0.80	5.6	5.54	8.76
FM 1887	TOM	1b	1.06	1.6		11.78
RM 12	UTOM	1	0.41	80.4	5.12	6.45
RM 12	UTOM	2	0.35	35.0	4.97	4.60
RM 12	UTOM	3	0.26		5.17	
RM 12	UTOM	4	0.50	3.8	4.14	12.83
RM 12	UTOM	5	0.60	2.0	3.91	14.86
RM 12	UTOM	6	0.48	5.9	4.09	12.25
RM 12	UTOM	7	0.44	6.6	4.17	12.08
RM 12	UTOM	8	0.39	38.9	4.41	9.06
RM 12	UTOM	9	0.38	6.6	4.29	8.74
RM 12	UTOM	10	0.41	12.2	4.36	
RM 12	UTOM	11	0.34	32.7	4.56	
RM 12	UTOM	12	0.39	33.2	4.59	

APPENDIX G
DEMONSTRATION PROJECT WRITE-UPS

Page

LP 1604 FRONTAGE–KNIPPA OVERLAYS

Figure G.1 shows two thin overlay test sections were constructed on the frontage road to Loop 1604, on the northeast side of San Antonio. The section ran from Nacogdoches Rd going south to the next turnaround, and also up the exit ramp. The existing surface was an aged chip seal with slight flushing in the wheel paths and slight raveling outside the wheel paths. The mean profile depth was 1.6 mm in the wheel paths and 1.8 mm outside the wheel paths. The AADT for this section is unknown, but considered moderate approaching the on-ramp and low towards the turnaround.

Figure G.1. Project Location of Lp 1604 Frontage–Knippa Overlays.

A TOM and a fine-PFC were both constructed on this project. Both designs used SAC A trap rock from Knippa for the coarse aggregate, 1 percent lime, and PG 76-22 asphalt. The TOM had 6.2 percent asphalt and the fine-PFC had 7.0 percent. The TOM passed the HWTT at 6.3 mm in 20,000 cycles, and passed the overlay with 1,000+ cycles. The fine-PFC tested in the HWTT with 11.6 mm in 10,000 cycles.

A trial batch and larger project were constructed in August 2013. E-Tac was applied at a residual rate of 0.02 gal/sy, as measured by ASTM D2995 (Standard Practice for Estimating Application Rate of Bituminous Distributors). This is much lower than the manufacturer's recommended rate of 0.06 gal/sy. The mixes were compacted to 1.0 inches. The area under the tack rate test was left untacked for a later bond strength comparison to the tacked section.

During the trial batch, compaction was done with one roller. The fine-PFC mix was 290 °F behind the paver and was compacted to 1.0 inches. TxDOT monitored the compaction density with a nuclear density gauge after each pass. Though this type of gauge is not appropriate for measuring actual density, it could give the operators an idea of change in density. After three slow static roller passes, the readings were 27 percent voids. After a fourth pass, the readings were 22 percent voids. The final rolling pattern was not noted.

The TOM was about 275 °F out of the paver. With one roller, compaction was done in one half lane first, then the other half. By the time the roller reached the second half lane, the mat had cooled to about 255 °F. Once more, TxDOT monitored compaction with a nuclear gauge. After one vibratory pass, the density reading was 106 pcf. It increased to 115 pcf after three passes. After a fourth vibratory pass, density dropped to 113 pcf, suggesting that not more than three vibratory passes is recommended. The final rolling pattern for the TOM was three vibratory passes and one static pass.

During paving of the larger section, the TOM was hotter, about 325 °F behind the screed. The contractor had two rollers working in tandem, applying three vibratory passes and one static pass. The final TOM macrotexture was between 0.58 and 0.82 mm, with an average of 0.71 mm. This is a low to moderate texture level. Density from a nuclear gauge was 92 to 94 percent with no water flow. Figure G.2 shows the completed TOM section.

Figure G.2. Lp 1604-Frontage-TOM.

Cores were taken from both the trial and full-scale sections for the TOM, and from the trial section only for the fine-PFC. Tacked and untacked locations were sampled, and the cores were allowed to cure at room temperature for 7 days. The cores were then tested for bond strength in shear and tension. Shear strength was tested in the interlayer shear tester at 0.5 in/min, and tensile strength was tested at 0.5 in/min. in the manually operated pull-off tester (see Figure G.3).

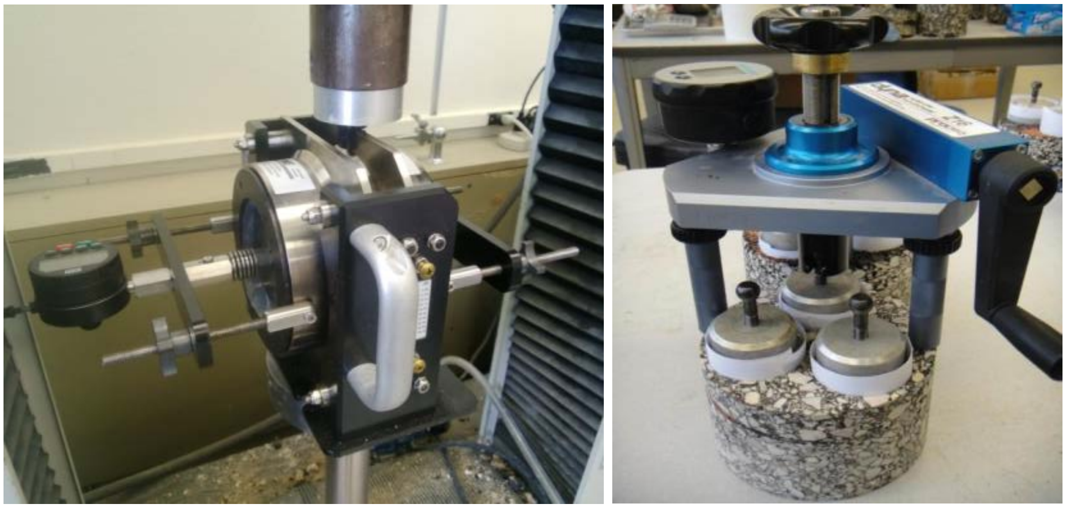
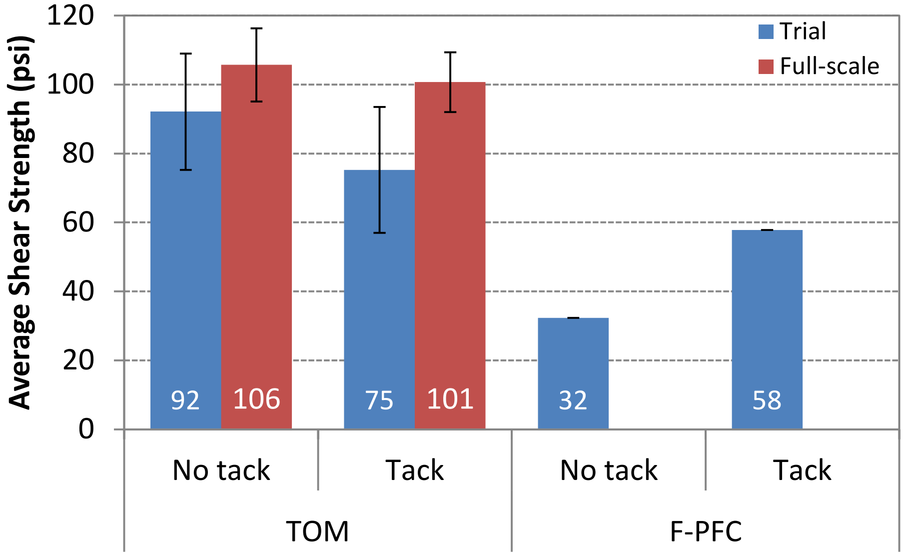


Figure G.3. Bond Strength Test Devices: Shear Test (Left) and Pull-Off Test (Right).

The test results are summarized in Table G.1 and Figure G.4. Overall, there was no difference between sections with and without tack, except for fine-PFC shear test, where the tacked section had higher strength. For both tests, the TOM consistently had higher strengths than the fine-PFC. The tensile failure mode for the fine-PFC was almost always within the overlay mix, and a little at the overlay-chip interface. For the TOM, the failure of tacked sections was in the old HMA, beneath the chip seal, and for non-tacked samples the failure was in different locations, including the overlay-chip interface, old HMA, within the TOM, and the chip pulling out of the seal. This suggests that the tack does help with bonding, but in this case the overall bond strength did not increase.

Table G.1. Shear and Tensile Strength Results.

			Project				**Failure Location**				
			Full-scale		Trial						
Strength Test	**Mix Type**	**Condition**	Average	StDev	Average	StDev	Within Overlay	Tack Interface	Chip from Seal	Seal from HMA	Within Existing
Shear	TOM	No tack	105.7	10.6	92.1	16.9		**X**	**X**	X	
		Tack	100.7	8.7	75.3	18.3		**X**	**X**	X	
	F-PFC	No tack	-	-	32.3	-	X	**X**	X		
		Tack	-	-	57.8	-	X	**X**	X		
Tensile	TOM	No tack	-	-	31.4	5.3	X	**X**	X		X
		Tack	-	-	30.9	4.0					**X**
	F-PFC	No tack	-	-	23.1	3.8	**X**	X	X		
		Tack	-	-	22.9	1.1	**X**	X	X		



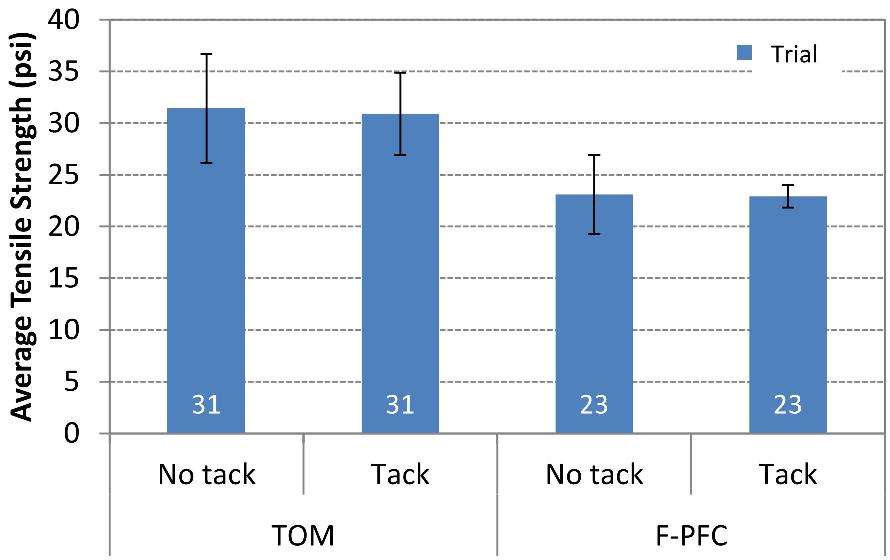


Figure G.4. Shear and Tensile Strength Results.

FM 1887-TOM

This TOM project is located south of Hempstead, in Waller County, on FM 1887 (Figure G.5). The full project runs several miles from FM 359 to FM 3346, but the focused study area for the research was near the southern curve by Youngblood Road, in the southbound lane. The road was recently paved with a Type D mix, and the condition of the underlying pavement was unknown. The road, serving a nursery and local residents, has a low AADT of 690.

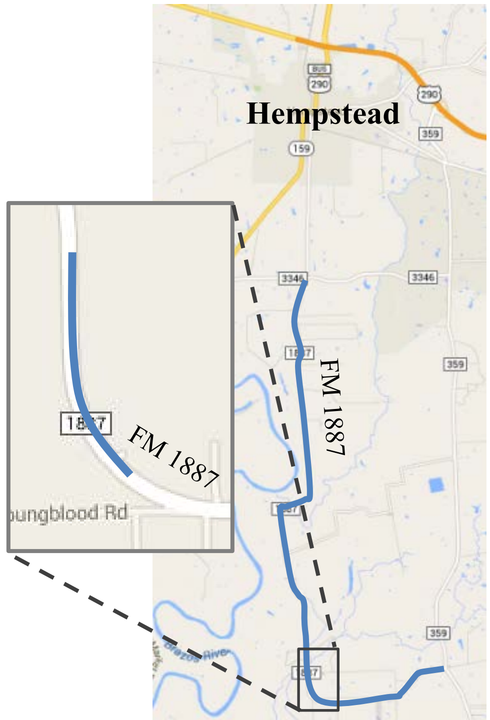


Figure G.5. Project Location of FM 1887-TOM.

The FM-1887 mix design used a SAC B dolomite from Burnet, 6.7 percent of PG 70-22 asphalt, and 1 percent lime. This is the only mix design in this report that used a SAC B aggregate and an asphalt PG lower than 76-22. The mix passed the HWTT at 4.82 mm in 15,000 cycles, and passed the overlay with 1,000+ cycles.

The Angel Brothers constructed this project in May and June 2014. A shuttle buggy transferred material from end dumps into the paver hopper. The paver was equipped with a pave IR bar, in addition to an IR scanner for testing purposes. The mix was compacted to 1.0 inch. Three compaction test sections were constructed, applying low, moderate, and high amounts of compaction effort. In general, construction went very smoothly.

The test compaction sections were tested with a Rolling Density Meter, circular track meter, and a water flow permeability test. These were performed as surrogate measures of density. The test locations were also cored for laboratory verification of densities. Although the complete results of these tests are given in 0-6814 TM-8, this report will touch on the density variability within a standard compaction area as the rolling density meter had recorded. The dielectric values were converted to percent voids using a non-linear regression equation found from correlation testing, and Figure G.6 presents the resulting distribution of voids for a small section. Figure G.7 shows the distribution of voids in the entire normal section. The variation in this section is really quite large, much more than expected. This may be due to the fact that the “normal compaction” test section was between two other test sections, and there may have been some unintended compaction overlap.

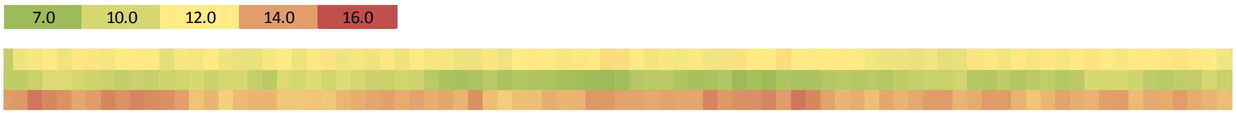


Figure G.6. Example Voids Distribution on FM 1887 Section.

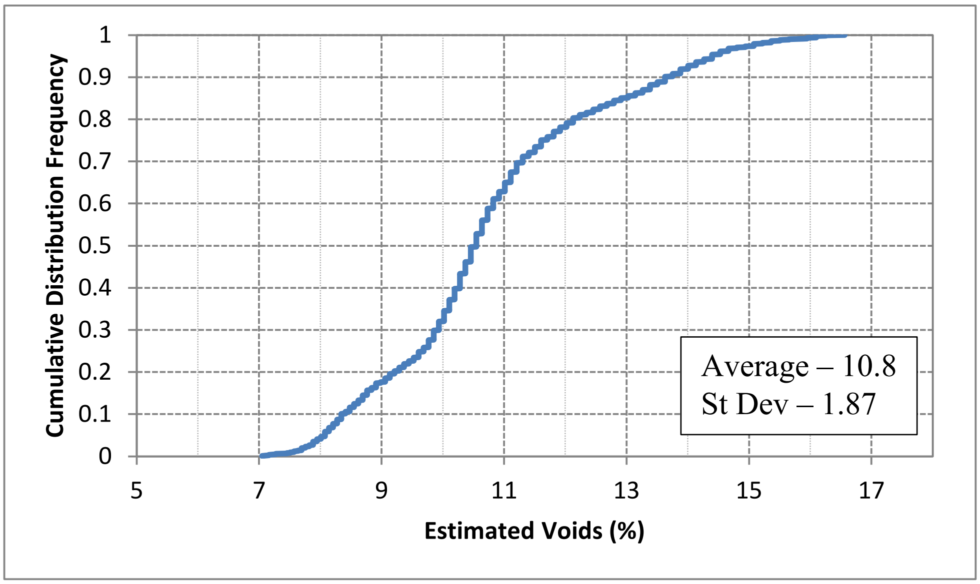


Figure G.7. Expected Void Distribution on FM 1887 Section.

ATLANTA-TOM-B

This TOM-B project is located in Atlanta, at the intersection of FM 251 and FM 785 (see Figure G.8). A longer 1,500-ft section was paved on FM 251 in front of Atlanta High School. The site has low traffic volumes (AADT of 2,400); however, when school is in session, several buses enter and exit the high school, putting severe stress on the existing pavement. This is evidenced by raveling in the surface treatment around many of the high school accesses. In these areas, most of the chip was missing from the wheel paths, exposing the rubber seal. The intersection and the approaches had a similar problem. In other areas, the chip was mostly intact, but perhaps a little sparse (see Figure G.9).

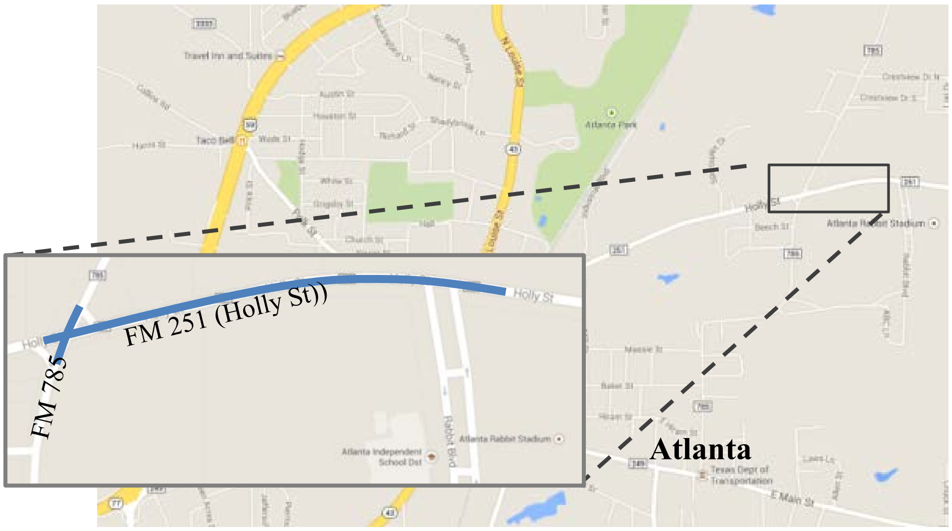


Figure G.8. Project Location on FM 251 and FM 785 (Atlanta-TOM-B).

(a)

Figure G.9. Existing Surface Condition: a) Raveled and b) Non-raveled.

(b)

Figure G.9. Existing Surface Condition: a) Raveled and b) Non-raveled. (cont.)

The Atlanta-TOM-B was designed according to TxDOT SS 3280, TOM Type B. The mix used a SAC A gravel from Hanson-Little River, 1 percent lime, and 6.6 percent of PG 76-22 binder. Plant mix from the job passed the HWTT with 2.3 mm rutting after 20,000 cycles and the overlay at 1,000+ cycles.

RK Hall constructed the TOM-B in June 2014. Calumet Trackless Tack was applied uniformly at a target residual rate of 0.05 gal/sq. Tack measurements were made in raveled and non-raveled locations with ASTM D2995 (Standard Practice for Estimating Application Rate of Bituminous Distributors) (Figure G.10). The results showed that the average residual tack rate was 0.04 gal/sy. Both these locations were later cored for bond strength tests with and without tack coat.

The TOM-B was foamed at the plant to extend the compactability. A shuttle buggy was used to transfer the mix from the trucks to the paver hopper. The paver screed vibrator was engaged, and the mix was compacted to 0.5 inch with one static-wheel roller. The mix behind the screed was approximately 280 °F. Initially, workers behind the screed attempted to taper the mat edges by hand. However, this became a detriment as it created a slight ridge, causing the roller to ride up higher on the edge and not fully compact portions of the lane. This problem was identified, and hand-working the edge was stopped. Average mix yield was 66 lb/sy.

The researchers made three water flow measurements after compaction. The location next to the ridge (low density) had a flow time of 4:35. On the area opposite the ridge (high density), no flow was recorded after 12 minutes. In the adjacent lane, where the ridge problem was corrected, flow time was 8:05. This last value is likely typical for the project.

Figure G.10. Measuring Tack Application Rate.

Figure G.11. Hand-Working Issue Causing Uneven Compaction.

Cores were pulled for laboratory bond-strength testing, and the results are shown in Table G.2 and Figure G.12. The data do not include results where the mix did not fail (the pull-off disk came off the sample). There was no statistical difference in maximum tensile strength for any of the sample types. The failure mode for raveled samples was within the new TOM-B layer or with the chip pulling out of the seal. A small fraction of the tacked samples failed at the tack interface between the TOM-B and the chip. For samples on the raveled section, all samples failed within the TOM-B layer. The data suggest that, for this project, tack did not increase bond strength. Also, an aged and partially raveled chip seal may create a weaker interface than a completely raveled chip.

Table G.2. Tensile Strength Results.

Sample Type		Sample Count	Tensile Strength (psi)		Average Failure Location (%)		
			Average	St Dev	Within TOM-B	Tack Interface	Chip from Seal
Non-raveled	No tack	2	97.3	5.5	55	-	45
	Tack	5	90.8	5.8	46	7	44
Raveled	No tack	5	96.9	-	100	-	NA
	Tack	1	101.7	12.6	100	-	NA

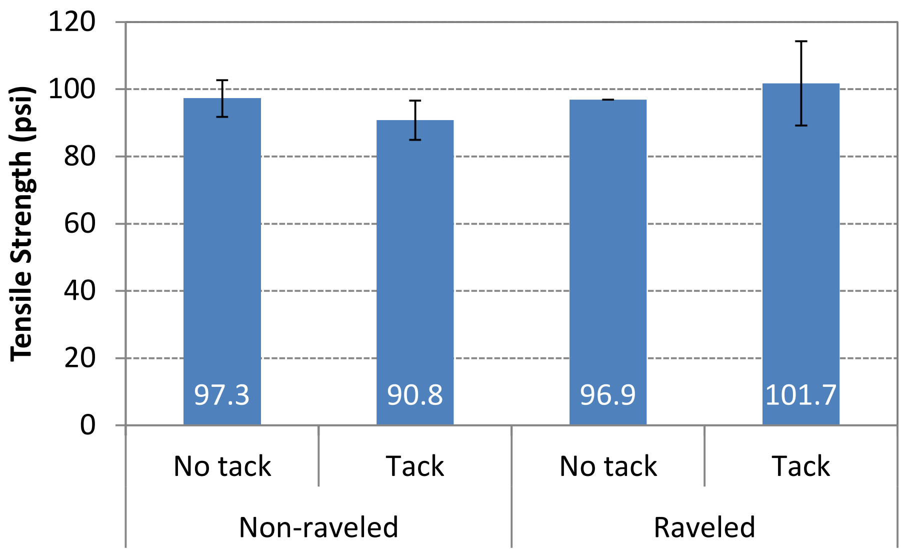


Figure G.12. Tensile Strength Results.

Overall, construction of the TOM-B went smoothly. Hand-working this thin mix should be avoided. Bond strength was no different in raveled vs. non-raveled sections, nor in samples with and without tack. Perhaps, since gap-graded thin overlays have a relatively high film thickness, the benefits of a tack coat are less notable than for traditional dense-graded mixes with much lower asphalt contents. A more detailed investigation into the benefits of tack coats for these types of mixes should be performed.

RM 12-TOM-B

This TOM-B project is located just north of Wimberley on RM 12 (Figure G.13). The full project actually extends to the south side of Wimberley, goes through the town, and then out north. The sections marked were those specific to the study. The site has low traffic volumes (AADT of 5,800). The existing pavement surface was an aged surface treatment with some longitudinal cracking in and out of the wheel paths.

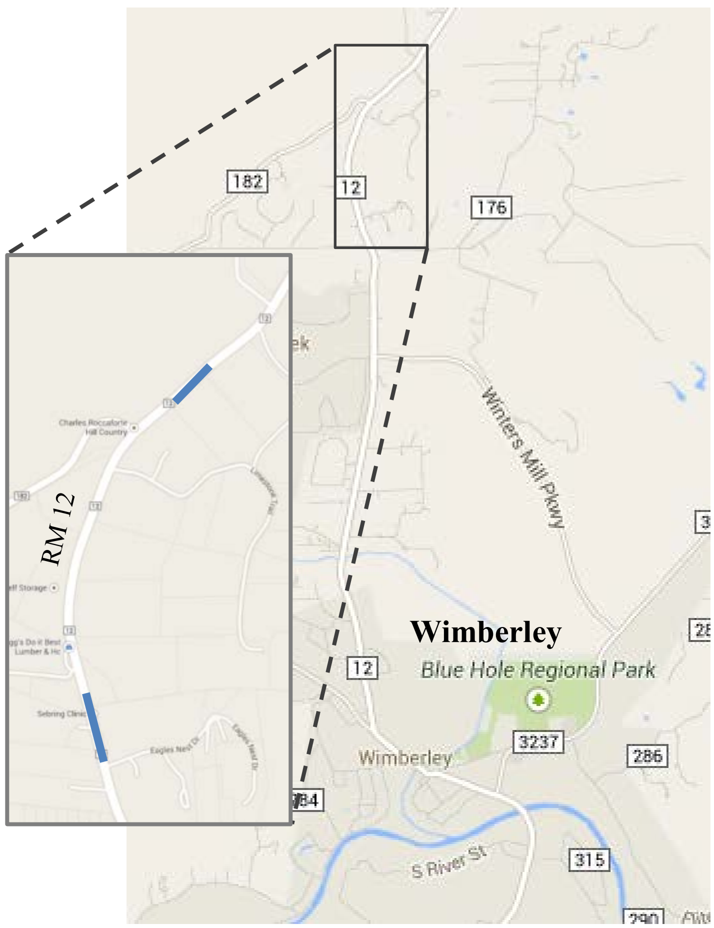


Figure G.13. Project Location on RM 12 North of Wimberley (RM 12-TOM-B).

The RM 12-TOM-B was designed according to TxDOT SS 3280, TOM Type B. The mix used a Class B dolomite coarse aggregate, 1 percent lime, and 6.7 percent of PG 70-22 binder from Century Asphalt. The design passed the HWTT with 4.8 mm rutting after 15,000 cycles and the overlay at 1,000+ cycles.

The project was evaluated on July 2014. Belly dump trucks transported the mix to the job site where a windrow elevator transferred the mix into the paver. The mix compacted to 0.5 in. thick with two rollers applying one vibratory pass, two static passes, then one finishing pass. The average core height was found to be closer to 0.6 inch. Two additional test sections were made with a higher and lower compaction effort. The higher effort section replaced one of the static passes with a vibratory pass. The lower effort section replaced the only vibratory pass with a static pass.

The paver was fitted with an IR scanner to measure thermal profiles (see example in Figure G.14). The IR scanner system measured a total paving time of approximately 4:49 h:m at an average paving speed of 31.1 ft./min. For the duration of the pull, the paver total idle time was 1:42 h:m due primarily to waiting for trucks.

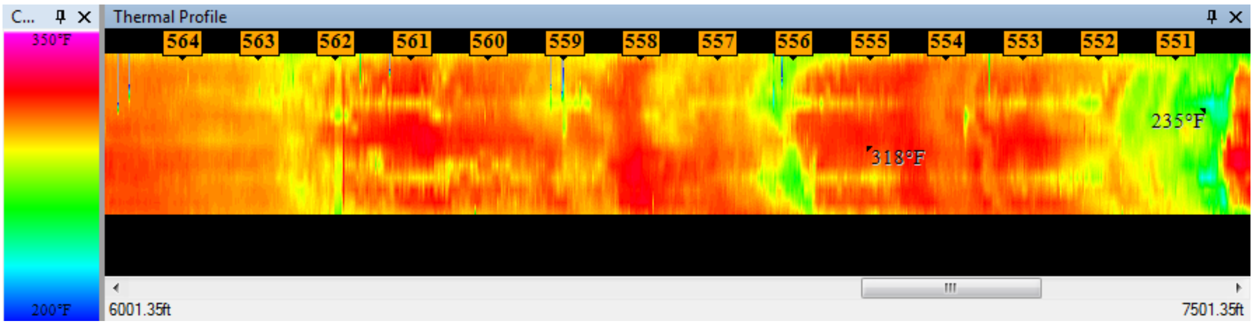


Figure G.14. IR Scanner Profile on RM 12.

Table G.3 shows the thermal profile results summary from the section. The results show 44 percent of the profiles with moderate, and 28 percent of the profiles with severe thermal segregation. With the newness of ultra-thin lift mixtures, it is not known whether these results are normal. However, the use of a remixing transfer device likely would improve the thermal uniformity.

Table G.3. Summary Results from Pave-IR Scanner Systems for RM 12.

Number of Profiles	Moderate		Severe	
	Number	Percent	Number	Percent
61	27	44	17	28

The test compaction sections were tested with a Rolling Density Meter, circular track meter, and a water flow permeability test. These were performed as surrogate measures of density. The test locations were also cored for laboratory verification of densities. While the complete details of the tests are given in 0-6814 TM-8, this report will touch on the density variability within a standard compaction area, as the rolling density meter had recorded.

Three passes of the rolling density meter were made over the sections at different offsets (both wheel paths and the mat centerline), with results collected every 6 inches of forward travel. Figure G.15 presents the results observed between the device's measurements and laboratory-measured core air void contents from RM 12. Assuming the data point in red truly is an outlier, Figure G.15 shows a good calibration between the rolling density meter and core air voids.

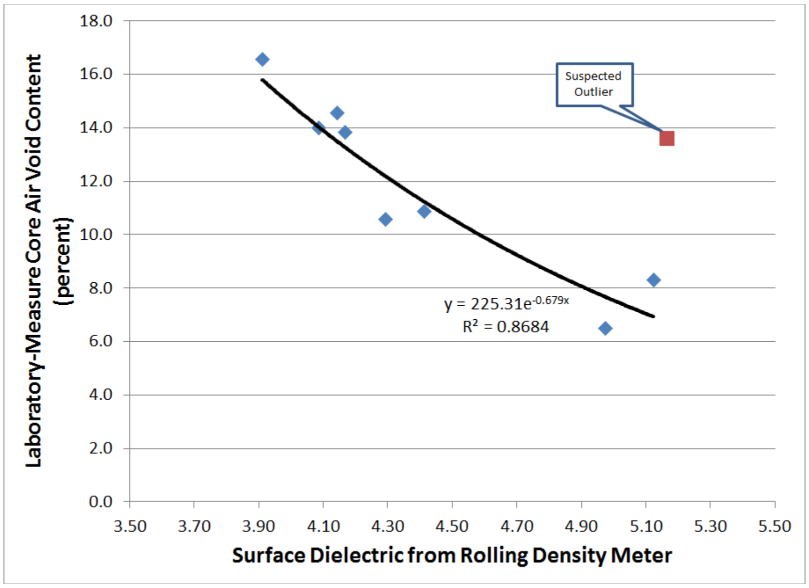


Figure G.15. Calibration of Rolling Density Meter to Cores on RM 12.

Using the relationship in Figure G.15 the rolling density meter results yielded the statistical distribution in Figure G.16. Since these results are from sections of purposefully applied different rolling patterns, they illustrate the concept of applying the rolling density meter to a project, but likely do not represent the actual air void distribution of the entire RM 12 operation.

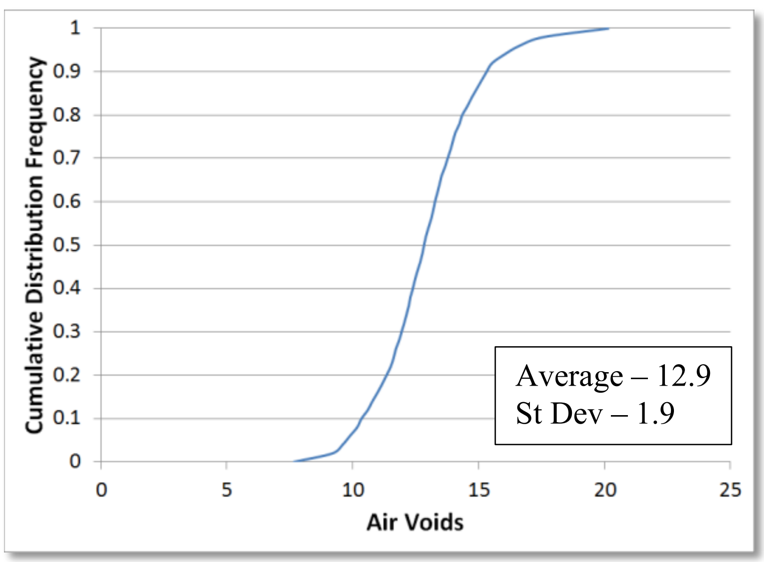


Figure G.16. Expected Distribution Frequency of Air Void on RM 12 Test Sections.

US 59-TOM

This TOM project is located in Houston on US 59, between Beltway 8 and Loop 610 (Figure G.17). This road has very high traffic with an AADT of around 248,000. The specific test section has a roughly estimated AADT of 20,000. The existing surface was continually reinforced concrete. A hot rubber seal and CAM were newly constructed on top in preparation for the TOM.

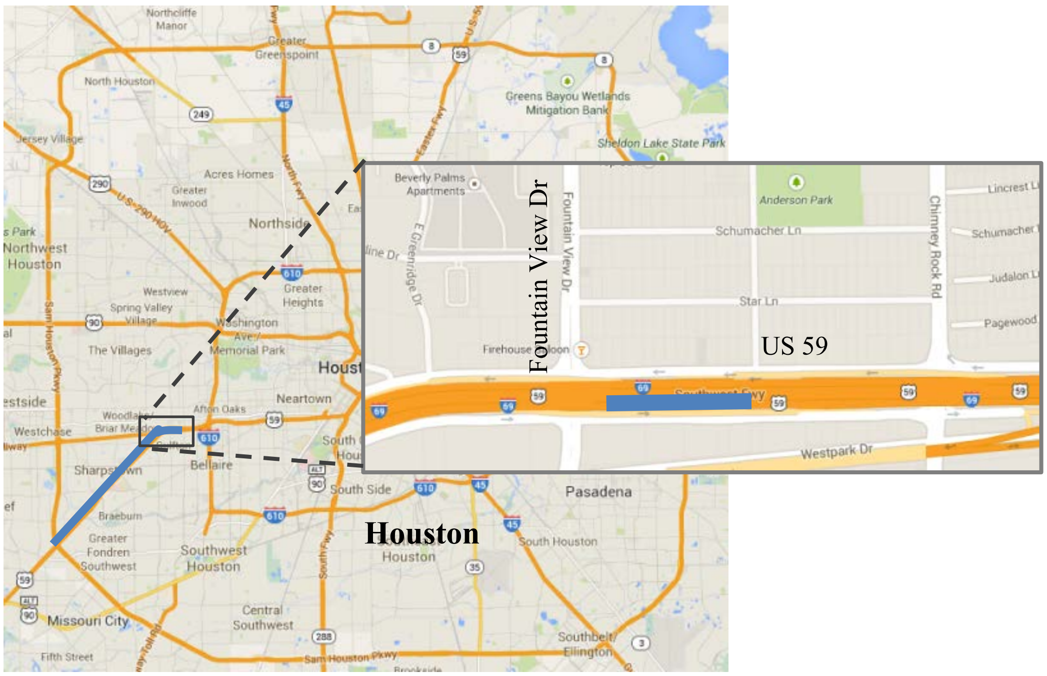


Figure G.17. Project and Test Location in Houston on US 59 (US 59-TOM).

The US 59-TOM was designed according to TxDOT SS 3280, TOM. The mix used SAC A granite from Jones Mill and 6.7 percent of PG 76-22 binder. The mix passed the HWTT with 2.7 mm rutting after 20,000 cycles and the overlay test at 1,000+ cycles.

Paving was done at night. A trackless tack was used, and equipment except the paver were kept off the tack. Compaction was done with two rollers in tandem, running two vibratory passes and then a finish pass. Additional test sections were constructed with one vibe, two static, and then with three vibe. The average water flow time for this project to date was just over 5 minutes, and all results fell between 2 and 7 minutes. This corresponds well with suggested limits.

The test compaction sections were tested with a Rolling Density Meter, circular track meter, and a water flow permeability test. These were performed as surrogate measures of density. The test locations were also cored for laboratory verification of densities. Although the complete results of these tests are given in 0-6814 TM-8, this report will touch on the density variability within a standard compaction area, as the rolling density meter had recorded. The dielectric values were converted to percent voids using a non-linear regression equation found from correlation testing, and the resulting distribution of voids for a small section is shown in Figure G.18. The distribution of voids in the entire normal section is shown in Figure G.19. The variation in this section is really quite large, much more than expected. This may be because the "normal compaction" test section was between two other test sections, and there may have been some unintended compaction overlap.

Figure G.18. Example Void Distribution on US 59.

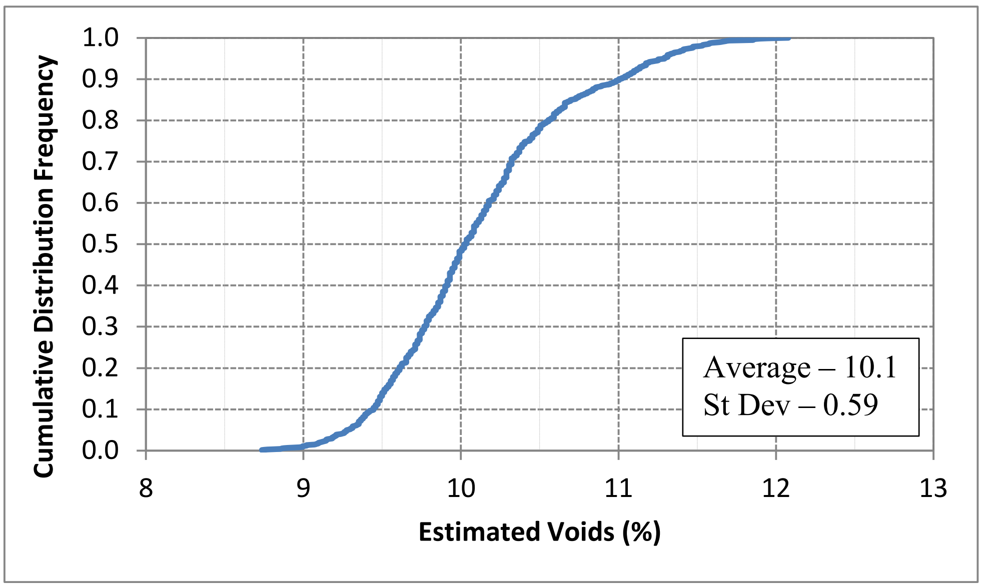


Figure G.19. Expected Void Distribution.

APPENDIX H
DRAFT SPECIFICATION FOR THIN OVERLAY MIXES

ITEM 347

NOTE: Recommended changes are highlighted

Thin Surface Mixtures (TSM)

1. **Description.** Construct a thin surface course composed of a compacted mixture of aggregate and asphalt binder mixed hot in a mixing plant. Produce a thin surface course with a minimum lift thickness of ½ inch for the Ultra-Thin (UT) mixture and 3/4 inch for the Thin Overlay Mixture (TOM). TOM can be suitable for high-speed sections, while UT Mix should only be used for lower speed, non-critical sections.

2. **Materials**. Furnish uncontaminated materials of uniform quality that meet the requirements of the plans and specifications.

- Notify the Engineer of all material sources. Notify the Engineer before changing any material source or formulation. When the Contractor makes a source or formulation change, the Engineer will verify that the specification requirements are met and may require a new laboratory mixture design, trial batch, or both. The Engineer may sample and test project materials at any time during the project to verify specification compliance in accordance with Item 6, "Control of Materials."

   A. **Aggregate.** Furnish aggregates from sources that conform to the requirements shown in Table 1 and as specified in this Section. Aggregate requirements in this Section, including those shown in Table 1, may be modified or eliminated when shown on the plans. Additional aggregate requirements may be specified when shown on the plans. Provide aggregate stockpiles that meet the definition in this Section for coarse, intermediate, or fine aggregate. Do not use reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS). Supply aggregates that meet the definitions in Tex-100-E for crushed gravel or crushed stone. The Engineer will designate the plant or the quarry as the sampling location. Samples must be from materials produced for the project. The Engineer will establish the surface aggregate classification (SAC) and perform Los Angeles abrasion, magnesium sulfate soundness, and Micro-Deval tests. Perform all other aggregate quality tests listed in Table 1. Document all test results on the mixture design report. The Engineer may perform tests on independent or split samples to verify Contractor test results. Stockpile aggregates for each source and type separately. Determine aggregate gradations for mixture design and production testing based on the washed sieve analysis given in Tex-200-F, Part II.

      1) **Coarse Aggregate.** Coarse aggregate stockpiles must have no more than 20% material passing the No. 8 sieve. Aggregate from sources listed in the Department's *Bituminous Rated Source Quality Catalog* (BRSQC) located at **http://www.txdot.gov/business/resources/producer-list.html** are preapproved for use.

         For sources not listed on the Department's BRSQC:

         - build an individual stockpile for each material;
         - request the Department test the stockpile for specification compliance; and

- once approved, do not add material to the stockpile unless otherwise approved.

Use only the rated values for hot mix listed in the BRSQC. Rated values for surface treatment (ST) do not apply to coarse aggregate sources used in hot mix asphalt. Provide aggregate from non-listed sources only when tested by the Engineer and approved before use. Allow 30 calendar days for the Engineer to sample, test, and report results for non-listed sources.

a. **Blending Class A and Class B Aggregates.** Class B aggregate meeting all other requirements in Table 1 may be blended with a Class A aggregate in order to meet requirements for Class A materials. When blending Class A and B aggregates to meet a Class A requirement, ensure that at least 50% by weight of material retained on the No. 8 sieve comes from the Class A aggregate source. Class B aggregate that does not meet LA Abrasion, microdeval, or soundness requirements may still be blended up to 25% on lower-speed, non-critical sections. Blend by volume if the bulk specific gravities of the Class A and B aggregates differ by more than 0.300.

When the Contractor blends Class A and B aggregates to meet a Class A requirement, the Engineer may perform tests at any time during production to ensure that at least 50% by weight of the material retained on the No. 8 sieve comes from the Class A aggregate source. In such cases where the Engineer elects to verify conformance, the Engineer will use the Department's mix design Excel template to calculate the percent of Class A aggregate retained on the No. 8 sieve by inputting the bin percentages shown from readouts in the control room at the time of production and stockpile gradations measured at the time of production. The Engineer may determine the gradations based on either washed or dry sieve analysis from samples obtained from individual aggregate cold feed bins or aggregate stockpiles. The Engineer may perform spot checks using the gradations supplied by the Contractor on the mixture design report as an input for the Excel template; however, a failing spot check will require confirmation with a stockpile gradation determined by the Engineer.

b. **Micro-Deval Abrasion.** The Engineer will perform a minimum of one Micro-Deval abrasion test in accordance with Tex-461-A for each coarse aggregate source used in the mixture design that has a Rated Source Soundness Magnesium (RSSM) loss value greater than 15 as listed in the BRSQC. The Engineer will perform testing prior to the start of production and may perform additional testing at any time during production. The Engineer may obtain the coarse aggregate samples from each coarse aggregate source or may require the Contractor to obtain the samples. The Engineer may elect to waive all Micro-Deval testing based on a satisfactory test history of the same aggregate source.
When tested, the Engineer will estimate the magnesium sulfate soundness loss for each coarse aggregate source using the following formula:

$$M_{gest.} = (RSSM)(MD_{act.}/RSMD)$$

where:

Mg_{est} = magnesium sulfate soundness loss

MD_{act} = actual Micro-Deval percent loss

RSMD = Rated Source Micro-Deval

When the estimated magnesium sulfate soundness loss is greater than the maximum magnesium sulfate soundness loss specified, the coarse aggregate source will not be allowed for use unless otherwise approved by the Engineer. The Engineer will consult the Geotechnical, Soils, and Aggregates Branch of the Construction Division, and additional testing may be required prior to granting approval.

2) **Intermediate Aggregate.** Aggregates not meeting the definition of coarse or fine aggregate will be defined as intermediate aggregate. When used, supply intermediate aggregates that are free from organic impurities. The Engineer may test the intermediate aggregate in accordance with Tex-408-A to verify the material is free from organic impurities. When used, supply intermediate aggregate from coarse aggregate sources that meet the requirements shown in Table 1 unless otherwise approved.

   If 10% or more of the stockpile is retained on the No. 4 sieve, test the stockpile and verify that it meets the requirements in Table 1 for coarse aggregate angularity (Tex-460-A) and flat and elongated particles (Tex-280-F).
3) **Fine Aggregate**. Fine aggregates consist of manufactured sands and screenings. Natural sands are not allowed in any mixture. Fine aggregate stockpiles must meet the gradation requirements in Table 2. Supply fine aggregates that are free from organic impurities. The Engineer may test the fine aggregate in accordance with Tex-408-A to verify that the material is free from organic impurities. Use fine aggregate from coarse aggregate sources that meet the requirements in Table 1, unless otherwise approved.

- If 10% or more of the stockpile is retained on the No. 4 sieve, test the stockpile and verify that it meets the requirements in Table 1 for coarse aggregate angularity (Tex-460-A) and flat and elongated particles (Tex-280-F).

Table 1.
Aggregate Quality Requirements.

Property	Test Method	Requirement
Coarse Aggregate		
SAC	AQMP	A[1]
Deleterious material, %, max	Tex-217-F, Part I	1.5
Decantation, %, max	Tex-217-F, Part II	1.5
Micro-Deval abrasion, %, max	Tex-461-A	Note 2
Los Angeles abrasion, %, max	Tex-410-A	30
Magnesium sulfate soundness, 5 cycles, %, max	Tex-411-A	20
Coarse aggregate angularity, 2 crushed faces, %, min[3]	Tex 460-A, Part I	100[4]
Flat and elongated particles @ 5:1, %, max	Tex-280-F	10
Fine Aggregate		
Linear shrinkage, %, max	Tex-107-E	3
Combined Aggregate[4]		
Sand equivalent, %, min	Tex-203-F	45

1. Surface aggregate classification of "A" is required unless otherwise shown on plans.
2. Used to estimate the magnesium sulfate soundness loss in accordance with Section 347.2.A.1, "Coarse Aggregate."
3. Only applies to crushed gravel.
4. Aggregates, without mineral filler, or additives, combined as used in the job-mix formula (JMF).

Table 2.
Gradation Requirements for Fine Aggregate.

Sieve Size	% Passing by Weight or Volume
3/8"	100
#8	70 – 100
#200	0 – 30

B. Mineral Filler. Mineral filler consists of finely divided mineral matter such as agricultural lime, crusher fines, hydrated lime, or fly ash. Mineral filler is allowed unless otherwise shown on the plans. Do not use more than 2% mineral hydrated lime unless otherwise shown on the plans. Test all mineral fillers except hydrated lime and fly ash in accordance with Tex-107-E to ensure specification compliance. The plans may allow or disallow specific mineral fillers. When used, provide mineral filler that:

- is sufficiently dry, free-flowing and free from clumping and foreign matter;
- does not exceed 3% linear shrinkage when tested in accordance with Tex-107-E; and
- meets the gradation requirements in Table 3.

Table 3.
Gradation Requirements for Mineral Filler.

Sieve Size	% Passing by Weight or Volume
#8	100
#200	55–100

C. **Baghouse Fines.** Fines collected by the baghouse or other dust-collecting equipment may be reintroduced into the mixing drum.

D. **Asphalt Binder.** Furnish performance-graded (PG) asphalt binder with a high temperature grade of PG 76 or 70 and a low temperature grade as shown on the plans, in accordance with Section 300.2.J, "Performance-Graded Binders."

E. **Tack Coat.** Furnish CSS-1H, SS-1H, or a PG binder with a minimum high-temperature grade of PG 58 for the tack coat binders unless otherwise shown on the plans, in accordance with Item 300, "Asphalts, Oils, and Emulsions." Do not dilute emulsion asphalts at the terminal, in the field, or at any other location before use.

The Engineer will obtain at least one sample of the tack coat binder per project and test it to verify compliance with Item 300. The Engineer will obtain the sample from the asphalt distributor immediately before use.

F. **Additives.** Use the type and rate of additive when shown on the plans. Other additives that facilitate mixing, compaction, or improve the quality of the mixture may be allowed when approved. Provide the Engineer with documentation such as the bill of lading showing the quantity of additives used in the project unless otherwise directed.

1) **Lime and Liquid Antistripping Agent.** When lime or a liquid antistripping agent is used, add in accordance with Item 301, "Asphalt Antistripping Agents." Do not use more than 1% hydrated lime when using crushed gravel. Do not add lime directly into the mixing drum of any plant where lime is removed through the exhaust stream unless the plant has a baghouse or dust collection system that reintroduces the lime into the drum.

2) **Warm Mix Asphalt (WMA). Warm Mix Asphalt (WMA).**

Department-approved WMA additives may be used to facilitate mixing and compaction of HMA produced at target discharge temperatures greater than 275ºF. WMA additives are allowed for use on all projects and is required when shown on plans. The Department's approved list of WMA additives processes is located at http://ftp.dot.state.tx.us/pub/txdot-info/cmd/mpl/wma.pdf.

G. **Recycled Materials.** Recycled materials are not allowed for use.

3. Equipment. Provide required or necessary equipment in accordance with Item 320, "Equipment for Hot-Mix Asphalt Materials."

4. **Construction**. Produce, haul, place, and compact the specified paving mixture. In addition to tests required by the specification, Contractors may perform other QC tests as deemed necessary. At any time during the project, the Engineer may perform production and placement tests as deemed necessary in accordance with Item 5, "Control of the Work." On or before the first day of paving, it is mandatory to schedule and participate in a pre-paving meeting with the Engineer unless otherwise shown on the plans.

   A. **Certification.** Personnel certified by the Department-approved hot-mix asphalt certification program must conduct all mixture designs, sampling, and testing in accordance with Table 4. Supply the Engineer with a list of certified personnel and copies of their current certificates before beginning production and when personnel changes are made. Provide a mixture design developed and signed by a Level II certified specialist. Provide a Level IA certified specialist at the plant during production operations. Provide a Level IB certified specialist to conduct placement tests.

Table 4.
Test Methods, Test Responsibility, and Minimum Certification Levels.

Test Description	Test Method	Contractor	Engineer	Level
1. Aggregate and Recycled Material Testing				
Sampling	Tex-400-A	✓	✓	IA
Dry sieve	Tex-200-F, Part I	✓	✓	IA
Washed sieve	Tex-200-F, Part II	✓	✓	IA
Deleterious material	Tex-217-F, Part I	✓	✓	2
Decantation	Tex-217-F, Part II	✓	✓	2
Los Angeles abrasion	Tex-410-A		✓	
Magnesium sulfate soundness	Tex-411-A		✓	
Micro-Deval abrasion	Tex-461-A		✓	
Coarse aggregate angularity	Tex-460-A	✓	✓	2
Flat and elongated particles	Tex-280-F	✓	✓	2
Linear shrinkage	Tex-107-E	✓	✓	2
Sand equivalent	Tex-203-F	✓	✓	2
Organic impurities	Tex-408-A	✓	✓	2
2. Asphalt Binder & Tack Coat Sampling				
Asphalt binder sampling	Tex-500-C, Part II	✓	✓	1A/1B
Tack coat sampling	Tex-500-C, Part III	✓	✓	1A/1B
3. Mix Design & Verification				
Design and JMF changes	Tex-204-F	✓	✓	2
Mixing	Tex-205-F	✓	✓	2
Molding (TGC)	Tex-206-F	✓	✓	IA
Molding (SGC)	Tex-241-F	✓	✓	IA
Laboratory-molded density	Tex-207-F	✓	✓	IA
VMA[1] (calculation only)	Tex-204-F	✓	✓	2
Rice gravity	Tex-227-F	✓	✓	IA
Drain-down	Tex-235-F	✓	✓	IA
Ignition oven calibration[2]	Tex-236-F	✓	✓	2
Indirect tensile strength	Tex-226-F	✓	✓	2
Overlay Test	Tex-248-F		✓	
Hamburg Wheel test	Tex-242-F	✓	✓	2
Boil test	Tex-530-C	✓	✓	IA

Table 4.
Test Methods, Test Responsibility, and Minimum Certification Levels (Continued).

4. Production Testing				
Selecting random numbers	Tex-225-F, Part I		✓	IA
Mixture sampling	Tex-222-F	✓	✓	IA
Molding (TGC)	Tex-206-F	✓	✓	IA
Molding (SGC)	Tex-241-F	✓	✓	IA
Laboratory-molded density	Tex-207-F	✓	✓	IA
VMA[1] (calculation only)	Tex-207-F	✓	✓	IA
Rice gravity	Tex-227-F	✓	✓	IA
Gradation & asphalt binder content[2]	Tex-236-F	✓	✓	IA
Drain-down	Tex-235-F	✓	✓	IA
Control charts	Tex-233-F	✓	✓	IA
Moisture content	Tex-212-F	✓	✓	IA
Hamburg Wheel Test	Tex-242-F	✓	✓	2
Overlay Test	Tex-248-F	✓	✓	
Micro-Deval abrasion	Tex-461-A		✓	
Boil Test	Tex-530-C	✓	✓	IA
Aging Ratio	Tex-211-F		✓	
5. Placement Testing				
Selecting random numbers	Tex-225-F, Part II		✓	IA/IB
Trimming roadway cores	Tex-207-F	✓	✓	IA/IB
In-place air voids	Tex-207-F	✓	✓	1A/1B
Establish rolling pattern	Tex-207-F	✓		IB
Control charts	Tex-233-F	✓	✓	IA
Ride quality measurement	Tex-1001-S	✓	✓	Note 3
Thermal profile	Tex-244-F	✓	✓	IB
Longitudinal joint density	Tex-207-F, Part VII	✓	✓	1B

1. Voids in mineral aggregates.
2. Refer to Section X.X.X.X for exception to using an ignition oven.
3. Profiler and operator are required to be certified at the Texas Transportation Institute facili when Surface Test Type B is specified.

B. Reporting. Use Department-provided Excel templates to record and calculate all test data including but not limited to mixture design, production and placement test results, control charts, thermal profiles, and longitudinal joint density. Obtain the latest version of the Excel templates at http://www.txdot.gov/inside-txdot/forms-publications/consultants-contractors/forms/site-manager.html or from the Engineer. The Engineer and the Contractor will provide any available test results to the other party when requested. The maximum allowable time for the Contractor and Engineer to exchange test data is as given in Table 5 unless otherwise approved. The Engineer and the Contractor will immediately report to the other party any test result that requires suspension of production or placement, a payment penalty, or that fails to meet the specification requirements. Record and submit all test results and pertinent information on Department-provided Excel templates to the Engineer electronically by means of a portable USB flash drive, compact disc, or via email.

Subsequent sublots placed after test results are available to the Contractor, which require them to suspend operations, may be considered unauthorized work. Unauthorized work will be accepted or rejected at the discretion of the Engineer in accordance with Item 5.3, “Conformity with Plans, Specifications, and Special Provisions.”

Table 5.
Reporting Schedule.

Description	Reported By	Reported To	To Be Reported Within
Production Quality Control			
Gradation[1] Asphalt binder content[1] Laboratory-molded density[2] Moisture content[3] Boil test[3]	Contractor	Engineer	1 working day of completion of the sublot
Production Quality Assurance			
Gradation[3] Asphalt binder content[3] Laboratory-molded density[1] Hamburg wheel test[2] Overlay test[2] Boil test[2] Binder tests[2]	Engineer	Contractor	1 working day of completion of the sublot
Placement Quality Control			
In-place air voids[2?] Longitudinal joint density[1] Thermal profile[1]	Contractor	Engineer	1 working day of completion of the lot
Placement Quality Assurance			
In-place air voids[1] Longitudinal joint density[1] Thermal profile[1] Aging ratio[2]	Engineer	Contractor	1 working day of receipt of the trimmed cores for in-place air voids[4]

1. These tests are required on every sublot.
2. Optional test. To be reported as soon as results become available.
3. To be performed at the frequency specified on the plans.
4. 2 days are allowed if cores can not be dried to constant weight within 1 day.

Use the procedures described in Tex-233-F to plot the results of all quality control (QC) and quality assurance (QA) testing. Update the control charts as soon as test results for each sublot become available. Make the control charts readily accessible at the field laboratory. The Engineer may suspend production for failure to update control charts.

C. **QCP.** Develop and follow the QCP in detail. Obtain approval from the Engineer for changes to the QCP made during the project. The Engineer may suspend operations if the Contractor fails to comply with the QCP.

Submit a written QCP to the Engineer before the mandatory prepaving meeting. Receive the Engineer’s approval of the QCP before beginning production. Include the following items in the QCP:

1) **Project Personnel.** For project personnel, include:

- a list of individuals responsible for QC with authority to take corrective action;

- contact information for each individual listed; and
- copies of certification documents for individuals performing specified QC functions.

2) **Material Delivery and Storage.** For material delivery and storage, include:

   - the sequence of material processing, delivery, and minimum quantities to assure continuous plant operations;
   - aggregate stockpiling procedures to avoid contamination and segregation;
   - frequency, type, and timing of aggregate stockpile testing to assure conformance of material requirements before mixture production; and
   - procedure for monitoring the quality and variability of asphalt binder.

3) **Production.** For production, include:

   - loader operation procedures to avoid contamination in cold bins;
   - procedures for calibrating and controlling cold feeds;
   - procedures to eliminate debris or oversized material;
   - procedures for adding and verifying rates of each applicable mixture component (e.g., aggregate, asphalt binder, lime, liquid antistrip);
   - procedures for reporting job control test results; and
   - procedures to avoid segregation and drain-down in the silo.

4) **Loading and Transporting.** For loading and transporting, include:

   - type and application method for release agents; and
   - truck loading procedures to avoid segregation.

5) **Placement and Compaction.** For placement and compaction, include:

   - proposed agenda for mandatory prepaving meeting, including date and location;
   - proposed paving plan (e.g., paving widths and lift thicknesses);
   - type and application method for release agents in the paver and on rollers, shovels, lutes, and other utensils;
   - procedures for the transfer of mixture into the paver, while avoiding segregation and preventing material spillage;
   - process to balance production, delivery, paving, and compaction to achieve continuous placement operations and good ride quality;
   - paver operations (e.g., operation of wings, height of mixture in auger chamber) to avoid physical and thermal segregation and other surface irregularities; and
   - procedures to construct quality longitudinal and transverse joints.

D. Mixture Design.

1) **Design Requirements.** The Contractor may elect to design the mixture using a Texas Gyratory Compactor (TGC) or a Superpave Gyratory Compactor (SGC) unless otherwise shown on the plans. Use the typical weight design example given in Tex-204-F, Part I, when using a TGC. Use the Superpave mixture design procedure given in Tex-204-F, Part IV, when using a SGC. Design a mixture meeting the requirements listed in Tables 1, 2, 3, 5, and 6.

   a. **Target Laboratory Molded Density When The TGC Is Used.** Design the mixture at a 97.5% target laboratory-molded density or as noted in Table 6.

   b. **Design Number of Gyrations (Ndesign) When The SGC Is Used.** Design the mixture at 50 gyrations (Ndesign). Use a target laboratory-molded density of 96.0% to design the mixture; however, adjustments can be made to the Ndesign value as noted in Table 6. The Ndesign level may be reduced to no less than 35 gyrations at the Contractor's discretion.

   Use an approved laboratory to perform the Hamburg Wheel test and the Department perform the Overlay test and provide results with the mixture design, or provide the laboratory mixture and request that the Department perform the Hamburg Wheel test and Overlay test. The Department maintains the Material Producer List of approved laboratories located at http://www.txdot.gov/business/resources/producer-list.html. The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel test and Overlay test results on the laboratory mixture design.

   The Engineer will provide the mixture design when shown on the plans. The Contractor may submit a new mixture design at any time during the project. The Engineer will approve all mixture designs (JMF1) before the Contractor can begin production.

   Provide the Engineer with a mixture design report using Department-provided Excel template. Include the following items in the report:

   - the combined aggregate gradation, source, specific gravity, and percent of each material used;
   - the target laboratory-molded density (or Ndesign level when using the SGC);
   - results of all applicable tests;
   - the mixing and molding temperatures;
   - the signature of the Level 2 person or persons that performed the design;
   - the date the mixture design was performed; and
   - a unique identification number for the mixture design.

Table 5.
Master Gradation Limits (% Passing by Weight or Volume) and Volumetric Requirements.

	Percent Passing		
Sieve Size	**TOM**	**–**	**UT**
1/2"	100.0[1]		100.0[1]
3/8"	95.0 – 100.0		98.0 – 100.0
#4	40.0 – 60.0		70.0 – 95.0
#8	17.0 – 27.0		40.0 – 65.0
#16	5.0 – 27.0		20.0 – 45.0
#30	5.0 – 27.0		10.0 – 35.0
#50	5.0 – 27.0		10.0 – 20.0
#200	5.0 – 9.0		2.0 – 12.0
Property	**Requirement**		
Binder Content, % Minimum[2]	6.0		6.5
Design VMA[3], % Minimum	16.0		16.5
Plant-Produced VMA[3], % Minimum	15.5		16.0

1. Defined as maximum sieve size. No tolerance allowed.
2. Unless otherwise shown on the plans or approved by the Engineer.
3. Voids in Mineral Aggregates (VMA)

Table 6.
Laboratory Mixture Design Properties.

Property	Test Method	Requirement
Target Laboratory-Molded Density, % (TGC)	Tex 207 F	97.5[1]
Design gyrations (Ndesign for SGC)	Tex-241-F	50[2]
Hamburg Wheel Test, Minimum # of passes @ 12.5 mm Rut Depth for PG 70 mixtures	Tex-242-F	15,000
Hamburg Wheel Test, Minimum # of passes@ 12.5 mm Rut Depth for PG 76 mixtures	Tex-242-F	20,000
Tensile Strength (dry), psi.	Tex-226-F	85-200
Overlay Test, Minimum number of cycles	Tex-248-F	300
Drain-down, Maximum %	Tex-235 - F	0.20

1. Unless otherwise shown on the plans or approved by the Engineer.
2. May be adjusted within the range of 35-100 gyrations when shown on the plans or specification or when mutually agree between the Engineer and Contractor.

2) **Job-Mix Formula Approval.** The job-mix formula (JMF) is the combined aggregate gradation, target laboratory molded density (or Ndesign level), and target asphalt percentage used to establish target values for hot mix production. JMF1 is the original laboratory mixture design used to produce the trial batch. When WMA is used, JMF1 may be designed and submitted to the Engineer without including the WMA additive. When WMA is used, document the additive or process used and recommend rate on the JMF1 submittal. The Engineer and the Contractor will verify JMF1 based on a plant-produced mixture from the trial batch unless otherwise approved. The Engineer may accept an existing mixture design previously used on a Department project and may waive the trial batch to verify JMF1. The Department may require the Contractor to reimburse the Department for verification tests if more than two trial batches per design are required.

a. **Contractor's Responsibilities.**

(1) **Providing Gyratory Compactor.** Use a TGC calibrated in accordance with Tex-914-F when electing or required to design the mixture in accordance with Tex-204-F, Part I, for molding production samples. Furnish a SGC calibrated in accordance with Tex-241-F when electing or required to design the mixture in accordance with Tex-204-F, Part IV, for molding production samples. If the SGC is used, locate the SGC at the Engineer's field laboratory and make the SGC available to the Engineer for use in molding production samples.

(2) **Gyratory Compactor Correlation Factors.** Use Tex-206-F, Part II, to perform a gyratory compactor correlation when the Engineer uses a different gyratory compactor. Apply the correlation factor to all subsequent production test results.

(3) **Submitting JMF1.** Furnish the Engineer a mix design report (JMF1) with representative samples of all component materials and request approval to produce the trial batch. If opting to have the Department perform Hamburg Wheel test on the laboratory mixture, provide the Engineer with approximately 25 lb. of the design mixture and request that the Department perform the Hamburg Wheel test. Provide the Engineer with approximately 60 lb. of the design mixture to perform the Overlay test.

(4) **Supplying Aggregate.** Provide the Engineer with approximately 40 lb. of each aggregate stockpile, unless otherwise directed.

(5) **Supplying Asphalt.** Provide the Engineer at least 1 gal. of the asphalt material and sufficient quantities of any additives proposed for use.

(6) **Ignition Oven Correction Factors.** Determine the aggregate and asphalt correction factors from the ignition oven in accordance with Tex-236-F. Prior to the trial batch production, provide the Engineer with split samples of the mixtures, including all additives (except water), and blank samples used to determine the correction factors for the ignition oven used for quality assurance testing during production. Correction factors established from a

previously approved mixture design may be used for the current mixture design, if the mixture design and ignition oven are the same as previously used, unless otherwise directed.

(7) **Boil Test.** Perform the test and retain the tested sample from Tex-530-C until completion of the project or as directed by the Engineer. Use this sample for comparison purposes during production. The Engineer may waive the requirement for the boil test.

(8) **Trial Batch Production.** Upon receiving conditional approval of JMF1 and authorization from the Engineer to produce a trial batch, provide a plant-produced trial batch, including the WMA additive or process, if applicable, for verification testing of JMF1 and development of JMF2. Produce a trial batch mixture that meets the requirements in Table 7. In lieu of a new trial batch, the Engineer may accept test results from recent production of the same mixture.

Obtain and provide the Engineer with approximately 60 lb. of trial batch mixture in a sealed container, box, or bags labeled with the CSJ number, mixture type, and date for the Overlay test.

(9) **Trial Batch Production Equipment.** To produce the trial batch, use only equipment and materials proposed for use on the project.

(10) **Trial Batch Quantity.** Produce enough quantity of the trial batch to ensure that the mixture meets the specification *requirements.*

(11) **Number of Trial Batches.** Produce trial batches as necessary to obtain a mixture that meets the specification requirements.

(12) **Trial Batch Sampling.** Obtain a representative sample of the trial batch and split it into three equal portions, in accordance with Tex-222-F. Label these portions as "Contractor," "Engineer," and "Referee." Deliver samples to the appropriate laboratory as directed.

(13) **Trial Batch Testing.** Test the trial batch to ensure that the mixture produced using the proposed JMF1 meets the mixture requirements in Table 5. The trial batch must also comply with the Hamburg Wheel test, Overlay test, and drain-down requirements listed in Table 6.

Use an approved laboratory to perform the Hamburg Wheel test on the trial batch mixture or request that the Department perform the Hamburg Wheel test. Obtain and provide the Engineer with approximately 60 lb. of trial batch mixture in sealed containers, boxes, or bags labeled with the CSJ, mixture type, lot, and sublot number for the Overlay test The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel test and Overlay test results on the trial batch. Provide the Engineer with a copy of the trial batch test results.

(14) Development of JMF2. After the Engineer grants full approval of JMF1 based on results from the trial batch, evaluate the trial batch test results, determine the optimum mixture proportions, and submit as JMF2. Adjust the asphalt content or gradation to achieve the specified target laboratory-molded density. The asphalt content established for JMF2 is not required to be within any tolerance of the optimum asphalt content established for JMF1; however, mixture produced using JMF2 must meet the voids in the mineral aggregate (VMA) requirements for production shown in Table 5. If the optimum asphalt content for JMF2 is more than 0.5% lower than the optimum asphalt content for JMF1, the Engineer may perform or require the contractor to perform Tex-226-F on Lot 1 production to confirm the indirect tensile strength does not exceed 200 psi and the Overlay test exceeds 500 cycles. Verify that JMF2 meets the mixture requirements in Table 6.

(15) Mixture Production. After receiving approval for JMF2 and receiving a passing result from the Department's or a Department-approved laboratory's Hamburg Wheel test and the Department's Overlay test on the trial batch, use JMF2 to produce Lot 1 as described in Section X.X.X.X.(X). As an option, once JMF2 is approved, proceed to Lot 1 production at the Contractor's risk without receiving the results from either the Department's Hamburg Wheel test or Overlay test on the trial batch.

If electing to proceed without the Hamburg Wheel test and Overlay test results from the trial batch, notify the Engineer. Note that the Engineer may require that up to the entire sublot of any mixture failing the Hamburg Wheel test or Overlay test be removed and replaced at the Contractor's expense.

(16) Development of JMF3. Evaluate the test results from Lot 1, determine the optimum mixture proportions, and submit as JMF3 for use in Lot 2.

(17) JMF Adjustments. If necessary, adjust the JMF before beginning a new lot. The adjusted JMF must:

- be provided to the Engineer in writing before the start on a new lot;
- be numbered in sequence to the previous JMF;
- meet the master gradation limits shown in Table 5; and
- be within the operational tolerances of JMF2 listed in Table 7.

(18) Requesting Referee Testing. If needed, use referee testing in accordance with Section X.X.X, "Referee Testing," to resolve testing differences with the Engineer.

Table 7
Operational Tolerances

Description	Test Method	Allowable Difference Between Trial Batch and JMF1 Target	Allowable Difference from Current JMF Target	Allowable Difference between Contractor and Engineer[1]
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	Must be Within Master Grading Limits in Table 5	±3.0[2, 3]	±5.0
Individual % retained for sieves smaller than #8 and larger than #200			±3.0[2, 3]	±3.0
% passing the #200 sieve			±2.0[2, 3]	±1.6
Binder content, %[4]	Tex-236-F	±0.3	±0.3[3]	±0.3
Laboratory-molded density, %	Tex-207-F	±1.0	±1.0	±1.0
Laboratory-molded bulk specific gravity		N/A	N/A	±0.020
VMA, % min	Tex-204-F	Note 4	Note 4	N/A
Theoretical maximum specific (Rice) gravity	Tex-227-F		N/A	±0.020
Drain-down, %	Tex-235-F	Note 5	Note 5	N/A

1. Contractor may request referee testing only when values exceed these tolerances.
2. When within these tolerances, mixture production gradations may fall outside the master grading limits; however, the % passing the #200 will be considered out of tolerance when outside the master grading limits.
3. Only applies to mixture produced for Lot 1 and higher.
4. Binder content is not allowed to be outside the limits shown in Table 5. May be obtained from asphalt meter readouts.
5. Test and verify that Table 6 requirements are met.

b. Engineer's Responsibilities.

(1) Gyratory Compactor. For mixtures designed in accordance with Tex-204-F, Part I, the Engineer will use a Department TGC, calibrated in accordance with Tex-914-K, to mold samples for trial batch and production testing. The Engineer will make the Department TGC and the Department field laboratory available to the Contractor for molding verification samples, if requested by the Contractor.

For mixtures designed in accordance with Tex-204-F, Part IV, the Engineer will use a Department SGC, calibrated in accordance with Tex-241-F, to mold samples for laboratory mixture design verification. For molding trial batch and production specimens, the Engineer will use the Contractor-provided SGC at the field laboratory or provide and use a Department SGC at an alternate location. The Engineer will make the Contractor-provided SGC in the Department field laboratory available to the Contractor for molding verification samples.

(2) Conditional Approval of JMF1. Within 2 working days of receiving the mixture design report (JMF1) and all required materials and Contractor-provided Hamburg Wheel test results and Department provided Overlay test results, the Engineer will review the Contractor's mix design report and verify conformance with all aggregates, asphalt, additives, recycled materials, and mixture specifications. The Engineer will grant the Contractor conditional approval of JMF1, if the information provided on the paper copy of JMF1 indicates that the Contractor's mixture design meets the specifications. When the Contractor does not provide Hamburg Wheel test and Overlay test results with laboratory mixture design, 10 working days is allowed for conditional approval of JMF 1. The Engineer will base full approval of JMF1 on test results on mixture from the trial batch.

Unless waived, the Engineer will determine the Micro-Deval abrasion loss in accordance with Section 347.X.X.X.X, “Micro-Deval Abrasion.” If the Engineer’s test results are pending after 2 working days, conditional approval of JMF1 will still be granted within 2 working days of receiving JMF1. When the Engineer’s test results become available, they will be used for specification compliance.

After conditionally approving JMF1, including either Contractor- or Department-supplied Hamburg Wheel test results, the Contractor is authorized to produce a trial batch.

(3) Hamburg Wheel and Overlay Testing of JMF1. If the Contractor requests the option to have the Department perform the Hamburg Wheel test on the laboratory mixture, the Engineer will mold samples in accordance with Tex-242-F to verify compliance with the Hamburg Wheel test requirement in Table 6. The Engineer will perform the Overlay test and mold samples in accordance with Tex-248-F to verify compliance with the Overlay test requirements in Table 6.

(4) Ignition Oven Correction Factors. The Engineer will use the split samples provided by the Contractor to determine the aggregate and asphalt correction factors for the ignition oven used for quality assurance testing during production in accordance with Tex-236-F.

(5) Testing the Trial Batch. Within 1 full working day, the Engineer will sample and test the trial batch to ensure that the mixture meets the requirements listed in Table 7. If the Contractor requests the option to have the Department perform the Hamburg Wheel test on the trial batch mixture, the Engineer will mold samples in accordance with Tex-242-F to verify compliance with Hamburg Wheel test requirements in Table 6. The Engineer will mold samples for the Overlay test in accordance with Tex-248-F to verify compliance with the Overlay test requirement in Table 6.

The Engineer will have the option to perform the following tests on the trial batch:

- Tex-226-F, to verify that the indirect tensile strength meets the requirement shown in Table 6; and
- Tex-530-C, to retain and use for comparison purposes during production.

(6) **Full Approval of JMF1.** The Engineer will grant full approval of JMF1 and authorize the Contractor to proceed with developing JMF2 if the Engineer's results for the trial batch meet the requirements in Table 7. The Engineer will notify the Contractor that an additional trial batch is required if the trial batch does not meet these requirements.

(7) **Approval of JMF2.** The Engineer will approve JMF2 within 1 working day if the gradation meets the master grading limits shown in Table 5 and is within the operational tolerances of JMF1 listed in Table 7. The asphalt content established for JMF2 is not required to be within any tolerance of the optimum asphalt content established for JMF1; however, mixture produced using JMF2 must meet the VMA requirements shown in Table 5. If the optimum asphalt content for JMF2 is more than 0.5% lower than the optimum asphalt content for JMF1, the Engineer may perform or require the Contractor to perform Tex-226-F on Lot 1 production to confirm the indirect tensile strength does not exceed 200 psi.

(8) **Approval of Lot 1 Production.** The Engineer will authorize the Contractor to proceed with Lot 1 production (using JMF2) as soon as a passing result is achieved from the Department's or an approved laboratory's Hamburg Wheel test and from the Department's Overlay test. As an option, the Contractor may, at their own risk, proceed with Lot 1 production without results from the Hamburg Wheel test and Overlay test on the trial batch.

If the Department's or approved laboratory's sample from the trial batch fails the Hamburg Wheel test or Overlay test, the Engineer will suspend production until further Hamburg Wheel tests or Overlay tests meet the specified values. The Engineer may require up to the entire sublot of any mixture failing the Hamburg Wheel test or Overlay test to be removed and replaced at the Contractor's expense.

(9) **Approval of JMF3 and Subsequent JMF Changes.** JMF3 and subsequent JMF changes are approved if they meet the master grading limits shown in Table 5, mixture requirements shown in Table 6, and are within the operational tolerances of JMF2 shown in Table 7.

E. Production Operations. Perform a new trial batch when the plant or plant location is changed. Take corrective action and receive approval to proceed after any production suspension for noncompliance to the specification.

1) **Storage and Heating of Materials.** Do not heat the asphalt binder above the temperatures specified in Item 300, "Asphalts, Oils, and Emulsions," or outside the manufacturer's recommended values. On a daily basis, provide the Engineer with the records of asphalt binder and hot-mix asphalt discharge temperatures (in legible discernible increments) in accordance with Item 320, "Equipment for Hot-Mix Asphalt Materials," unless otherwise directed. Do not store mixture for a period long enough to affect the quality of the mixture, nor in any case longer than 12 hr unless otherwise approved.

2) **Mixing and Discharge of Materials.** Notify the Engineer of the target discharge temperature and produce the mixture within 25°F of the target. Monitor the temperature of the material in the truck before shipping to ensure that it does not exceed 350°F (or 275ºF for WMA) and is not lower than 215°F. The Department will not pay for or allow placement of any mixture produced at more than 350°F.

   When WMA is required, produce the WMA within the target temperature discharge range of 215ºF and 275ºF. Take corrective action any time the discharge temperature of the WMA exceeds the target discharge range. The Engineer may suspend production operations if the Contractor's corrective action is not successful at controlling the production temperature within the target discharge range. Note that when WMA is produced, it may be necessary to adjust burners to ensure complete combustion such that no burner fuel residue remains in the mixture.
   Control the mixing time and temperature so that substantially all moisture is removed from the mixture before discharging from the plant. If requested, determine the moisture content by oven-drying in accordance with Tex-212-F, Part II, and verify that the mixture contains no more than 0.2% of moisture by weight. Obtain the sample immediately after discharging the mixture into the truck, and perform the test promptly.

F. **Hauling Operations.** Before use, clean all truck beds to ensure that mixture is not contaminated. When a release agent is necessary, use a release agent on the Department's Material Producer List to coat the inside bed of the truck.

Use only equipment for hauling as defined in Section X.X.X.X, "Hauling Equipment." Other hauling equipment may be used when allowed by the Engineer.

G. **Placement Operations.** Collect haul tickets from each load of mixture delivered to the project and provide the Department's copy to the Engineer approximately every hour, or as directed by the Engineer. When the Pave-IR system is not used for specification compliance, use a non-contact infrared thermometer to measure and record the internal temperature of the mixture as discharged from the truck or material transfer device prior to or as the mix enters the paver and an approximate station number or GPS coordinates on each ticket. Calculate the daily yield and cumulative yield for the specified lift and provide to the Engineer. The Engineer may suspend production if the Contractor fails to produce and provide haul tickets and yield calculations by the end of paving operations for each day.

Prepare the surface by removing raised pavement markers and objectionable material such as moisture, dirt, sand, leaves, and other loose impediments from the surface before placing mixture. Remove vegetation from pavement edges. If surface milling is required (improve ride, remove contaminated material, remove raveled and oxidized surface, etc.) the final surface should be micro-milled in accordance with Item XXX.

Place the mixture to meet the typical section requirements and produce a smooth, finished surface with a uniform appearance and texture. Place mixture so that longitudinal joints on the surface course coincide with lane lines, or as directed. Ensure that all finished surfaces will drain properly. Place the mixture at the rate or thickness shown on the plans.

The Engineer will use the guidelines in Table 8 to determine the compacted lift thickness. The thickness determined is based on the rate of 110–115 lb/sq. yd. for each inch of pavement unless otherwise shown on the plans.

Table 8.
Compacted Lift Thickness.

	Compacted Lift Thickness[1]	
Thin Mixture Type	**Minimum (in.)**	**Maximum (in.)**
TOM	0.75	1.25
UT	0.5	0.75

1 Compacted target lift thickness will be specified on the plans.

1) **Weather Conditions**. Place mixture when the air temperature is equal to or higher than 70°F unless otherwise approved. The Engineer may allow mixture placement to begin prior to reaching the required temperature, if conditions are such that the required temperature is reached within 1 hour of beginning placement operations. Place mixtures only when weather conditions and moisture conditions of the roadway surface are suitable in the opinion of the Engineer. The Engineer may restrict the Contractor from paving when the air temperature is 70°F and falling.

   Produce mixture with a Department approved WMA additive to facilitate compaction when the air temperature is below 70ºF, but greater than 60 ºF. Produce the mixture with the WMA additive at a target discharge temperature higher than 300 ºF.

2) **Tack Coat.** Clean the surface before placing the tack coat. Unless otherwise approved, apply tack coat uniformly at the rate directed by the Engineer. The Engineer will set the rate between 0.04 and 0.1 gal. of residual asphalt per square yard of surface area, unless otherwise approved or shown on the plans. A tack coat may not be necessary when surfacing new construction or a surface treatment/underseal (aggregate should be clean and unpolished). Apply a uniform tack coat to all contact surfaces of curbs, structures, and all joints. Allow adequate time for emulsion to break completely prior to placing any material. Prevent splattering of tack coat when placed adjacent to curb, gutter, and structures. Roll the tack coat with a pneumatic-tire roller to remove streaks and other irregularities patterns when directed. The Engineer may suspend paving operations until there is adequate coverage.

   If the Engineer suspects any area has bonding issues after construction (slippage, delamination, etc.) they may also require bond strength testing of field cores with a shear test (Tex-X-XXX) and/or tensile strength test (Tex-X-XXX). The average shear strength of three cores should be 100 psi or greater with no single core below 80 psi. The average tensile strength should be 40 psi or greater with no single core below 20 psi.

3) Lay-Down Operations.

a. Thermal Profile. Use a handheld thermal camera or the Pave-IR system (paver mounted infrared bar) to obtain continuous thermal profiles in accordance with Tex-244-F. Thermal profiles are not applicable in miscellaneous areas as described in Section 347.X.X.X.X(X), "Miscellaneous Areas."

(1) Thermal Segregation.

(a) **Moderate Thermal Segregation.** Any areas that have a temperature differential greater than 25°F but not exceeding 50°F are deemed as having moderate thermal segregation.

(b) **Severe Thermal Segregation.** Any areas that have a temperature differential greater than 50°F are deemed as having severe thermal segregation.

(2) Pave-IR System. When the Pave-IR system is used, review the output results and provide the automated report described in Tex-244-F to the Engineer on a daily basis unless otherwise directed. Modify the paving process as necessary to eliminate any recurring (moderate or severe) thermal segregation identified by the Pave-IR system. The Engineer may suspend paving operations if the Contractor cannot successfully modify the paving process to eliminate recurring severe thermal segregation. Upon completion of the project or as requested by the Engineer, provide the Engineer with electronic copies of all daily data files that can be used with the Pave-IR system software to generate temperature profile plots.

(3) Thermal Camera. When a handheld thermal camera is used, take immediate corrective action to eliminate moderate thermal segregation. Evaluate areas with moderate thermal segregation by performing water flow testing in accordance to Tex-246-F and verify the water flow is greater than 60 seconds. Within 1 working day of the completion of each lot, provide the Engineer with the thermal profile of every sublot within the lot. Report the results of each thermal profile in accordance with Section 341.4.B, "Reporting and Responsibilities." The Engineer will use a handheld thermal camera to obtain a thermal profile at least once per project. Suspend operations and take immediate corrective action to eliminate severe thermal segregation unless otherwise directed. Resume operations when the Engineer determines that subsequent production will meet the requirements of this Section. Evaluate areas with severe thermal segregation by performing water flow testing in accordance to Tex-246-F and verify the water flow is greater than 60 seconds. Remove and replace the material in any areas that have both severe thermal segregation and a failing result for water flow test, unless otherwise directed.

b. Windrow Operations. When hot mix is placed in windrows, operate windrow pickup equipment so that substantially all the mixture deposited on the roadbed is picked up and loaded into the paver.

c. **Hauling Equipment**. The Contractor may elect to use belly dumps, live bottom, or end dump trucks to haul and transfer mixture; however, with exception of paving miscellaneous areas, end dump trucks are only allowed when used in conjunction with a MTD with remixing capability unless otherwise allowed by the Engineer.

d. **Screed Heaters**. If the paver stops for more than 5 minutes, turn off screed heaters to prevent overheating of the mat. If the screed heater remains on for more than 5 minutes while the paver is stopped, the Engineer may evaluate the suspect area in accordance with Section 4.I.3.c(4), "Recovered Asphalt Dynamic Shear Rheometer (DSR)."

e. **Hand work.** Hand-working of the mat should be avoided.

H. Compaction. Roll the freshly placed mixture with a steel-wheeled roller without excessive breakage of the aggregate to provide a smooth surface and uniform texture. Operate the roller in static mode for UT mixture only. Do not use pneumatic-tire rollers. Use the control strip method given in Tex-207-F, Part IV, to establish the rolling pattern. The density measurements made are for comparative purposes only and are not indicative of the actual mat density. Thoroughly moisten the roller drums with a soap and water solution to prevent adhesion. Use only water or an approved release agent on rollers, tamps, and other compaction equipment unless otherwise directed.

Use tamps to thoroughly compact the edges of the pavement along curbs, headers, and similar structures and in locations that will not allow thorough compaction with rollers. The Engineer may require rolling with a trench roller on widened areas, in trenches, and in other limited areas.

The Engineer may require the Contractor to use Tex-246-F to test and verify that the compacted mixture is adequately compacted, especially if the placed mix is allowed to cool below 275°F before compaction occurs and WMA is not used. The water flow rate for the TOM mix should be greater than 150 seconds and less than 6 minutes to avoid loss of macrotexture. If the water flow rate is less than 150 seconds, the mix design or construction methods may need to be adjusted. Permeability test should be conducted at least on the first sublot of a day's or night's production and a minimum of two sublots per day's production. The water flow for the UT mix should be greater than 300 seconds with no upper limit.

If full-coverage density measurements are desired for a specialized study, the TTI rolling density meter may be employed to assist on request.

Allow the compacted pavement to cool to 160°F or lower before opening to traffic, unless otherwise directed. When directed, sprinkle the finished mat with water or limewater to expedite opening the roadway to traffic.

I. Acceptance Plan. Sample and test the hot mix asphalt on a lot and sublot basis. If production test results fail to meet the operational tolerance requirements in Table 7 for any material property for four consecutive sublots, suspend production until test results or other information indicates to the satisfaction of the Engineer that the next material produced or placed will meet specification requirements.

1) **Referee Testing.** The Construction Division is the referee laboratory. The Contractor may request referee testing if the differences between Contractor and Engineer test results exceed the maximum allowable difference shown in Table 7 and the differences cannot be resolved. The Contractor may also request referee testing if the Engineer's test results require suspension of production and the Contractor's test results are within specification limits. Make the request within 5 working days after receiving test results from the Engineer. Referee tests will be performed only on the sublot in question and only for the particular test in question. Allow 10 working days from the time the samples are received at the referee laboratory for test results to be reported. The Department may require the Contractor to reimburse the Department for referee tests if more than three referee tests per project are required and the Engineer's test results are closer than the Contractor's test results to the referee test results.

   The Construction Division will determine the laboratory-molded density based on the molded specific gravity and the maximum theoretical specific gravity of the referee sample.

2) **Production Acceptance.**

   a. **Production Lot.** A production lot consists of four equal sublots. The default quantity for Lot 1 is 500 tons; however, when requested by the Contractor, the Engineer may increase the quantity for Lot 1 to no more than 2,000 tons. The Engineer will select subsequent lot sizes based on the anticipated daily production such that approximately three to four sublots are produced each day. The lot size will be between 500 tons and 2,000 tons. The Engineer may change the lot size before the Contractor begins any lot.

      (1) **Incomplete Production Lots.** If a lot is begun but cannot be completed, such as on the last day of production or in other circumstances deemed appropriate, the Engineer may close the lot. Close all lots within 5 working days unless otherwise allowed by the Engineer.

   b. **Production Sampling.**

      (1) **Mixture Sampling.**

      Obtain hot mix samples from trucks at the plant in accordance with Tex-222-F. The sampler will split each sample into three equal portions in accordance with Tex-200-F and label these portions as "Contractor," "Engineer," and "Referee." The Engineer will perform or witness the sampling and take immediate possession of the samples labeled "Engineer" and "Referee." The Engineer will maintain the custody of the samples labeled "Engineer" and "Referee" until the Department's testing is completed.

(a) **Random Sample.** At the beginning of the project, the Engineer will select random numbers for all production sublots. Determine sample locations in accordance with Tex-225-F. For each sublot, take one sample at the location randomly selected. The Engineer will perform or witness the sampling of production sublots.

(b) **Blind Sample.** For one sublot per lot, the Engineer will obtain and test a "blind" sample in lieu of the random sample collected by the Contractor. The Contractor may test either the "blind" or the random sample; however, referee testing (if applicable) will be based on a comparison of results from the "blind" sample. The location of the Engineer's "blind" sample will not be disclosed to the Contractor. The Engineer's "blind" sample may be randomly selected in accordance with Tex-225-F for any sublot or selected at the discretion of the Engineer. The Engineer will use the Contractor's split sample for sublots not sampled by the Engineer.

(2) **Asphalt Binder Sampling.** Obtain a 1 qt. **sample** of the asphalt binder for each lot of mixture produced. Obtain the sample at approximately the same time the mixture random is obtained. Sample from a port located immediately upstream from the mixing drum or pug mill in accordance with Tex-500-C, Part II. Label the can with the corresponding lot and sublot numbers, and deliver the sample to the Engineer. The Engineer may also obtain independent samples. If obtaining an independent asphalt binder sample, the Engineer will split a sample of the asphalt binder with the Contractor. The Engineer will test at least one asphalt binder sample per project to verify compliance with Item 300, "Asphalts, Oils, and Emulsions."

c. Production Testing. The Contractor and Engineer must perform production tests in accordance with Table 9. The Contractor has the option to verify the Engineer's test results on split samples provided by the Engineer. Determine compliance with operational tolerances listed in Table 7 for all sublots.

If the Engineer's laboratory-molded density on any sublot is less than 95.0% or greater than 98.0% when using the SGC or less than 96.5% or greater than 98.5% when using the TGC, take immediate corrective action to bring the mixture within these tolerances. The Engineer may suspend operations if the Contractor's corrective actions do not produce acceptable results. The Engineer will allow production to resume when the proposed corrective action is likely to yield acceptable results.

If the aggregate mineralogy is such that Tex-236-F does not yield reliable results, the Engineer may allow alternate methods for determining the asphalt content and aggregate gradation. Provide evidence that results from Tex-236-F are not reliable before requesting permission to use an alternate method unless otherwise directed. If an alternate test method is allowed, use the applicable test procedure as directed.

Table 9.
Production and Placement Testing Frequency.

Description	Test Method	Minimum Contractor Testing Frequency	Minimum Engineer Testing Frequency
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	1 per sublot	1 per 12 sublots
Individual % retained for sieves smaller than #8 and larger than #200			
% passing the #200 sieve			
Laboratory-molded density	Tex-207-F	N/A	1 per sublot
Laboratory-molded bulk specific gravity			
VMA	Tex-204-F		
Moisture content	Tex-212-F, Part II	When directed	
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	1 per sublot
Asphalt binder content	Tex-236-F	1 per sublot	1 per lot
Overlay Test[1]	Tex-248-F	N/A	1 per project
Cantabro Loss[1]	Tex-245-F	N/A	1 per project
Hamburg Wheel test	Tex-242-F	N/A	1 per project
		1 per sublot	
Thermal profile	Tex-244-F		
Asphalt binder sampling and testing[1]	Tex-500-C	1 per sublot (sample only)	
Boil test[2]	Tex-530-C	1 per lot	

1. Testing performed by the Construction Division or as directed by the Engineer. Cantabro Loss is for informational purposes only.
2. The Engineer may reduce or waive the sampling and testing requirements based on a satisfactory test history.

d. Operational Tolerances. Control the production process within the operational tolerances listed in Table 7. When production is suspended, the Engineer will allow production to resume when test results or other information indicates that the next mixture produced will be within the operational tolerances.

(1) **Gradation.** Suspend production and take corrective action if any aggregate is retained on the maximum sieve size shown in Table 5. A sublot is defined as out of tolerance if either the Engineer's or the Contractor's test results are out of operational tolerance. Unless otherwise directed, suspend production when test results for gradation exceed the operational tolerances for three consecutive sublots on the same sieve or four consecutive sublots on any sieve. The consecutive sublots may be from more than one lot.

(2) **Asphalt Content.** A sublot is defined as out of operational tolerance if either the Engineer's or the Contractor's test results exceed the values listed in Table 5. Suspend production when two or more sublots within a lot are out of operational tolerance or below the minimum asphalt content specified in Table 5 unless otherwise directed. Suspend production and shipment of mixture if the asphalt content deviates from the current JMF by more than 0.5% for any sublot.

(3) **Voids in Mineral Aggregate (VMA).** The Engineer will determine the VMA for every sublot. For sublots when the Engineer does not determine asphalt content, the Engineer will use the asphalt content results from quality control testing performed by the Contractor to determine VMA.

Take immediate corrective action if the VMA value for any sublot is less than the minimum VMA requirement for production listed in Table 5. Suspend production and shipment of the mixture if the Engineer's VMA results on two consecutive sublots are below the minimum VMA requirement for production listed in Table 5.

Suspend production and shipment of the mixture if the Engineer's VMA result is more than 0.5% below the minimum VMA requirement for production listed in Table 5. In addition to suspending production, the Engineer may require removal and replacement or may allow the sublot to be left in place without payment.

(4) **Hamburg Wheel and Overlay Test.** The Engineer may perform a Hamburg Wheel or Overlay test at any time during production, including when the boil test indicates a change in quality from the materials submitted for JMF1. In addition to testing production samples, the Engineer may obtain cores and perform the Hamburg Wheel test on any area of the roadway where rutting is observed. When the production or core samples fail to meet the Hamburg Wheel or Overlay test criteria in Table 6, suspend production until further Hamburg Wheel or Overlay tests meet the specified values. Core samples, if taken, will be obtained from the center of the finished mat or other areas excluding the vehicle wheel paths. The Engineer may require up to the entire sublot of any mixture failing the Hamburg Wheel or Overlay test to be removed and replaced at the Contractor's expense.

If the Department's Hamburg Wheel or Overlay test or Department-approved laboratory's Hamburg Wheel test results in a "remove and replace" condition, the Contractor may request that the Department confirm the results by retesting the failing material. The Construction Division will perform the Hamburg Wheel and Overlay tests and determine the final disposition of the material in question based on the Department's test results.

e. Individual Loads of Mix. The Engineer can reject individual truckloads of mix. When a load of mix is rejected for reasons other than temperature, contamination, or excessive uncoated particles, the Contractor may request that the rejected load be tested. Make this request within 4 hr. of rejection. The Engineer will sample and test the mixture. If test results are within the operational tolerances shown in Table 7, payment will be made for the load. If test results are not within operational tolerances, no payment will be made for the load, and the Engineer may require removal.

3) **Placement Acceptance.**

a. **Placement Lot.** A placement lot consists of four placement sublots. A placement sublot consists of the area placed during a production sublot.

(1) **Recovered Asphalt Dynamic Shear Rheometer (DSR). T**he Engineer may take production samples or cores from suspect areas of the project to determine recovered asphalt properties. Asphalt binders with an aging ratio greater than 3.5 do not meet the requirements for recovered asphalt properties and may be deemed defective when tested and evaluated by the Construction Division. The aging ratio is the DSR value of the extracted binder divided by the DSR value of the original unaged binder. Obtain DSR values in accordance with AASHTO T 315 at the specified high temperature performance grade of the asphalt. The Engineer may require removal and replacement of the defective material at the Contractor's expense. The asphalt binder will be recovered for testing from production samples or cores in accordance with Tex-211-F.

(2) **Irregularities.** Identify and correct irregularities including but not limited to segregation, rutting, raveling, flushing, fat spots, mat slippage, irregular color, irregular texture, roller marks, tears, gouges, streaks, uncoated aggregate particles, or broken aggregate particles. The Engineer may also identify irregularities, and in such cases, the Engineer will promptly notify the Contractor. If the Engineer determines that the irregularity will adversely affect pavement performance, the Engineer may require the Contractor to remove and replace (at the Contractor's expense) areas of the pavement that contain irregularities and areas where the mixture does not bond to the existing pavement. If irregularities are detected, the Engineer may require the Contractor to immediately suspend operations or may allow the Contractor to continue operations for no more than 1 day while the Contractor is taking appropriate corrective action.

4) **Exempt Production.** When the anticipated daily production is less than 100 tons, all quality control and quality assurance sampling and testing are waived. When the anticipated daily production is more than 100 tons but less than 250 tons, the total production for the project is less than 2,500 tons, when paving miscellaneous areas, or when mutually agreed between the Engineer and the Contractor, the Engineer may deem the mixture as exempt production. Production may also be exempt when shown on the plans.

For exempt production, the Contractor is relieved of all production and placement sampling and testing requirements. All other specification requirements apply, and the Engineer will perform acceptance tests for production and placement listed in Table 9.

For exempt production:

- produce, haul, place, and compact the mixture as directed by the Engineer; and
- control mixture production to yield a laboratory-molded density that is within ± 1.0% of the target density as tested by the Engineer.

5) **Ride Quality.** Unless otherwise shown on the plans, measure ride quality in accordance with Item 585, "Ride Quality for Pavement Surfaces."

5. **Measurement.** TOM and UT will be measured by the ton of composite TOM and UT. The composite TOM and UT is defined as the asphalt, aggregate, and additives. The weights of asphalt and aggregate will be calculated based on the measured weight of TOM and UT and the target percentage of asphalt and aggregate. Measure the weight on scales in accordance with Item 520, "Weighing and Measuring Equipment."

A. Asphalt. The asphalt weight in tons will be determined from the total weight of TOM and UT. Measured asphalt percentage will be obtained using Tex-236-F or asphalt flow meter readings, as determined by the Engineer. Provide the Engineer with a daily summary of the asphalt mass flow meter readings when used for measuring asphalt percentage unless otherwise directed.

2) **Target Percentage.** The JMF target asphalt percentage will be used to calculate the weight of asphalt binder unless the measured asphalt binder percentage is more than 0.3 percentage points below the JMF target asphalt percentage or less than the minimum percentage specified in Table 5. Volumetric meter readings will be adjusted to 140°F and converted to weight.

3) **Measured Percentage.** The average measured asphalt percentage from each sublot will be used for payment for that lot's production when the measured percentage for any sublot is more than 0.3 percentage points below the JMF target asphalt percentage or less than the minimum percentage specified in Table 5.

B. Aggregate. The aggregate weight in tons will be determined from the total weight of TOM and UT less the weight of the asphalt.

6. **Payment.** The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for "Thin Surface Mixtures (Asphalt)" of the binder specified and for "Thin Surface Mixtures (Aggregate)" of the grade and surface aggregate classification specified. These prices are full compensation for surface preparation, materials including tack coat, placement, equipment, labor, tools, and incidentals.

Trial batches will not be paid for unless they are included in pavement work approved by the Department.

Pay adjustment for ride quality will be determined in accordance with Item 585, "Ride Quality for Pavement Surfaces."