Texas A&M Transportation Institute

Evaluation of Mix Design Variables for Full Depth Reclamation (FDR) with Asphalt

Technical Report 0-7076-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

sponsored by the
Federal Highway Administration and the
Texas Department of Transportation
https://tti.tamu.edu/documents/0-7076-R1.pdf

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-25/0-7076-R1		

4. Title and Subtitle	5. Report Date
EVALUATION OF MIX DESIGN VARIABLES FOR FULL DEPTH RECLAMATION (FDR) WITH ASPHALT	Published: January 2025
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Edith Arambula-Mercado, Stephen Sebesta, Jinho Kim, and Ross Taylor	Report 0-7076-R1

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Project 0-7076

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483	Technical Report: September 2020–August 2024
	14. Sponsoring Agency Code

15. Supplementary Notes

Project sponsored by the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Develop Laboratory Mix Design for Full Depth Reclamation (FDR) Projects Using Foamed Asphalt Binder and Emulsified Asphalt
URL: https://tti.tamu.edu/documents/0-7076-R1.pdf

16. Abstract

This study on full depth reclamation (FDR) with asphalt binders was aimed at updating FDR mix design procedures for the Texas Department of Transportation's (TxDOT's) 2024 Standard Specifications. The study included a literature review, a laboratory factors study, an interlaboratory study, and field evaluations. The literature review examined the use of FDR in Texas, various mix design procedures, and the impact of specimen size and test temperature on indirect tensile (IDT) strength. Findings suggested optimization opportunities in the compaction and IDT strength limits. The laboratory study involved conducting a mix design and characterizing field-collected materials to assess factors affecting the IDT strength of mix design specimens, such as specimen size, compaction level, emulsion temperature, curing time, curing temperature, testing temperature, and cement type. Statistical analyses indicated significant impacts of most of these variables. The interlaboratory study, which involved various TxDOT laboratories and one private laboratory, was conducted to establish a preliminary precision statement for the FDR mix design procedures. Field evaluations of sections from two of the projects included in the study indicated the FDR treatments positively impacted pavement performance, with backcalculated base layer modulus meeting or exceeding design assumptions with only a few exceptions. Recommendations for TxDOT's FDR procedures include using only 4-inch diameter specimens, maintaining a minimum curing time of 72 hours at 104°F, continuing use of 104°F for curing temperature, and tightening the IDT test temperature range to 72° ± 2°F. These changes aim to ensure consistent and high-quality FDR practices across Texas, extending the service life of rehabilitated pavements.

17. Key Words	18. Distribution Statement
Full Depth Reclamation, FDR, Mix Design, Laboratory Study, Interlaboratory Study, Emulsified Asphalt, Emulsion, Foamed Asphalt	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia https://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	152	

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

EVALUATION OF MIX DESIGN VARIABLES FOR FULL DEPTH RECLAMATION (FDR) WITH ASPHALT

by

Edith Arambula-Mercado
Research Engineer
Texas A&M Transportation Institute

Stephen Sebesta
Research Scientist
Texas A&M Transportation Institute

Jinho Kim
Assistant Research Scientist
Texas A&M Transportation Institute

and

Ross Taylor
Research Specialist IV
Texas A&M Transportation Institute

Report 0-7076-R1
Project 0-7076
Project Title: Develop Laboratory Mix Design for Full Depth Reclamation (FDR) Projects Using Foamed Asphalt Binder and Emulsified Asphalt

Sponsored by the
Texas Department of Transportation
and the
Federal Highway Administration

Published: January 2025

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

DISCLAIMER

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

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

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

ACKNOWLEDGMENTS

This project was sponsored by TxDOT and FHWA. The authors thank Joanne Steele and Tom Schwerdt, the project managers, as well as members of the Project Monitoring Committee, including Gisel Carrasco, James Robbins, Lacy Peters, Michael Dawidczik, and Richard Izzo, for the input throughout the execution of this project. The authors also appreciate the district representatives for helping identify field pavement sections, aiding with material collection, and providing field monitoring data. Many thanks to the Materials and Tests Division laboratory, the districts laboratories, and the private laboratory that participated in the interlaboratory study. Appreciation is also extended to the asphalt material suppliers that donated products for the execution of the mix designs and interlaboratory study. Finally, recognition is extended to Juan Romero, Tony Barbosa, and Jason Huddleston for their assistance with laboratory and field activities and to Ivette Arambula Mercado and Eun Sug Park for their assistance with data analysis.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER 1:
LITERATURE REVIEW

Full depth reclamation (FDR) is a cost-effective recycling strategy that reuses both asphalt bound and unbound granular materials. FDR was implemented in Texas in the early 1990s in the Bryan and Lubbock Districts using cement, lime, or fly ash. In the past 5 years, the Texas Department of Transportation (TxDOT) has implemented FDR using foamed or emulsified asphalt in Special Specifications 3088 and 3089, respectively.

FDR provides a rapid, cost-effective solution to rehabilitate failing pavements. This tool can renew a pavement for about half the cost of more traditional approaches while reusing existing materials. The Asphalt Recycling and Reclaiming Association (ARRA) defines FDR as follows: "a reclamation technique in which the full flexible pavement section and a predetermined portion of the underlying materials are uniformly crushed, pulverized, or blended, resulting in a stabilized base course; further stabilization may be obtained through the use of available additives" (*1*). Figure 1 summarizes key benefits of FDR.

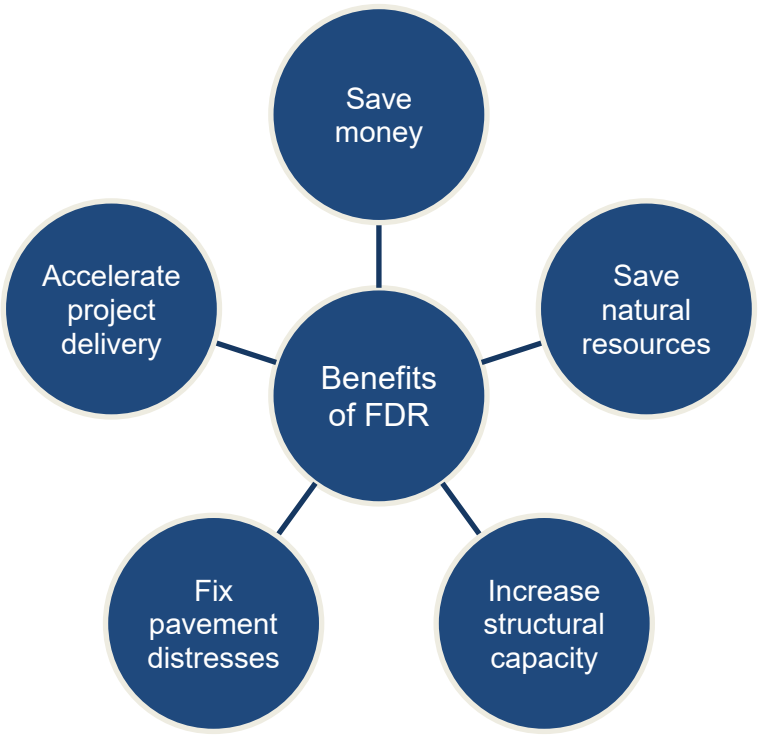


Figure 1. Benefits of FDR.

The TxDOT draft mix design procedures for FDR using emulsified asphalt or foamed asphalt binder employ the cured (dry) and moisture-conditioned (wet) indirect tensile (IDT) strength with specimens compacted using the Superpave gyratory compactor (SGC) with a setup similar to the one shown in Figure 2.

Figure 2. IDT testing sample setup.

Historically, TxDOT allowed the use of SGC 4-inch diameter by 2-inch high samples or 6-inch diameter by 3.75-inch high specimens with a single IDT strength mix design criteria for both specimen sizes. This practice raised concern regarding the effect of sample size on the IDT strength because larger 6-inch diameter specimens usually exhibited lower IDT strength compared to 4-inch diameter specimens regardless of material source, binder type, binder content, or conditioning procedure (*2*).

In addition, under the draft mix design procedures, after determining the mixture met IDT requirements, an impact compactor was used to produce 6-inch diameter by 8-inch high samples to measure the moisture-conditioned unconfined compressive strength (UCS). Figure 3 shows typical IDT and UCS specimens.

Figure 3. Side-by-side comparison of representative IDT and UCS mix design samples.

As part of the initial effort of gathering and summarizing information, the research team conducted a brief survey of TxDOT staff to identify the state of the practice for designing these materials in Texas. A literature review was also conducted to document (a) the FDR mix design procedures being used within TxDOT and by other agencies, and (b) recent efforts to understand the impact of specimen size on the performance of FDR specimens prepared with either emulsified asphalt or foamed asphalt. The results of these efforts are summarized in this chapter.

CURRENT USE OF FDR IN TEXAS

To gather up-to-date information and specifics on how current FDR mix designs are being conducted, the research team selected several districts that perform routine FDR projects to complete an online questionnaire. Representatives from the Bryan, Lubbock, San Antonio, and Waco Districts, as well as TxDOT's Materials and Tests Division (MTD), were contacted because these districts and MTD possess the FDR equipment required to perform FDR mix designs with asphalt treatments. The questionnaire focused on documenting preferred materials and practices and the rationale behind those choices. The questionnaire is included in Appendix A.

The responses to the questionnaire show that the districts surveyed typically employ foamed asphalt in FDR projects (the Bryan District indicated employing emulsified asphalt in 1 mile out of 29 miles of total project length in a recent construction). The selection of foamed asphalt is primarily driven by recommendations from recently completed research projects, traffic volume, or quality of the base material. MTD indicated that statewide from 2014 through 2019, 21 FDR projects employed emulsified asphalt and 10 projects used foamed asphalt, which is an opposite trend to the districts' responses.

With respect to specimen size, all districts surveyed and MTD indicated employing 4-inch diameter by 2-inch high specimens for FDR mix design. The three main reasons the districts gave for selecting a 4-inch diameter specimen size included:

- Lower amount of material to process in the laboratory.
- Ability to evaluate more specimens.
- Availability of existing molds.

The type of compactor used by the Lubbock, San Antonio, and Waco Districts was the SGC, while the Bryan District employed the Texas gyratory compactor (TxGC) because the district no longer applies the TxGC for asphalt mixture testing. The Lubbock District indicated that, based on its experience, the SGC compacted the specimens more consistently than the TxGC and required less human input (and thus was less prone to human error) during compaction.

The reported test temperature used when conducting the IDT strength as part of the FDR mix design varied from 70°F (reported by MTD) through 75°F (reported by the Waco District). The

reported temperatures are likely estimated laboratory ambient temperature. None of the districts indicated adjusting the IDT strength criteria depending on the type of asphalt (i.e., emulsified asphalt or foamed asphalt), specimen size, or IDT test temperature.

Regarding performance, the districts reported adequate performance of current FDR projects, although the San Antonio District, for example, reported that it had not constructed recent FDR projects but planned to commence in 2021. MTD reported mixed results, noting some projects with adequate performance and others with inadequate performance. However, since MTD is not involved with construction at the project level, it was not able to offer specifics on the performance issues.

Last, the Bryan District reported some issues regarding the current FDR mix design procedure. Representatives described one case in which they encountered a few areas of the project where the soil properties varied from what was originally evaluated during mix design. The district collected samples and replicated the mix design test procedures, and the samples failed to meet IDT strength requirements, but falling weight deflectometer (FWD) data collected on the project showed robust sections despite the failing laboratory test results.

MIX DESIGN PROCEDURES

Table B-1 through Table B-4 in Appendix B summarize FDR mix design procedures with emulsified asphalt and foamed asphalt. These tables include the draft mix design procedures from TxDOT as well as specifications from other organizations such as ARRA and the American Association of State Highway and Transportation Officials (AASHTO); other state DOTs including California, Illinois, Maryland, Virginia, and West Virginia; and other countries including South Africa and Australia. These tables provide details about sampling, mixing water content determination, mixing methods, compaction, conditioning, test method, test temperature, and acceptance criteria.

Some unique features of the various FDR mix design procedures are discussed next.

State DOTs

State DOT FDR mix design procedures include the following:

- California uses 4-inch diameter specimens and requires compaction at 77°F. In addition, California determines the optimum moisture with the additive included and limits the additive content to 1 percent.
- Illinois requires a laboratory temperature for specimen preparation and testing.
- Maryland does not allow polymer-modified binders.

- Virginia requires the mix design to report the minimum emulsion cure time, and for foamed asphalt binder treatment, the specimens must be compacted at or below optimum.
- West Virginia uses the same specification for cement, emulsion, or foam.

Other Countries

FDR mix design procedures in other countries include the following:

- Australia excludes the use of polymer-modified asphalt binders and asphalt binders containing silicon from FDR with foamed binder because they tend to resist foaming. The use of foaming agents or anti-strip additives is recommended to help with foaming. In addition, a maximum plasticity index (PI) value of 10 is advised, along with pretreatment with lime materials with PI values between 10 and 20. Finally, an acceptance criterion as a function of truck traffic is recommended.
- South Africa includes a limit on the cement content of 1.0 percent for FDR with asphalt emulsion and foamed asphalt and recommends pretreatment of the material with lime if plasticity is the primary concern. In addition, South Africa recommends material with PI values lower than 6 percent for FDR with asphalt emulsion or foamed asphalt. The target asphalt emulsion content is prescribed between 2.8–4.2 percent (1.7–2.5 percent residual binder), while 1.7–2.5 percent is recommended for foamed binder. Triaxial test criteria are provided, and acceptance criteria are given as a function of truck traffic and climate.

Other Agencies

FDR mix design procedures used by other agencies include the following:

- Wirtgen typically uses cement or lime in FDR with asphalt emulsion, with cement being employed in cases where the PI value is less than 10 and lime in cases where the PI value is more than 10. Also, the Wirtgen procedure mentions that typical asphalt emulsion contents range from 3.3 percent to 5.3 percent depending on the amount of material passing the No. 200 and No. 4 sieves: the higher the percent passing these two sieves, the greater the emulsion content.
- Wirtgen also provides additional FDR with foamed asphalt mix design guidelines, including for the use of cement or lime; for materials with a PI value less than 10, cement is recommended, whereas for materials with a PI value larger than 10, lime is advised. Also, the method specifies typical foamed asphalt contents from 2.0 percent to 3.2 percent depending on the material passing the No. 200 and No. 4 sieves; higher percentages passing these two sieves should incorporate larger foamed asphalt content. Finally, the method prescribes a maximum filler (cement or lime) content of 1.0 percent.

PREVIOUS RESEARCH ON SPECIMEN SIZE

Since the development of the Superpave volumetric mix design method under the Strategic Highway Research Program, there has been a need to evaluate differences in performance between samples prepared using Marshall or Hveem devices and the SGC. The samples prepared with the former two devices are 4-inch diameter versus 6-inch diameter specimens commonly fabricated in the SGC.

Under National Cooperative Highway Research Program (NCHRP) Project 09-13, researchers evaluated the moisture sensitivity per AASHTO T 283 of 4-inch and 6-inch diameter specimens prepared according to the Superpave mix design method and compared the results to the values obtained using 4-inch diameter Marshall- and Hveem-compacted specimens based on IDT strength and resilient modulus (*3*). In addition, besides the specimen size and compaction method, the researchers evaluated other variables including aging method on loose mix and compacted specimens, degree of saturation of the specimens as part of the moisture conditioning procedure, type of aggregate, effect of the freeze/thaw cycles, and type of anti-strip agent used in the mix. The results of that study indicated that the dry IDT strengths of the 4-inch diameter SGC, Marshall, and Hveem specimens were in most cases larger than the results obtained from 6-inch SGC specimens. Regarding tensile strength ratio (TSR), the 4-inch specimens demonstrated a more significant drop in wet (soaked) IDT strength and therefore a lower TSR compared to the 6-inch specimens.

In a separate study sponsored by TxDOT, a laboratory and field evaluation of FDR stabilization with asphalt emulsion was conducted to evaluate TxDOT's mix design specification that was current at the time of the study (*4*). Material was collected from five FDR field projects to conduct the laboratory evaluation. In addition, a full-scale investigation using ground penetrating radar (GPR), FWD, and field cores was performed for a larger set of field projects. For the laboratory evaluation, the materials obtained from the five FDR field projects were mixed with various asphalt emulsion contents and 1.0 percent additive (i.e., cement or lime). The water added during sample preparation was 65 percent of the optimum moisture content (OMC). The samples were cured for 48 hours at 140°F followed by 24 hours at room temperature prior to testing. UCS and retained UCS per Tex-117-E, IDT strength per Tex-226-F, dielectric value with the tube suction test, resilient modulus per AASHTO T 307, and seismic modulus with the free-free resonant column were measured. The researchers obtained mixed results, with some samples passing the recommended thresholds of the mix design specification for certain tests but not others. Their recommendation was to vary the mix design requirements according to the type and source of material being stabilized and the traffic level, with lower UCS and IDT strength requirements for roads with less traffic.

In another study, researchers evaluated a trial version of a TxDOT special specification for the use of asphalt emulsion in FDR applications (*5*). Their objective was to develop a laboratory test procedure for mix design of FDR stabilization using a combination of asphalt emulsion and

calcium-based additives such as cement, lime, or fly ash. Five types of base materials were included in the study. Emulsion contents from 0 percent through 7 percent and OMC of 45 percent, 60 percent, and 75 percent were selected to prepare the specimens. All specimens were 6-inch diameter by 2.4-inch height prepared using an SGC with a fixed number of 30 gyrations. The researchers conducted a parametric study to identify the factors that affected performance, including gradation, emulsion type, curing time and temperature, mixing method, compaction method, and mixing temperature. Based on laboratory observations and validation using field projects, the researchers recommended using IDT strength (minimum 50 psi) and retained IDT strength (minimum 80 percent) as opposed to UCS strength and retained UCS strength for mix design criteria, despite many of the 6-inch diameter samples not meeting the minimum 50 psi criteria. In addition, they recommended a mixing water content of 60 percent of the OMC for compaction. Finally, a 2-day curing at 140°F was recommended.

The research team conducted preliminary laboratory work analyzing the effect of specimen size on IDT strength (*2*). Figure 4 and Figure 5 show IDT values measured with smaller and larger sample sizes for materials of various sources around Texas (i.e., NE = northeast, W = west, and C = central) and condition (i.e., dry, soak, and vacuum saturation [Vac. Sat.]). The IDT strength of the larger 6-inch diameter specimens is clearly lower than the smaller 4-inch diameter specimens for all three material sources. The difference in IDT strength between smaller and larger specimens could be related to the level of curing attained by the different sample sizes from the 72-hour curing stage or could indicate bias in results between the different sample sizes. Moisture content values at the time of IDT testing were not available to evaluate the level of curing.

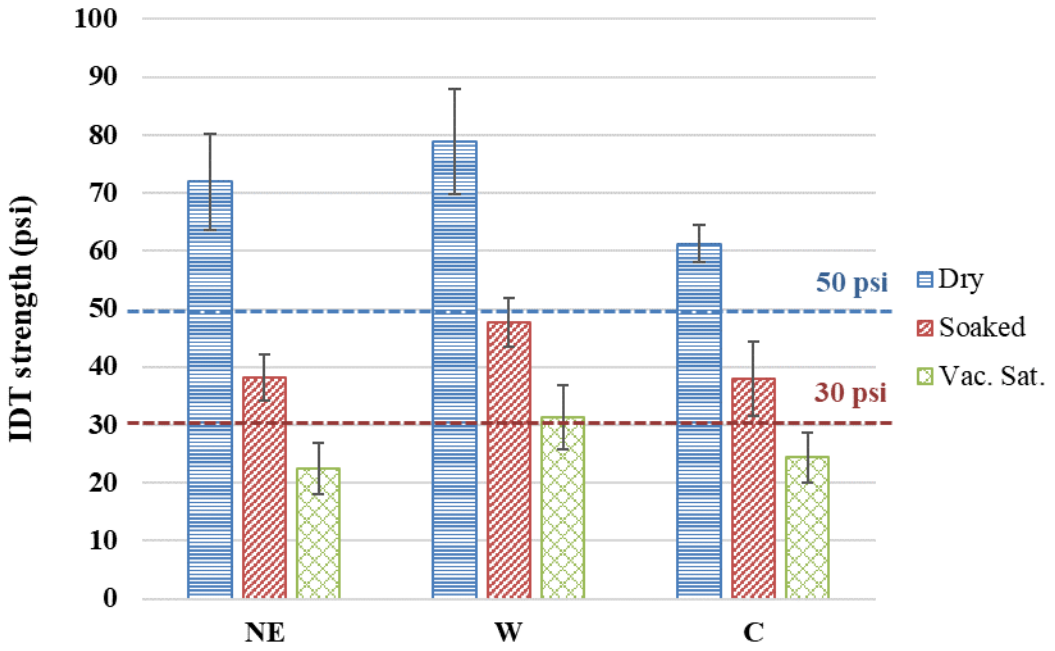


Figure 4. IDT strength for 4-inch diameter specimens (*2*).

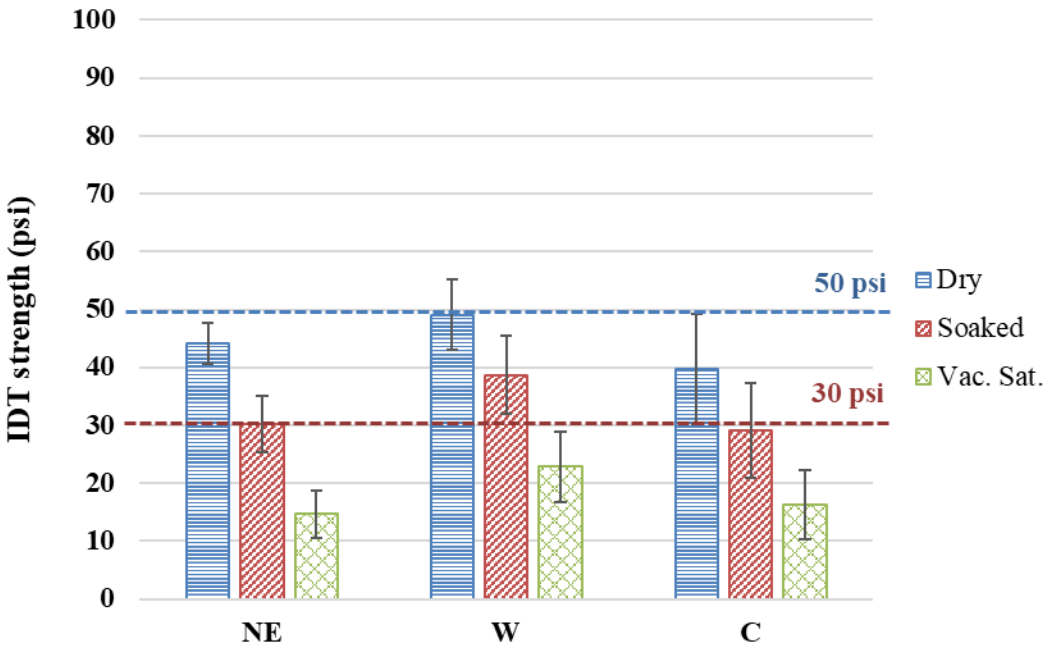


Figure 5. IDT strength for 6-inch diameter specimens (*2*).

CHAPTER 2:
FIELD PROJECTS

The research team identified six candidate field projects in various districts to gather materials and conduct a laboratory study exploring factors that could have an effect on IDT strength. The research team made efforts to select project locations in west, central, and east Texas. Researchers then conducted GPR, selected sampling locations, and coordinated with TxDOT to collect representative roadway samples for laboratory testing.

This chapter documents the location of each FDR project, provides visual examples of the roadway materials that were collected, and summarizes the GPR survey efforts.

LOCATION OF THE FDR FIELD PROJECTS

Table 1 presents a list of the six field projects that the research team identified and selected for sampling. The information in Table 1 includes the roadway ID, the county where the field project is located, the control section job (CSJ) number, and the project limits. Figure 6 and Figure 7 show maps of the districts and counties where these projects are located.

Table 1. FDR Projects.

District	Roadway	County	CSJ	Limits
Atlanta (ATL)	FM 3129	Cass	0945-05-022	From US 59 to Paper Mill, 7.2 mi. north of FM 250
ATL	US 80	Upshur	0096-03-075	From SH 155 N leg to SH 155 S leg in Big Sandy, TX
Bryan (BRY)	OSR	Madison	0475-01-056	From Brazos County Line to FM 1452
BRY	FM 39	Madison	0639-02-034	From OSR to SH 21
Lubbock (LBB)	SH 207	Crosby	0453-04-024	From 763 ft north of the intersection of FM 40E and SH 207 to the Crosby/Garza County Line
Odessa (ODA)	BI 20	Midland	005-03-079	Fairgrounds road to IH 20

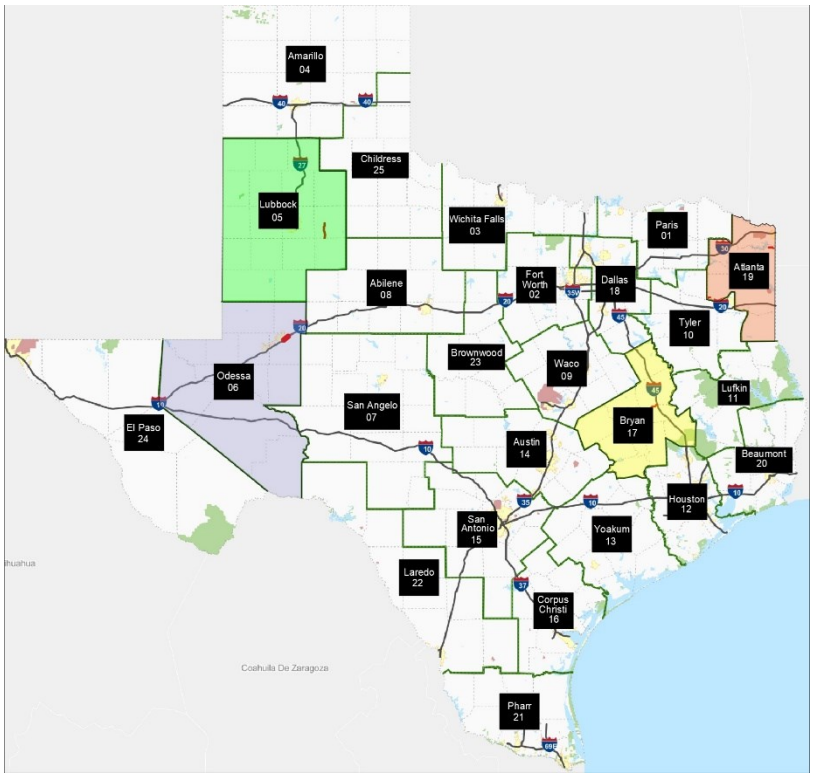


Figure 6. Location of the selected FDR field project districts.

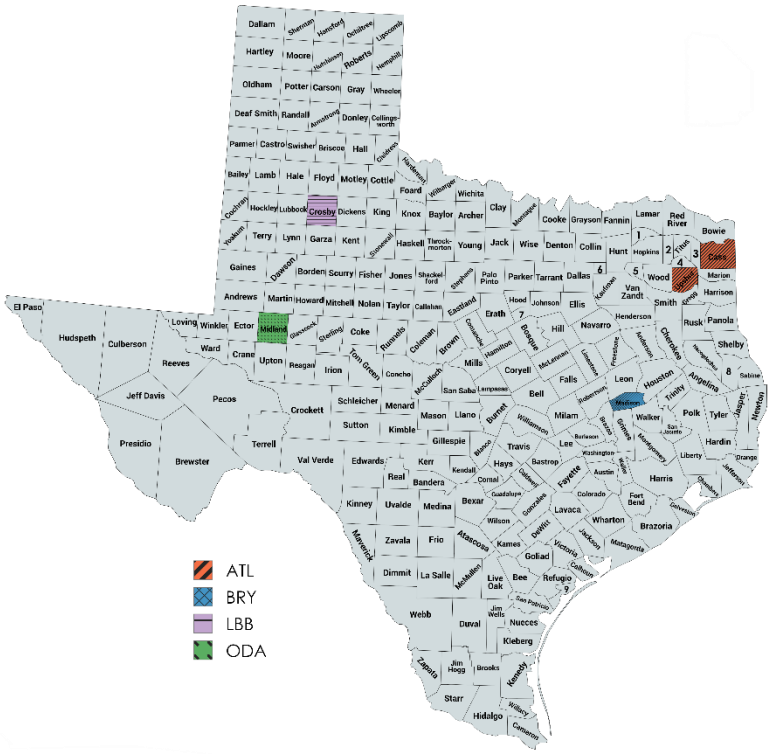


Figure 7. Location of the selected FDR field project counties.

COLLECTION OF REPRESENTATIVE ROADWAY SAMPLES

Figure 8 through Figure 13 show the sampling locations and representative materials from each of the selected projects except for ODA BI 20. Figure 13 shows the project extents and representative materials from ODA BI 20; GPR data were not available from this project. Material from BRY OSR was collected from the top 9 inches of the existing pavement and included a surface treatment.

The research team coordinated with TxDOT to sample materials between October 2020 and July 2021. Based on needed quantities for the laboratory research test factorial, researchers collected around 2,000 lb of materials from each field project.

(a) (b)

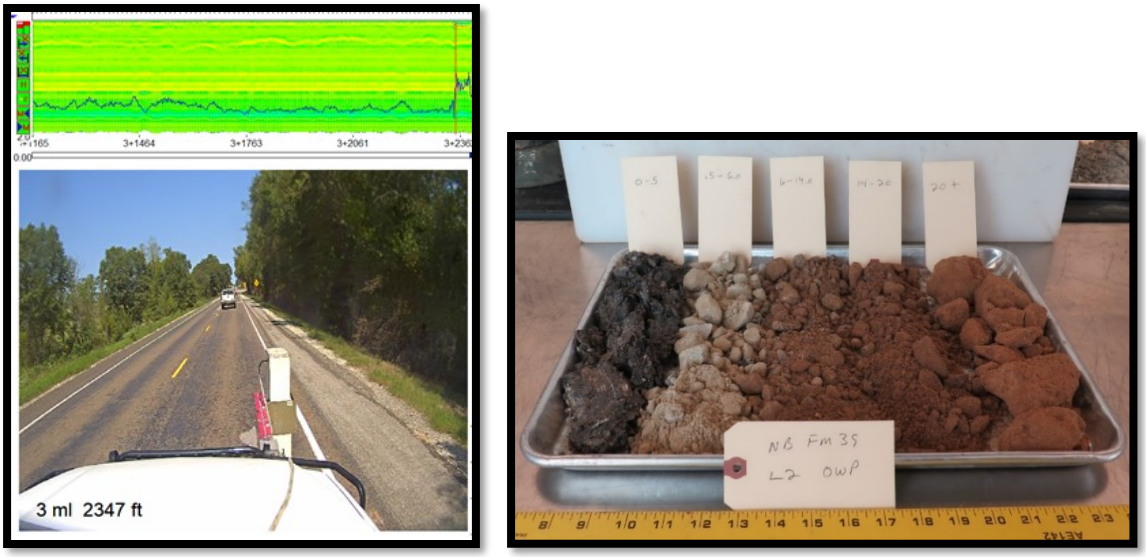
Figure 8. ATL FM 3129: (a) roadway sampling location, (b) representative materials.

(a) (b)

Figure 9. ATL US 80: (a) roadway sampling location, (b) representative materials.

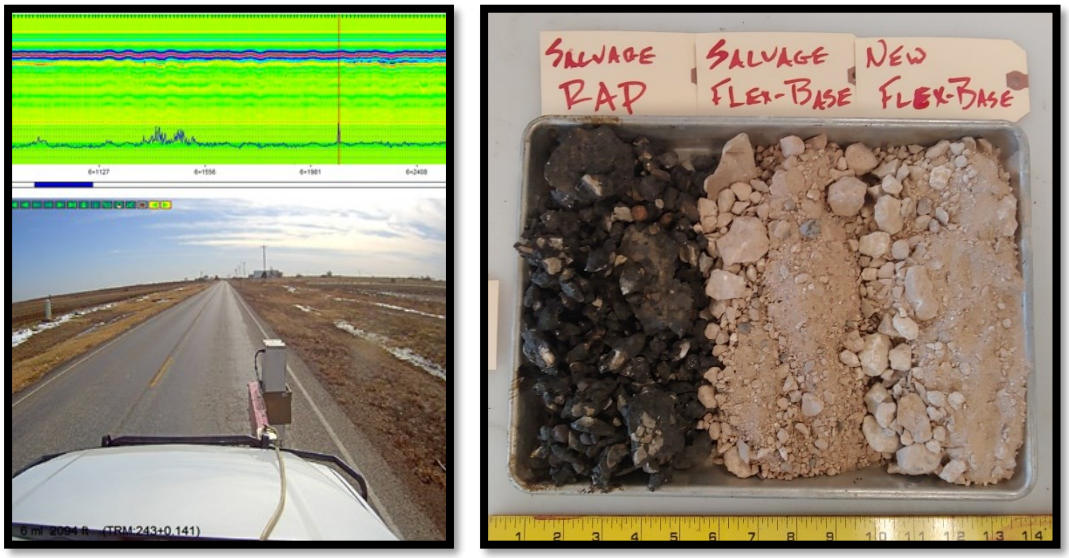
(a) (b)

Figure 10. BRY OSR: (a) roadway sampling location, (b) representative material.



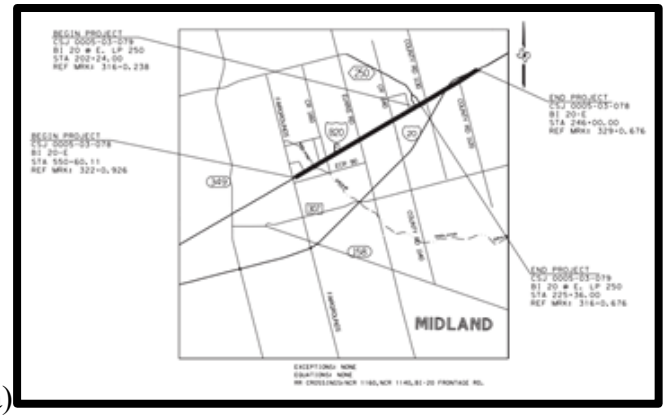
(a) (b)

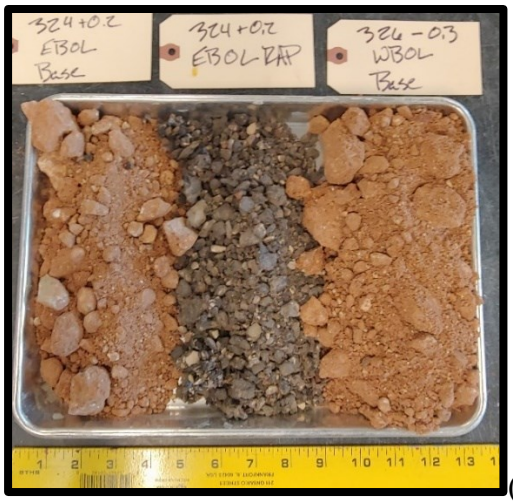
Figure 11. BRY FM 39: (a) roadway sampling location, (b) representative materials.



(a) (b)

Figure 12. LBB SH 207: (a) roadway sampling location, (b) representative materials.

(a) 



(b)

Figure 13. ODA BI 20: (a) project location, (b) representative materials.

OBSERVATIONS FROM GPR SURVEYS

ATL FM 3129

GPR was acquired on November 19, 2021. The results showed a thick asphalt surface typically 10–12 inches. The results also indicated that a similar pavement structure existed in the shoulders as in the lanes.

ATL US 80

GPR was acquired on April 6, 2021. The results showed typically around a 9-inch total of asphalt layers, with periodic indications of buried damage either mid-depth, at the bottom of, or in some cases both at mid-depth and at the bottom of the asphalt layers. The GPR signatures were similar across all travel lanes evaluated (both travel directions and both inside and outside lanes).

BRY OSR

GPR was acquired on September 29, 2020. The results showed a thin surfacing with about an 8-inch base. Localized level-ups existed. Some of these level-ups were estimated by the GPR to be 4–8 inches of material; these thicker level-ups are probably bladed-on material at the pavement edges.

BRY FM 39

GPR was acquired on September 28, 2020. The results agreed well with the plan sets, showing a thin surface with a thin (about 5- to 7-inch) layer of flexible base. GPR also showed several locations that appeared reworked to a depth of about 10 inches. Subsequent drilling and discussions with the district confirmed prior activities along the section had included spot base repair.

LBB SH 207

GPR was acquired on January 14, 2021. The results suggested the section was uniform, with a 2- to 3-inch layer at the surface and a 4- to 7-inch layer of base. In addition, the GPR indicated that about 5,100 ft of pavement located at the southern end of the project had a history of more intensive maintenance. With this information, researchers proposed a location for sampling and recommended expanded limits of subgrade treatment.

ODA BI 20

GPR data were not available for this project. Existing typical sections showed 12.5 inches of existing flexible base and 2 inches of existing asphalt concrete pavement.

CHAPTER 3:
LABORATORY STUDY

The research team conducted a laboratory study employing the materials collected from the FDR field projects described in Chapter 2. Mix designs were developed for each field project following draft mix design procedures Tex-122-E for emulsified asphalt and Tex-134-E for foamed asphalt. The properties of the materials collected at each location, the resulting mix designs, and the factors and levels that were explored as part of the laboratory study are described in this chapter.

CHARACTERIZATION OF REPRESENTATIVE ROADWAY SAMPLES

The research team coordinated with TxDOT to sample materials between October 2020 and July 2021, as presented in Chapter 2. Based on needed quantities for the laboratory study, researchers collected around 2,000 lb of materials from each field project. Table 2 summarizes the measured Atterberg limits of these materials per Tex-104-6-E.

Table 2. Atterberg Limits Results.

District	ATL	ATL	ATL	BRY	BRY	LBB	LBB	ODA
Roadway	**FM 3129 Emulsion 100% RAP**	**FM 3129 Foam 20% Base + 80% RAP**	**US 80**	**OSR**	**FM 39**	**SH 207**	**SH 207**	**BI 20**
Material	**Salv. RAP**	**Salv. Base**	**Salv. Base**	**Salv. Base**	**New Base**	**Salv. Base**	**New Base**	**Salv. Base**
Liquid Limit (LL)	–	22	16	18	25	22	22	27
Plastic Limit (PL)	–	11	9	14	12	9	12	14
Plastic Index (PI)	–	11	7	4	13	13	10	13

Note: RAP = reclaimed asphalt pavement. A dash indicates properties were not measured for the roadway material.

MIX DESIGNS

The roadway materials were blended in certain proportions, and the combined aggregate gradation was determined for each field project. The mixture proportions used to develop the mix designs are listed in Table 3. These mix design proportions represented the actual proportions of materials expected in the anticipated field FDR process. The combined washed aggregate gradations per Tex-200-F are shown in Table 4. With the combined aggregate gradation, but only employing materials processed down to sieve No. 40, researchers used a moisture-density (M-D) curve without binder or additive to establish the OMC per Tex-113-E. For mixtures employing foamed asphalt, expansion ratio and half-life were measured at various

foaming water contents and temperatures to determine the optimum foamed water content and the optimum foaming temperature.

Table 3. Mix Design Proportions.

District	Roadway	Mixture Proportions
ATL	FM 3129	100% Salvage RAP
ATL	FM 3129	20% Salvage Base + 80% Salvage RAP
ATL	US 80	50% Salvage Base + 50% Salvage RAP
BRY	OSR	100% Salvage Base Mix
BRY	FM 39	100% Frost Pit New Base
LBB	SH 207	55% Salvage Base + 21% Salvage RAP + 24% DWG Pit New Base
ODA	BI 20	100% Salvage Base Mix

Table 4. Combined Washed Aggregate Gradations.

District	ATL	ATL	ATL	BRY	BRY	LBB	ODA
Roadway	FM 3129 Emulsion 100% RAP	FM 3129 Foam 20% Base + 80% RAP	US 80	OSR	FM 39	SH 207	BI 20
Sieve Size	Cumulative Percent Passing (%)						
1¾"	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1¼"	100.0	98.8	97.1	96.8	84.1	96.7	98.2
⅞"	99.6	98.5	95.0	91.0	72.0	89.0	94.4
⅝"	97.2	93.9	92.4	82.8	63.4	78.9	87.6
⅜"	78.5	76.9	84.5	68.8	52.9	62.9	73.2
No. 4	53.8	54.0	61.2	52.0	42.9	43.5	55.4
No. 40	16.6	19.6	31.9	29.5	27.5	23.9	33.1
No. 100	7.2	11.6	17.4	24.3	24.4	18.2	22.1
No. 200	4.7	7.0	12.1	21.1	10.6	12.4	18.8

The same type of emulsified asphalt (i.e., CSS-1H) and type of asphalt binder (i.e., PG 64-22) were used when performing the mix designs. However, the source of the emulsion or asphalt binder differed because a concerted effort was made to employ sources commonly used or easily accessible in the district where the field project was located. IDT strength specimens were prepared using at least two asphalt contents. One subset of three specimens was tested without conditioning, and the other subset of three specimens was submerged in water for a specified period (i.e., conditioned). Both subsets of specimens were evaluated, and the results were verified against the standard criteria. Finally, UCS specimens were also crafted and tested to verify the minimum passing criteria. All mix designs included 1.0 percent cement to meet the

requirements. The resulting mix design parameters are listed in Table 5. Additional results for each asphalt type and asphalt content evaluated, along with the final mix design parameters, are summarized in Appendix C.

Table 5. Mix Design Asphalt Type and Design Asphalt Content.

District	ATL	ATL	ATL	BRY	BRY	LBB	ODA
Roadway	**FM 3129 Emulsion 100% RAP**	**FM 3129 Foamed 20% Base + 80% RAP**	**US 80**	**OSR**	**FM 39**	**SH 207**	**BI 20**
Design Asphalt Content (%)	4.0	2.4	4.3	2.6	2.4	2.6	4.2
Asphalt Type	CSS-1H Emulsion	PG 64-22 Foam	CSS-1H Emulsion	PG 64-22 Foam	PG 64-22 Foam	PG 64-22 Foam	CSS-1H Emulsion
Cement Content (%)	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Optimum Moisture Content (%)	6.0	7.2	7.8	6.7	7.9	7.3	6.4
Maximum Dry Density (pcf)	118.1	122.8	131.8	132.0	131.7	128.6	131.7
Unconditioned IDT Strength (psi)	60	64	65	97	62	73	76
Conditioned IDT Strength (psi)	50	46	60	53	35	35	52
UCS (psi)	121	170	170	146	138	123	136

In the case of ATL FM 3129, a 100 percent RAP mixture was only able to pass the mix design requirements when emulsified asphalt was used, while for the mixture with 20 percent salvage base + 80 percent salvage RAP, the foamed asphalt yielded a passing design.

The research team conducted an exploratory analysis on the effect of incorporating emulsified asphalt or foamed asphalt and additive (i.e., cement or lime) on the compacted dry density. The dataset included 13 untreated and 3 treated foamed asphalt M-D measurements, plus 29 untreated and 3 treated emulsified asphalt M-D measurements. Researchers compared the maximum dry density obtained from the untreated M-D curve to the density obtained from the treated UCS specimens. The research team also compared the maximum dry density from a treated M-D curve to the treated UCS density using a limited dataset.

The results for untreated foamed asphalt showed that the UCS density (i.e., treated density) was as much as 7.0 pcf below the untreated M-D maximum dry density, with all measured values

showing a decrease in dry density with treatment and an average decrease of 4.3 pfc. The results for untreated emulsified asphalt showed that the UCS density was as much as 8.1 pcf below the untreated M-D maximum dry density or as much as 3.9 pcf above it. In general, most of the untreated emulsified asphalt data points (i.e., 79 percent) showed a decrease in dry density with treatment (i.e., UCS density), with an average decrease of 2.8 pfc. The average results are summarized in Table 6. This table also shows that when performing a treated M-D curve, the differences between the treated M-D maximum dry density and the UCS density are smaller, as expected. Also, the UCS samples averaged 99.8 percent density for both foamed and emulsified asphalt specimens when compared to a treated M-D curve maximum dry density. Therefore, the density obtained from treated UCS samples is practically equal to the density obtained using the treated M-D curve optimum moisture content. However, the treated M-D curve procedure is more time consuming and requires higher moisture contents, which often proves problematic when handling and compacting the materials. Therefore, alternative methods to obtain the optimum moisture content for the treated M-D curve should be explored.

Table 6. Average Differences between M-D Curve Maximum Dry Density and Treated UCS Density.

M-D Curve	Asphalt Type	Sample Size	[M-D Curve Max Dry Density – Treated UCS Density] (pcf)	Percent Compaction [Treated UCS Density / M-D Curve Max Dry Density] (%)
Untreated	Foamed	13	4.3	96.8
Untreated	Emulsified	29	2.8	97.8
Untreated	Foamed and Emulsified	42	3.3	97.5
Treated	Foamed	3	0.9	99.3
Treated	Emulsified	3	-0.4	100.3
Treated	Foamed and Emulsified	6	0.2	99.8

LABORATORY STUDY FACTORS AND EXPERIMENT

The research team designed a laboratory experiment to identify factors having an influence on IDT strength and potentially requiring a stricter control or limits in their specified values. Mixtures for the laboratory experiment used the design asphalt contents that were shown in Table 5. When a passing mix design was obtained with either emulsified asphalt or foamed asphalt, the optimum for the other type of asphalt was obtained assuming 60 percent residual binder in the emulsified asphalt.

Table 7 shows the selection of the laboratory test factors and their levels. The selection followed principles of ruggedness testing (ASTM E 1169). The level for each factor that is **highlighted**

and in bold font in Table 7 corresponds to the condition noted in the draft mix design procedures Tex-122-E or Tex-134-E available at the time of the experiment. Factors that are not highlighted in Table 7 were not specified in the draft mix design procedures at the time of the experiment.

Table 7. Laboratory Study Factors and Levels.

Factor	Level 1	Level 2	Level 3	Level 4
Specimen Size	**4.0 in. diameter × 2 in. ± 0.06 height**	**6.0 in. diameter × 3.75 in. ± 0.2 height**	–	–
Compaction Level	**Target density**	N = 50	N = 100	N = 75
Emulsion Temperature[a]	**Room temperature**	140 ± 5°F	–	–
Curing Time[b]	**72 hr**	Constant mass	–	–
Curing Temperature[b]	**104 ± 5°F**	140 ± 5°F	–	–
IDT Test Temperature[c]	**72 ± 1°F**	77 ± 1°F	67 ± 1°F	–
Cement Type	Type I/II	Type IL	–	–

[a] Applicable to emulsion specimens only.
[b] Measure specimen weight initially and periodically to estimate when the specimen achieves constant mass.
[c] IDT test temperature is noted as 72 ± 5°F in Tex-122-E and Tex-134-E but was adjusted to 72 ± 1°F for the purpose of the laboratory experiment.
Note: A dash indicates that a Level was not applicable for the corresponding Factor.

Specimen size pertains to preparing emulsified asphalt and foamed asphalt specimens that are 4-inch diameter by 2-inch height and 6-inch diameter by 3.75-inch height and comparing their IDT strength both unconditioned and after moisture conditioning by submersion.

Compaction level could influence total air void content in the specimen and subsequent IDT strength. Draft mix design procedures Tex-122-E and Tex-134-E at the time of this research required adjusting the weight of the specimen to meet the target height (i.e., 2 inch or 3.75 inch) without exceeding 200 gyrations in the SGC. Based on the research team's experience, around 50 to 100 gyrations are usually required to achieve the target height, although there have been instances where the target height was not reached within 200 gyrations, and instances where the target height was reached in less than 50 gyrations. These observations, along with current practice by other agencies that employ a fixed number of gyrations for FDR specimen preparation, made exploring this factor relevant.

Emulsion temperature is relevant to specimens prepared with emulsified asphalt only. The draft mix design procedure prescribes incorporating the emulsion at room temperature; however, in practice, the emulsion is often stored and delivered at an elevated temperature of around 140°F. Therefore, it was pertinent to explore the impact of adding the emulsion at an elevated emulsion temperature on the resulting IDT strength of both 4-inch diameter and 6-inch diameter specimens.

Curing time and **curing temperature** factors were explored to determine the necessary time to reach constant mass and the effect of an elevated curing temperature on the final moisture content and IDT strength of 4-inch diameter and 6-inch diameter specimens.

For **IDT test temperature,** Tex-122-E emulsified asphalt and Tex-134-E foamed asphalt draft mix design procedures required storing the three IDT strength specimens that would not be subjected to moisture conditioning "in an area or room at a temperature of 72 ± 5°F for 24 ± 1 hr" and measuring the IDT strength of the moisture-conditioned and unconditioned tests in accordance with Tex-226-F. The IDT strength test procedure Tex-226-F specifies storing the specimens at 77 ± 2°F for no more than 24 hours to ensure consistent temperature throughout the specimen before testing. Therefore, there is a discrepancy between the condition required to store the unconditioned IDT specimens in the draft mix design procedures Tex-122-E and Tex-134-E methods and the test temperature specified in Tex-226-F. Since test temperature may influence IDT strength, it was considered relevant to explore its effect using three values within the tolerance noted in the draft mix design procedures.

Last, **cement type** was added to the list of factors since use of cement Type IL has become more prevalent and seemingly the direction that industry is headed.

Compactor type was not explored since previous limited studies conducted by the research team have demonstrated that similar IDT strength values are obtained regardless of the compactor type being used (i.e., TxGC versus SGC). Thus, only the use of the SGC was considered in the laboratory study.

Additional variables that were considered although not part of the list of laboratory study factors included binder content and moisture content. Binder content consisted of increasing (or decreasing) the emulsified asphalt content by 0.7 percent and increasing the foamed asphalt content by 0.4 percent from the mix design optimum. This was explored for specimens compacted to target density, 50, and 100 gyrations for the BRY OSR and ATL FM 3129 field projects and the 4-inch diameter foamed asphalt specimens from the LBB SH 207 field project. To evaluate moisture content, the weight and height of each specimen were acquired at different moments in the testing process (i.e., after molding, after curing, after moisture conditioning, and after IDT strength testing plus 24 hours drying at 230°F). Moisture content (MC) in percent was then calculated using Eq. 1, where $Weight_{COND}$ represents the weight of the specimen after moisture conditioning, and $Weight_{OD}$ is the weight of the specimen after IDT strength testing

plus 24 hours drying at 230°F. The MC measurements were acquired for all but the BRY OSR field project and ATL FM 3129 emulsified asphalt specimens.

$$MC\ (\%) = \frac{Weight_{COND} - Weight_{OD}}{Weight_{OD}} \times 100 \qquad \text{(Eq. 1)}$$

The factors and levels listed in Table 7 were not applied as a full factorial experiment due to the excessive number of all possible factor-level combinations; thus, a subset of those factor-level combinations was utilized to estimate the main effects of interest. Table 8 and Table 9 list the combination of factors as applied to the various field projects for both the 4.0-inch diameter by 2.0-inch high specimens and the 6.0-inch diameter by 3.75-inch high specimens. The text **highlighted and in bold font** in Table 8 and Table 9 corresponds to the factor that was different from the control case. All factors except **cement type** were applied to three field projects—ATL FM 3129, BRY OSR, and LBB SH 207—as shown in Table 8.

As detailed later, based on a preliminary trend analysis of the results from ATL FM 3129, BRY OSR, and LBB SH 207, **emulsion temperature**, **curing time**, and **curing temperature** were dropped from the experiment. At that time, a new level was added for compaction (i.e., N = 75 gyrations), and cement type was added as a new factor with two levels: Type I/II and Type IL. Therefore, **specimen size**, **compaction level**, **IDT test temperature**, and **cement type** were considered for the last three field projects, which included ATL US 80, ODA BI 20, and BRY FM 39, as shown in Table 9. These test program modifications were made with input and agreement from the technical project monitoring committee and approval of the project manager.

Table 8. Laboratory Study Experiment for a Given Specimen Size for ATL FM 3129, BRY OSR, and LBB SH 207.

Specimen Set (6 replicates)[a]	Compaction	Emulsion Temp.[b,c]	Curing Time[d]	Curing Temp.[d]	IDT Test Temp.
Control	Target density	Room	72 hr	104 ± 5°F	72 ± 1°F
S1	**N = 50**	Room	72 hr	104 ± 5°F	72 ± 1°F
S2	**N = 100**	Room	72 hr	104 ± 5°F	72 ± 1°F
S3	Target density	**140 ± 5°F**	72 hr	104 ± 5°F	72 ± 1°F
S4	Target density	Room	**Constant Mass**	104 ± 5°F	72 ± 1°F
S5	Target density	Room	72 hr	**140 ± 5°F**	72 ± 1°F
S6	Target density	Room	72 hr	104 ± 5°F	**77 ± 1°F**
S7	Target density	Room	72 hr	104 ± 5°F	**67 ± 1°F**

[a] Number of 4-inch & 6-inch diameter specimens per field project for emulsified asphalt, 96; for foamed asphalt, 84.
[b] Only applicable to emulsified asphalt specimens.
[c] This factor was only conducted for the ATL FM 3129 and BRY OSR field projects.
[d] These factors were not conducted for the LBB SH 207 6-inch diameter specimens due to material constraints.

Table 9. Laboratory Study Experiment for a Given Specimen Size for ATL US 80, ODA BI 20, and BRY FM 39.

Specimen Set (6 replicates)[a]	Compaction	IDT Test Temp.	Cement Type
Control	Target density	72 ± 1°F	Type I/II
S1	**N = 50**	72 ± 1°F	Type I/II
S2	**N = 100**	72 ± 1°F	Type I/II
S8	**N = 75**	72 ± 1°F	Type I/II
S6	Target density	**77 ± 1°F**	Type I/II
S7	Target density	**67 ± 1°F**	Type I/II
S9	Target density	72 ± 1°F	**Type IL**

[a] Number of 4-inch & 6-inch diameter specimens per field project for emulsified asphalt, 84; for foamed asphalt, 84.

CHAPTER 4:
DATA ANALYSIS

The analysis methodology that was pursued to explore the effect of the laboratory factors and other variables on the IDT strength of the test specimens is presented in this chapter. To recapitulate, roadway materials were collected from six distinct field projects and blended in certain proportions to develop mix designs using CSS-1H emulsified asphalt and PG 64-22 foamed asphalt. Four-inch diameter IDT strength specimens were prepared using at least two asphalt contents. After curing for a minimum of 72 hours at 104°F, one subset of three specimens was submerged in water for 24 hours, while the other subset was stored at constant room temperature (around 72°F) for this same period. Both subsets of specimens were evaluated, and the results were verified against the draft specification criteria (i.e., 50 psi for unconditioned specimens and 30 psi for submerged specimens). All mix designs used 1.0 percent cement. When a passing mix design was obtained with either emulsified asphalt or foamed asphalt, the optimum for the other type of asphalt was obtained assuming 60 percent residual binder in the emulsified asphalt.

APPROACH

A series of questions, shown in Table 10, were formulated, and the experimental data were used to find answers via trend analysis and one-way analysis of variance (ANOVA). The response variable for each factor of interest was first visualized using boxplots, which consist of a box bounded by the first and third quartiles (Q1 and Q3) as lower and upper limits, respectively; a horizontal line inside the box representing the median; an × inside the box representing the mean; and whiskers that extend 1.5 × IQR = 1.5 × (Q3 – Q1). This is a useful way of observing the range and spread of the results.

Trend analysis consisted of creating a scatterplot of the IDT strength of the specimens being compared, depending on the variable or factor of interest, along with a 45-degree equality line. Then, a linear trendline was fitted through the data with a forced intercept at the origin (0,0). The magnitude of the slope of the trendline indicated if the factor of interest influenced IDT strength as compared to the control and how large the effect was.

The one-way ANOVA along with multiple comparisons (Tukey's Honest Significant Differences [HSD]) were employed to assess each variable or factor-level significance by testing the null hypothesis (H_o) that there is no factor effect (i.e., the mean IDT strength values across different levels of the factor are equal). The selected significance level to reject the H_o in favor of the alternative hypothesis (there is a factor effect, i.e., the mean IDT strength values for different levels of the factor are different) for the one-way ANOVA and HSD was $\alpha = 0.05$. In the one-way ANOVA tables that are presented in the next section, *df* stands for degrees of freedom, *F* is the F-value calculated as the ratio of between-group mean square and within-group mean square values, and *Sig.* is the significance level or p-value.

Table 10. Analysis Questions.

No.	Question	Justification
1	Are the IDT strength mix design values (control) of the emulsified asphalt and foamed asphalt the same?	Since the optimum for the type of asphalt not employed in the mix design was obtained assuming 60% residual binder in the emulsified asphalt, there is a possibility that they are not equivalent.
2	Is the conditioning procedure reducing the IDT strength mix design values (control)?	The IDT strength of the specimens after water conditioning should reduce regardless of binder type or specimen size.
3	Does increasing or decreasing the binder content influence the IDT strength?[a]	This is to study the influence of additional variable: binder content on IDT strength.
4	Does the specimen moisture content at the time of the IDT strength test influence the IDT strength?[b]	This is to study the influence of additional variable: moisture content on IDT strength.
5	Are the IDT strength results in dry or wet condition the same for 4-inch diameter specimens vs. 6-inch diameter specimens?	This is to study the influence of main effect (S0): specimen size on IDT strength.
6	Does fixing the compaction level (i.e., number of gyrations) influence the IDT strength as compared to the control compacted to density?[c]	This is to study the influence of main effect (S1, S2, and S8): compaction on IDT strength.
7	Does an elevated emulsion temperature influence the IDT strength for specimens prepared with emulsified asphalt?[d]	This is to study the influence of main effect (S3): emulsion temperature on IDT strength.
8	Does curing to constant mass influence the IDT strength?[e]	This is to study the influence of main effect (S4): curing time on IDT strength.
9	Does an elevated curing temperature influence the IDT strength?[e]	This is to study the influence of main effect: curing temperature (S5) on IDT strength.
10	Does the IDT strength test temperature influence the IDT strength?	This is to study the influence of main effect (S6 and S7): IDT strength test temperature on IDT strength.
11	Does changing the cement type to Type IL influence the IDT strength?[f]	This is to study the influence of main effect (S9): cement type on IDT strength.

[a] Only the BRY OSR, ATL FM 3129, and LBB SH 207 4-inch diameter foamed asphalt specimens included binder content as a factor at different compaction levels.
[b] Moisture content measurements were missing for BRY OSR and ATL FM 3129 emulsified asphalt specimens and BRY OSR foamed asphalt specimens.
[c] BRY OSR, ATL FM 3129, and LBB SH 207 included three levels for compaction: density, N = 50, and N = 100; ODA BI 20, ATL US 80, and BRY FM 39 included four levels for compaction: density, N = 50, N = 75, and N = 100.
[d] Only BRY OSR and ATL FM 3129 included emulsion temperature as a factor.
[e] Only BRY OSR, ATL FM 3129, and LBB SH 207 4-inch diameter specimens included curing time and curing temperature as factors.
[f] Only ODA BI 20, ATL US 80, and BRY FM 39 included cement type as a factor.

RESULTS

The first two questions listed in Table 10 were analyzed using only the mix design IDT strength results (labeled *Control* in Table 8 and Table 9) since changing other factors and variables could confound the effect of binder type and conditioning.

Mix Design Variable: Binder Type

The relationship results between the emulsified asphalt and foamed asphalt is shown in Figure 14 and Figure 15. Figure 14 shows the data in boxplots, which is useful to appreciate the range and spread of the results. Figure 15 shows a scatterplot, where the horizontal axis represents the emulsified asphalt values, the vertical axis shows the foamed asphalt values, the solid line is the 45-degree line of equality, and the dashed line is the trendline of the pair of results.

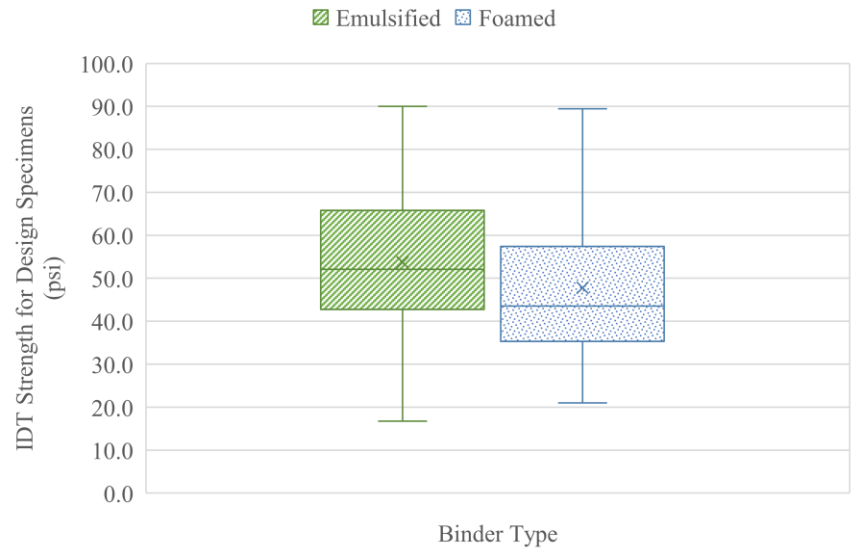


Figure 14. Boxplot illustrating the difference in emulsified asphalt versus foamed asphalt mix design values.

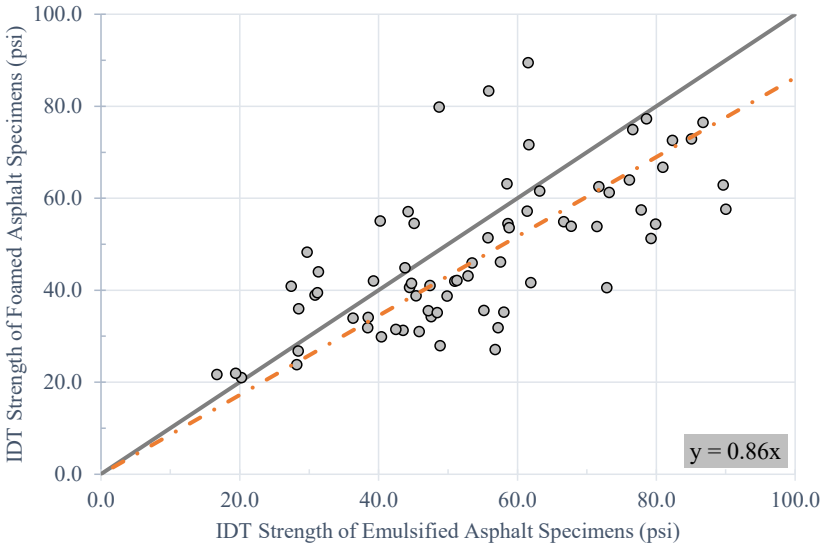


Figure 15. Scatterplot with trendline illustrating the difference in emulsified asphalt versus foamed asphalt mix design values.

The scatterplot in Figure 15 shows that most values aligned below the line of equality, indicating that the foamed asphalt specimens yielded lower IDT strength values than the emulsified asphalt specimens. Based on the trendline, the foamed asphalt specimens were about 14 percent lower than the values obtained for emulsified asphalt specimens. In other words, 0.86 psi was observed for foamed asphalt specimens for every 1.0 psi for emulsified asphalt specimens. Nevertheless, values existed above the equality line, meaning that there were exceptions based on specimen size (4-inch diameter vs. 6-inch diameter) or conditioning (dry vs. submerged).

The one-way ANOVA results for this set of data are shown in Table 11. The resulting F-value was 4.124, and the p-value was 0.044. Comparison of the p-value to a selected significance limit of $\alpha = 0.05$ revealed that the null hypothesis that the emulsified asphalt and foamed asphalt specimens yield the same IDT strength results was rejected, confirming the observations from the scatterplot trendline.

Table 11. One-Way ANOVA for Binder Type on IDT Strength Mix Design (Control) Results.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
Emulsion	Foamed	Emulsion	Foamed						
70	70	53.7	47.8	Between Groups	1,227.2	1	1,227.2	4.124	0.044
				Within Groups	41,061.4	138	297.5		
				Total	42,288.6	139			

Mix Design Variable: Conditioning

To answer question 2 in Table 10, the research team conducted a similar analysis to the one used for binder type. The boxplot in Figure 16 shows the range and spread of all dry and submerged values. A few data points for the submerged dataset went beyond (Q3 + 1.5 × IQR) and could be considered as outliers but were left as part of the dataset for this assessment that considered emulsified asphalt, foamed asphalt, 4-inch diameter specimens, and 6-inch diameter specimens.

The scatterplot in Figure 17 shows that practically all values aligned below the line of equality, indicating that the submerged specimens yielded lower IDT strength values than the dry specimens. Based on the trendline, the submerged specimens were about 38 percent lower than the dry specimens. In other words, 0.68 psi was observed for submerged specimens for every 1.0 psi for dry specimens. This finding agrees with the draft specifications that prescribe a passing dry IDT strength of 50 psi and a passing submerged IDT strength of 30 psi (i.e., 60 percent lower value).

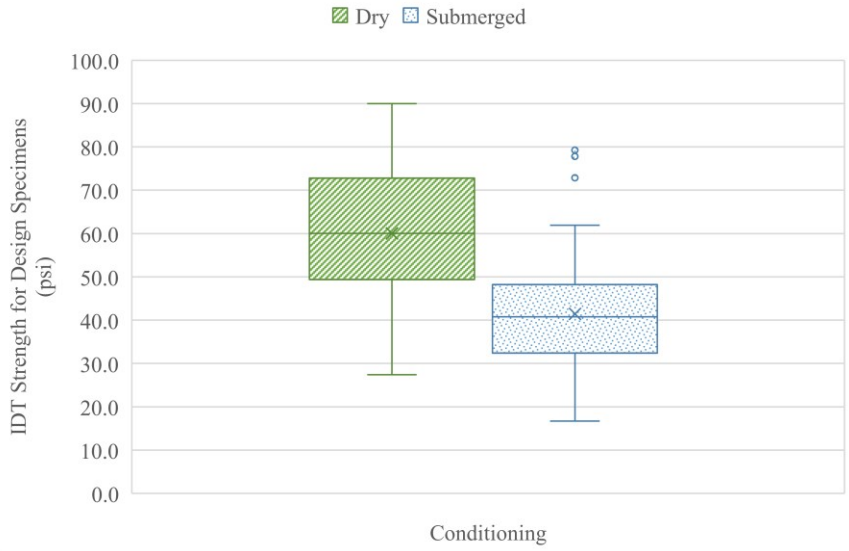


Figure 16. Boxplot illustrating the difference in dry versus submerged mix design values.

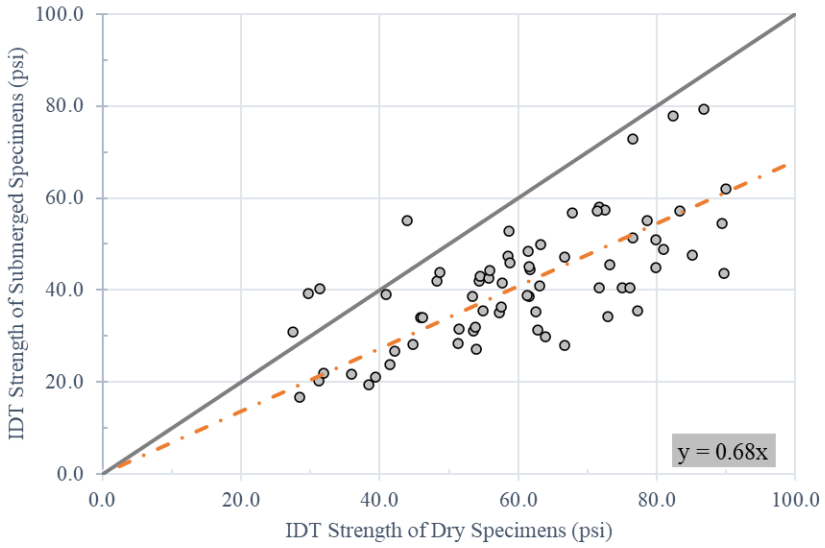


Figure 17. Scatterplot with trendline illustrating the difference in dry versus submerged mix design values.

The one-way ANOVA results for this dataset are show in Table 12. The resulting F-value was 55.046, and the p-value was < 0.001. Comparison of the p-value to a selected significance limit of $\alpha = 0.05$, the null hypothesis that the dry and submerged specimens yield the same IDT strength results was rejected, confirming the observations from the scatterplot trendline.

To explore the effect of conditioning on the smaller and larger specimen size, the research team further divided the control dataset into IDT strength results for the 4-inch and 6-inch diameter specimens before conducting the one-way ANOVA. The results of this analysis are also listed in Table 12 and indicate that conditioning influenced both specimen sizes, with p-values < 0.001 for 4-inch diameter and 0.002 for 6-inch diameter. It is noteworthy that even though conditioning influenced both specimen sizes, since the average dry IDT strength values for the 6-inch diameter specimens were lower than the average dry IDT strength 4-inch diameter specimens, the reduction in IDT strength after conditioning was less severe for the 6-inch diameter (i.e., smaller drop from the dry value).

Table 12. One-Way ANOVA for Conditioning on IDT Strength Mix Design (Control) Results.

Dataset	Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
	Dry	Sub.	Dry	Sub.						
Control	70	70	60.0	41.5	Between Groups	12,058.4	1	12,058.4	55.046	<.001
					Within Groups	30,230.2	138	219.1		
					Total	42,288.6	139			
Control, 4-inch	36	36	68.4	44.1	Between Groups	10,599.7	1	10,599.7	99.268	<.001
					Within Groups	7,474.5	70	106.8		
					Total	18,074.2	71			
Control, 6-inch	34	34	51.2	38.6	Between Groups	2,665.0	1	2,665.0	10.338	0.002
					Within Groups	17,014.1	66	257.8		
					Total	19,679.1	67			

Additional Variable: Binder Content

To answer question 3 in Table 10, researchers considered the BRY OSR, ATL FM 3129, and LBB SH 207 4-inch diameter foamed asphalt specimens compacted to density, N = 50, and N = 100. Figure 18 shows the range and spread of these values by binder type, including 4-inch diameter specimens and 6-inch diameter specimens in dry and submerged conditions. From the boxplot, it is apparent that the alternative binder content tended to slightly reduce the IDT strength values. As previously mentioned, the change in binder content consisted of increasing (for BRY OSR) or decreasing (for ATL FM 3129) the emulsified asphalt content by 0.7 percent and increasing the foamed asphalt content by 0.4 percent from the mix design optimum.

The scatterplot of the data in Figure 19 illustrates the change in IDT strength for both binder types as a function of binder content, with the emulsified asphalt having alternative binder contents both above and below the mix design value. The scatterplot shown in Figure 20 shows that most design and alternative binder content values, regardless of the compaction level (i.e., density, N = 50, or N = 100), were equally spread around the equality line, with negligible negative effect of binder content on IDT strength. In fact, the trendlines of the observations had slopes of 1.070 for the specimens compacted to density, 1.096 for specimens compacted at N = 50, and 0.985 for specimens compacted at N = 100. The average of these three slopes was 1.05, which indicates that the IDT strength of the specimens prepared with the design binder

content was only about 5.0 percent larger than the IDT strength of the specimens prepared with an alternative binder content.

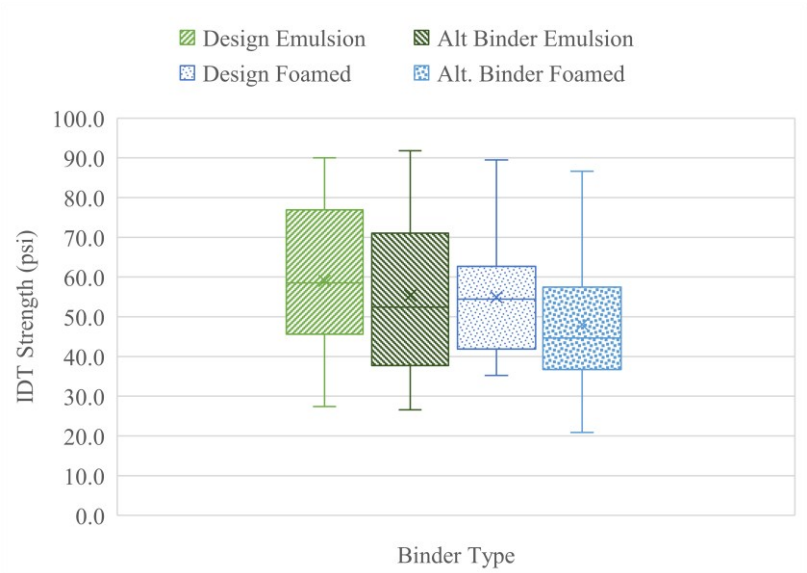


Figure 18. Boxplot illustrating effect of binder content on IDT strength.

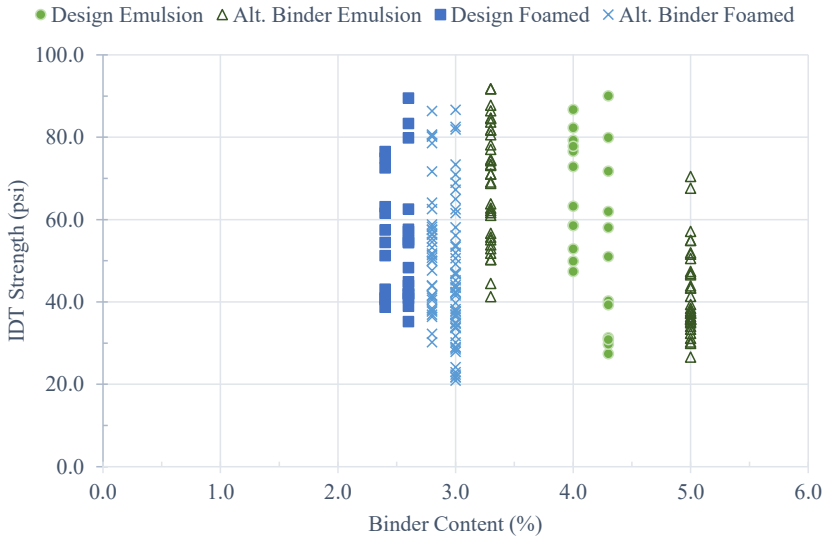


Figure 19. Scatterplot illustrating effect of binder content on IDT strength.

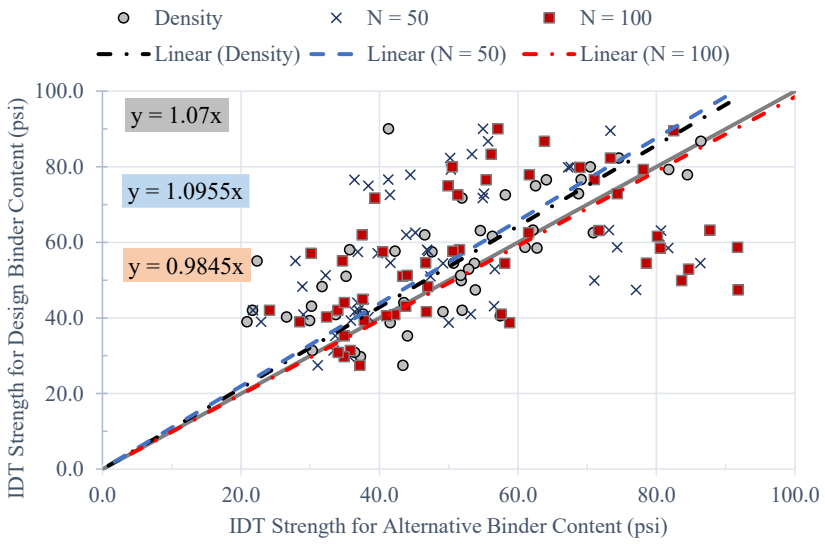


Figure 20. Scatterplot with trendline illustrating effect of binder content on IDT strength.

A one-way ANOVA was conducted with the results separated by binder type and by field project in the case of the emulsified asphalt. The results for the emulsified asphalt specimens are displayed in Table 13 and Table 14, which show that the effect of binder content was not statistically significant at $\alpha = 0.05$ within each field project. For the foamed asphalt specimens, the one-way ANOVA showed a statistically significant effect of binder content with a p-value of $0.013 < \alpha = 0.05$, as noted in Table 15; however, Tukey's HSD test indicated that there was not a significant difference across different levels of binder content, as shown in Table 16. The average values for each binder content as considered in the one-way ANOVA are illustrated in Figure 21.

In general, the emulsified asphalt specimens were more sensitive to changes in binder content than the foamed asphalt specimens. This result could be because the emulsified asphalt contents had a wider range in binder content values (i.e., 3.3 to 5.0 percent for emulsified asphalt versus 2.4 to 3.0 percent for foamed asphalt). In general, increasing the binder content for both emulsified asphalt and foamed asphalt specimens decreased the IDT strength, which was unexpected, but the change in IDT strength was statistically insignificant. In addition, the draft mix design procedures require two binder contents to be tested, which seemed sufficient for obtaining an optimum binder content.

Table 13. One-Way ANOVA for Binder Content on IDT Strength Emulsified Asphalt Results for BRY OSR.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
4.3% (Control)	5.0%	4.3% (Control)	5.0%						
12	36	50.9	41.7	Between Groups	759.9	1	759.9	4.028	0.051
				Within Groups	8,677.9	46	188.7		
				Total	9,437.8	47			

Table 14. One-Way ANOVA for Binder Content on IDT Strength Emulsified Asphalt Results for ATL FM 3129.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
4.0% (Control)	3.3%	4.0% (Control)	3.3%						
12	36	67.2	69.0	Between Groups	29.6	1	29.6	0.155	0.696
				Within Groups	8,787.5	46	191.0		
				Total	8,817.1	47			

Table 15. One-Way ANOVA for Binder Content on IDT Strength Foamed Asphalt Results.

Sum of Squares		df	Mean Square	F	Sig.
Between Groups	2,730.5	3	910.2	3.727	0.013
Within Groups	28,326.3	116	244.2		
Total	31,056.8	119			

Table 16. Tukey's HSD Homogenous Subsets for Binder Content on IDT Strength Foamed Asphalt Results.

Number of Observations	Binder Content (%)	Mean IDT Strength (psi) for Homogeneous Subset[a,b]
54	3.0	44.5
36	2.8	53.2
18	2.6 (Control)	54.0
12	2.4 (Control)	56.3
Sig.		0.071

Note: Means for groups in homogeneous subsets are displayed.
[a] Uses harmonic mean sample size = 18.000.
[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

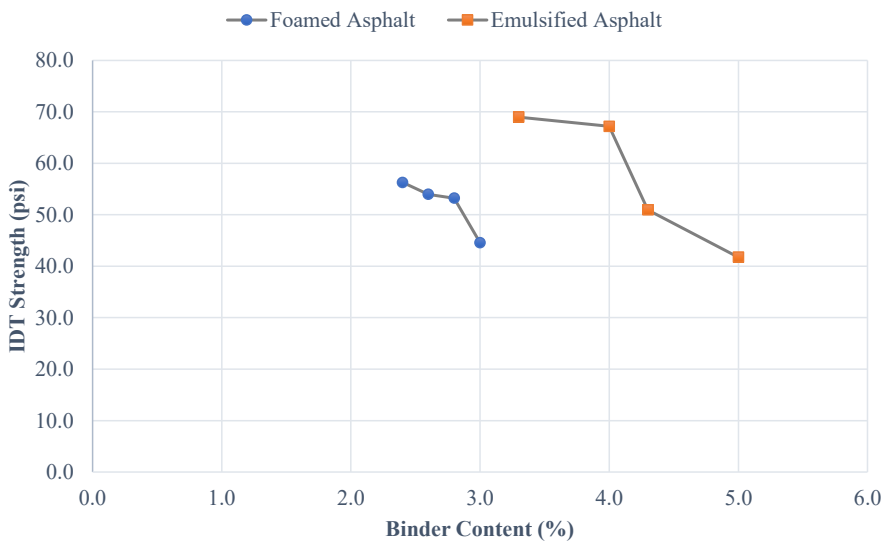


Figure 21. Plot of mean IDT strength values for design and alternative binder content.

Additional Variable: Moisture Content

To answer question 4 in Table 10—Does the specimen moisture content at the time of the IDT strength test influence the IDT strength?—researchers created boxplots of the data for emulsified asphalt and foamed asphalt, as shown in Figure 22. These datasets included all available MC datapoints regardless of specimen size, conditioning, or laboratory study factor. Scatterplots of the IDT strength as a function of MC were also crafted, as shown in Figure 23 and Figure 24. A linear trendline was added to these scatterplots to quantify the reduction in IDT strength with changes in moisture content; however, other trendlines such as power or logarithmic may yield a more accurate representation of the test result behavior.

The scatterplots in Figure 23 and Figure 24 show that both the emulsified asphalt and foamed asphalt specimens exhibited a reduction in IDT strength with increasing MC. About 6.0 psi reduction in IDT strength was observed for every 1.0 percent reduction in MC. It is also noteworthy that the foamed asphalt specimens had a larger range in MC values at the time of IDT strength testing, up to 9.0 percent, while the emulsified asphalt specimens had a maximum MC at the time of IDT strength testing of about 7.0 percent.

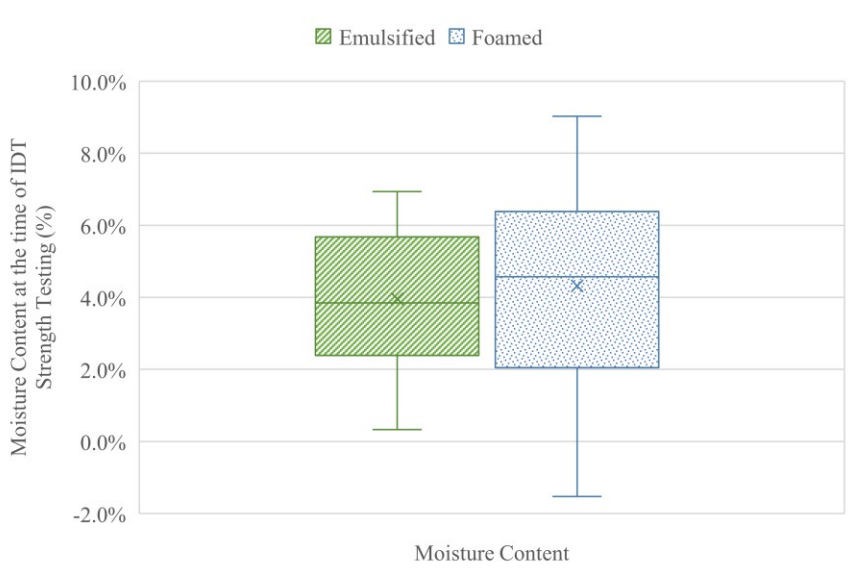


Figure 22. Boxplot to illustrate the effect of moisture content on IDT strength.

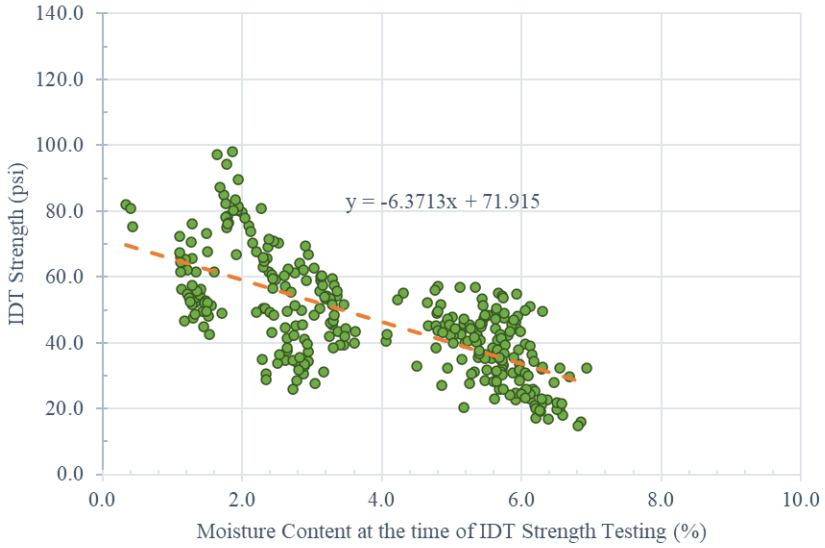


Figure 23. Scatterplot with trendline illustrating the effect of moisture content on IDT strength for emulsified asphalt specimens.

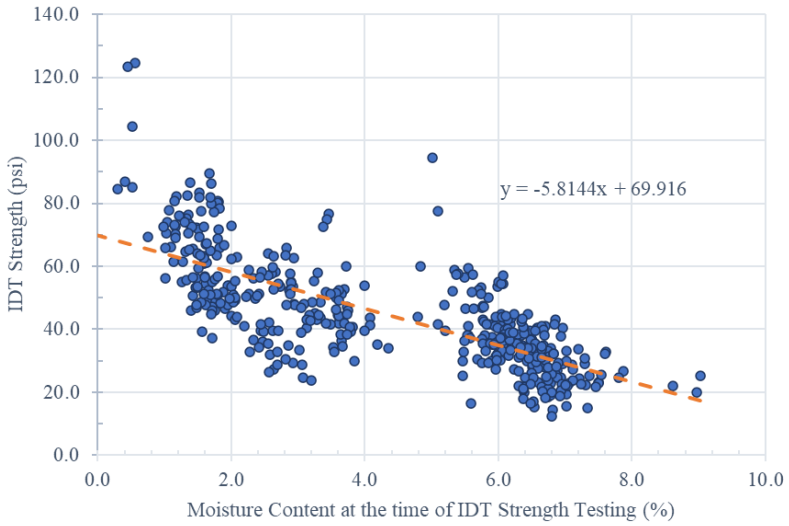


Figure 24. Scatterplot with trendline illustrating the effect of moisture content on IDT strength for foamed asphalt specimens.

Laboratory Study Factor: Specimen Size (S0)

One of the crucial aspects of this study was to evaluate the influence of specimen size on IDT strength (question 5 in Table 10). The boxplot of all results is shown in Figure 25. From this figure, it is apparent that there were some larger-than-expected results for the 6-inch diameter specimens (points beyond the upper whisker at 1.5 × IQR). These larger values corresponded to factor levels such as elevated emulsion temperature and elevated curing temperature, which tended to increase the IDT strength results.

The scatterplot in Figure 26 shows the average IDT strength of two or three replicates for the 4-inch and 6-inch diameter specimens. The reason the average values are shown (and not individual replicate results) is because LBB SH 207 had only two replicate measurements for most of the 6-inch diameter specimens due to material availability constraints, and not all 4-inch diameter specimens could be paired with a corresponding 6-inch diameter specimen value.

As shown in Figure 26, most of the IDT strength values aligned above the equality line, which indicated that the 4-inch diameter specimens overall had a larger IDT strength. The slope of the trendline in Figure 26 indicated a difference between the IDT strength values for the 4-inch diameter versus 6-inch diameter specimens of about 11 percent.

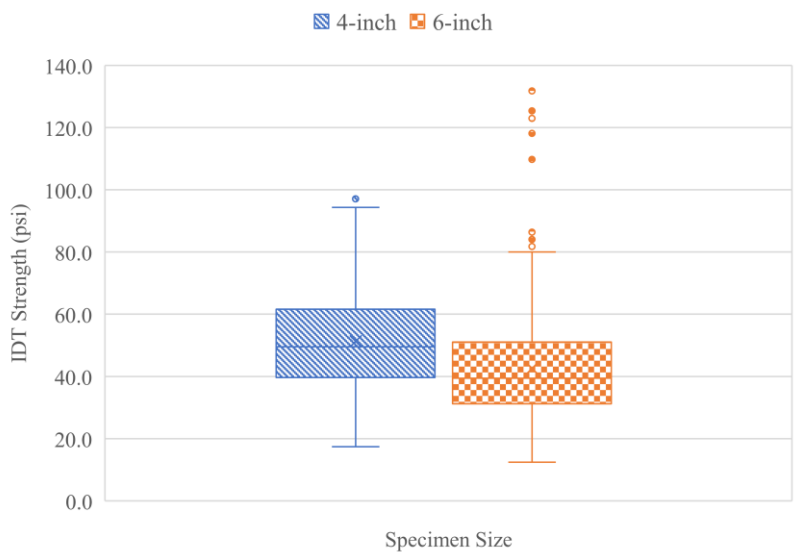


Figure 25. Boxplot illustrating the effect of specimen size on IDT strength.

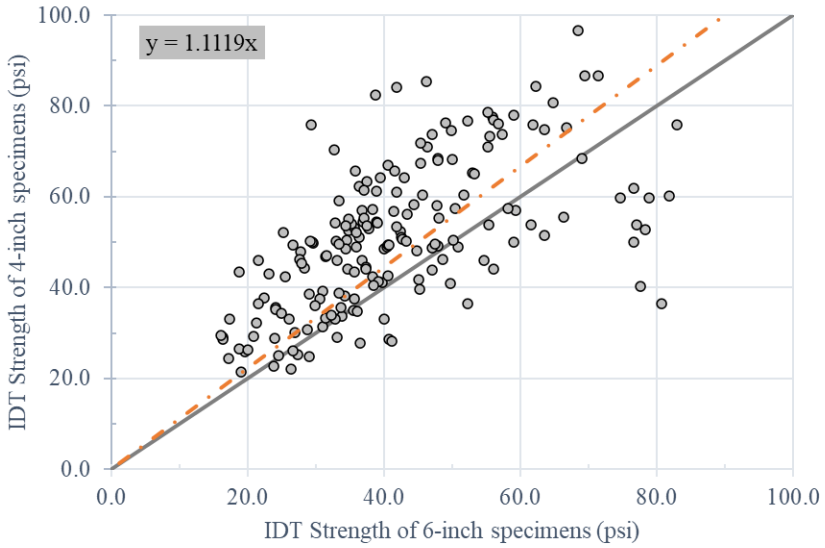


Figure 26. Scatterplot with trendline illustrating the effect of specimen size on IDT strength.

The statistical analysis of the complete dataset shown in Figure 25 is detailed in Table 17, including the average IDT strength value for both the 4-inch and 6-inch diameter specimens. Since analyzing the effect of specimen size was one of the main objectives of this study, further analysis of the data considering other datasets (i.e., grouping of the response variable) was also performed, including the following:

- All Emulsion.
- All Foamed.
- All Dry.
- All Submerged.
- Emulsion Dry.
- Emulsion Submerged.
- Foamed Dry.
- Foamed Submerged.

Table 17. One-Way ANOVA for Specimen Size on IDT Strength for Various Datasets.

Dataset	# of Obs.		Avg. IDT Strength		Sum of Squares		df	Mean Square	F	Sig.
	4-in.	6-in.	4-in.	6-in.						
All	606	552	51.8	42.6	Between Groups	24,531.6	1	24,531.6	80.159	<.001
					Within Groups	353,776.5	1156	306.0		
					Total	378,308.1	1157			
Emulsion	300	278	54.5	47.0	Between Groups	8,177.9	1	8,177.9	24.505	<.001
					Within Groups	192,226.0	576	333.7		
					Total	200,403.9	577			
Foamed	306	274	49.2	38.2	Between Groups	17,553.3	1	17,553.3	69.296	<.001
					Within Groups	146,411.6	578	253.3		
					Total	163,964.9	579			
Dry	303	276	62.3	48.1	Between Groups	29,371.1	1	29,371.1	131.386	<.001
					Within Groups	128,986.7	577	223.5		
					Total	158,357.8	578			

Dataset	# of Obs.		Avg. IDT Strength		Sum of Squares		df	Mean Square	F	Sig.
	4-in.	6-in.	4-in.	6-in.						
Submerged	303	276	41.3	37.1	Between Groups	2,512.2	1	2,512.2	10.253	0.001
					Within Groups	141,383.9	577	245.0		
					Total	143,896.2	578			
Emulsion, Dry	150	139	63.0	51.3	Between Groups	9,770.7	1	9,770.7	38.192	<.001
					Within Groups	73,423.3	287	255.8		
					Total	83,194.0	288			
Emulsion, Submerged	150	139	46.1	42.7	Between Groups	843.5	1	843.5	2.625	0.106
					Within Groups	92,218.1	287	321.3		
					Total	93,061.6	288			
Foamed, Dry	153	137	61.7	44.8	Between Groups	20,748.3	1	20,748.3	113.879	<.001
					Within Groups	52,472.5	288	182.2		
					Total	73,220.8	289			
Foamed, Submerged	153	137	36.6	31.5	Between Groups	1,877.0	1	1,877.0	15.967	<.001
					Within Groups	33,855.5	288	117.6		
					Total	35,732.5	289			

Except for the *Emulsion, Submerged* dataset, all other combinations showed a statistically significant difference between specimen sizes (i.e., p-value < 0.05), which rejected the null hypothesis H_o that the mean values of the 4-inch dimeter and 6-inch diameter specimens are equal. In the case of the *Emulsion, Submerged* dataset, the difference between the IDT strength values was less than 5 psi, which may indicate what could be considered a practically significant difference limit for the IDT strength results.

To estimate equivalent dry and submerged thresholds for the 6-inch diameter specimens, researchers plotted a cumulative distribution curve for each specimen size. The results are shown in Figure 27. For the dry condition (Figure 27), the 4-inch diameter specimens showed 79 percent of the measured IDT strength values were above the 50-psi minimum limit, while only 38 percent of the 6-inch diameter IDT strength values were above that same minimum

value. An equivalent 79 percent of the 6-inch diameter specimen observations exceeded an IDT strength value of 35 psi.

The submerged dataset shown in Figure 28 indicated that 83 percent of the measured IDT strength values for the 4-inch diameter specimens were above the 30-psi minimum limit, while only 63 percent of the 6-inch diameter IDT strength values were above that same minimum value. An equivalent 83 percent of the 6-inch diameter specimen observations exceeded an IDT strength value of 22.5 psi.

Therefore, if considering 6-inch diameter specimens in the draft specifications, it is recommended to revise the dry passing IDT strength threshold to 35 psi and the submerged IDT strength threshold to 22.5 psi.

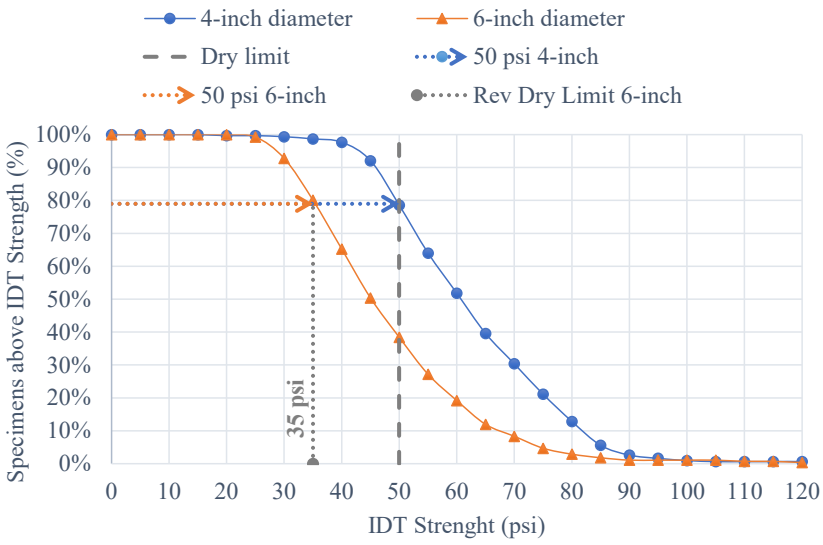


Figure 27. Cumulative distribution of IDT strength for each specimen size in dry condition.

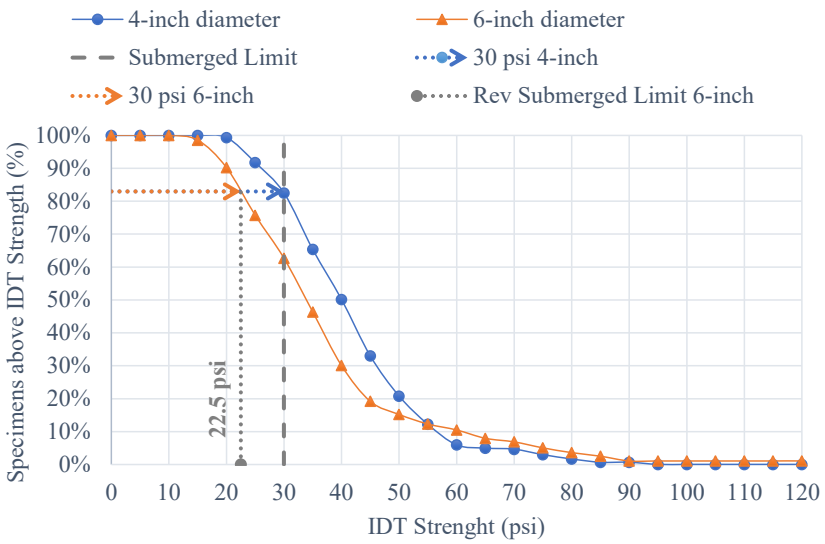


Figure 28. Cumulative distribution of IDT strength for each specimen size in submerged condition.

Laboratory Study Factor: Compaction Level (S1, S2, S8)

To answer question 6 in Table 10, the research team used the IDT strength of specimens produced at the optimum binder content (not the alternative binder content explored previously). The boxplot for the dataset separated by compaction level is shown in Figure 29, and the scatterplot is shown in Figure 30. From the boxplot, it is apparent that all values had a similar range, with N = 100 being closest to the control specimens (i.e., specimens compacted to a target density). The scatterplot in Figure 30 shows the spread of the data points around the equality line and the respective trendlines. The slope of the trendlines were 1.169 for N = 50, 1.166 for N = 75, and 1.089 for N = 100. Thus, N = 50 and N = 75 resulted in IDT strength values about 16 percent smaller than the ones obtained for the control specimens, while N = 100 resulted in IDT strength values about 9 percent smaller than those obtained for the control specimens.

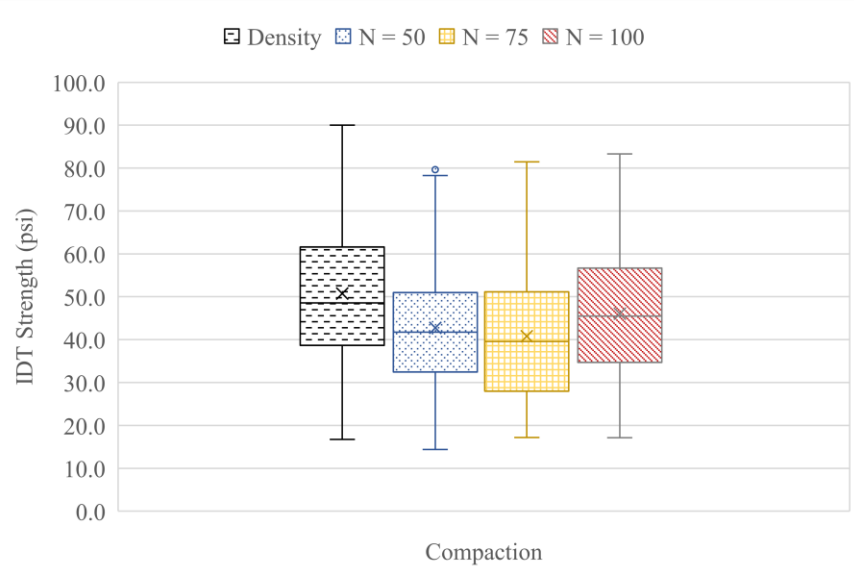


Figure 29. Boxplot illustrating the effect of compaction level on IDT strength.

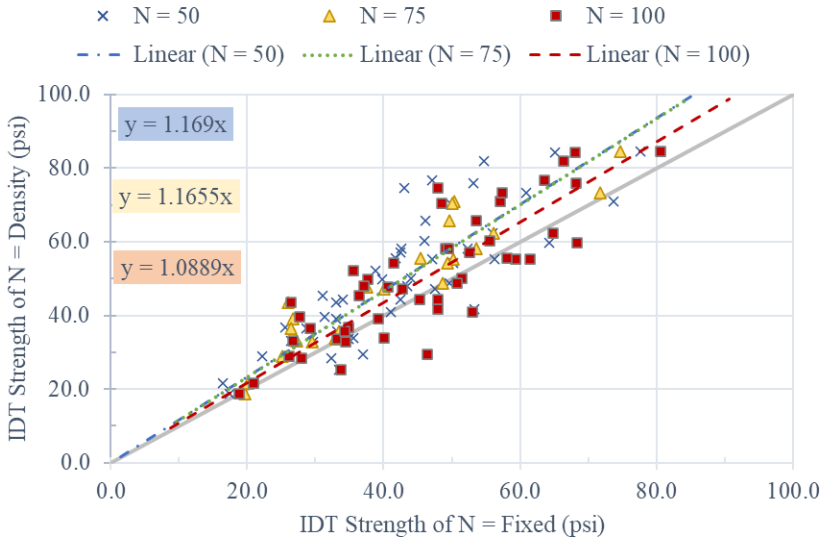


Figure 30. Scatterplot with trendlines illustrating the effect of compaction level on IDT strength.

A one-way ANOVA of these same results showed statistically significant differences between the compaction levels, with a p-value < 0.001, as shown in Table 18. Tukey's HSD test indicated that specimens compacted to density were uniquely different from N = 50 and N = 75, but similar to N = 100, while there was not a statistically significant difference among specimens compacted to N = 75, N = 50, and N = 100, as shown in Table 19. The one-way ANOVA and Tukey's HSD test confirmed the observations from the boxplot and scatterplot that demonstrated that N = 100 yields closer IDT strength values compared to the control specimens. Nevertheless, the average IDT strength values of specimens compacted to a fixed number of gyrations were at

least 5 psi lower than the ones compacted to target density, which could be considered a practically significant difference, as identified in the factor analysis of specimen size.

In addition, the number of gyrations for the control specimens that were compacted to a target density from all field projects ranged from a minimum of 15 gyrations to a maximum of 200 gyrations, with an average value of 148 and a median of 168. Thus, the number of gyrations needed to achieve target density for the control specimens was, on average, larger than any of the selected fixed values, with N = 100 being the closest to the average or median number of the gyrations needed to achieve target density in the control specimens.

Table 18. One-Way ANOVA for Compaction Level on IDT Strength.

Sum of Squares		df	Mean Square	F	Sig.
Between Groups	6,545.8	3	2,181.9	9.155	<.001
Within Groups	117,259.3	492	238.3		
Total	123,805.2	495			

Table 19. Tukey's HSD Homogenous Subsets for Compaction Level.

Number of Observations	Compaction Level	Mean IDT Strength (psi) for Homogeneous Subset[a,b,c]	
		B	A
72	75	40.8	
142	50	42.7	
142	100	46.0	46.0
140	Density		50.7
Sig.		0.054	0.099

Note: Means for groups in homogeneous subsets are displayed.
[a] Uses harmonic mean sample size = 113.907.
[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
[c] Levels not connected by same letter are significantly different.

Laboratory Study Factor: Emulsion Temperature (S3)

To answer question 7 in Table 10, researchers poured the emulsified asphalt in a 1-gallon metal container and stored it in a temperature-controlled chamber at 140°F for 2–3 hours, stirring the emulsion every 45 minutes to 1 hour to ensure homogeneity and avoid the formation of a skin on the surface of the emulsified asphalt. Once the aggregate batches were ready, the emulsion was extracted from the chamber and used during mixing. After specimen compaction, the conditioning and other test procedures proceeded like usual (i.e., same as control). The IDT strength results of the BRY OSR and ATL FM 3129 specimens, which are the two field projects that included this laboratory study factor, prepared with emulsion at room temperature and prepared with emulsion at an elevated temperature of 140°F are shown in Figure 31. The scatterplot of this same dataset is shown in Figure 32. As these two figures illustrate, this

laboratory study factor did not impact the IDT strength results. The slope of the linear trendline was practically 1.0 (i.e., 0.97), indicating equivalent IDT strength values for the specimens prepared with emulsion at room temperature and specimens prepared with emulsion at elevated temperature.

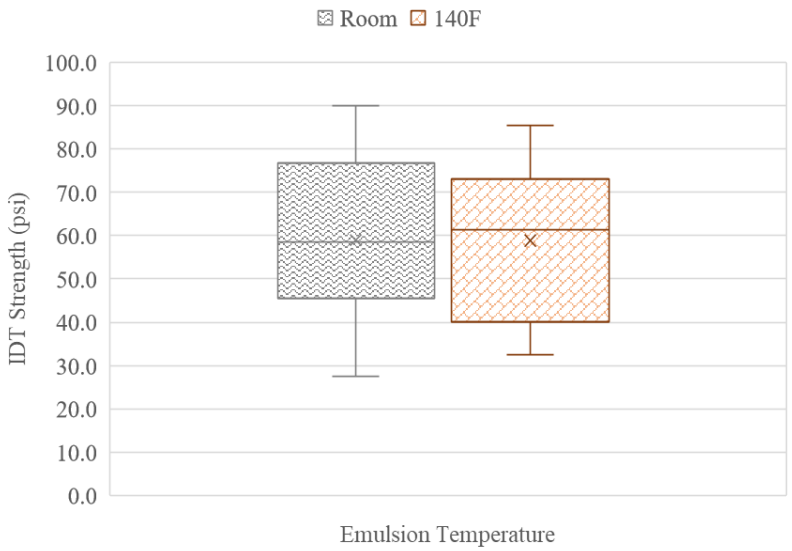


Figure 31. Boxplot illustrating the effect of emulsion temperature on IDT strength.

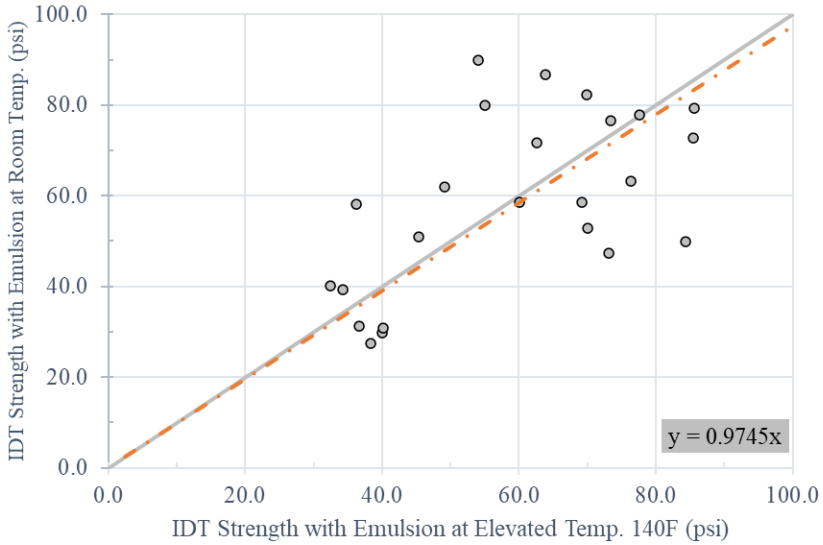


Figure 32. Scatterplot with trendline illustrating the effect of emulsion temperature on IDT strength.

The one-way ANOVA confirmed the trend analysis observations. The results, shown in Table 20, revealed an exceedingly small F-value and a p-value of almost 1.0. The resulting p-value accepted the null hypothesis H_o that the mean values of the IDT strength results of the specimens prepared with the emulsion at room temperature and elevated temperature are equal.

Based on the analysis of these two field projects, it was determined to drop this laboratory study factor from further consideration. Moreover, based on the experience of the research team during the execution of the laboratory study, the procedure to elevate the temperature of the emulsified asphalt was not practical due to the need to homogenize and transfer the product from a plastic to a metal container and the need to do periodic stirring during the warming period.

Table 20. One-Way ANOVA for Emulsion Temperature on IDT Strength.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
Room Temp.	Elevated Temp.	Room Temp.	Elevated Temp.						
24	24	59.1	58.9	Between Groups	0.3	1	0.3	0.001	0.977
				Within Groups	15,942.5	46	346.6		
				Total	15,942.7	47			

Laboratory Study Factor: Curing Time (S4)

To answer question 8 in Table 10, the research team considered specimens from BRY OSR and ATL FM 3129, as well as the 4-inch LBB SH 207 specimens. The boxplot of this dataset is shown in Figure 33, and the scatterplot is displayed in Figure 34. As these figures illustrate, curing time had a significant effect on IDT strength, with specimens cured to constant mass showing significantly lower values than the ones cured to the control 72 hours. Based on the slope of the trendline shown in Figure 34, the difference in IDT strength values for the two curing conditions was about 24 percent.

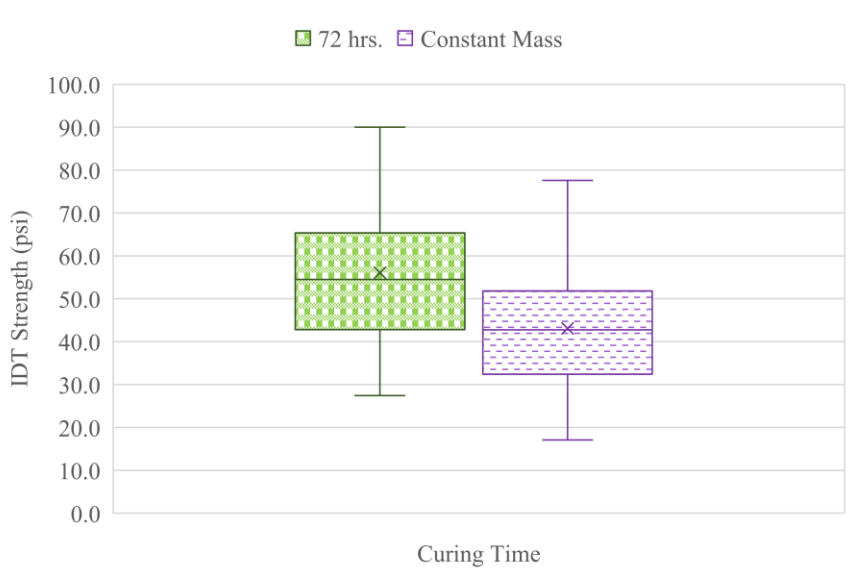


Figure 33. Boxplot illustrating the effect of curing time on IDT strength.

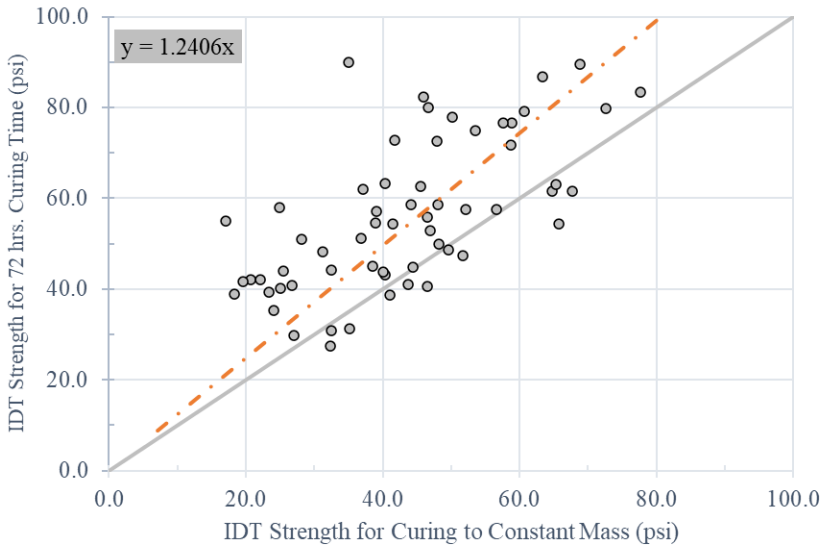


Figure 34. Scatterplot with trendline illustrating the effect of curing time on IDT strength.

The one-way ANOVA results shown in Table 21 confirm the graphic observations. The resulting F-value was 20.63, and the corresponding p-value was < 0.001, which rejected the null hypothesis H_o in favor of the alternative hypothesis that the mean values are statically different.

Table 21. One-Way ANOVA for Curing Time on IDT Strength.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
72 hr	Constant Mass	72 hr	Constant Mass						
60	60	56.1	43.1	Between Groups	5,027.2	1	5,027.2	20.63	<.001
				Within Groups	28,754.5	118	243.7		
				Total	33,781.7	119			

The number of hours required to achieve constant mass ranged between a minimum of 23 hours and a maximum of 70 hours for the different field projects, with an average of 44 hours and a median of 46 hours. In all cases, the number of hours required to achieve constant mass was less than the control 72 hours. For this reason, the researchers decided to drop this laboratory study factor from further consideration and follow the current minimum 72-hour curing time. However, an upper bound to the conditioning time should be added to avoid obtaining larger IDT strength values.

Laboratory Study Factor: Curing Temperature (S5)

To answer question 9 in Table 10, the researchers considered specimens from BRY OSR and ATL FM 3129, as well as the 4-inch LBB SH 207 specimens. The boxplot is shown in Figure 35, while Figure 36 displays the scatterplot. These figures show that curing temperature had a

significant effect on IDT strength, with specimens cured at the control temperature of 104°F showing significantly lower values than the ones cured at an elevated temperature of 140°F. Based on the slope of the trendline shown in Figure 36, the difference in IDT strength values for the two curing temperatures was about 26 percent.

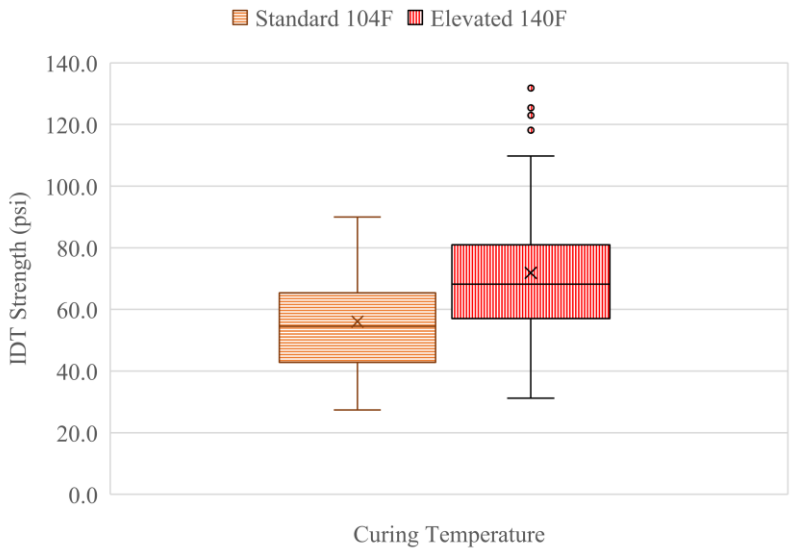


Figure 35. Boxplot illustrating the effect of curing temperature on IDT strength.

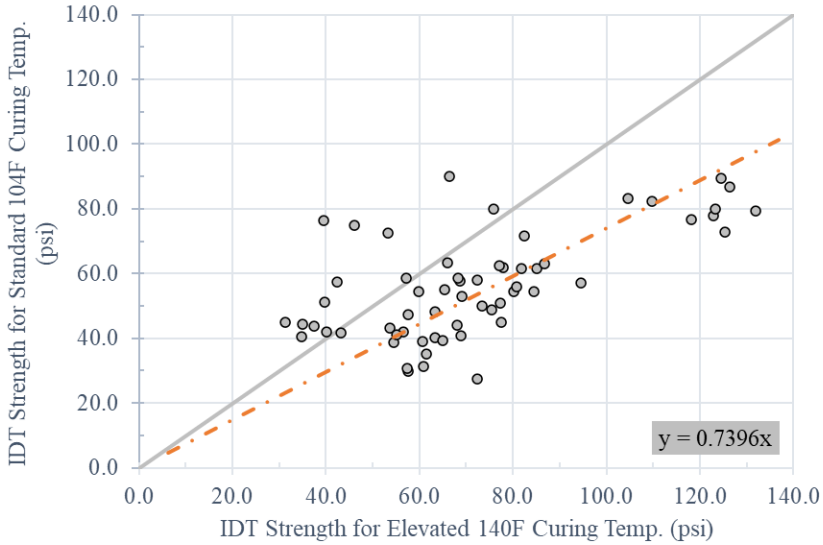


Figure 36. Scatterplot with trendline illustrating the effect of curing temperature on IDT strength.

The one-way ANOVA results shown in Table 22 yielded an F-value of 16.427 and a p-value < 0.001, which rejected the null hypothesis H_o in favor of the alternative hypothesis that the mean values are statically different. Because it is not desirable to obtain larger IDT strength values than the ones obtained during mix design, this laboratory study factor was dropped from

further consideration, and the control 104°F curing temperature was favored in lieu of the elevated curing temperature.

Table 22. One-Way ANOVA for Curing Temperature on IDT Strength.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
104°F	140°F	104°F	140°F						
60	60	56.1	71.8	Between Groups	7,473.4	1	7,473.4	16.427	<.001
				Within Groups	53,682.7	118	454.9		
				Total	61,156.1	119			

In the average IDT strength results shown in Table 22, there was about a 0.5 psi change in IDT strength for every 1°F. Therefore, the current allowable range in the draft specifications of 104 ± 5°F should be adequate since that range will yield a difference of ± 2.5 psi from a given value, which is less than the practically significant difference of 5 psi identified in the factor analysis of specimen size.

Laboratory Study Factor: Testing Temperature (S6, S7)

To respond to question 10 in Table 10, researchers compared the IDT strength of the control specimens (i.e., conditioned and tested at 72°F) to the IDT strength of specimens conditioned and tested at 67°F or 77°F. To achieve the alternate higher and lower temperatures, after curing at 104°F for at least 72 hours, researchers stored the unconditioned and conditioned specimens in a temperature-controlled chamber for 24 hours to achieve the desired alternate testing temperature prior to conducting the IDT strength test. All six specimens were then extracted from the chamber and evaluated concurrently.

The IDT strength results at the three testing temperatures are shown in boxplot and scatterplot formats in Figure 37 and Figure 38, respectively. The specimens tested at 72°F had the largest IDT strength, while the ones tested at 77°F had the lowest IDT strength. The slope of the trendlines was used to estimate the difference in results, with the control IDT strength (i.e., tested at laboratory room temperature of around 72°F) being about 19 percent higher than the specimens tested at 77°F and about 7.5 percent higher than the specimens tested at 67°F. Researchers expected to obtain a smaller IDT strength value at a higher temperature since the specimens would tend to be less stiff. What was not expected was to obtain a lower IDT strength for specimens tested at the lower testing temperature of 67°F.

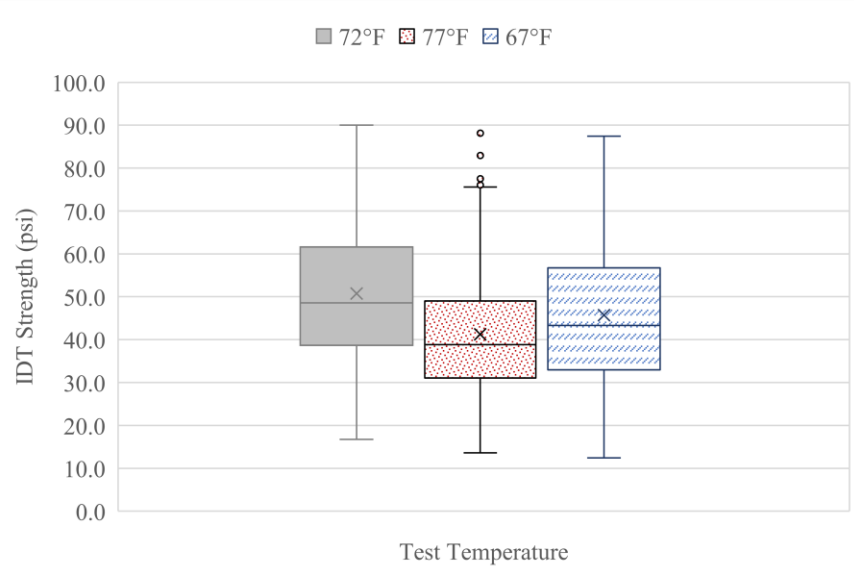


Figure 37. Boxplot illustrating the effect of testing temperature on IDT strength.

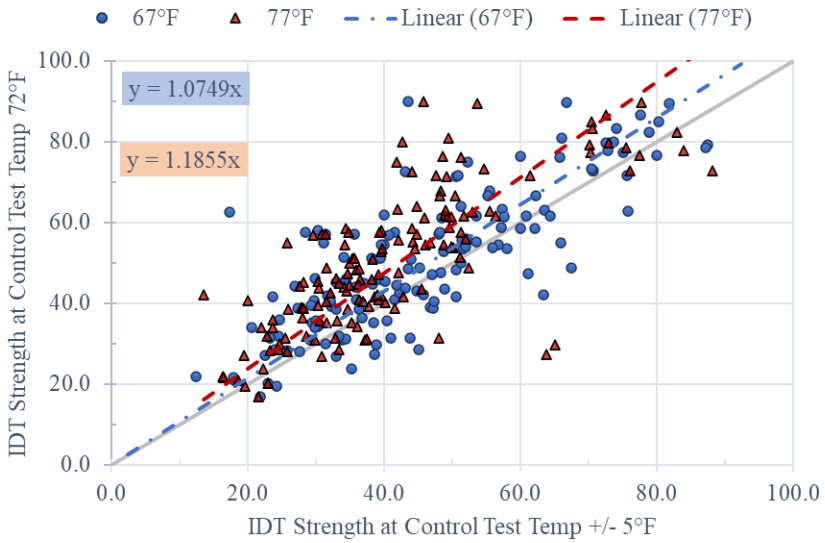


Figure 38. Scatterplot with trendline illustrating the effect of testing temperature on IDT strength.

The one-way ANOVA and Tukey's HSD results of this same dataset are listed in Table 23 and Table 24, respectively. The p-value of the one-way ANOVA was < 0.001, rejecting the null hypothesis H_o that the means of the IDT strengths conducted at the three testing temperatures are equal in favor of the alternative hypothesis that the means are statistically different. Tukey's HSD analysis resulted in two distinct groups: (a) the IDT strength test results of specimens tested at 72°F, and (b) the IDT strength test results of specimens tested at 77°F and 67°F together.

In the extreme average IDT strength results shown in Table 23 (i.e., 72°F and 77°F), there was about a 2.0 psi change in IDT strength for every 1°F. Therefore, it is recommended to record the

temperature at the time of testing, and to limit the allowable temperature range to ± 2°F, which is consistent with the current range specified in the IDT strength standard test method Tex-226-F. In addition, for testing temperatures above 72°F, it is recommended to consider an adjustment factor like the one shown in Eq. 2.

$$IDT\ Strength_{Corrected} = IDT\ Strength_{Measured} + 2 \times (Testing\ Temp. - 72°F) \quad \text{(Eq. 2)}$$

Table 23. One-Way ANOVA for Testing Temperature on IDT Strength.

Avg. IDT Strength (psi)			Sum of Squares		df	Mean Square	F	Sig.
67°F	72°F	77°F						
45.7	50.7	41.3	Between Groups	6,345.5	2	3,172.7	11.678	<.001
			Within Groups	114,378.2	421	271.7		
			Total	120,723.7	423			

Table 24. Tukey's HSD Homogenous Subsets for Testing Temperature.

Number of Observations	Testing Temperature	Mean IDT Strength (psi) for Homogeneous Subset[a,b,c]	
		B	A
142	77	41.3	
142	67	45.7	
140	72		50.7
	Sig.	0.06	1

Note: Means for groups in homogeneous subsets are displayed.
[a] Uses harmonic mean sample size = 141.327.
[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.
[c] Levels not connected by same letter are significantly different.

Laboratory Study Factor: Cement Type (S9)

To answer question 11 in Table 10—Does changing the cement type to Type IL influence the IDT strength? —the research team used data from ODA BI 20, ATL US 80, and BRY FM 39. The boxplot and scatterplot of these results are shown in Figure 39 and Figure 40, respectively. The IDT strength results for both cement types were practically equivalent, with a trendline slope of 1.017. The one-way ANOVA (see Table 25) confirmed this observation, resulting in a p-value of 0.502, thereby accepting the null hypothesis H_o that the mean values are statistically equivalent.

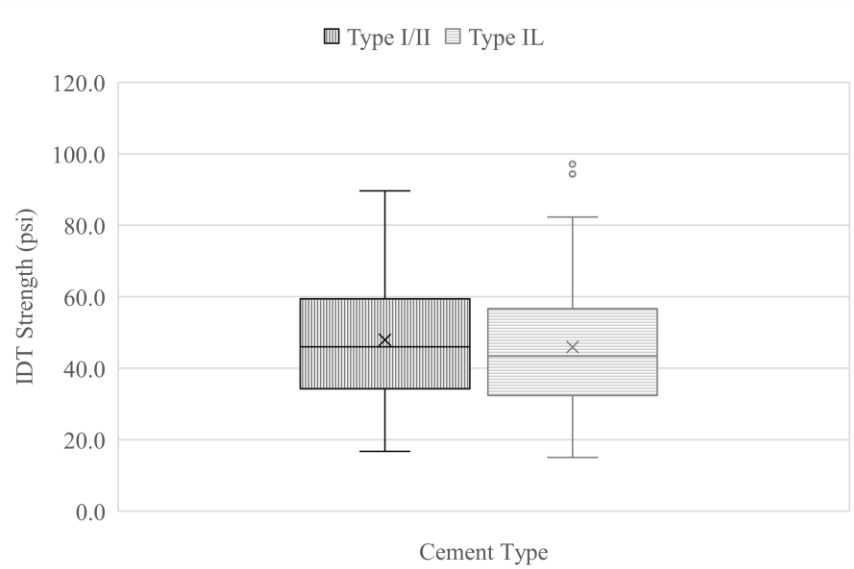


Figure 39. Boxplot illustrating the effect of cement type on IDT strength.

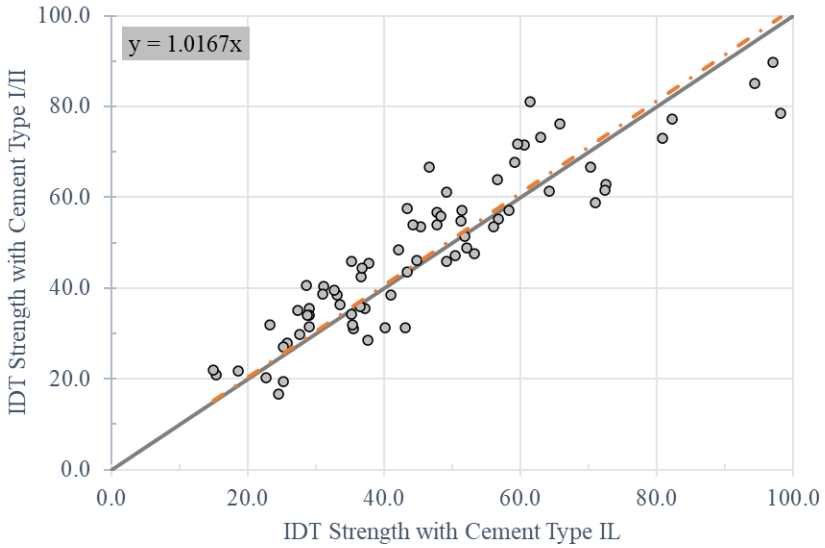


Figure 40. Scatterplot with trendline illustrating the effect of cement type on IDT strength.

Table 25. One-Way ANOVA for Cement Type on IDT Strength.

Number of Observations		Avg. IDT Strength (psi)		Sum of Squares		df	Mean Square	F	Sig.
Type I/II	Type IL	Type IL	Type IL						
72	72	48.0	46.0	Between Groups	148.4	1	148.4	0.452	0.502
				Within Groups	46,613.9	142	328.3		
				Total	46,762.3	143			

SUMMARY

The results of the trend analysis and one-way ANOVA were compiled and are summarized in Table 26, where S0 refers to specimen size and S1 through S9 refer to the laboratory study factors identified in Table 8 and Table 9. For the trend analysis, a slope larger than 1.10 or smaller than 0.9 was considered significant (i.e., ±10 percent difference in IDT strength values). For the one-way ANOVA, the selected significant level was p-value < 0.05.

In Table 26, factors that resulted in significant differences are noted with "Yes," while factors that were not different are noted with "No." In cases where there was agreement between the conclusion of the trend analysis and one-way ANOVA, the significant differences are noted in *italic* font and highlighted in *purple*, while the ones that were not different are noted in **bold** font and highlighted in **orange**. As can be observed, five out of the seven laboratory study factors showed significant differences versus the control based on the two types of analyses.

Table 26. Summary of the Effect of Mix Design Variables, Additional Variables, and Laboratory Study Factors on IDT Strength Results.

Type	Name	Trend Analysis		One-Way ANOVA	
		Slope	Significant (slope > 1.10 or < 0.90)	p-value	Significant (p-value < 0.05)
Mix Design Variables	Binder Type	0.86	*Yes*	0.044	*Yes*
	Conditioning	0.68	*Yes*	<0.001	*Yes*
Laboratory Study Factor	Specimen Size (S0)	1.11	*Yes*	<0.001	*Yes*
	Compaction Level (S1, S2, S8)	1.14[a]	*Yes*	<0.001	*Yes*
	Emulsion Temp. (S3)	0.98	**No**	0.977	**No**
	Curing Time (S4)	1.24	*Yes*	<0.001	*Yes*
	Curing Temp. (S5)	0.74	*Yes*	<0.001	*Yes*
	Testing Temp. (S6, S7)	1.13[b]	*Yes*	<0.001	*Yes*
	Cement Type (S9)	1.02	**No**	0.502	**No**

[a] Average of the slopes at N = 50, N = 75, and N = 100.
[b] Average of the slopes at 67°F and 77°F.

CHAPTER 5:
INTERLABORATORY STUDY

The research team conducted an interlaboratory study (ILS) to determine the repeatability (within laboratory) and reproducibility (between laboratory) limits for the dry and wet IDT strength results for both emulsified asphalt and foamed asphalt 4-inch diameter specimens. ASTM D691, Standard Practice for Conducting and Interlaboratory Study to Determine the Precision of a Test Method, was followed for the calculations, but it should be noted that the standard mentions the following: "under no circumstances should the final statement of precision of a test method be based on acceptable test results for each material from fewer than 6 laboratories." In this study, data from only four laboratories were available, including the Texas A&M Transportation Institute (TTI) laboratory, the TxDOT MTD laboratory, the San Antonio (SAT) District laboratory, and the Terracon laboratory. Therefore, the calculations presented here are not meant to be final precision statements but rather preliminary precision statements, and further information should be collected in order to comply with the standard requirements.

MATERIALS

Three distinct materials were selected for the ILS; two were sampled from the roadway, as shown in Figure 41 and Figure 42—one in the Atlanta District (i.e., ATL US 80) and the other in the Brownwood District (i.e., BWD FM 2214). The third material was sampled from a stockpile in the San Angelo District (i.e., SJT SH 137 bedrock caliche).

Figure 41. ILS materials sampled from the roadway ATL US 80.

Figure 42. ILS materials sampled from the roadway BWD FM 2214.

The research team processed the materials and developed the emulsified asphalt and foamed asphalt mix designs per the draft mix design procedures Tex-122-E and Tex-134-E available at the time of the ILS (i.e., April 2023). The main changes to the previous version of the draft mix design procedures at the time of the ILS included (a) use of a treated moisture-density curve to determine optimum moisture content, (b) use of 4-inch diameter specimens for IDT strength testing, (c) specimen compaction to a fixed number of 75 gyrations, and (d) no UCS requirement. The final mix design parameters for the selected materials are shown in Appendix C, Table C-2.

Based on the results of the mix designs, the research team prepared all materials for shipment in accordance with Tex-101-E, Part II. Each shipment included two 5-gallon buckets of aggregate for each ILS material (i.e., one 5-gallon bucket for the emulsified asphalt specimens and one 5-gallon bucket for the foamed asphalt specimens), 2 gallons of asphalt binder, 1 gallon of emulsion, and one container of Type I/II cement. The package sent to each participating laboratory also included detailed step-by-step instructions for specimen preparation, as shown in Appendix D; a datasheet for capturing all results, as shown in Appendix E; and the April 2023 draft mix design procedures of Tex-122-E and Tex-134-E.

The type of binder selected for the ILS foamed specimens was a PG 64-22. The half-life and expansion ratio of the binder were verified as required by Tex-134-E, and the results are shown in Appendix F. The type of emulsion selected for the ILS was a CSS-1H.

RESULTS

Each participating laboratory performed the dry and conditioned IDT strength on each ILS material and with each type of asphalt treatment and reported four replicate values for each case.

In addition to capturing the information required by Tex-122-E and Tex-134-E, the research team requested measuring additional parameters including the height and mass of the specimen after molding, the height and mass of the specimen after conditioning, the specimen temperature after conditioning, the mass of the specimen after testing, and the mass of the specimen after drying for 24 hours at 100°C. The purpose of collecting these additional parameters was to calculate the specimen density after molding and conditioning, as well as the moisture content and dry density at the moment of IDT strength testing. The temperature at IDT strength testing was also captured to observe if it had a significant effect on IDT strength and evaluate a realistic spread in the testing temperatures between laboratories. The temperature of the specimen at IDT strength testing varied between laboratories from 63°F to 73°F but did not seem to impact the IDT strength results in a consistent manner. The IDT strength results and moisture content are summarized in Figure 43 through Figure 54. Each bar represents the average value of four replicates, and the error bars extend ± one standard deviation from the average value.

The IDT strength results for the ATL US 80 roadway material treated with emulsified asphalt were significantly higher than the IDT strength results obtained when the roadway material was treated with foamed asphalt (Figure 43 vs. Figure 44). In addition, there was a minimal difference between most unconditioned (dry) and conditioned (submerged) IDT strength results for both emulsified asphalt and foamed asphalt. The moisture content was higher for the conditioned (submerged) specimens, especially for the specimens treated with foamed asphalt (Figure 46). The moisture content for the unconditioned (dry) specimens was about twice as high for laboratory *I* compared to the other three laboratories, which may be due to the type of chamber (not an oven) being used to cure the specimens.

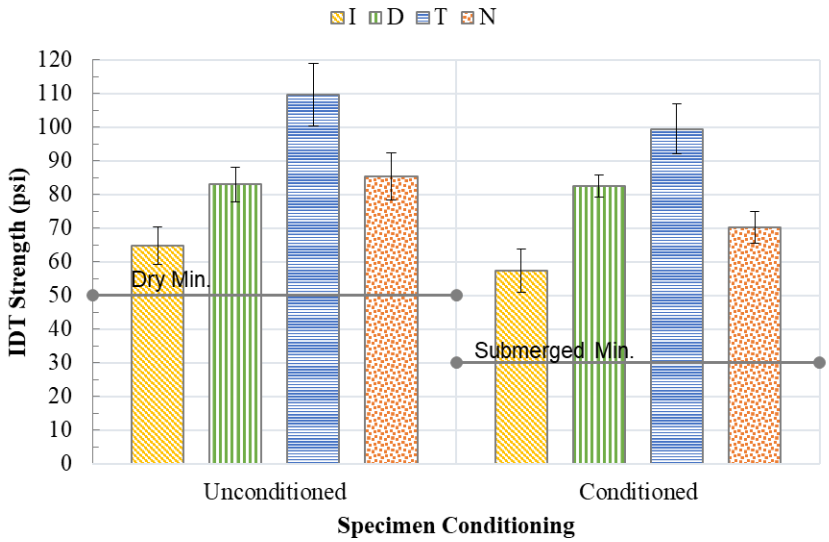


Figure 43. ATL US 80 IDT strength results for emulsified asphalt specimens.

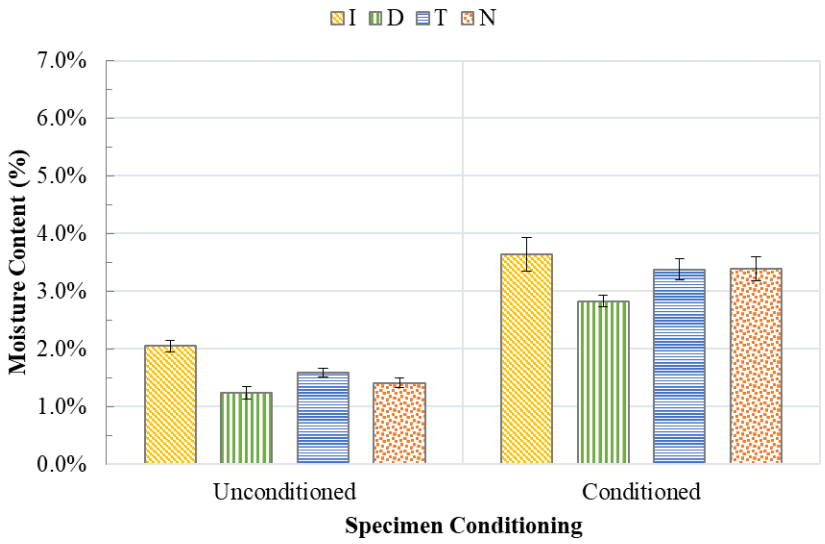


Figure 44. ATL US 80 moisture content for emulsified asphalt specimens.

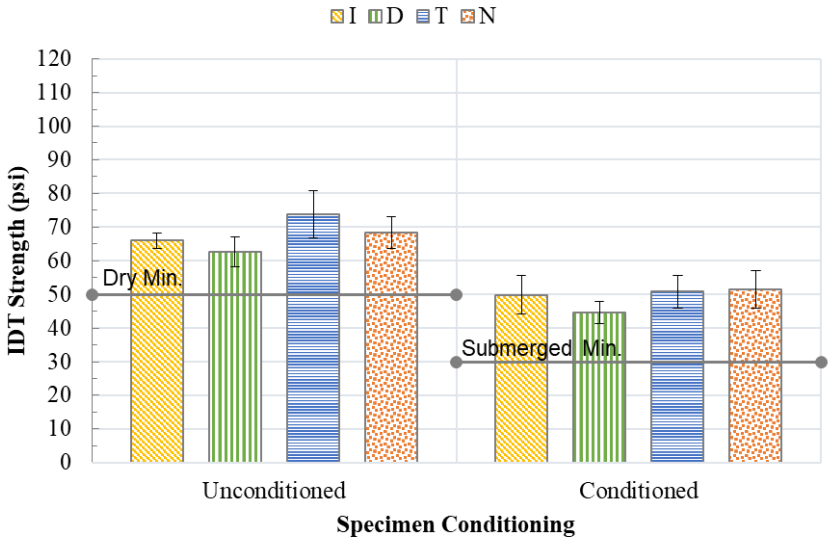


Figure 45. ATL US 80 IDT strength results for foamed asphalt specimens.

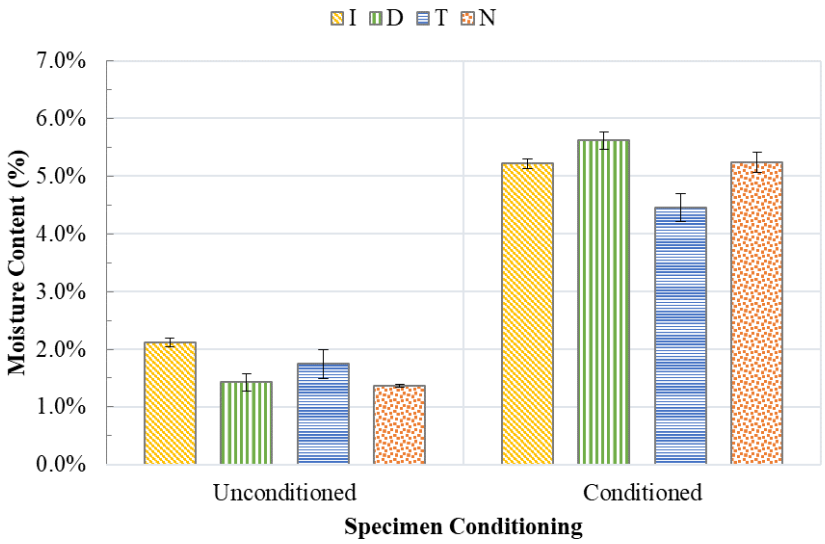


Figure 46. ATL US 80 moisture content for foamed asphalt specimens.

The results for the BWD FM 2214 roadway material showed similar or slightly higher IDT strength results of the emulsified asphalt specimens compared to the foamed asphalt specimens. In this case, the IDT strength results had a more significant reduction after conditioning (submerged), yielding values below the recommended threshold of 30 psi for two laboratories in the case of the emulsified asphalt specimens and for all laboratories in the case of the foamed asphalt specimens (Figure 47 and Figure 49). The difference in moisture content was more pronounced between the unconditioned (dry) and conditioned (submerged) specimens for both asphalt types (Figure 48 and Figure 50). Similar to the ATL US 80 specimens, the moisture content for the unconditioned (dry) specimens was about twice as high for laboratory *I* compared to the other three laboratories, which may be due to the type of chamber (not an oven) being used to cure the specimens.

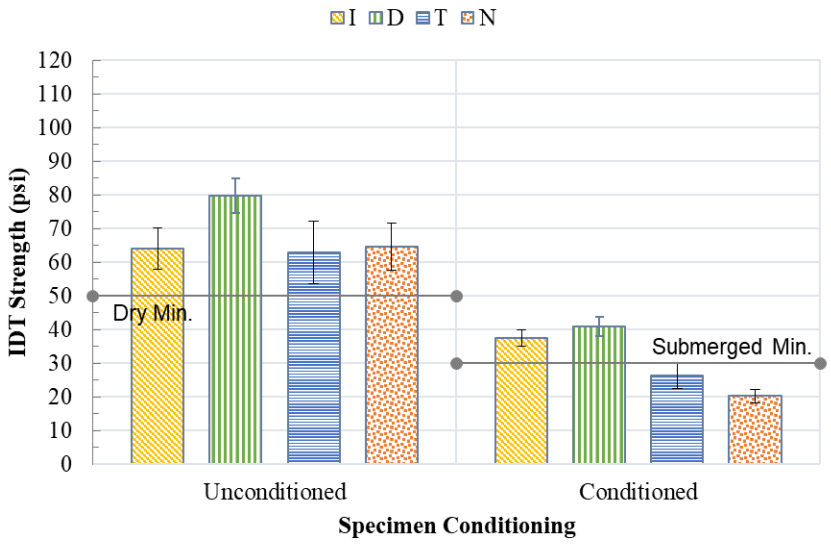


Figure 47. BWD FM 2214 IDT strength results for emulsified asphalt specimens.

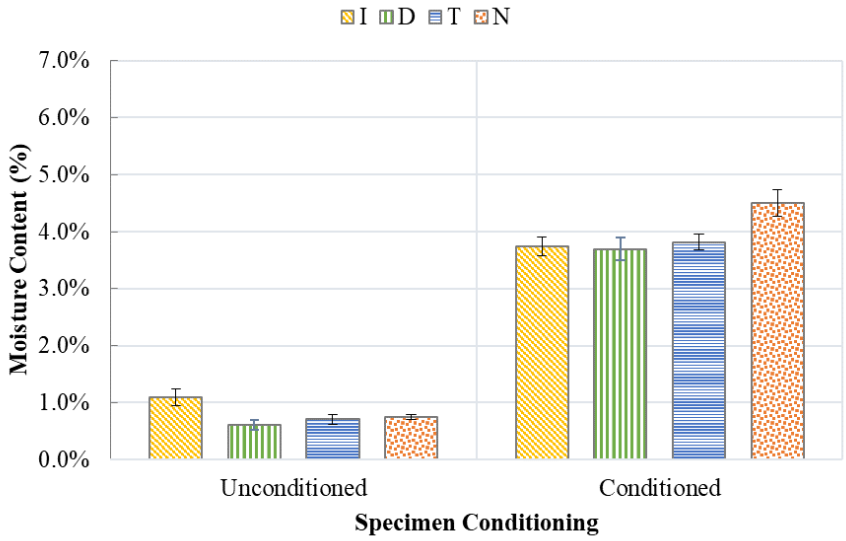


Figure 48. BWD FM 2214 moisture content results for emulsified asphalt specimens.

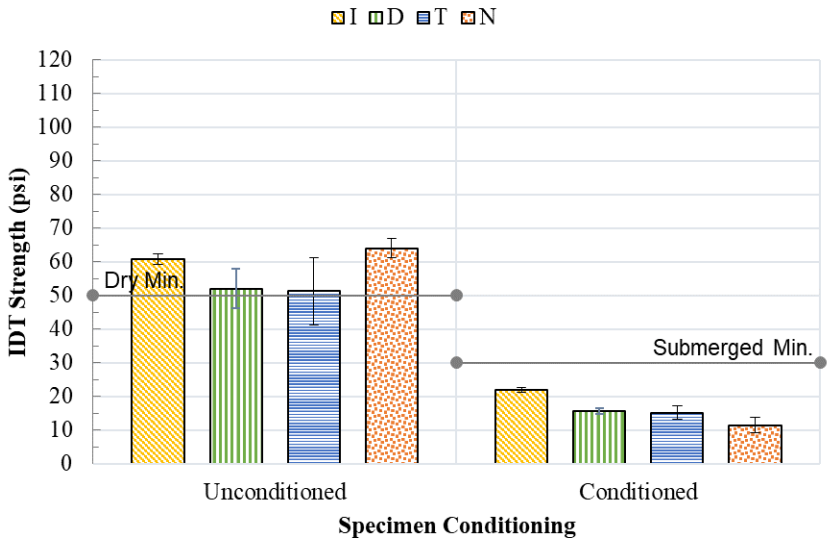


Figure 49. BWD FM 2214 IDT strength results for foamed asphalt specimens.

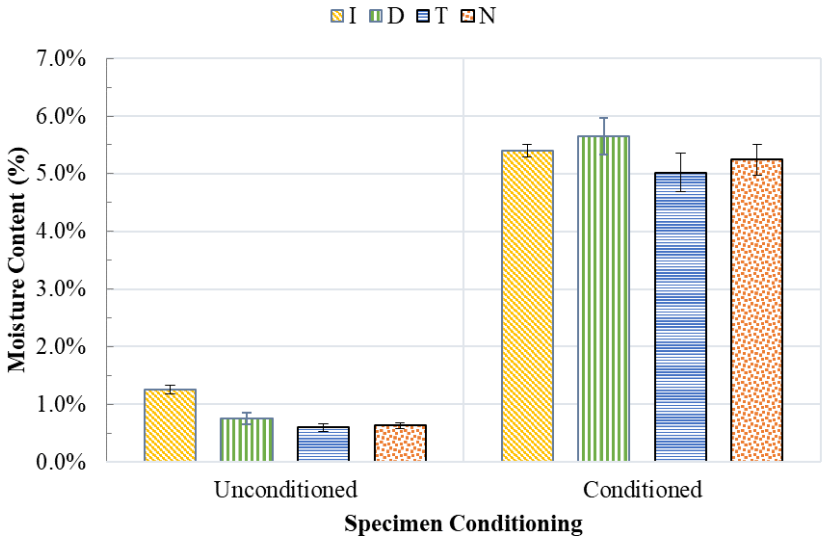


Figure 50. BWD FM 2214 moisture content for foamed asphalt specimens.

Finally, for the SJT SH 137 bedrock caliche material, the emulsified asphalt and foamed asphalt IDT strength results were closer to each other (Figure 51 and Figure 53). This result could probably be due to the fact that this material was sampled from a stockpile rather than from the roadway. There was an effect of conditioning, but it was not as pronounced as with the other two roadway materials, and only one laboratory had IDT strength results that were right at the 30 psi threshold for conditioned (submerged) specimens. However, the difference in moisture content between the unconditioned and conditioned specimens for both asphalt types was very pronounced, with unconditioned (dry) specimens showing moisture contents of less than

1 percent and conditioned (submerged) specimens showing values of about 6 percent or above in most cases (Figure 52 and Figure 54). As with the other two roadway materials, the moisture content for the unconditioned (dry) specimens was about twice as high for laboratory *I* compared to the other three laboratories, which may be due to the type of chamber (not an oven) being used to cure the specimens.

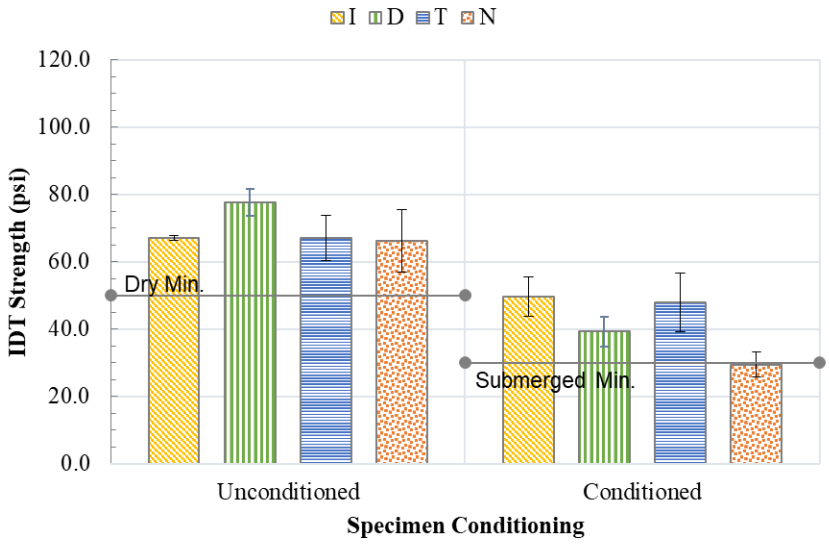


Figure 51. SJT SH 137 bedrock IDT strength results for emulsified asphalt specimens.

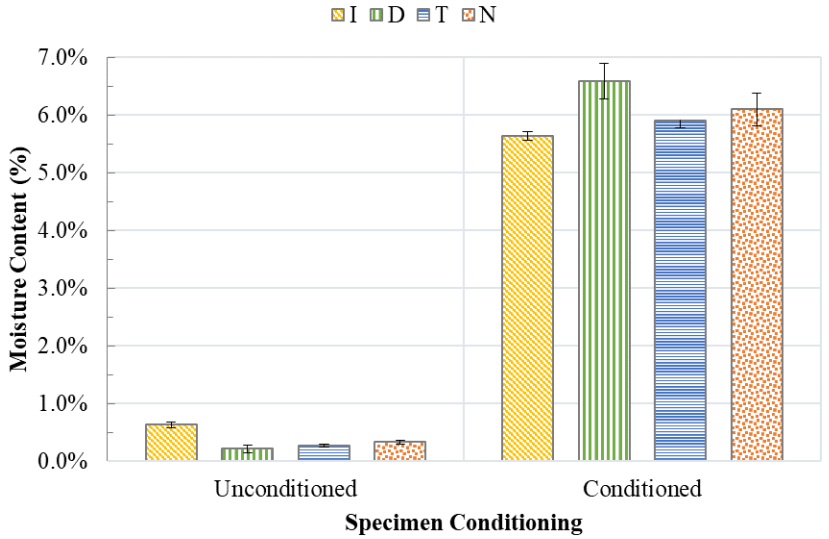


Figure 52. SJT SH 137 bedrock moisture content for emulsified asphalt specimens.

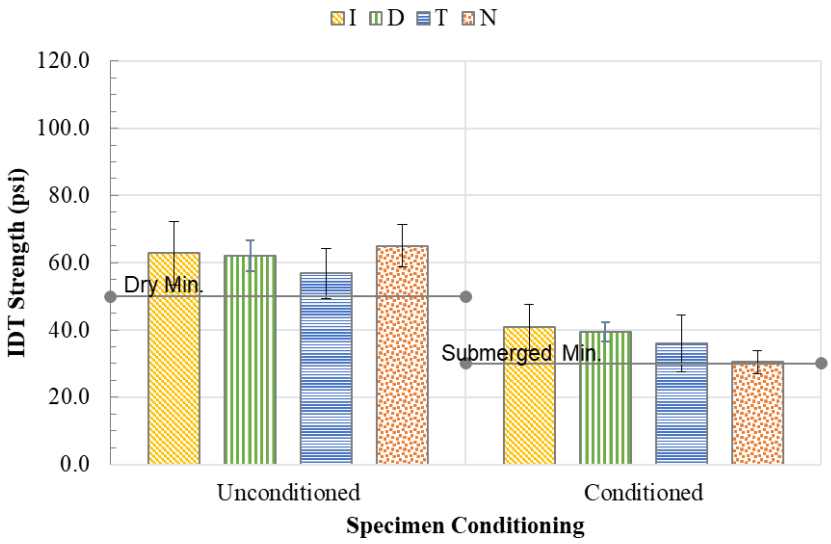


Figure 53. SJT SH 137 bedrock IDT strength results for foamed asphalt specimens.

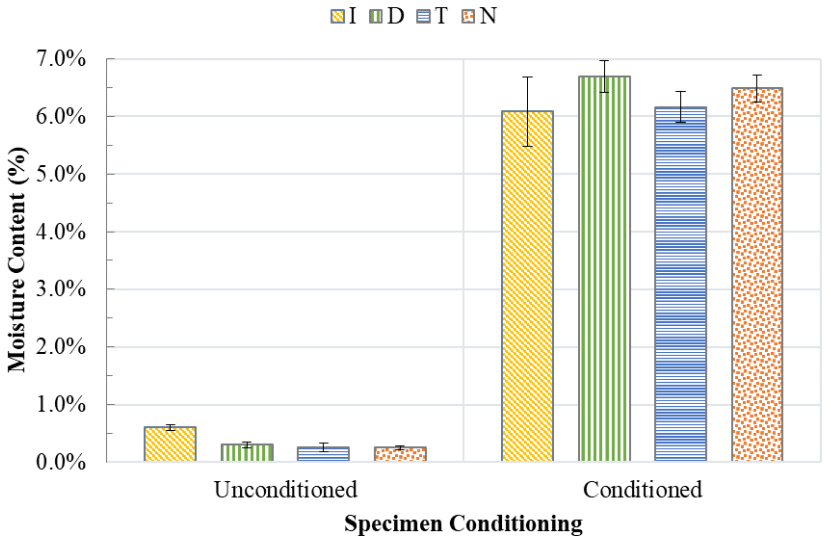


Figure 54. SJT SH 137 bedrock moisture content for foamed asphalt specimens.

ANALYSIS

The research team used the IDT strength results to determine the preliminary precision limits according to ASTM E691. Four distinct cases were considered: emulsified asphalt unconditioned (dry) specimens, emulsified asphalt conditioned (submerged) specimens, foamed asphalt unconditioned (dry) specimens, and foamed asphalt conditioned (submerged) specimens. The IDT strength results for these four cases are shown in Appendix G, where each column contains the data obtained from all laboratories for one ILS material, and each row contains the data from one laboratory for all three ILS materials. The laboratory names were coded to preserve anonymity.

Based on the standard test method, the analysis of the data for precision estimates consists of a one-way ANOVA conducted separately for each material. Because outliers influence the analysis, it was important to examine the data and identify any extreme results. For this purpose, the individual test results for each laboratory were averaged, $\bar{x}$ (Eq. 3), and the standard deviation, s (Eq. 4), was calculated, followed by calculations of the average and standard deviation for all laboratories, $\bar{\bar{x}}$ and $S_{\bar{x}}$ (Eq. 5 and Eq. 6).

$$\bar{x} = \sum_{1}^{n} x/n \qquad \text{(Eq. 3)}$$

where:
$\bar{x}$ = the average of the test results for one laboratory on one material,
x = the individual test results for one laboratory on one material, and
n = the number of test results for one laboratory on one material.

$$s = \sqrt{\sum_{1}^{n} (x - \bar{x})^2/(n-1)} \qquad \text{(Eq. 4)}$$

$$\bar{\bar{x}} = \sum_{1}^{p} \bar{x}/p \qquad \text{(Eq. 5)}$$

where:
$\bar{\bar{x}}$ = the average of the laboratory averages for one material,
$\bar{x}$ = the individual laboratory average, and
p = the number of laboratories in the ILS.

$$s_{\bar{x}} = \sqrt{\sum_{1}^{p} d^2/(p-1)} \qquad \text{(Eq. 6)}$$

The deviation of each laboratory from all laboratories, *d* (Eq. 7), was then calculated by subtracting the average of all laboratories from the average of each laboratory. Further, the precision statistics were calculated using the repeatability standard deviation, S_r (Eq. 8); the between-laboratory variance, S_L^2 (Eq. 9); the between-laboratory standard deviation, S_L (Eq. 10); and the reproducibility standard deviation, S_R (Eq. 11). If S_L^2 is negative, then $S_L^2 = 0$ and $S_L = 0$.

$$d = \bar{x} - \bar{\bar{x}} \quad \text{(Eq. 7)}$$

$$s_r = \sqrt{\sum_1^p s^2/p} \quad \text{(Eq. 8)}$$

where:
s_r = the repeatability standard deviation,
s = the standard deviation of the test results for one laboratory on one material (from Eq. 4), and
p = the number of laboratories.

$$s_L^2 = s_{\bar{x}}^2 - s_r^2 / n \quad \text{(Eq. 9)}$$

$$s_L = \sqrt{s_L^2} \quad \text{(Eq. 10)}$$

$$s_R = \sqrt{s_L^2 + s_r^2} \quad \text{(Eq. 11)}$$

Finally, the consistency statistics, *h* and *k*, were calculated using Eq. 12 and Eq. 13, respectively.

$$h = d/s_{\bar{x}} \quad \text{(Eq. 12)}$$

where:
h = the between-laboratory consistency statistic,
d = the deviation of each laboratory from all laboratories (Eq. 7), and
$S_{\bar{x}}$ = the standard deviation for all laboratories (Eq. 6).

$$k = s/s_r \quad \text{(Eq. 13)}$$

where:
k = the within-laboratory consistency statistic,
s = the standard deviation for one laboratory (Eq. 4), and
S_r = the repeatability standard deviation of the material (Eq. 8).

The results for each distinct case are shown in Table 27 through Table 30, and their respective plots are displayed in Figure 55 through Figure 62. The critical values for *h* and *k* at the

0.5 percent significance level, which is what ASTM E691 recommends using, depend on the number of laboratories and the number of replicates. For four laboratories, the critical *h* value is 1.49, while for four test replicates, the critical *k* value is 1.73. These thresholds are shown in Figure 55 through Figure 62.

Table 27. Consistency Statistics for Emulsified Asphalt Unconditioned (Dry).

Consistency Statistic	Laboratory	Material		
		ATL US 80	BWD FM 2214	SJT SH 137
Within Laboratory, *k*	I	0.80	0.88	0.12
	D	0.74	0.73	0.66
	T	1.34	1.31	1.10
	N	1.01	0.99	1.53
Between Laboratory, *h*	I	−1.13	−0.47	−0.44
	D	−0.15	1.49	1.49
	T	1.30	−0.62	−0.44
	N	−0.02	−0.40	−0.61

Table 28. Consistency Statistics for Emulsified Asphalt Conditioned (Submerged).

Consistency Statistic	Laboratory	Material		
		ATL US 80	BWD FM 2214	SJT SH 137
Within Laboratory, *k*	I	0.97	1.13	0.87
	D	0.73	0.56	1.03
	T	1.46	1.31	1.31
	N	0.63	0.84	0.69
Between Laboratory, *h*	I	0.87	−1.11	0.65
	D	−0.26	0.29	1.00
	T	0.69	1.23	−0.52
	N	−1.30	−0.40	−1.14

Table 29. Consistency Statistics for Foamed Asphalt Unconditioned (Dry).

Consistency Statistic	Laboratory	Material		
		ATL US 80	BWD FM 2214	SJT SH 137
Within Laboratory, *k*	I	0.46	0.25	1.31
	D	0.91	0.96	0.63
	T	1.42	1.67	1.05
	N	0.98	0.48	0.88
Between Laboratory, *h*	I	−0.37	0.60	0.33
	D	−1.08	−0.79	0.10
	T	1.29	−0.91	−1.40
	N	0.15	1.10	0.96

Table 30. Consistency Statistics for Foamed Asphalt Conditioned (Submerged).

Consistency Statistic	Laboratory	Material		
		ATL US 80	BWD FM 2214	SJT SH 137
Within Laboratory, *k*	I	1.17	1.14	0.47
	D	0.48	0.67	0.53
	T	1.44	0.98	1.25
	N	0.58	1.14	1.39
Between Laboratory, *h*	I	0.88	0.21	1.35
	D	0.61	−1.47	−0.09
	T	−0.14	0.53	−0.20
	N	−1.35	0.73	−1.06

The values for the within-laboratory, or *k*, consistency statistic for one laboratory being either very large or very small for most or all materials may indicate within-laboratory imprecision (large *k* values) or measurement problems (small *k* values). In this study, all four laboratories showed adequate *k* values, with no apparent concerning patterns of very high or very low values, as shown in Figure 55, Figure 57, Figure 59, and Figure 61. In addition, none of the values exceeded the critical value of *k* of 1.73.

Values for the *h* consistency statistic can be considered normal when the laboratories have both positive and negative values or when individual laboratories tend to be either positive or negative for all materials and the number of laboratories with negative values is balanced with respect to the number of laboratories with positive values. It is only when one laboratory's *h* values (either positive or negative) are opposed to the results of all other laboratories that the results should be considered suspect. In this study, the *h* statistic for all four laboratories had positive and negative

values and seemed balanced, as shown in Figure 56, Figure 58, Figure 60, and Figure 62. In addition, only two results were right at the critical limit of 1.49.

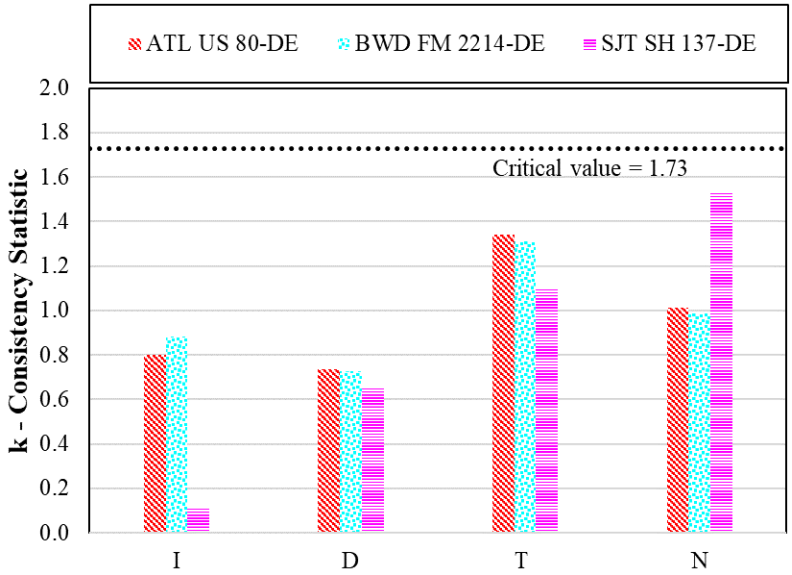


Figure 55. Consistency statistic *k* for emulsified asphalt unconditioned (dry) specimens.

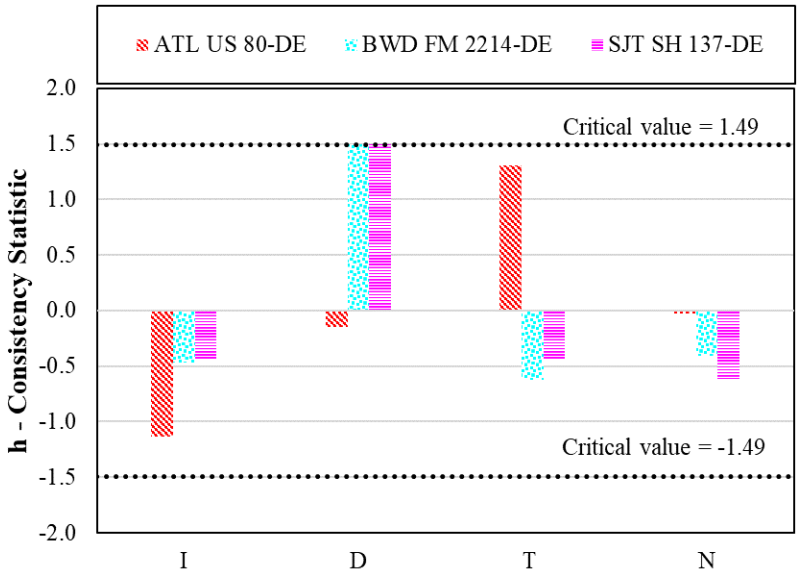


Figure 56. Consistency statistic *h* for emulsified asphalt unconditioned (dry) specimens.

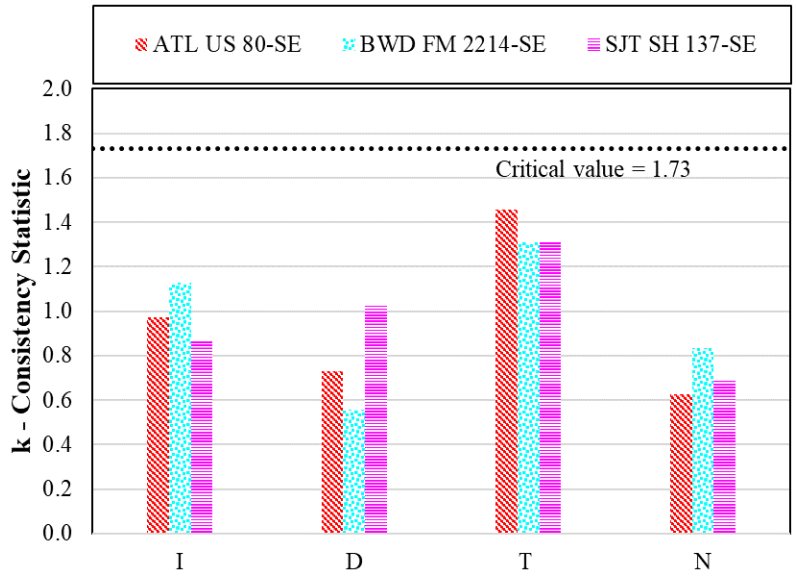


Figure 57. Consistency statistic *k* for emulsified asphalt conditioned (submerged) specimens.

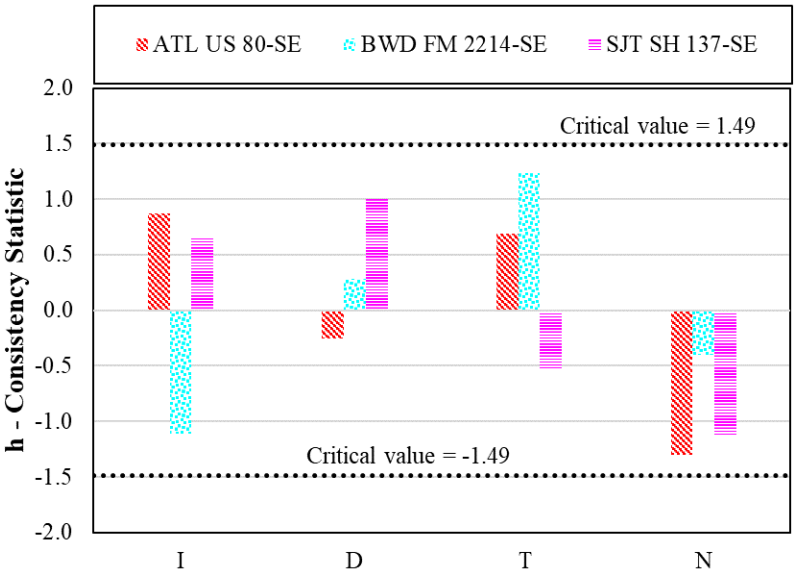


Figure 58. Consistency statistic *h* for emulsified asphalt conditioned (submerged) specimens.

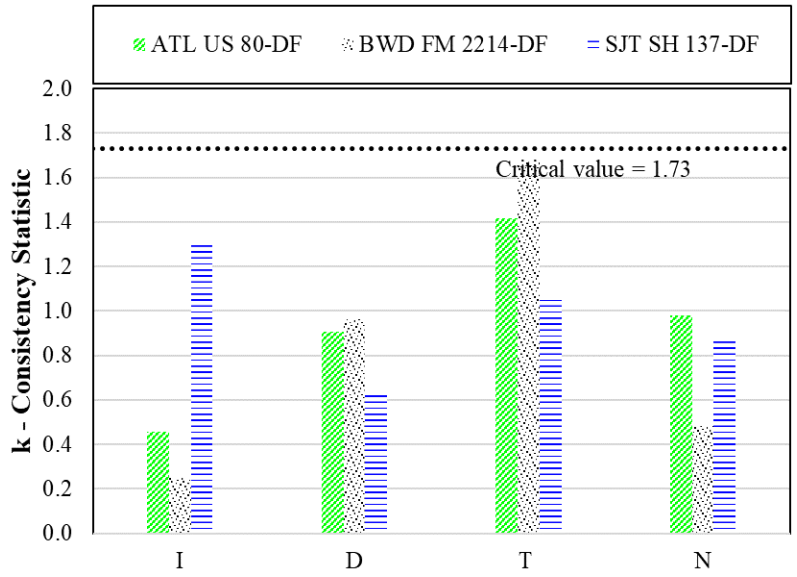


Figure 59. Consistency statistic *k* for foamed asphalt unconditioned (dry) specimens.

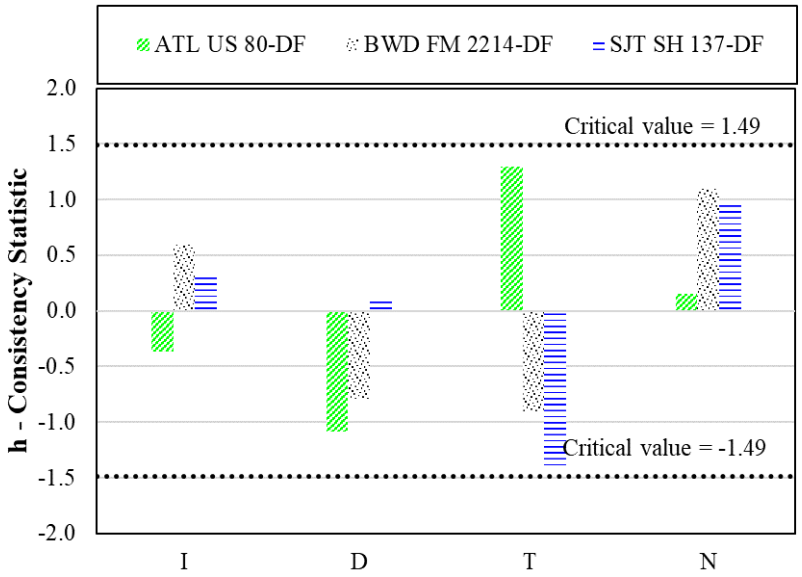


Figure 60. Consistency statistic *h* for foamed asphalt unconditioned (dry) specimens.

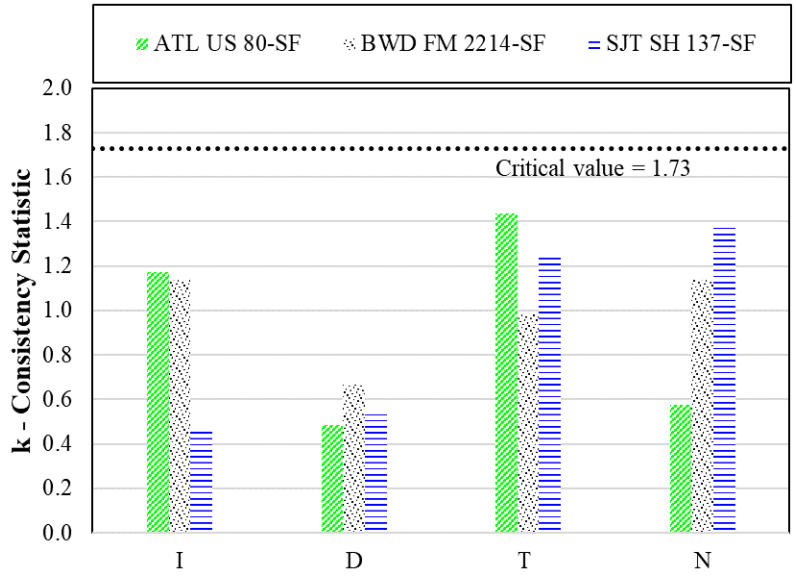


Figure 61. Consistency statistic *k* for foamed asphalt conditioned (submerged) specimens.

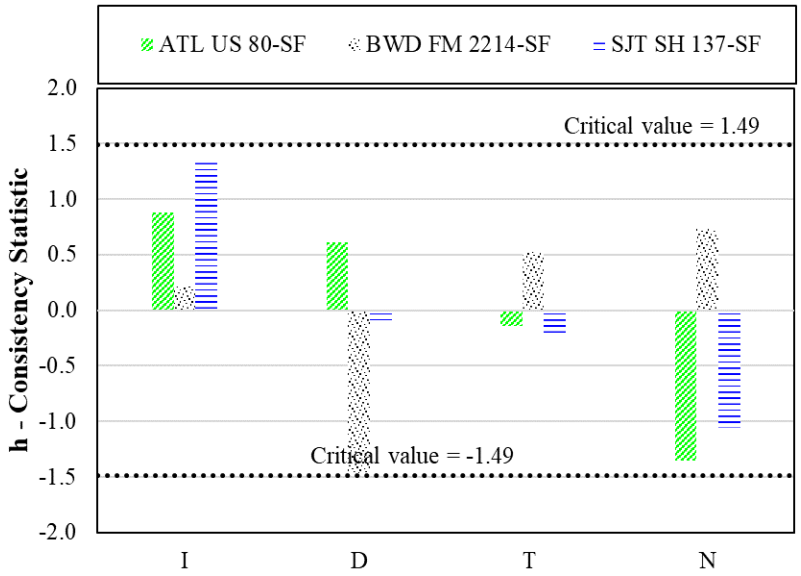


Figure 62. Consistency statistic *h* for foamed asphalt conditioned (submerged) specimens.

Since the IDT strength results from all four laboratories seemed adequate and there was no reason to investigate clerical, sampling, or procedural errors, all data were retained for estimating the preliminary 95 percent precision statement using Eq. 14 and Eq. 15.

$$r = 2.8\, s_r \qquad \text{(Eq. 14)}$$

$$R = 2.8\, s_R \qquad \text{(Eq. 15)}$$

The resulting precision statistics are shown in Table 31. In addition, the resulting values plotted with respect to the average IDT strength for each case are shown in Figure 63 through Figure 66.

Table 31. Precision Statistics for IDT Strength (psi).

Case	Material	Average Test Results, $\bar{x}$	Repeatability Standard Deviation, S_r	Reproducibility Standard Deviation, S_R	Repeatability Limit, r	Reproducibility Limit, R
Emulsified Asphalt Unconditioned (Dry)	ATL US 80	85.76	6.90	19.41	19.32	54.33
	BWD FM 2214	67.78	7.08	10.08	19.81	28.23
	SJT SH 137	69.58	6.11	7.54	17.10	21.12
Emulsified Asphalt Conditioned (Submerged)	ATL US 80	77.43	5.73	18.63	16.03	52.17
	BWD FM 2214	31.20	2.79	9.96	7.82	27.89
	SJT SH 137	41.62	5.99	10.69	16.76	29.94
Foamed Asphalt Unconditioned (Dry)	ATL US 80	67.69	4.89	6.34	13.69	17.76
	BWD FM 2214	57.05	6.04	8.24	16.92	23.07
	SJT SH 137	61.66	7.18	7.18	20.10	20.10
Foamed Asphalt Conditioned (Submerged)	ATL US 80	49.17	4.96	5.35	13.89	14.98
	BWD FM 2214	16.09	1.60	4.61	4.48	12.90
	SJT SH 137	36.71	5.87	6.86	16.44	19.21

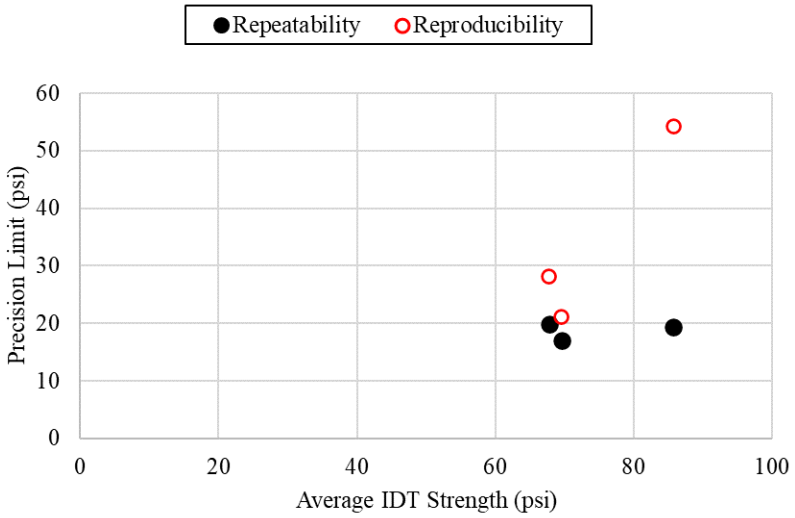


Figure 63. Emulsified asphalt unconditioned (dry) precision limits.

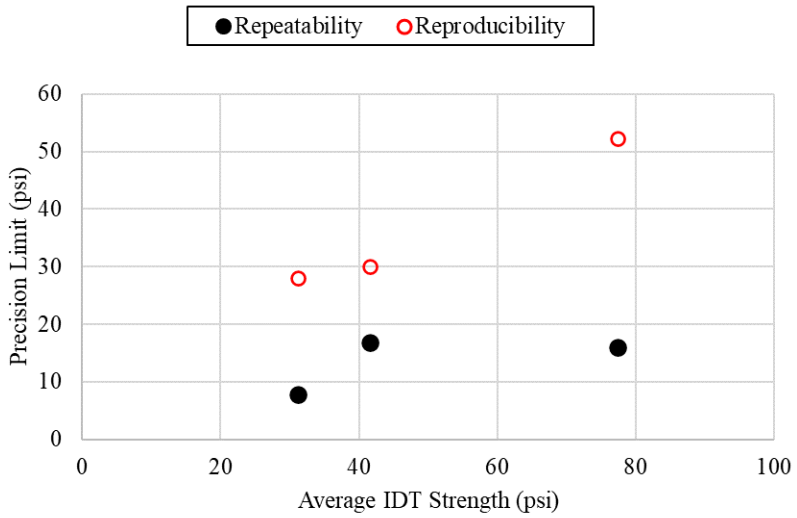


Figure 64. Emulsified asphalt conditioned (submerged) precision limits.

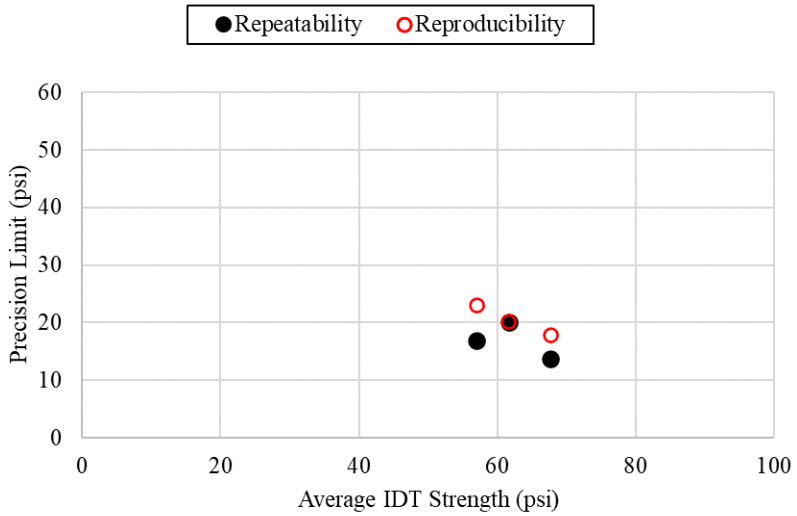


Figure 65. Foamed asphalt unconditioned (dry) precision limits.

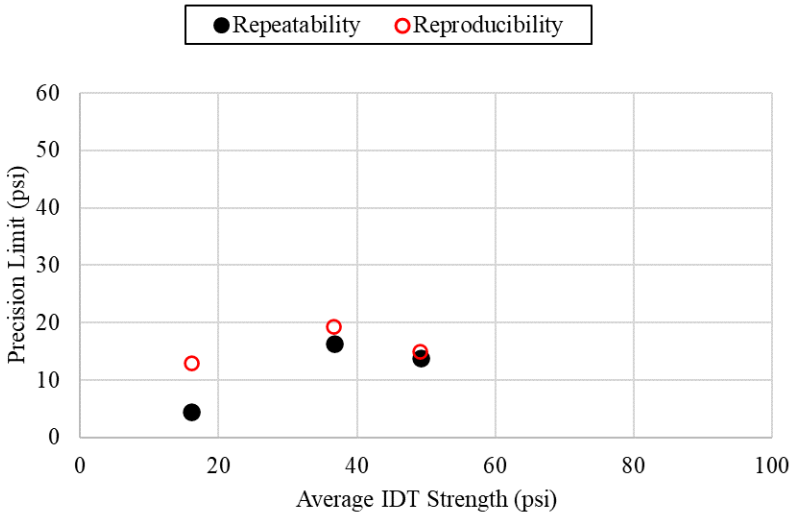


Figure 66. Foamed asphalt conditioned (submerged) precision limits.

The repeatability (within laboratory, *r*) limit was relatively flat, which is desirable. In other words, the property was not affected by average IDT strength. In addition, in all cases, the maximum repeatability limit, *r*, was at 20 or less, which is reasonable for these types of measurements. The reproducibility (between laboratory, *R*) limit was larger than repeatability, which is expected. The reproducibility limit was especially large for the ATL US 80 material treated with emulsified asphalt, with some *R* values above 50. For the other two materials, the reproducibility, *R*, was about 20 for foamed asphalt results and about 30 for emulsified asphalt results.

Previously, as part of TxDOT Project 0-6880, Full Depth Reclamation in Maintenance Operations Using Emerging Technologies, researchers determined precision statistics for the same four cases considered here (*6*). They concluded that the repeatability was slightly better for the material treated with emulsified asphalt but that the reproducibility was better for materials treated with foamed asphalt. In their study, the repeatability limit ranged from 9.5 to 20.1, while the reproducibility limit ranged from 23.9 to 43.6.

Conversely, in this study, the materials treated with foamed asphalt (both dry and submerged) showed better repeatability, with *r* values ranging from 4.5 to 20.1. The materials treated with emulsified asphalt showed larger values of *r* and *R* for both dry and submerged, with values ranging from 7.8 to 19.8 and from 21.1 to 54.3, respectively. When the ATL US 80 results were excluded, the repeatability and reproducibility limits for both dry and submerged emulsified asphalt values ranged from 7.8 to 19.8 and from 21.1 to 29.9, respectively.

PRELIMINARY PRECISION STATEMENT

The preliminary precision of this test method is based on an interlaboratory study of Tex 122-E, Emulsified Asphalt Treatment Mixture Design, and Tex 134-E, Foamed Asphalt Mixture Design,

conducted in 2024. Four laboratories evaluated three distinct materials. Every test result represents an individual determination. Each laboratory was asked to submit four replicate test results, from a single operator, for each material. ASTM E691 was followed for the analysis of the data. The output of the analysis are the repeatability and reproducibility limits for the four distinct cases that were considered. The results are shown below. The repeatability limit represents the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day the same laboratory. The reproducibility limit represents the critical difference between two test results for the same material, obtained by different operators, using different equipment in different laboratories.

Repeatability limit (r)

- Two emulsified asphalt dry test results obtained within one laboratory shall be judged not equivalent if they differ by more than about 20 psi.
- Two emulsified asphalt submerged test results obtained within one laboratory shall be judged not equivalent if they differ by more than about 17 psi.
- Two foamed asphalt dry test results obtained within one laboratory shall be judged not equivalent if they differ by more than about 20 psi.
- Two foamed asphalt submerged test results obtained within one laboratory shall be judged not equivalent if they differ by more than about 16 psi.

Reproducibility limit (*R*)

- Two emulsified asphalt dry test results shall be judged not equivalent if they differ by more than 54 psi.
- Two emulsified asphalt submerged test results shall be judged not equivalent if they differ by more than 52 psi.
- Two foamed asphalt dry test results shall be judged not equivalent if they differ by more than 23 psi.
- Two foamed asphalt submerged test results shall be judged not equivalent if they differ by more than 19 psi.

Disclaimer—This preliminary precision statement shall not be treated as exact mathematical quantities that are applicable to all circumstances and uses. The limited number of laboratories and of materials included in this ILS guarantees that there will be times when differences greater than predicted by these ILS results will arise, sometimes with greater or smaller frequency than the 95 percent probability limit would imply. The repeatability limit and the reproducibility limit should be considered as general guides, and the associated probability of 95 percent should be only a rough indicator of what can be expected. If more precise information is needed in specific circumstances, those laboratories directly involved in a material comparison must conduct interlaboratory studies specifically aimed at the material of interest.

CHAPTER 6:
FIELD EVALUATION

The research team evaluated the performance of available field project sections constructed during the execution of this project that employed the emulsified asphalt or foamed asphalt mix designs developed as part of the laboratory factor study. The objective of the evaluation was to validate if the modulus of the asphalt stabilized layers met current pavement design recommendations (i.e., 200 ksi design value). The evaluation consisted of scanning the pavement with GPR and conducting FWD measurements. Only two of the six field projects included in the laboratory factor study were constructed and available for evaluation during the performance period of this research, specifically BRY FM 39 and ODA BI 20. The other field projects were not available for evaluation due to either work not having started yet, scope of work being changed to a different pavement strategy, or locations being active construction zones.

BRY FM 39

This pavement section is located in Madison County, in the Bryan District. Visual inspection of the surface after FDR showed a crack on the shoulder part of the widening. The as-built FWD survey was conducted in October 2023 and consisted of 41 drops within the limits shown in Figure 67. Of these 41 drops, approximately 20 drops were through the area of the observed longitudinal crack. The total length evaluated was about 2,300 ft.

The typical section as shown on the project plans is displayed in Figure 68. Note that the FDR depth was increased to 10 inches. In addition, at the time of FWD testing, the hot-mix asphalt (HMA) surface layer (i.e., SP-C, SAC-A, PG 64-22) was not yet placed. The FWD results are summarized in Table 32, and the backcalculated base layer modulus is shown in Figure 69. A careful segmentation of the base and subgrade modulus is shown in Figure 70 and Figure 71, respectively. Overall, the backcalculated base layer modulus was adequate, with 2 out of 41 (or less than 5 percent) observations falling below the 200 ksi design assumption.

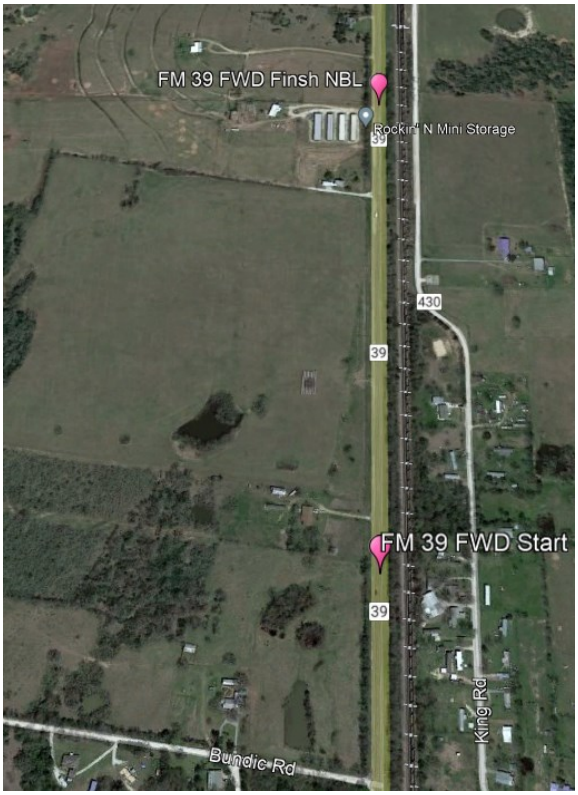


Figure 67. Location of the FWD test limits on BRY FM 39.

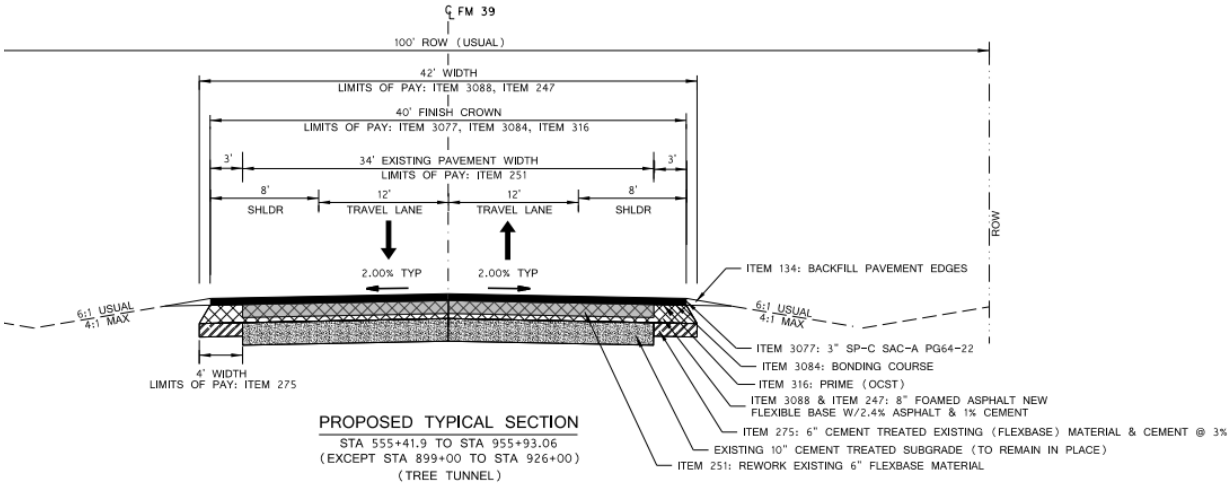


Figure 68. Typical pavement section on BRY FM 39.

Table 32. Summary of FWD Results from BRY FM 39.

Direction	3-Layer Backcalculated	4-Layer Backcalculated[a]
Avg. Normalized Deflection (mi)	10.79	10.79
Adjusted Mean Base Modulus (ksi)	734	818
Adjusted Mean Subbase Modulus (ksi)	Not applicable	14.7
Adjusted Mean Subgrade Modulus (ksi)	12.1	12.7
Avg. Absolute Error/Sensor	3.44	2.55
% of Observations w/ Base Modulus < 200 psi	4.9	7.3

[a] Includes 10-inch treated subgrade shown on plans (Figure 68).

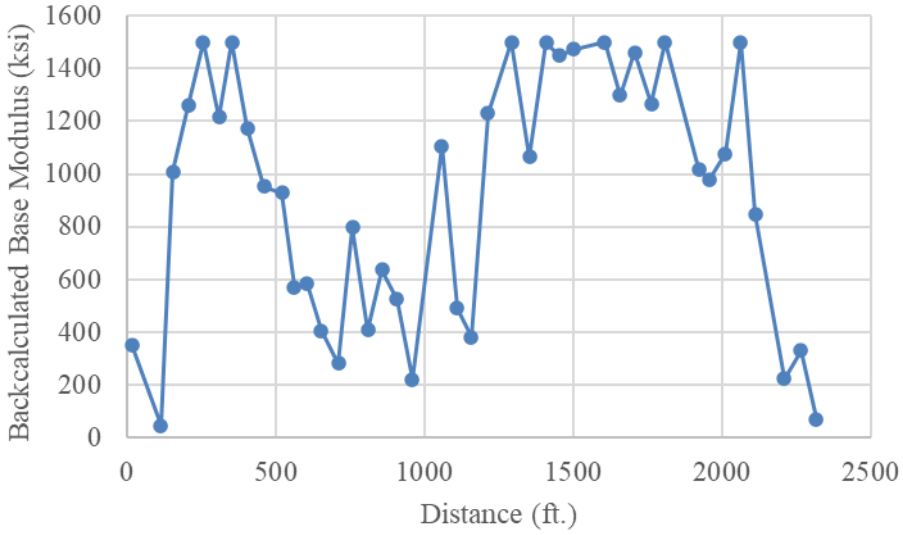


Figure 69. BRY FM 39 three-layer backcalculated base layer modulus with distance northbound.

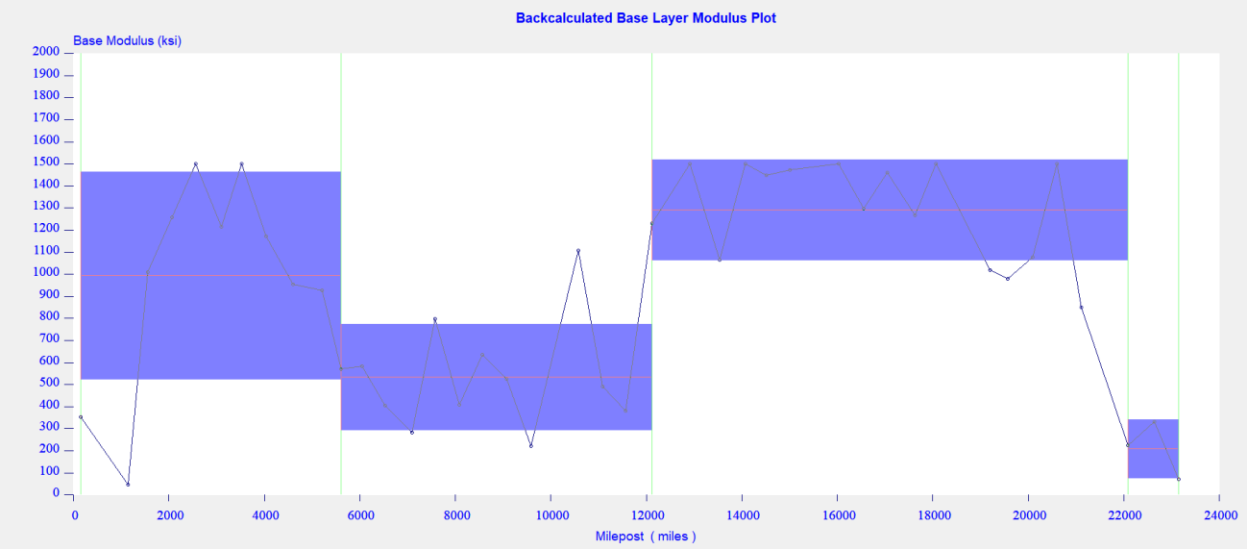


Figure 70. Base layer modulus segments for BRY FM 39.

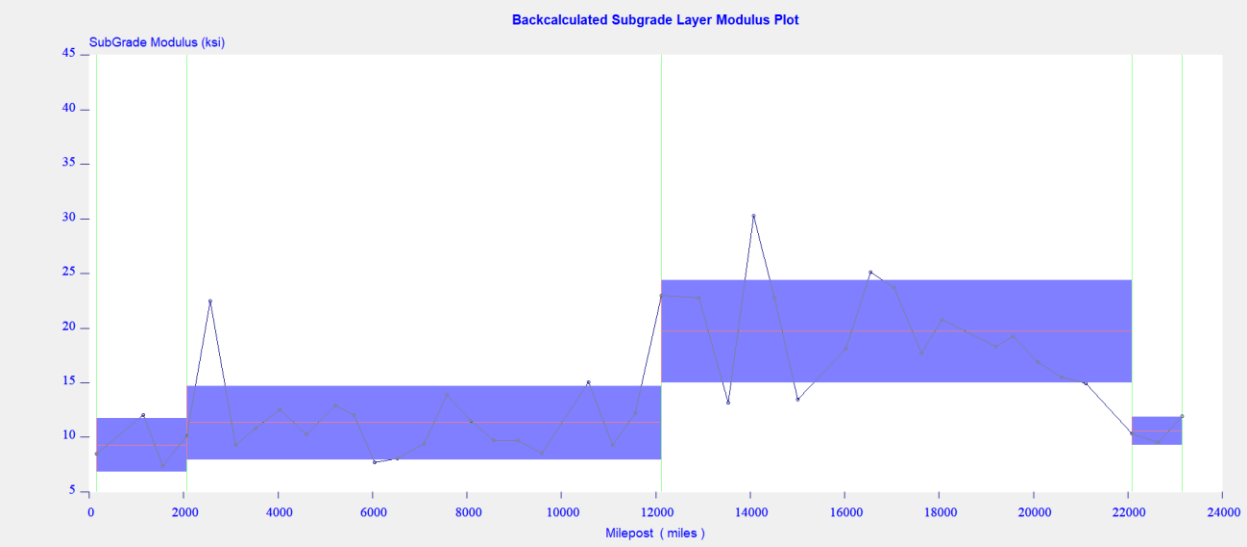


Figure 71. Subgrade layer modulus segments for BRY FM 39.

ODA BI 20

This pavement section is located in Midland County, from Fairground Road to IH 20, in the Odessa District. Visual inspection of the surface of the pavement indicated no apparent distress. The as-built FWD survey was conducted in November 2023 within the limits shown in Figure 72.

The typical section of the pavement structure as shown on the project plans is displayed in Figure 73, with a 2-inch HMA surface layer over a 12-inch emulsion-treated base layer. The FWD results are summarized in Table 33, and the backcalculated base layer modulus is shown in Figure 74 for the eastbound direction and Figure 75 for the westbound direction.

Figure 72. Location of the FWD test limits on ODA BI 20.

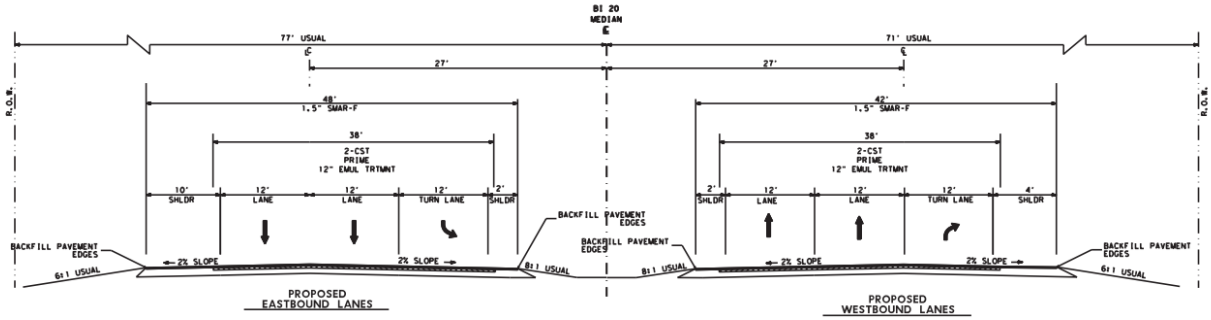


Figure 73. Typical pavement section on ODA BI 20.

Table 33. Summary of FWD Results from ODA BI 20.

Direction	Eastbound	Westbound
Avg. Normalized Deflection (mi)	7.36	6.2
Adjusted Mean Base Modulus (ksi)	238	351
Adjusted Mean Subgrade Modulus (ksi)	29.8	33.4
Avg. Absolute Error/Sensor	5.38	4.77
% of Observations w/ Base Modulus < 200 ksi	35.6	19.0

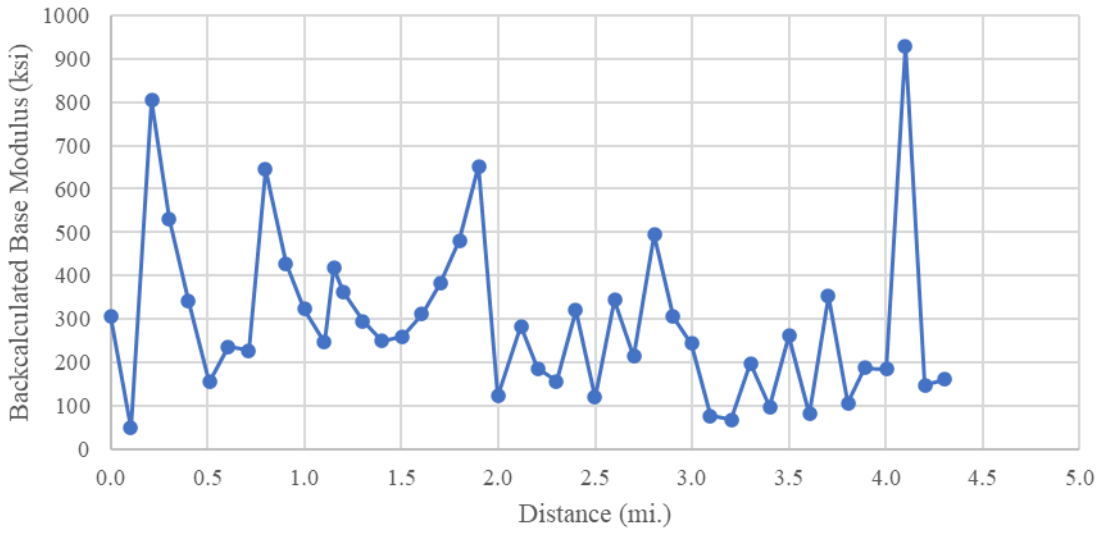


Figure 74. Backcalculated base layer modulus with distance eastbound for ODA BI 20.

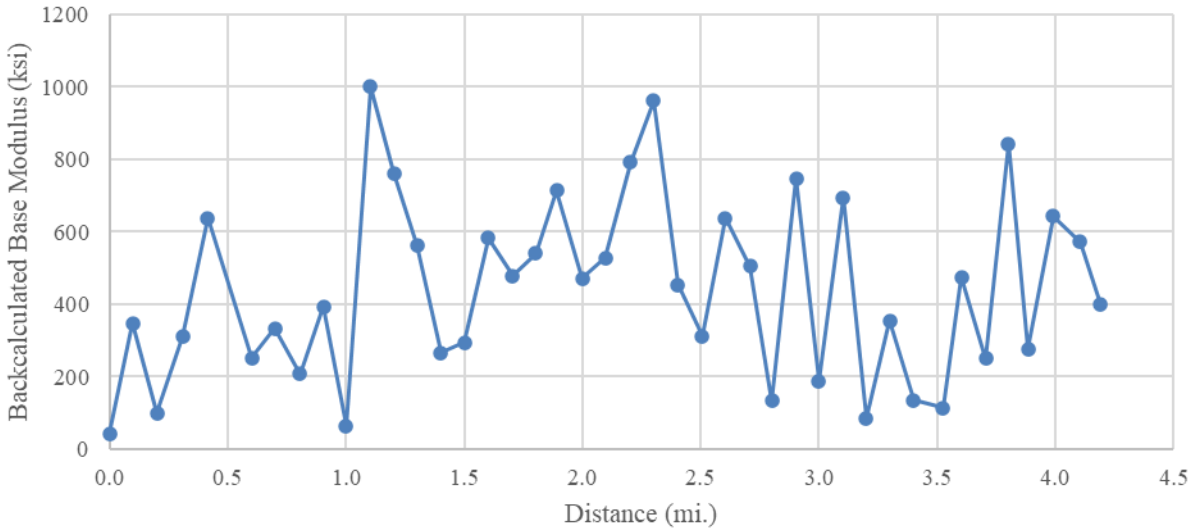


Figure 75. Backcalculated base layer modulus with distance westbound for ODA BI 20.

Overall, the backcalculated adjusted mean base layer modulus exceeded the design assumption in both directions, although around 35 percent and 19 percent of the observations had a base modulus below the 200 ksi design assumption for the eastbound and westbound directions, respectively.

CHAPTER 7:
SUMMARY AND RECOMMENDATIONS

LITERATURE REVIEW

FDR with asphalt binders continues to garner strong interest within TxDOT. Current experiences with FDR in Texas were obtained via an online questionnaire. The responses from several districts (i.e., Bryan, Lubbock, San Antonio, and Waco) and the MTD demonstrate that all TxDOT labs with the capability to perform FDR mix designs with emulsion or foamed asphalt are using 4-inch diameter specimens, and most of these labs are using the SGC to prepare specimens. These laboratories cited the ability to process less material, evaluate more specimens, and/or secure available equipment as reasons for using that specimen size. In addition, these labs are not adjusting the mix design procedure or IDT strength thresholds or employing a standardized IDT strength test temperature. More importantly, most of these districts report adequate field performance of FDR projects (although the experience is not recent). These observations indicate that the current TxDOT FDR mix design procedures produce pavement layers that, when constructed properly, perform well in the field. However, based on recent laboratory measurements reported in the literature, it is also apparent that specimen size and test temperature can be key factors in the output IDT strength.

Other relevant literature review information indicates:

- Sample sizes used by other agencies for mix design vary widely. Some agencies only use 6-inch diameter, some allow 6-inch or 4-inch diameter, and one agency only uses 4-inch diameter specimens.
- SGC with 30 gyrations and Marshall compaction with 75 blows per face were the most common reported compaction methods.
- Some agencies place tighter controls on laboratory climate and testing conditions, implying temperature at time of mixing and time of testing may need consideration in the test procedure.

Acceptance criteria also vary widely across agencies. In general, agencies that design using IDT strength employ thresholds that are lower than the 50 and 30 psi dry and moisture-conditioned minimum values currently included in TxDOT's FDR specification requirements. Many other agencies use IDT strength mix design requirements in the range of approximately 15 to 35 psi (*7*, *8*). This observation may suggest that the current TxDOT procedures and requirements could produce mixtures that are over-stabilized or too stiff. In addition, the allowance of different sample sizes in the mix design may result in mixes designed to different standards or produce different recommended treatment rates. In preparation for the launch of the 2024 Standard Specifications, TxDOT needed accepted, adopted test procedures to support the anticipated items of work for FDR using emulsified asphalt or foamed asphalt. The objective of this research project was to provide information needed to update these test procedures.

LABORATORY STUDY

The research team identified six candidate field projects in various districts located in west (ODA), central (BRY), and east (ATL) Texas. The materials were characterized and used to develop mix designs with emulsified asphalt or foamed asphalt following Tex-122-E and Tex-134-E, respectively. Further, the research team designed a laboratory experiment to identify factors having an influence on IDT strength, including specimen size, compaction level, emulsion temperature, curing time, curing temperature, IDT test temperature, and cement type. The effect of additional variables including binder type, conditioning, binder content, and moisture content were also explored. The research team formulated a series of questions and employed trend analysis and one-way ANOVA to identify which factors had an influence on IDT strength and the magnitude of that influence.

The results of the analysis showed that IDT strength decreased with added binder content for the specimens of the two field projects in which that laboratory study factor was explored (i.e., BRY OSR and ATL FM 3129), and IDT strength decreased with increasing MC. IDT strength was significantly influenced by the conditioning procedure (i.e., water submersion) and to a lesser extent by binder type, with water submersion reducing IDT strength and foamed asphalt specimens yielding less IDT strength than emulsified asphalt specimens. The laboratory study factors that had a significant effect on IDT strength of the specimens in this study based on the two types of analyses (trend and one-way ANOVA) included:

- Specimen Size.
- Compaction Level.
- Curing Time.
- Curing Temperature.
- Testing Temperature.

The laboratory study factors that did not significantly influence IDT strength based on the two types of analyses included emulsion temperature and cement type.

INTERLABORATORY STUDY

The research team conducted an ILS and determined repeatability (within laboratory, *r*) and reproducibility (between laboratory, *R*) limits for the dry and wet IDT strength results for both emulsified asphalt and foamed asphalt 4-inch diameter specimens. Four laboratories participated in this study: TTI, MTD, SAT, and Terracon. Three materials were collected and processed for the ILS: two roadway-sampled materials and one stockpile-sampled material.

ASTM E691 was used to calculate the precision statement. Because the standard test method recommends a minimum of six laboratories for developing precision statements, the calculations shown herein should be considered preliminary. Four distinct cases were considered: emulsified

asphalt unconditioned (dry) and conditioned (submerged) as well as foamed asphalt unconditioned (dry) and conditioned (submerged).

According to the standard test method, the results were summarized, and consistency statistics were calculated to flag any outliers. None were identified, and all reported results were used in the calculations. The resulting repeatability and reproducibility limits based on the maximum *r* and *R* values obtained for the three types of materials included in the ILS ranged between 16 and 20 and between 19 and 54, respectively.

FIELD EVALUATION

The field evaluation showed that constructed projects had adjusted mean base modulus values exceeding the 200 ksi design assumption. Some individual FWD drops revealed spot locations below 200 ksi, which is not desirable but also not necessarily unusual with field variability. The percentage of individual observations less than 200 ksi ranged from about 5 to 35 percent. Overall, the field evaluation showed that projects developed with the mix design procedures met design assumptions. Future efforts should include monitoring the long-term performance of FDR sections.

RECOMMENDATIONS

Test Procedures

Based on the findings in this research and feedback from stakeholders, the test procedures for FDR mixture design with emulsified asphalt or foamed asphalt should be updated with the following changes:

- Based on practical considerations in laboratory material quantities, specimen preparation, and testing, for **specimen size**, the procedures should only use the 4-inch diameter sample size. If both 4-inch and 6-inch diameter specimen sizes were to be included in the mix design methods, it is recommended to adjust the pass/fail thresholds for the 6-inch diameter specimens to a minimum of 35 psi for dry specimens and a minimum of 22.5 psi for submerged specimens.
- For **compaction**, the number of gyrations should be fixed. While the data suggest 100 to 150 gyrations should be used to compact to target density, given that N = 100 yielded IDT strength values closely aligned with the ones obtained when compacting to target density, and N = 150 was the average number of gyrations required to achieve compaction to target density for the control specimens, the research team (in discussion with stakeholders) decided to instead require a moisture-density curve on treated material and then use 75 gyrations for compacting treated IDT mix design specimens.
- **Curing time** should remain minimum 72 hours at 104°F given that curing to constant mass required less than the control 72 hours, which yielded lower IDT strength values.

However, an upper limit should be considered to avoid obtaining larger IDT strength values.

- **Curing temperature** should also remain at 104°F given that curing at an elevated temperature of 140°F significantly increased the IDT strength.
- The **IDT test temperature** should be recorded, and the allowable temperature range should be tightened to 72° ± 2°F. However, in discussion with stakeholders, the tighter temperature tolerance was deemed difficult to implement. An adjustment factor could be considered for cases when the testing temperature exceeds the revised upper limit.

Appendix H and Appendix I present the updated draft mix design procedures for FDR with emulsified asphalt and foamed asphalt, respectively.

Construction Specifications

This research focused primarily on laboratory mixture design factors that could impact the IDT strength result. In the context of construction specifications, the key recommendation from this research is to eliminate the UCS requirement from the construction specification.

FUTURE RESEARCH

Based on the information collected in this project during the literature review, laboratory factor study, interlaboratory study, and field observations, researchers recommended further exploring the following items:

- Review the mix design criteria in the current procedures to avoid overdesigning the emulsified asphalt or foamed asphalt specimens.
- Evaluate the long-term performance of existing FDR field projects to ensure they have adequate durability and are achieving their intended service life when designed using the current mix design procedures.
- Evaluate the increase in IDT strength with curing time in order to incorporate an upper bound to the curing time specified in the current mix design procedures.
- Explore alternative methods to obtain treated M-D curves that are more practical and less time consuming.

REFERENCES

1. Asphalt Recycling and Reclaiming Association (ARRA). *Basic Asphalt Recycling Manual*. ARRA, Glen Ellyn, IL, 2015.

2. Kaseer, F., Arambula-Mercado, E., Epps, J., Epps Martin, A., and Ceccovilli, R. Full-Depth Reclamation (FDR) Mix Design: Proposed Revisions to the Indirect Tensile Strength Thresholds. *Construction and Building Materials*, Vol. 254, 2020. doi:10.1016/j.conbuildmat.2020.119283

3. Epps, J., Sebaaly, P.E., Penaranda, J., Maher, M.R., McCann, M.B., and Hand, A.J. *Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design*. NCHRP Report 444, National Academies Press, 2000.

4. Hilbrich, S., and Scullion, T. *Laboratory and Field Evaluation of Mix Design Specifications for Asphalt Emulsion Full Depth Reclamation Stabilization*. Report No. 401741-1, SemMaterials, LP, Texas Transportation Institute, 2008.

5. Franco, S., Moss, S.P., Yuan, D., and Nazarian, S. *Design, Constructability Review and Performance of Dual Base Stabilizer Applications*. Report FHWA/TX-09-0-5797-1, Center for Transportation Infrastructure Systems, Texas Department of Transportation, 2009.

6. Taylor, R., Sebesta, S., Al-Khayat, H., and Rew, Y. *Precision Statistics*. Product 0-6880-P4, Texas A&M Transportation Institute, Texas Department of Transportation, 2021.

7. Wirtgen GmbH. *Wirtgen Cold Recycling Technology.* Wirtgen GmbH, Windhagen, Germany, 2012.

8. Council for Scientific and Industrial Research. *Technical Guideline: Bitumen Stabilised Materials—A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials.* Asphalt Academy, CSIR, South Africa, 2009.

APPENDIX A:
QUESTIONNAIRE ON FDR MIX DESIGN AND FIELD PERFORMANCE

Q1 Please provide your name and contact information.

- ☐ Name _____
- ☐ E-mail address _____
- ☐ Phone number _____

Q2 Please indicate the District or Division you represent.

Abilene	Laredo
Amarillo	Lubbock
Atlanta	Lufkin
Austin	Materials and Testing
Beaumont	Odessa
Brownwood	Paris
Bryan	Pharr
Childress	San Angelo
Corpus Christi	San Antonio
Dallas	Tyler
El Paso	Waco
Fort Worth	Wichita Falls
Houston	Yoakum

Q3 What type of asphalt binder is typically employed in Full Depth Reclamation (FDR) projects?
(select one below)

- ○ Asphalt emulsion
- ○ Foamed asphalt
- ○ Both asphalt emulsion and foamed asphalt (please specify approximate portion for each type in percent) _____

Q4 What specimen size is used for asphalt emulsion and/or foamed asphalt FDR mix design?
(select one below)

- ○ 6-inch diameter (please specify thickness)
  _____
- ○ 150 mm diameter (please specify thickness)
  _____
- ○ 4-inch diameter (please specify thickness)
  _____
- ○ 100 mm diameter (please specify thickness)
  _____
- ○ Other (please specify) _____

Q5 What type of compactor is employed for asphalt emulsion and/or foamed asphalt FDR specimen preparation?
(select one below)

- ○ Superpave Gyratory Compactor (please specify brand)
  _____
- ○ Texas Gyratory Compactor (please specify brand)
  _____
- ○ Other (please specify type and brand)
  _____

Q6 What are the primary reasons of conducting asphalt emulsion and/or foamed asphalt FDR mix designs using the specimen size, type of compactor, and type of binder indicated in the previous questions?
(please describe)

_____

_____

_____

_____

_____

Q7 Select the test temperature used when conducting the indirect tensile strength test as part of the asphalt emulsion and/or foamed asphalt FDR mix design.

60 63 66 69 72 75 78 81 84 87 90

Temperature (F) ()	

Q8 Are any adjustments being done to the indirect tensile strength test criteria for asphalt emulsion and/or foamed asphalt mix design as currently noted in TxDOT specifications? (please describe)

- ○ No adjustments are being done to the specification
- ○ Yes, adjustments are being done to the specification (please describe) _____

Q9 What has been the observed or reported asphalt emulsion and/or foamed asphalt FDR field performance?
(select one below)

- ○ Adequate (please describe) _____
- ○ Inadequate (please describe) _____
- ○ A mix of good performing and bad performing field projects (please describe) _____

Q10 Are there any issues or concerns regarding the current asphalt emulsion and/or foamed asphalt mix design procedure or construction processes?
(select one below)

- ○ There are no major issues
- ○ Yes, there are some issues (please describe) _____

APPENDIX B:
FDR MIX DESIGN PROCEDURES

Table B-1. FDR with Emulsified Asphalt: Sample Fabrication.

Organization (Standard)	Sampling	Mixing Water Content	Mixing	Compaction
AASHTO (draft PP standard)	Coring, test pits, or milling Crush with jaw crusher or laboratory milling machine Type 1 < 8% passing No. 200 sieve Type 2 >= 8% passing No. 200 sieve RAP sieved per AASHTO T 27	Maximum dry density and optimum moisture content of the combined FDR material per AASHTO T 180	Mechanical bucket mixer or laboratory-sized pugmill Room temp. (68–77°F) Emulsified asphalt at expected delivery temp. Mixing time 60s Four emulsified asphalt contents between 1–4%	Cure loose specimens in plastic containers at 104°F for 30 min prior to compaction SGC 30 gyrations 6-in. by 2.95-in. (IDT)
ARRA (FDR 201A)	Representative samples and crush or milled in laboratory Wet (soaked) or dry coring or slabs Milled RAP	ASTM D 698 or D 1557 (standard or modified) 1.5–3.0% typical of that added at milling head	Manual or mechanical mixer (bucket or lab pugmill) Mix water first then emulsified asphalt Mixing water content should be 50 to 75% of optimum Room temp. (77 ± 9°F) Three emulsified asphalt contents Coating test	104°F for 30 min prior to compaction Room temp. SGC 30 gyrations 6.0 in. by 3.0 in Marshall 75 blows per face for 4-in. by 2.5-in. samples No conditioning prior to extrusion

Organization (Standard)	Sampling	Mixing Water Content	Mixing	Compaction
California (CT 313 draft)	Smaller than ¾-in. sieve	—	Mechanical pugmill 77°F	Within 30 min of adding water 77°F AASHTO T 312, SGC 30 gyrations for 100-mm by 2.5-in. samples AASHTO T 245, Marshall 75 blows per face for 4.0-in. by 2.5-in. samples Vibratory hammer for 4-in. by 2.5-in. samples
Illinois (LR 1000-1)	—	—	Mechanical bowl with counter-rotating paddle Mixing temperature 58°F–79°F	104°F for 30 min prior to compaction Room temp. (68–86°F) SGC 30 gyrations for 6.0 in. by 2.75–3.25 in. samples
South Africa (Sabita TG-2)	Bulk samples from test pits, borrow pits, or quarries	Min. 1–2% moisture in the aggregate prior to adding the emulsified asphalt	Aggregate temp. min. 10°C Emulsified asphalt temp. 50–60°C Optimum water minus gross emulsified asphalt content 30-sec mixing time Add emulsified asphalt 45-sec mixing time	Vibratory hammer compactor 152 ± 0.5 mm by 95 mm in two layers for ITS specimens Vibratory hammer compactor 150 ± 0.5 mm by 300 mm in five layers for triaxial specimens

Organization (Standard)	Sampling	Mixing Water Content	Mixing	Compaction
Texas (Tex-122-E)	Use equipment that produces a similar gradation as field production	70% of optimum with Tex-113-E without additive or emulsified asphalt	Mechanical lab mixer	Compact immediately after mixing SGC 4-in. by 2-in. or 6.0 in. by 3.75 in. samples for IDT testing Texas impact compactor for 6-in. by 8-in. samples for unconfined compression testing TxGC allowed but not specified
Virginia (SP315-000420-00)	—	—	ASTM 5581 for 6-in. specimens AASHTO T 245 for 4-in. specimens	SGC 30 gyrations Marshall 75 blows per face
West Virginia (U335-31-2.60 applies to emulsified asphalt or foamed asphalt)	—	—	Follows ASTM D1633, Method A	Cure wrapped in plastic sealed for 7 days
Wirtgen (Wirtgen Manual)	Test pit or milling	Add various percentages of emulsified asphalt and adjust water content to obtain optimum fluids content by standard compaction	Laboratory pugmill	Marshall 75 blows per face for 4.0-in. by 2.5-in. samples Modified AASHTO (T 180) for 6-in. by 4-in. samples when using large maximum size aggregates

Table B-2. FDR with Emulsified Asphalt: Sample Conditioning and Testing.

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
AASHTO (draft PP standard)	IDT dry	140°F to constant mass for 16–48 hr Cool down at 77°F for 12–24 hr Soak in plastic bag at 77 ± 9°F for min. 2 hr	77°F	Min. 40 psi for Type 1 Min. 35 psi for Type 2	—
	IDT wet	140°F to constant mass for 16–48 hr Cool down at 77°F for 12–24 hr Vacuum saturation to 55–75% per AASHTO T 283 Soak at 77 ± 9°F for 24 hr	77°F	Min. 25 psi for Type 1 Min. 20 psi for Type 2	—
	Ratio residual emulsified asphalt to cement	—	—	Min. 2.5:1	—
ARRA (FDR 201A)	IDT dry	140°F to constant weight for 16–48 hr Room temp. for 12–24 hr Plastic bag in water for 30–45 min at 77 ± 2°F	77°F	Min. 40 psi	Mix water 1–2% Asphalt binder 0.5%
	IDT wet	140°F to constant weight for 16–48 hr Room temp. for 12–24 hr Vacuum saturation to 55–75% Soak at 77 ± 2°F for 24 hr	77°F	Min. 25 psi	—
	TSR	—	77°F	Min. 0.70	—
	Marshall dry	140°F to constant weight for 16–48 hr Room temp. for 12–24 hr Plastic bag in water for 30–45 min at 104 ± 2°F		Min. 1,250 lb	—

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
	Marshall wet	140°F to constant weight for 16–48 hr Room temp. for 12–24 hr Soak at 77 ± 2°F for 23 hr Soak at 104 ± 2°F for 1 hr	—	—	—
	Marshall retained stability	104°F	104°F	Min. 0.70	—
	Raveling	—	—	Max. 7%	—
	RAP coating	—	—	Min. “good”	—
	Ratio residual emulsified asphalt to cement	—	—	Min. 3:1	—
California (CT 313 draft)	IDT dry	104°F to constant weight or min. 72 hr Cool down at 77°F for 24 hr	77°F	—	
	IDT wet TSR	104°F to constant weight or min. 72 hr Cool down at 77°F for 24 hr Vacuum saturation to 55–75% Soak at 77 ± 2°F for 23 hr	77°F	—	
	Marshall stability dry	104°F for 2 hr	—	—	—
	Marshall stability wet	Soak at 104°F for 1 hr	—	Min. 1,500 lb Min. 70% retained	
Illinois (LR 1000-1)	IDT dry	72 hr at 104 ± 4°F	77°F	45 psi	—
	IDT wet	72 hr at 104 ± 4°F Vacuum saturation to min. 55 percent Soak at 77 ± 2°F for 24 hr	77°F	30 psi	—

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
South Africa (Sabita TG-2)	IDT dry	Min. 72 hr at 104°F + 4 hr at 104°F + 24 hr at 104°F if needed (until constant mass) Cool down min. 20 hr at 77°F	77°F	33 psi for high strength material (G4) 25 psi for medium strength material (G5 and G6)	—
	IDT wet	Min. 72 hr at 104°F + 4 hr at 104°F + 24 hr at 104°F if needed (until constant mass) Cool down min. 20 hr at 77°F Soak 24 hr at 77°F Surface dry	77°F	18 psi for high strength material (G4) 14.5 psi for medium strength material (G5 and G6)	
	Triaxial dry	8 hr at 104°F Seal in plastic bags 48 hr at 104°F Seal in fresh plastic bags Cool down min. 12 hr at 77°F	77°F	36–38 psi cohesion for high strength material 29–33 psi cohesion for medium strength material	
	Triaxial wet	8 hr at 104°F Seal in plastic bags 48 hr at 104°F Remove from bag and soak 24 hr Surface dry	77°F	75% retained cohesion for high strength material 65–75% retained cohesion for medium strength material	
Texas (Tex-122-E)	IDT dry TxGC 4-in. diameter samples and SGC 4-in. or 6-in. diameter samples	72 hr at 104 ± 4°F 24 hr at room temp.	Room temp.	50 psi	—

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
	IDT wet TxGC 4-in. diameter samples and SGC 4-in. or 6-in. diameter samples	72 hr at 104 ± 4°F 24 hr soak at room temp.	Room temp.	30 psi	—
	Unconfined compressive strength	72 hr at 104 ± 4°F 24 hr soak at room temp.	Room temp.	120 psi	—
Virginia (SP315-000420-00)	Marshall stability 4-in. and 6-in. diameter specimens	140°F to constant mass 104°F for 2 hr immediately prior to testing	—	Min. 2,500 lb for 6-in. specimens Min. 1,250 lb for 4-in. specimen	—
West Virginia (U335-31-2.60 applies to emulsified asphalt or foamed asphalt)	UCS dry	—	—	200–400 psi at 7 days	—
Wirtgen (Wirtgen Manual)	IDT dry 4-in or 6-in. diameter samples	72 hr at 104°F, cool to 77°F	77°F	18 to 33 psi depending on class of material	—
	IDT wet 4-in. or 6-in. samples	72 hr at 104°F plus 24 hr soak at 77°F	77°F	7 to 14 psi depending on class of material	
	IDT equal 6-in. diameter samples only	24 hr at 86°F plus 48 hr sealed at 104°F, cool to 77 F	77°F	14 to 25 psi depending on class of material	
	IDT soak 6-in. diameter samples only	24 hr at 86°F plus 48 hr sealed at 104°F plus 24 hr soak at 77°F	77°F	7 to 14 psi depending on class of material	

Table B-3. FDR with Foamed Asphalt: Sample Fabrication.

Organization (Standard)	Sampling	Mixing Water Content	Mixing	Compaction
ARRA (CR 202)	Representative samples and crush or milled in laboratory Wet or dry coring or slab Milled samples	ASTM D1557 (modified proctor) If not well-defined optimum, use 3–4%	Mechanical bucket mixer or pugmill Mix water first then emulsified asphalt Mixing water content should be 75% of optimum Three foamed asphalt contents Typical binder contents of 1.5 to 3.0 Room temp. 77 ± 9°F	No conditioning prior to compaction Room temp. 77 ± 9°F SGC 30 gyrations 6.0-in. by 3.7-in. samples Marshall 75 blows per face 4.0-in. by 2.5-in. samples Extrude within 24 hr after compaction
Australia (Austroads AP-T178/11)	Coring and test pits	PI < 6, 70% of opt. water content PI 6–10, 75% of opt. water content	Laboratory mixer or pugmill 3–4% asphalt binder, 1.0–2.0% lime	No curing prior to compaction Marshall 4.0-in. by 2.5-in. with 50 blows per face Gyropac 80 cycles
California (CT 313 draft)	Smaller than ¾-in. sieve	—	Mechanical pugmill 77°F	Within 30 min of adding water 77°F AASHTO T 312, SGC 30 gyrations for 4-in. by 2.5-in. samples AASHTO T 245, Marshall 75 blows per face for 4.0-in. by 2.5-in. samples Vibratory hammer for 4-in. by 2.5-in. samples
Illinois (LR 1000-2)	—	—	Mechanical pugmill	Marshall 75 blows for 6.0 in. by 2.5 in. samples
Maryland (SS 926.01)	—	—	Follows AASHTO T 245 or AASHTO T 312	SGC 30 gyrations Marshall 75 blows

Organization (Standard)	Sampling	Mixing Water Content	Mixing	Compaction
South Africa (Sabita TG-2)	Bulk samples from test pits, borrow pits or quarries	—	Aggregate temp min. 15°C Twin-shaft pugmill mixer 75% OMC 30 sec mixing time Add foamed asphalt 30 sec mixing time Remaining 25% OMC Further 30 sec mixing time	Vibratory hammer compactor 152 ± 0.5 mm by 95 mm in two layers for ITS specimens Vibratory hammer compactor 150 ± 0.5 mm by 300 mm in five layers for triaxial specimens
Texas (Tex-134-E)	Use equipment that produces a similar gradation as field production	Optimum with Tex-113-E without additive or foamed asphalt	Laboratory mixer or pugmill	Compact immediately after mixing TxGC-4.0-in. by 2.0-in. samples for IDT testing SGC-4.0-in. by 20-in. or 6.0-in. by 3.75-in. samples for IDT testing Texas impact compactor for 6.0-in. by 8.0-in. samples for UCS testing
Virginia (SP315-000420-00)	—	—	Follows AASHTO T 312	SGC 30 gyrations Marshall 75 blows per face
West Virginia (U335-31-2.60 applies to emulsified asphalt or foamed asphalt)	—	—	Follows ASTM D1633, Method A	Cure wrapped in plastic sealed for 7 days
Wirtgen (Wirtgen Manual)	Test pit or milling	75% (range from 70–90% of optimum moisture content by modified AASHTO [T 180])	Laboratory pugmill	Marshall 75 blows per face for 2.5-in. by 4-in. samples Modified AASHTO (T 180) for 6.0-in. by 4.0-in. samples when use large maximum size aggregates

Table B-4. FDR with Foamed Asphalt: Sample Conditioning and Testing.

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
ARRA (CR 202)	IDT dry	104°F for 16–72 hr Room temp for 12–24 hr Plastic bag in water for 30–45 min at 77 ± 2°F	77°F	Min. 45 psi	Mix water 1-2% Asphalt binder 0.5%
	IDT wet	104°F for 16–48 hr Room temp for 12–24 hr Vacuum saturation to 55–75% Soak at 77 ± 9°F for 24 hr	77°F		
	TSR	—	77°F	Min. 0.70	
	Ratio residual asphalt to cement	—	—	Min. 2.5:1	
Australia (Austroads AP-T178/11)	IDT Mr	3 hr at 77°F 3 days at 104°F 3 days at 104°F plus vacuum saturation for 10 min	77°F	100,000 psi 435,000 psi 260,000 psi for 100 to 1,000 ESA per day	—
	IDT Mr retained ratio	3 days at 104°F plus vacuum saturation for 10 min	77°F	0.45	—
	Rut resistance	Slabs and wheel tracking test after curing for 3 days at 104°F	77°F	7 mm	—
California (CT 313 Draft)	IDT dry	72 hr at 104°F or constant mass, whichever is longer Cooling at 77°F	77 ± 4°F	None	—
	IDT wet	72 hr at 104°F plus soak for 24 hr in water 68–77°F, cover with damp cloth at ambient temp. of 77 ± 4°F	77 ± 4°F	Min. 30 psi	
	TSR	—	77 ± 4°F	Min. 0.70	
	Temperature sensitivity (optional)	Make samples at 68°F and 86°F and test for IDT strength	68°F	Min. 15 psi above 77°F samples	

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
Illinois (LR 1000-2)	IDT dry	72 hr at 104 ± 4°F	77°F	45 psi	—
	IDT wet	72 hr at 104 ± 4°F Vacuum saturation to min. 55% Soak at 77 ± 2°F for 24 hr	77°F	30 psi	—
Maryland (SS 926.01)	IDT wet	24 hr soak at 77°F	—	Min. 45 psi	—
	TSR	—	—	Min. 0.70	
South Africa (Sabita TG-2)	IDT dry	Min. 72 hr at 104°F + 4 hr at 104°F + 24 hr at 104°F if needed (until constant mass) Cool down min. 20 hr at 77°F	77°F	33 psi for high strength material (G4) 25 psi for medium strength material (G5 and G6)	—
	IDT wet	Min. 72 hr at 104°F + 4 hr at 104°F + 24 hr at 104°F if needed (until constant mass) Cool down min. 20 hr at 77°F Soak 24 hr at 77°F Surface dry	77°F	18 psi for high strength material (G4) 14.5 psi for medium strength material (G5 and G6)	
	Triaxial dry	8 hr at 104°F Seal in plastic bags 48 hr at 104°F Seal in fresh plastic bags Cool down min. 12 hr at 77°F	77°F	36–38 psi cohesion for high strength material 29–33 psi cohesion for medium strength material	
	Triaxial wet	8 hr at 104°F Seal in plastic bags 48 hr at 104°F Remove from bag and soak 24 hr Surface dry	77°F	75% retained cohesion for high strength material 65–75% retained cohesion for medium strength material	

Organization (Standard)	Test Method	Conditioning	Test Temperature	Criteria	Field Adjustments
Texas (Tex-134-E)	IDT dry TxGC 4-in. diameter samples and SGC 4-in. or 6-in. diameter samples	72 hr at 104 ± 4°F plus 24 hr at room temp.	Room temp.	50 psi	—
	IDT wet TxGC 4-in. diameter samples and SGC 4-in. or 6-in. diameter samples	72 hr at 104 ± 4°F plus 24 hr soak at room temp.	Room temp.	30 psi	
	Unconfined compressive strength wet	72 hr at 104 ± 4°F plus 24 hr soak at room temp.	Room temp.	120 psi	
Virginia (SP315-000420-00)	IDT dry	104°F for 72 hr Cool down for 24 hr	—	45 psi	—
West Virginia (U335-31-2.60 applies to emulsified asphalt or foamed asphalt)	UCS dry	—	—	200–400 psi at 7 days	—
Wirtgen (Wirtgen Manual)	IDT dry 4-in. or 6-in. diameter samples	72 hr at 104°F, cool to 77°F	77°F	18 to 33 psi depending on class of material	—
	IDT wet 4-in. or 6-in. samples	72 hr at 104°F plus 24 hr soak at 77°F	77°F	7 to 14 psi depending on class of material	
	IDT equal 6-in. diameter samples only	30 hr at 86°F plus 48 hr sealed at 104°F, cool to 77°F	77°F	14 to 25 psi depending on class of material	
	IDT soak 6-in. diameter samples only	24 hr at 86°F plus 48 hr sealed at 104°F plus 24 hr soak at 77 ± 4°F	77°F	7 to 14 psi depending on class of material	

APPENDIX C:
FDR MIX DESIGN RESULTS

Table C-1. Mixture Design Development Strength Results.

Roadway	Mixture Proportions	Asphalt Type	Asphalt Content (%)	Cement Content (%)	Unconditioned IDT Strength (psi)	Conditioned IDT Strength (psi)	UCS (psi)
FM 3129 Emulsion	100% Salvage RAP	Foam	2.0	1	65	61	86
		Foam	2.4	1	72	63	103
		Emulsion	4.0	1	60	50	121
FM 3129 Foam	20% Salvage Base + 80% Salvage RAP	Foam	2.4	1	64	46	170
		Foam	2.8	1	54	40	–
US 80	50% Salvage Base + 50% Salvage RAP	Emulsion	4.3	1	65	60	170
		Emulsion	4.8	1	68	52	138
		Emulsion	5.3	1	60	48	123
OSR	100% Salvage Base	Foam	2.6	1	97	53	146
		Foam	3.0	1	86	51	–
FM 39	100% Frost Pit New Base	Foam	2.4	1	62	35	138
		Foam	2.8	1	58	36	131
SH 207	55% Salvage Base + 21% Salvage RAP + 24% DWG Pit New Base	Foam	2.6	1	73	35	123
		Foam	3.0	1	65	37	–
		Emulsion	4.3	1	86	53	121
		Emulsion	5.0	1	80	60	–
BI 20	100% Salvage Base	Emulsion	4.2	1	76	52	136
		Emulsion	4.8	1	78	43	135

Note: Underlined results correspond to the selected final mixture design parameters.

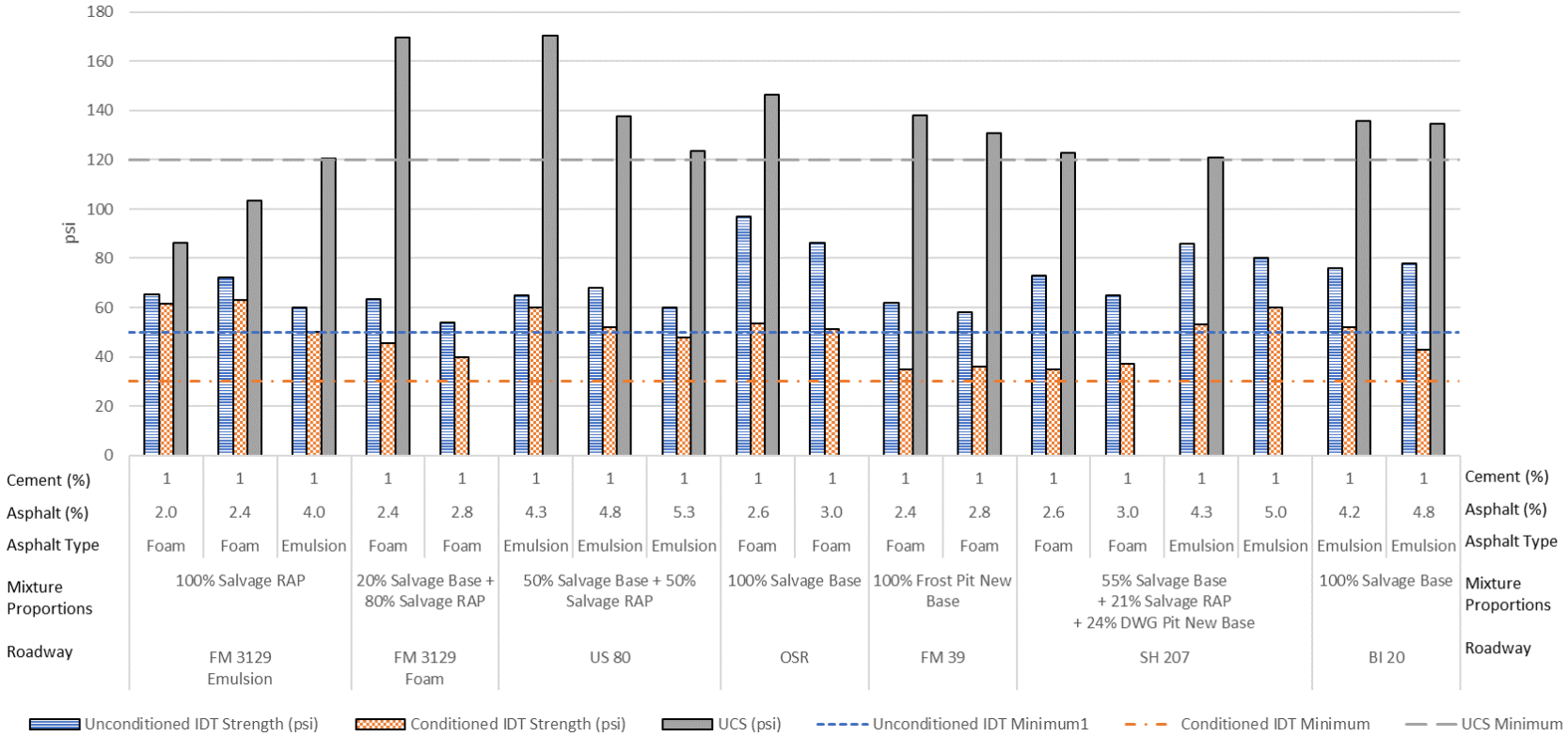


Figure C-1. Mixture design development strength results with test method thresholds.

Table C-2. Mix Design Parameters for the ILS Materials.

District	**ATL**		**BWD**		**SJT**	
Roadway	**US 80**		**FM 2214**		**SH 137**	
Asphalt Type	Emulsified	Foamed	Emulsified	Foamed	Emulsified	Foamed
Material Proportions	100% Salvage Base	100% Salvage Base	100% Salvage Base	100% Salvage Base	100% Stockpile Base	100% Stockpile Base
Design Asphalt Content (%)	3.8	2.2	4.0	2.4	4.0	2.4
Asphalt Type	CSS-1H	PG 64-22	CSS-1H	PG 64-22	CSS-1H	PG 64-22
Cement Content (%)	1.0	1.0	1.0	1.0	1.0	1.0
Optimum Moisture Content (%)	7.4	7.4	5.7	5.8	8.3	7.9
Maximum Dry Density (pcf)	130.5	127.9	139.3	137.2	127.8	130.6
Unconditioned IDT Strength (psi)	62*	50*	–^	73	79*	71*
Conditioned IDT Strength (psi)	49*	32*	–^	37	53*	42*

* Indicates value was measured using the untreated moisture-density curve optimum moisture content.
^ Indicates that the IDT strength was not measured.

APPENDIX D: ILS INSTRUCTIONS

FDR Mixture Designs Round Robin Testing

Tex-122-E Emulsified Asphalt (Emulsion) Mixture Design & Tex-134-E Foamed Asphalt Mixture Design

ATL US 80

Step 1:
Add the amount of water listed in Table 1, to each sample in accordance with Tex-122-E and Tex-134-E and allow the sample to stand for 18-24 hours.

Add cement and asphalt stabilizer listed in Table 1 to each sample in accordance with Tex-134-E for foamed asphalt samples or Tex-122-E for asphalt emulsion samples.

Use the foamed asphalt plant or the Superpave gyration compactor (SGC) settings listed in Table 2.

Table 1: Material Weight per Aggregate Split

Aggregate Split	Foam Sample	Emulsion Sample
Mass Water, (lb.):	1.780 lb.	1.418 lb.
Mass Cement, (lb.):	0.240 lb.	0.240 lb.
Mass Asphalt:	239 g Foam	0.912 lb. Emulsion

Table 2: Equipment Settings

Foamed Asphalt Plant	Set Point	SGC	Set Point
Asphalt, Nozzle, and Chamber Temperature	160 °C	Compact threshold	Gyration
Asphalt Pump and Lines Temperature	165 °C	Gyrations (n)	75
Foaming Water Percentage	2.3% (8.3 L/hr.)	Mold Diameter (mm)	100
Air Pressure	5.5 bar	Angle E (deg)	1.25
		Pressure (kPa)	600

Step 2:
Use the single sample wet weight per Table 3 to compact a trial sample.

- Compact **8** IDT test specimens with a diameter of 4 inches and a height of 2 ± 0.1 inches. If the trial sample is not 2± 0.1 inches, adjust the weight in accordance with Tex-122 Section 7.2 /134-E Section 9.2.
- Cure **8** specimens for 72 hours at 104°F ± 5 (40°C).
- Condition **4** specimen for 24 ± 1 hour at 72°F ± 5 (22°C) in air.
- Condition **4** specimen for 24 ± 15 min. at 72°F ± 5 (22°C) in water.

Table 3: Single Sample Wet Weight per Specimen

Aggregate Split	Single Sample Wet Weight
Foam Sample	1.935 lb.
Emulsion Sample	1.975 lb.

During molding, curing, and conditioning phases, record at 0-7076 Data Sheet):

- Height after molding
- Mass after molding
- Number of gyrations
- Height after conditioning
- Mass after conditioning
- Specimen temperature after conditioning (°F), use a handheld infrared thermometer to measure

Step 3:
Perform IDT strength tests on all specimens in accordance with the Tex-122-E and Tex-134-E standards.

After IDT testing, oven dry for 24 ± 1 hour at 230°F (110°C) ± 9 specimen individually to determine moisture content.

During and after IDT testing, record:

- **Maximum load (lb.)**
- Mass of pan
- Wet mass of pan & specimen after testing
- Dry mass of pan & specimen after testing

Send results to Jinho Kim at jinho-kim@tti.tamu.edu
If any questions, contact Jinho Kim at (979) 317-2324
or Ross Taylor at (979) 317-1224

Figure D-1. Instructions for ILS specimen preparation for the ATL US 80 material.

FDR Mixture Designs Round Robin Testing

Tex-122-E Emulsified Asphalt (Emulsion) Mixture Design & Tex-134-E Foamed Asphalt Mixture Design

BWD FM 2214

Step 1:
Add the amount of water listed in Table 1, to each sample in accordance with Tex-122-E and Tex-134-E and allow the sample to stand for 18-24 hours.

Add cement and asphalt stabilizer listed in Table 1 to each sample in accordance with Tex-134-E for foamed asphalt samples or Tex-122-E for asphalt emulsion samples.

Use the foamed asphalt plant or the Superpave gyration compactor (SGC) settings listed in Table 2.

Table 1: Material Weight per Aggregate Split

Aggregate Split	Foam Sample	Emulsion Sample
Mass Water, (lb.):	1.392 lb.	1.000 lb.
Mass Cement, (lb.):	0.240 lb.	0.240 lb.
Mass Asphalt:	261 g Foam	0.960 lb. Emulsion

Table 2: Equipment Settings

Foamed Asphalt Plant	Set Point	SGC	Set Point
Asphalt, Nozzle, and Chamber Temperature	160 °C	Compact threshold	Gyration
Asphalt Pump and Lines Temperature	165 °C	Gyrations (n)	75
Foaming Water Percentage	2.3% (8.3 L/hr.)	Mold Diameter (mm)	100
Air Pressure	5.5 bar	Angle E (deg)	1.25
		Pressure (kPa)	600

Step 2:
Use the single sample wet weight per Table 3 to compact a trial sample.

- Compact **8** IDT test specimens with a diameter of 4 inches and a height of 2 ± 0.1 inches. If the trial sample is not 2± 0.1 inches, adjust the weight in accordance with Tex-122 Section 7.2 /134-E Section 9.2.
- Cure **8** specimens for 72 hours at 104°F ± 5 (40°C).
- Condition **4** specimen for 24 ± 1 hour at 72°F ± 5 (22°C) in air.
- Condition **4** specimen for 24 ± 15 min. at 72°F ± 5 (22°C) in water.

Table 3: Single Sample Wet Weight per Specimen

Aggregate Split	Single Sample Wet Weight
Foam Sample	2.045 lb.
Emulsion Sample	2.142 lb.

During molding, curing, and conditioning phases, record at 0-7076 Data Sheet):

- Height after molding
- Mass after molding
- Number of gyrations
- Height after conditioning
- Mass after conditioning
- Specimen temperature after conditioning (°F), use a handheld infrared thermometer to measure

Step 3:
Perform IDT strength tests on all specimens in accordance with the Tex-122-E and Tex-134-E standards.

After IDT testing, oven dry for 24 ± 1 hour at 230°F (110°C) ± 9 specimen individually to determine moisture content.

During and after IDT testing, record:

- **Maximum load (lb.)**
- Mass of pan
- Wet mass of pan & specimen after testing
- Dry mass of pan & specimen after testing

Send results to Jinho Kim at jinho-kim@tti.tamu.edu
If any questions, contact Jinho Kim at (979) 317-2324
or Ross Taylor at (979) 317-1224

Figure D-2. Instructions for ILS specimen preparation for the BWD FM 2214 material.

FDR Mixture Designs Round Robin Testing

Tex-122-E Emulsified Asphalt (Emulsion) Mixture Design & Tex-134-E Foamed Asphalt Mixture Design

SJT SH 137 (Bedrock)

Step 1:
Add the amount of water listed in Table 1, to each sample in accordance with Tex-122-E and Tex-134-E and allow the sample to stand for 18-24 hours.

Add cement and asphalt stabilizer listed in Table 1 to each sample in accordance with Tex-134-E for foamed asphalt samples or Tex-122-E for asphalt emulsion samples.

Use the foamed asphalt plant or the Superpave gyration compactor (SGC) settings listed in Table 2.

Table 1: Material Weight per Aggregate Split

Aggregate Split	Foam Sample	Emulsion Sample
Mass Water, (lb.):	1.956 lb.	1.436 lb.
Mass Cement, (lb.):	0.240 lb.	0.240 lb.
Mass Asphalt:	261 g Foam	0.960 lb. Emulsion

Table 2: Equipment Settings

Foamed Asphalt Plant	Set Point	SGC	Set Point
Asphalt, Nozzle, and Chamber Temperature	160 °C	Compact threshold	Gyration
Asphalt Pump and Lines Temperature	165 °C	Gyrations (n)	75
Foaming Water Percentage	2.3% (8.3 L/hr.)	Mold Diameter (mm)	100
Air Pressure	5.5 bar	Angle E (deg)	1.25
		Pressure (kPa)	600

Step 2:
Use the single sample wet weight per Table 3 to compact a trial sample.

- Compact **8** IDT test specimens with a diameter of 4 inches and a height of 2 ± 0.1 inches. If the trial sample is not 2± 0.1 inches, adjust the weight in accordance with Tex-122 Section 7.2 /134-E Section 9.2.
- Cure **8** specimens for 72 hours at 104°F ± 5 (40°C).
- Condition **4** specimen for 24 ± 1 hour at 72°F ± 5 (22°C) in air.
- Condition **4** specimen for 24 ± 15 min. at 72°F ± 5 (22°C) in water.

Table 3: Single Sample Wet Weight per Specimen

Aggregate Split	Single Sample Wet Weight
Foam Sample	2.050 lb.
Emulsion Sample	2.013 lb.

During molding, curing, and conditioning phases, record at 0-7076 Data Sheet):

- Height after molding
- Mass after molding
- Number of gyrations
- Height after conditioning
- Mass after conditioning
- Specimen temperature after conditioning (°F), use a handheld infrared thermometer to measure

Step 3:
Perform IDT strength tests on all specimens in accordance with the Tex-122-E and Tex-134-E standards.

After IDT testing, oven dry for 24 ± 1 hour at 230°F (110°C) ± 9 specimen individually to determine moisture content.

During and after IDT testing, record:

- **Maximum load (lb.)**
- Mass of pan
- Wet mass of pan & specimen after testing
- Dry mass of pan & specimen after testing

Send results to Jinho Kim at jinho-kim@tti.tamu.edu
If any questions, contact Jinho Kim at (979) 317-2324
or Ross Taylor at (979) 317-1224

Figure D-3. Instructions for ILS specimen preparation for the SJT SH 137 material.

APPENDIX E:
ILS RESULTS DATASHEET TEMPLATE

TEXAS DEPARTMENT OF TRANSPORTATION

FDR Round Robin

Refresh Workbook

	Specimen Number	Conditioning	Height After molding, (in):	Mass After molding, (lb):	Number of Compaction Gyrations (n):	Height After Conditioning, (in):	Mass after conditioning, (lb):	Specimen temperature after conditioning (°F)	Maximum load @ IDT test (lb)	Mass of Pan, (lb):	Wet Mass of Pan & Specimen After Testing, (lb):	Dry Mass of Pan & Specimen After Testing, (lb):
Foam Sample	1	Cure specimens for 72 hours at 104°F (40°C). Condition specimens for 24 ± 1 hour at 72°F (22°C) in air.										
	2											
	3											
	4											
	5	Cure specimens for 72 hours at 104°F (40°C). Condition specimen for 24 ± 15 min at 72°F (22°C) in water.										
	6											
	7											
	8											
Emulsion Sample	1	Cure specimens for 72 hours at 104°F (40°C). Condition specimens for 24 ± 1 hour at 72°F (22°C) in air.										
	2											
	3											
	4											
	5	Cure specimens for 72 hours at 104°F (40°C). Condition specimen for 24 ± 15 min at 72°F (22°C) in water.										
	6											
	7											
	8											

Remarks:

Test Method:	Tested By:		Tested Date:	

Test Stamp Code:	Omit Test:		Completed Date:	Reviewed By:

Locked By:	TxDOT:					District:	Area:

Authorized By:	Authorized Date:

Figure E-1. ILS data capture sheet.

APPENDIX F:
FOAMED ASPHALT HALF-LIFE AND EXPANSION RATIO

TEXAS DEPARTMENT OF TRANSPORTATION

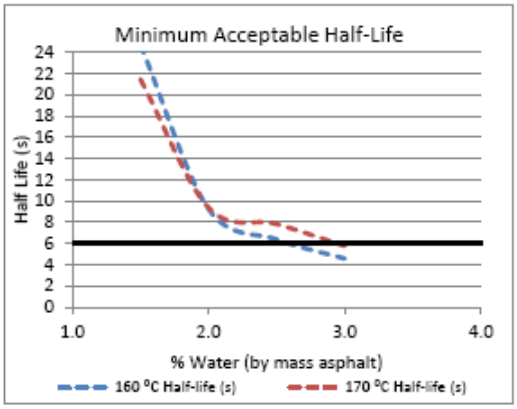
Half-Life and Expansion Ratio

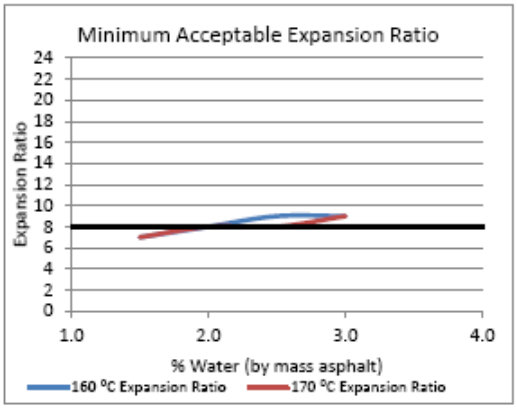
Refresh Workbook

Asphalt Binder Source	Alon	Asphalt Binder Grade	PG 64-22

Temperature	160 °C	
Foaming Water (% by weight asphalt)	Half-life (s)	Expansion Ratio
1.5	24.72	7
2.0	9.26	8
2.5	6.38	9
3.0	4.58	9

Temperature	170 °C	
Foaming Water (% by weight asphalt)	Half-life (s)	Expansion Ratio
1.5	21.47	7
2.0	9.38	8
2.5	7.83	8
3.0	5.77	9





RESULT					
Temperature	160	°C	Temperature	170	°C
Foaming Water (%) at minimum half-life:	2.60%		Foaming Water (%) at minimum half-life:	2.80%	
Foaming Water (%) at minimum expansion:	2.00%		Foaming Water (%) at minimum expansion:	2.00%	
Optimum Temperature				160	°C
Optimum Foaming Water (% by weight asphalt)				2.3%	

Remarks:

Additional data point @ 160C
1% water - HL 60s - ER 6
ILS Binder

Figure F-1. Half-life and expansion ratio measurements for the PG 64-22 foamed asphalt binder.

APPENDIX G:
ILS IDT STRENGTH TEST RESULTS

Table G-1. Emulsified Asphalt Unconditioned (Dry) IDT Strength Results.

Laboratory	Material		
	ATL US 80	**BWD FM 2214**	**SJT SH 137**
I	68.26	68.04	67.32
	70.23	66.64	66.79
	58.00	54.73	66.61
	62.98	66.72	68.18
D	75.99	77.30	72.86
	83.12	83.29	75.72
	85.22	73.68	81.09
	87.83	84.69	80.80
T	112.63	66.23	73.69
	96.11	74.36	70.88
	114.22	54.46	65.90
	116.29	56.18	58.34
N	78.36	68.82	54.67
	95.00	55.44	62.80
	84.25	62.88	72.95
	83.72	71.02	74.67

Table G-2. Emulsified Asphalt Conditioned (Submerged) IDT Strength Results.

Laboratory	Material		
	ATL US 80	BWD FM 2214	SJT SH 137
I	65.37	39.47	52.65
	59.12	37.65	53.95
	50.13	34.07	41.17
	55.08	38.87	51.28
D	84.81	43.63	41.70
	85.76	36.94	37.35
	79.23	40.83	34.06
	80.49	42.18	43.82
T	104.08	21.93	59.23
	106.13	30.72	38.26
	98.62	26.86	49.23
	89.32	25.21	45.54
N	69.69	18.95	26.01
	76.16	19.11	29.67
	64.46	23.06	34.57
	70.46	19.67	27.44

Table G-3. Foamed Asphalt Unconditioned (Dry) IDT Strength Results.

Laboratory	Material		
	ATL US 80	BWD FM 2214	SJT SH 137
I	63.26	59.46	69.12
	67.67	60.61	50.80
	67.93	60.32	71.44
	64.99	62.99	59.92
D	58.19	51.21	56.84
	65.30	49.00	64.10
	59.52	47.47	59.98
	67.34	60.46	67.16
T	79.41	61.16	57.20
	67.11	37.46	67.08
	68.55	51.31	53.26
	80.13	55.24	49.57
N	71.63	63.86	74.34
	73.40	60.00	61.57
	64.86	65.66	60.79
	63.80	66.61	63.43

Table G-4. Foamed Asphalt Conditioned (Submerged) IDT Strength Results.

Laboratory	Material		
	ATL US 80	BWD FM 2214	SJT SH 137
I	47.65	21.58	33.43
	56.30	22.47	39.35
	52.21	21.22	50.02
	43.22	22.84	40.26
D	43.15	14.80	37.70
	46.41	16.69	43.76
	40.52	15.21	38.18
	47.91	16.07	38.50
T	47.92	12.85	44.74
	56.39	17.31	41.27
	45.79	16.30	26.42
	53.31	14.30	31.80
N	59.54	11.10	34.41
	47.36	9.05	26.18
	47.83	14.41	30.30
	51.27	11.18	31.03

APPENDIX H:
DRAFT MIX DESIGN PROCEDURE FOR EMULSIFIED ASPHALT

The following pages present the updated draft mix design procedure for emulsified asphalt.

Test Procedure for

EMULSIFIED ASPHALT TREATMENT MIXTURE DESIGN

TxDOT Designation: Tex-122-E

Effective Date: XXXX 2023

1. SCOPE

1.1 Use this test procedure to develop a laboratory mixture design for the full depth reclamation (FDR) of roadways using emulsified asphalt (emulsion). This procedure will determine a moisture-density curve, optimum emulsion content, and when necessary, a target additive content based on the indirect tensile (IDT) strength of unconditioned and moisture conditioned test specimens.

1.2 This procedure requires a Superpave Gyratory Compactor (SGC) for molding IDT test specimens using 75 gyrations. Test specimens are compacted to 4 inches in diameter and 2 inches in height. The automatic tamper (compaction) device is required for compacting samples to 6 inches in diameter and 8 inches in height for a moisture-density curve.

1.3 *This test procedure does not claim to address the safety concerns associated with its use. It is the responsibility of the user of this test procedure to establish the appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations before use*.

2. APPARATUS

2.1 *Balance,* Class G2 in accordance with Tex-901-K, minimum capacity 35 lb.

2.2 *Container*, adequate height and volume to completely submerge compacted specimen.

2.3 *Mechanical mixer*, capable of mixing virgin and reclaimed materials with emulsion to produce a homogenous blend for laboratory compaction and testing.

2.4 *Temperature Chamber or Heating Oven,* capable of maintaining a temperature of 104 ± 5°F.

2.5 *Thermometer*, digital, handheld, infrared, and non-contact capable of measuring the temperature specified in this test procedure.

3. REPORTING AND DOCUMENTATION

3.1 Contact the Soils and Aggregates Section of the Materials and Tests Division to request a spreadsheet to calculate test results and to report and document pertinent information to this mixture design.

3.2 This spreadsheet includes worksheets for the following.

3.2.1 Gradation and weigh-up worksheets to batch samples.

3.2.2 Moisture-Density curve.

3.2.3 Indirect Tensile strength.

3.2.4 Mixture design summary including the optimum emulsion content.

4. MATERIAL SAMPLING AND PREPARATION

4.1 Obtain a minimum of 2 gallons of emulsion from the material supplier sampled in accordance with Tex-500-C.

4.1.1 Measure the percent residue by distillation in accordance with AASHTO T59.

4.2 Obtain a minimum of 1 gallon of additive (cement or lime) in a sealed one gallon can from a fresh supply of an approved source from TxDOT's Material Producer List.

4.3 Sample a minimum of 400 lbs. of in-place roadway material to the depth as shown on plans. Use equipment to produce a gradation similar to the gradation of the material reclaimed from the full depth reclamation process in the field.

4.3.1 Reclaimed roadway material may include flexible base, seal coat, and reclaimed asphalt pavement (RAP).

4.3.2 When the reclaimed base for sampling and testing is greater than 1-3/4 in., resize the material to pass the 1-3/4 in. sieve.

4.3.3 When RAP is greater than 1-3/4 in., break up and resize the RAP to pass the 1-3/4 in. sieve. If necessary, heat the RAP to a maximum temperature of 140°F to help break up and resizing it.

4.4 When the thickness of the asphalt pavement is greater than 2 in., separate the reclaimed asphalt material from the material sampled.

4.5 When applicable, sample a minimum of 150 lbs. of additional material of flexible base or RAP in accordance with Tex-400-A.

4.6 Prepare the material sampled in accordance with Tex-101-E, Part II '*Preparing Samples for Compaction and Triaxial Tests.*'

PART I — MOISTURE-DENSITY CURVE

5. PROCEDURE

5.1 Determine the optimum moisture content and maximum dry density for the material prepared from Section 4 in accordance with Tex-113-E.

5.1.1 Determine the moisture-density (M-D) curve for the material treated with 4% emulsion or a different percentage as deemed necessary.

5.1.1.1 When shown on the plans or approved by the Engineer, select an additive type and content. Include the additive in the M-D curve when applicable.

5.1.2 Determine a percentage for each material from Section 4 and when applicable including an additive. Calculate the gradation of the blend using these percentages.

5.1.3 Estimate the weight of air-dry material and a moisture content.

5.1.4 Weigh a trial sample. When applicable, add lime additive.

5.1.5 Weigh the amount of water in a sprinkling jar on a tared scale.

5.1.6 Place the total sample in the mixing pan, mix thoroughly, and wet with the appropriate amount of mixing water by sprinkling water in increments onto the sample during mixing.

5.1.6.1 Mix thoroughly, breaking up soil lumps. Do not break any aggregate particles in the sample.

5.1.7 After it is thoroughly mixed, scrape all material off the mixing trowel into the pan. Weigh the sample and pan and record the weight.

5.1.8 Cover the mixture with a non-absorptive lid to prevent moisture evaporation and allow to stand for 18–24 hours.

5.1.9 Prior to mixing with emulsion, weigh the sample (without the lid), replace evaporated water, and thoroughly mix to ensure even distribution of water throughout the sample. Scrape material off mixing tools and into pan.

5.1.10 Place sample in mechanical mixer from Section 2.3.

5.1.11 When applicable, add the cement additive and mix thoroughly to ensure even distribution of the additive throughout the sample.

5.1.12 While mixing, add emulsion to each sample and mix thoroughly to ensure even distribution of the emulsion throughout the sample.

5.1.13 Scrape as much material as possible off the mixing paddle(s) of the mechanical mixer and place the mixture into a pan.

5.1.13.1 Do not allow the mixture to stand for any period of time after mixing. Start the compaction process immediately after mixing.

5.1.14 Mold the trial sample in accordance with the applicable sections of Tex-113-E.

5.1.15 Measure and record the trial sample weight and height.

5.1.16 Correct the weight from the trial sample to a height of 8.000 in. using equation 7.2. Use this weight to estimate weights of four samples.

5.1.17 Compact at moisture contents such that two are on the dry-side of the curve and two are on the wet-side of the curve.

5.1.18 Weigh the four samples.

5.1.19 Repeat Sections 5.1.5 to 5.1.13.1 to mix each sample.

5.1.20 Follow the applicable sections of Tex-113-E to compact the four samples and to determine the moisture-density curve.

PART II — MIXTURE DESIGN

6. PROCEDURE

6.1 Select a minimum of three emulsion contents for the mixing and compaction of Indirect Tensile (IDT) strength test specimens.

6.2 Use equation from Section 7.1 to calculate the moisture content for samples with different emulsion contents.

6.3 Produce a minimum of 18 lbs. sample for each emulsion content. Determine the weight of each material, water, emulsion, and when applicable an additive.

6.3.1 Replace aggregate retained on the 7/8 in. sieve with an equivalent amount of material retained on the 5/8 in. sieve.

6.3.2 When applicable, add lime additive.

6.3.3 Weigh the amount of water for the moisture content determined from Section 6.2.

6.3.4 Place the total sample in the mixing pan, mix thoroughly, and wet with the appropriate amount of mixing water by sprinkling water in increments onto the sample during mixing.

6.3.4.1 Mix thoroughly, breaking up soil lumps. Do not break any aggregate particles in the sample.

6.3.5 Turn the wet material over with the mixing trowel to allow the aggregate particles to absorb water.

6.3.6 After it is thoroughly mixed, scrape all material off the mixing trowel into the pan. Weigh the sample and pan and record the weight.

6.3.7 Cover the mixture with a non-absorptive lid to prevent moisture evaporation and allow to stand for 18–24 hours.

6.3.8 Prior to mixing with emulsion, weigh the sample (without the lid), replace evaporated water, and thoroughly mix to ensure even distribution of water throughout the sample. Scrape material off mixing tools and into pan.

6.3.9 Place sample in mechanical mixer from Section 2.3.

6.3.10 When applicable, add the cement additive and mix thoroughly to ensure even distribution of the additive throughout the sample.

6.3.11 While mixing, add emulsion to each sample and mix thoroughly to ensure even distribution of the emulsion throughout the sample.

6.3.12 Scrape as much material as possible off the mixing paddle(s) of the mechanical mixer and place the mixture into a pan.

6.3.13 Do not allow the mixture to stand for any period after mixing. Start the compaction process immediately after mixing.

6.3.14 Estimate a weight for the trial height sample and weigh up this amount of material.

6.3.15 Configure the SGC to compact to 75 gyrations and compact the trial height sample using an unheated mold in accordance with Tex-241-F.

6.3.16 Measure and record the weight to the nearest 0.001 lbs. and height to the nearest 0.01 in. of the compacted trial sample.

6.3.16.1 When the height does not meet the requirements of 2 ± 0.10 in., use equation 7.2 to calculate a corrected weight of material for a height of 2 in.

6.3.17 Weigh the other samples from the mixed material and compact a minimum of six specimens in accordance with Section 6.3.15.

6.3.18 Measure and record the weight to the nearest 0.001 lbs. and height to the nearest 0.01 in. for each compacted specimen.

6.3.19 When the height of any specimen does not meet 2 ± 0.10 in., confirm if the weight was approximately the weight from Section 6.3.17 or corrected from the trial sample. Mix additional material and compact as many samples as needed to replace those that did not meet the height requirement.

6.3.20 Label each specimen appropriately and proceed to Section 6.4 to cure the compacted IDT specimens.

6.4 ***Curing***

6.4.1 Cure the test specimens in an oven at 104 ± 5 °F for a minimum of 72 hours.

6.4.2 Remove the test specimens from the oven and allow to cool to 72 ± 5 °F.

6.4.3 Store a minimum of three IDT specimens that will not be moisture conditioned in an area or room at a temperature of 72 ± 5 °F for 24 ± 1 hrs.

6.4.4 Proceed to Section 6.5 to moisture condition the other IDT specimens. A minimum of three specimens must be moisture conditioned.

6.5 ***Moisture Conditioning by 24-hr. Submersion***

6.5.1 Place each individual specimen into the container from Section 2.2.

6.5.2 Fill the container to approximately ½ to 1 in. above the top of the specimens with tap water in a manner that does not disturb and contact the specimens.

6.5.3 Soak each specimen in the container at a water temperature of 72 ± 5 °F for 24-hrs ± 15 minutes.

6.5.4 Remove each specimen from the container and use an absorptive cloth or paper towel to remove free water on the surface of the specimen.

6.5.5 Proceed to Section 6.6 for IDT strength testing.

6.6 ***IDT Strength Testing***

6.6.1 Measure and record the surface temperature of the test specimen using a thermometer from Section 2.5. Temperature of each test specimen must be 72 ± 5 °F.

6.6.2 Measure and record the IDT strength of the moisture conditioned and the unconditioned test specimens following Sections 4.5 to 4.11 of Tex-226-F using the appropriate loading strips for 4 in. diameter test specimens.

6.6.3 When the test results do not meet specifications, modify the mixture design as deemed necessary.

6.6.3.1 When adjusting the percent asphalt or additive content proceed to Section 6.2. A new M-D curve is not required.

6.6.3.2 When adjusting the percentages of reclaimed base, RAP, and when applicable, additional material of flexible base or choosing to add additional material of flexible base proceed to Section 5. A new M-D curve is required.

6.7 Proceed to Section 8 when the test results meet specifications.

7. CALCULATIONS

7.1 Use the following equation to calculate the moisture content of the sample when using additive or emulsion contents that are different from the Moisture-Density (M-D) curve from Section 5.

$$MC = OMC + [0.25 \times (ADTV_1 - ADTV_0)] - \left[1 - \left(\frac{RES}{100}\right)\right] \times (EM_1 - EM_0)$$

Where:

MC = Moisture Content of the sample.

OMC = Optimum Moisture Content, % from M-D curve.

$ADTV_1$ = New additive content, %.

$ADTV_0$ = Additive content, % from the M-D curve.

RES = Residue by distillation of the emulsion, %.

EM_1 = New emulsion content, %.

EM_0 = Emulsion content, % from the M-D curve.

0.25 = Adjustment factor from Tex-120-E, Section 8.1.

7.2 Use the following equation to calculate the corrected weight of material for a compacted specimen when the height is less or more than the target height.

$$Corrected\ Weight = Target\ Height \times \left(\frac{Weight}{Height}\right)$$

Where:

Target Height = 2.0 in. for an IDT sample or 8.000 in. for a M-D curve sample;

Weight = Weight of compacted sample, lbs.; and

Height = Height of compacted sample, in.

8. TEST REPORT

8.1 Report the type of emulsion.

8.2 Report the type of additive, if applicable.

8.3 Report the following information to the nearest 0.1:

- Additive content, when applicable;
- Design emulsion content;
- Gradation of aggregate blend;
- Maximum dry density; and
- Optimum moisture content.

8.4 Report the following information to the nearest whole number:

- Average IDT strength for unconditioned test specimens;
- Average IDT strength for moisture conditioned test specimens;
- Percent of additional material when applicable;
- Percent of existing material; and
- Residue by distillation of the emulsion.

APPENDIX I:
DRAFT MIX DESIGN PROCEDURE FOR FOAMED ASPHALT

The following pages present the updated draft mix design procedure for foamed asphalt.

Test Procedure for

FOAMED ASPHALT MIXTURE DESIGN

TxDOT Designation: Tex-134-E

Effective Date: XXXX 2023

1. SCOPE

1.1 Use this test procedure to develop a laboratory mixture design for full depth reclamation (FDR) of roadways using foamed asphalt binder. This procedure will determine a moisture-density curve, optimum foamed asphalt content, and when necessary, a target additive content based on the indirect tensile (IDT) strength of unconditioned and moisture conditioned test specimens.

1.2 This procedure requires a Superpave Gyratory Compactor (SGC) for molding IDT test specimens using 75 gyrations. Test specimens are compacted to 4 inches in diameter and 2 inches in height. The automatic tamper (compaction) device is required for compacting samples to 6 inches in diameter and 8 inches in height for a moisture-density curve.

1.3 *This test procedure does not claim to address the safety concerns associated with its use. It is the responsibility of the user of this test procedure to establish the appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

2. APPARATUS

2.1 *Balance,* Class G2 in accordance with Tex-901-K, minimum capacity 35 lb.

2.2 *Container*, adequate height and volume to completely submerge compacted specimens.

2.3 *Digital or mercury thermometer*, marked in 1 °F (0.5 °C) divisions capable of measuring the temperatures specified in the test procedure.

2.4 *Dipstick and 275 mm diameter steel bucket*.

2.5 *Laboratory Foaming System (Foaming System),* capable of the following:

2.5.1 Heated asphalt reservoir tank with a minimum capacity of 2.5 gallons, asphalt temperature adjustable from 212 to 392 °F (100 to 200 °C), and built-in circulation pump.

2.5.2 Foam water percentage adjustable from 1 to 5%.

2.5.3 Air with the source equipped with a pressure gauge and drying desiccator.

2.5.4 Water pressure adjustable from 0 to 115 psi.

2.5.5 Displays for reading working parameters.

2.6 *Mechanical mixer*, capable of mixing virgin and reclaimed materials with foamed asphalt to produce a homogenous blend for laboratory compaction and testing.

2.7 *Temperature Chamber or Heating Oven,* capable of maintaining a temperature of 104 ± 5 °F.

2.8 *Thermometer*, digital, handheld, infrared, and non-contact capable of measuring the temperature specified in this test procedure.

2.9 *Timer or stopwatch*, capable of measuring to the nearest 0.1 second.

3. REPORTING AND DOCUMENTATION

3.1 Contact the Soils and Aggregates Section of the Materials and Tests Division to request a spreadsheet to calculate test results and to report and document pertinent information to this mixture design.

3.2 This spreadsheet includes worksheets for the following.

3.2.1 Verification of the foaming system.

3.2.2 Determining half-life and expansion ratio of the foamed asphalt.

3.2.3 Gradation and weigh-up worksheets to batch samples.

3.2.4 Moisture-Density curve.

3.2.5 Indirect Tensile strength.

3.2.6 Mixture design summary including the optimum foamed asphalt content.

4. MATERIAL SAMPLING AND PREPARATION

4.1 Obtain a minimum of 10 gallons of asphalt binder from the material supplier sampled in accordance with Tex-500-C. Sample the asphalt using 10 one-gallon cans.

4.2 Obtain a minimum of one gallon of additive (cement or lime) in a sealed one gallon can from a fresh supply of an approved source from TxDOT's Material Producer List.

4.3 Sample a minimum of 400 lbs. of in-place roadway material to the depth as shown on plans using equipment that produces a gradation similar to the gradation of the material reclaimed from the FDR process in the field.

4.3.1 Reclaimed roadway material may include flexible base, seal coat, and reclaimed asphalt pavement (RAP).

4.3.2 When the reclaimed base for sampling and testing is greater than 1-3/4 in., resize the material to pass the 1-3/4 in. sieve.

4.3.3 When RAP is greater than 1-3/4 in., break up and resize the RAP to pass the 1-3/4 in. sieve. If necessary, heat the RAP to a maximum temperature of 140 °F to help break up and resizing it.

4.4 When the thickness of the asphalt pavement is greater than 2 in., separate the reclaimed asphalt material from the material sampled.

4.5 When applicable, sample a minimum of 150 lbs. of additional material of flexible base or RAP in accordance with Tex-400-A.

4.6 Prepare the material sampled in accordance with Tex-101-E, Part II '*Preparing Samples for Compaction and Triaxial Tests*'.

5. LABORATORY FOAMING SYSTEM VERIFICATION

5.1 Prepare and use the laboratory foaming system (foaming system) from Section 2.5 in accordance with the manufacturer's recommendations.

5.1.1 When the test procedure is different from the manufacturer's recommendations, perform the procedure in accordance with the manufacturer's recommendations.

5.1.2 Verify the foaming water discharge and asphalt temperature in accordance with the manufacturer's recommended frequency.

5.1.3 Verify the asphalt discharge every day prior to testing and any time the asphalt temperature is changed in the foaming system.

5.2 ***Foaming Water Discharge Verification***

5.2.1 Start the verification with the foaming system at room temperature and the heating elements off.

5.2.2 Fill the water reservoir of the foaming system completely.

5.2.3 Set the air and water pressure regulators to 4.5 bar.

5.2.4 Place a clean one gallon can on a balance and tare the balance.

5.2.5 Verify the water discharge at 1, 2, 3 and 4% which is equivalent to 3.7, 7.3, 10.9, and 14.5 L/h.

5.2.6 Set the water flow rate to 1% or 3.7 L/hr.

5.2.7 Manually discharge *water with air* into a tared gallon can for 60 seconds.

5.2.8 Use a timer or stopwatch from Section 2.9 and record the total time of the observed flow rate from the flow meter while discharging the water with air.

5.2.9 If the air supply is insufficient to maintain a flow rate within ± 0.2 L/hr. over 60 seconds, reduce discharge time to 30 seconds.

5.2.10 Weigh the gallon can and record the mass of water discharged. Calculate the observed foam water (%), the actual flow rate (L/hr), and the actual foam water (%).

5.2.11 Perform an additional reading by repeating Sections 5.2.7 through 5.2.10. A total of two readings are required at each water flow rate.

5.2.12 Increase the water flow rate by 1% and repeat Sections 5.2.7 through 5.2.11. Proceed to Section 5.2.13 after verifying the water flow rate at 4%.

5.2.13 When the calculated actual foam water percentage is not within 0.15 percentage points of the observed foam water percentage, repeat this procedure to verify. If the verification is not within 0.15 percentage points, contact the manufacturer for service.

5.2.14 When the foaming system is expected to not be in use for more than a month, completely drain water from the system after use.

5.3 ***Asphalt Binder Preparation***

5.3.1 Place asphalt into an oven at a maximum temperature of 320 ± 5 °F until the asphalt may be poured into the foaming system. The amount of asphalt will vary depending on the tests. Table 1 lists the approximate amounts of asphalt needed per test.

Table 1 – Minimum Asphalt Quantity per Test

Test	Approximate Minimum Asphalt Required
Asphalt Temperature Verification	2 gallons
Asphalt Discharge Calibration	2 gallons
Optimum Foaming Water Percentage	4 gallons
Mixture Design Specimen	2 gallons

5.3.2 Pour the asphalt into the foaming system.

5.3.3 Configure the foaming system to the desired temperature.

5.3.4 When the temperature readings of foaming system read greater than 285 °F (140 °C), the asphalt pump may be turned on to circulate asphalt in the foaming system.

5.3.5 Prior to testing, maintain the desired asphalt temperature with the asphalt pump circulating for a minimum of 5 minutes.

5.4 ***Asphalt Temperature Verification***

5.4.1 Prepare the foaming system and asphalt binder according to Sections 5.1 and 5.3.

5.4.2 Once temperature equilibrium has been achieved, verify the asphalt temperature using a thermometer from Section 2.3 by placing the end of the thermometer into the liquid asphalt without contacting the sides of the asphalt pot. Record the controller temperature of the asphalt pot and the measured temperature.

5.4.3 If the temperature from the reference thermometer is not within ± 3.6 °F (± 2 °C) of the set value, contact the manufacturer for service.

5.5 ***Asphalt Discharge Verification***

5.5.1 Prepare the foaming system and asphalt binder according to Sections 5.1 and 5.3.

5.5.2 Place a clean one-gallon container on a balance and tare the balance.

5.5.3 Set an asphalt discharge amount. Typical discharge rates are 200g when preparing for mixing materials with foamed asphalt, or 500g when preparing for expansion ratio and half-life tests.

5.5.4 Discharge the asphalt without any foaming water from the foaming system into the clean container.

5.5.5 Weigh the container and record the mass of asphalt discharged.

5.5.6 When the discharged amount of asphalt is not within ± 5g of the set value, adjust the metering knob and repeat Sections 5.5.2 to 5.5.5.

5.5.7 If the asphalt discharge amount cannot be adjusted within ± 5 g of the set value, the foaming system cannot be used. Contact the manufacturer.

5.5.8 When testing is complete, turn off the asphalt circulation pump and drain the asphalt reservoir.

5.5.9 Drain the asphalt pump and circulation lines by reversing flow of the asphalt pump. Asphalt drained from the foaming system that has not been foamed may be reused two additional times.

6. OPTIMUM FOAMING WATER PERCENTAGE AND TEMPERATURE

6.1 Prepare and use the laboratory foaming system (foaming system) from Section 2.5 in accordance with the manufacturer's recommendations.

6.1.1 When the test procedure is different from the manufacturer's recommendations, perform the procedure in accordance with the manufacturer's recommendations.

6.2 Place approximately 4 gallons of asphalt from Section 4.1 into an oven at a maximum temperature of 320 ± 5 °F (160 ± 2.8 °C) until the asphalt may be poured into the foaming system.

6.3 Pour the asphalt into the foaming system.

6.4 Configure the foaming system to 320 °F (160 °C) and maintain this temperature for a minimum of 5 minutes.

6.5 ***Asphalt Discharge Verification***

6.5.1 Perform asphalt discharge verification in accordance with Section 5.

6.6 ***Optimum Foaming Water Percentage***

6.6.1 Preheat the steel bucket from Section 2.4 in an oven to a minimum temperature of 140 °F (60 °C).

6.6.2 Ensure the pump of the foaming system is circulating prior to testing.

6.6.3 Configure the water-flow meter to achieve 1% foaming water.

6.6.4 Discharge 500g of foamed asphalt into the preheated bucket.

6.6.5 Measure the expansion ratio and half-life of the foamed asphalt binder in accordance with the manufacturer's recommendations.

6.6.5.1 Measure the expansion ratio as the ratio of the maximum volume of foam relative to its original volume.

6.6.5.2 Measure the half-life as the time for the foamed asphalt to collapse to half of its maximum volume from the time the foam nozzle shuts off.

6.6.6 Record the foaming water percentage, expansion ratio, and half-life.

6.6.7 Discard asphalt from the bucket.

6.6.8 Repeat steps 6.6.4 to 6.6.7 using 2% and 3% foaming water. Use other percentages of foaming water as deemed necessary.

6.6.9 Determine the optimum foaming water percentage at 335 °F (168 ºC) and 350 °F (177 ºC) by repeating Sections 6.6.1 to 6.6.8 for each temperature. Additional temperatures may be tested as deemed necessary.

6.6.10 Determine the optimum foaming water percentage and temperature.

6.6.11 Proceed to Section 7 when the asphalt meets the specification or approved by the Engineer.

PART I — MOISTURE-DENSITY CURVE

7. PROCEDURE

7.1 Determine the optimum moisture content and maximum dry density for the material prepared from Section 4 in accordance with Tex-113-E.

7.1.1 Determine the moisture-density (M-D) curve for the material treated with 2.4% foamed asphalt or a different percentage as deemed necessary.

7.1.1.1 When shown on the plans or approved by the Engineer, select an additive type and content. Include the additive in the M-D curve when applicable.

7.1.2 Determine a percentage for each material from Section 4 and when applicable including an additive. Calculate the gradation of the blend using these percentages.

7.1.3 Estimate the weight of air-dry material and moisture content.

7.1.4 Weigh a trial sample. When applicable, add lime additive.

7.1.5 Weigh the amount of water in a sprinkling jar on a tared scale.

7.1.6 Place the total sample in the mixing pan, mix thoroughly, and wet with the appropriate amount of mixing water by sprinkling water in increments onto the sample during mixing.

7.1.6.1 Mix thoroughly, breaking up soil lumps. Do not break any aggregate particles in the sample.

7.1.7 After it is thoroughly mixed, scrape all material off the mixing trowel into the pan. Weigh the sample and pan and record the weight.

7.1.8 Cover the mixture with a non-absorptive lid to prevent moisture evaporation and allow to stand for 18–24 hours.

7.1.9 Prior to mixing with foamed asphalt, weigh the sample (without the lid), replace evaporated water, and thoroughly mix to ensure even distribution of water throughout the sample. Scrape material off mixing tools and into pan.

7.1.10 Place sample in mechanical mixer from Section 2.6.

7.1.11 When applicable, add the cement additive and mix thoroughly to ensure even distribution of the additive throughout the sample.

7.1.12 While mixing, add foamed asphalt to each sample and mix thoroughly to ensure even distribution of the asphalt throughout the sample.

7.1.13 Scrape as much material as possible off the mixing paddle(s) of the mechanical mixer and place the mixture into a pan.

7.1.13.1 Do not allow the mixture to stand for any period of time after mixing. Start the compaction process immediately after mixing.

7.1.14 Mold the trial sample in accordance with the applicable sections of Tex-113-E.

7.1.15 Measure and record the trial sample weight and height.

7.1.16 Correct the weight from the trial sample to a height of 8.000 in. using equation 9.2. Use this weight to estimate weights of four samples.

7.1.17 Compact at moisture contents such that two are on the dry-side of the curve and two are on the wet-side of the curve.

7.1.18 Weigh the four samples.

7.1.19 Repeat Sections 7.1.5 to 7.1.13.1 to mix each sample.

7.1.20 Follow the applicable sections of Tex-113-E to compact the four samples and to determine the moisture-density curve.

PART II — MIXTURE DESIGN

8. PROCEDURE

8.1 Select a minimum of three asphalt contents for the mixing and compaction of Indirect Tensile (IDT) strength test specimens.

8.2 Use equation from Section 9.1 to calculate the moisture content for samples with different foamed asphalt contents.

8.3 Produce a minimum of 18 lbs. for each foamed asphalt content. Determine the weight of each material, water, asphalt binder, and when applicable an additive.

8.3.1 Replace aggregate retained on the 7/8 in. sieve with an equivalent amount of material retained on the 5/8 in. sieve.

8.3.2 When applicable, add lime additive.

8.3.3 Weigh the amount of water for the moisture content calculated from Section 9.1.

8.3.4 Place the total sample in the mixing pan, mix thoroughly, and wet with the appropriate amount of mixing water by sprinkling water in increments onto the sample during mixing.

8.3.4.1 Mix thoroughly, breaking up soil lumps. Do not break any aggregate particles in the sample.

8.3.4.2 Turn the wet material over with the mixing trowel to allow the aggregate particles to absorb water.

8.3.5 After it is thoroughly mixed, scrape all material off the mixing trowel into the pan. Weigh the sample and pan and record the weight.

8.3.6 Cover the mixture with a non-absorptive lid to prevent moisture evaporation and allow to stand for 18–24 hours.

8.3.7 Place approximately 2 gallons of asphalt from Section 4.1 into an oven at 320 ± 5 °F (160 ± 2.8 °C) until the asphalt may be poured into the foaming system.

8.3.8 Pour the asphalt into the foaming system.

8.3.9 Configure the foaming system to the optimum foaming water percentage and temperature determined from Section 6.6 and maintain this temperature for a minimum of 5 minutes.

8.3.10 Prior to mixing with foamed asphalt, weigh the sample (without the lid), replace evaporated water, and thoroughly mix to ensure even distribution of water throughout the sample. Scrape material off mixing tools and into pan.

8.3.11 Place sample in mechanical mixer from Section 2.6.

8.3.12 When applicable, add the cement additive and mix thoroughly to ensure even distribution of the additive throughout the sample.

8.3.13 While mixing, add foamed asphalt to each sample and mix thoroughly to ensure even distribution of the foamed asphalt throughout the sample.

8.3.14 Scrape as much material as possible off the mixing paddle(s) of the mechanical mixer and place the mixture into a pan.

8.3.14.1 Do not allow the mixture to stand for any period after mixing. Start the compaction process immediately after mixing.

8.3.15 Estimate a weight for the trial height sample and weigh up this amount of material.

8.3.16 Configure the SGC to compact to 75 gyrations and compact the trial sample using an unheated mold in accordance with Tex-241-F.

8.3.17 Measure and record the weight to the nearest 0.001 lb. and height to the nearest 0.01 in. of the compacted trial specimen.

8.3.17.1 When the height does not meet the requirements of 2 ± 0.10 in., use equation 9.2 to calculate a corrected weight of material for a height of 2 in.

8.3.18 Weigh the other samples from the mixed material and compact a minimum of six specimens with a SGC in accordance with Section 8.3.16.

8.3.19 Measure and record the weight to the nearest 0.001 lb. and height to the nearest 0.01 in. for each compacted specimen.

8.3.20 When the height of any specimen does not meet 2 ± 0.10 in., confirm if the weight was approximately the weight from Section 8.3.18 or corrected from the trial sample. Mix additional material and compact as many samples as needed to replace those that do not meet the height requirement.

8.3.21 Label each specimen appropriately and proceed to Section 8.4 to cure the compacted IDT specimens.

8.4 ***Curing***

8.4.1 Cure the test specimens in an oven at 104 ± 5 °F for a minimum of 72 hours.

8.4.2 Remove the test specimens from the oven and allow to cool to 72 ± 5 °F.

8.4.3 Store a minimum of three IDT specimens that will not be moisture conditioned in an area or room at a temperature of 72 ± 5 °F for 24 ± 1 hr.

8.4.4 Proceed to Section 8.5 to moisture condition the other IDT specimens. A minimum of three specimens must be moisture conditioned.

8.5 ***Moisture Conditioning by 24-hr. Submersion***

8.5.1 Place each individual specimen into the container from Section 2.2.

8.5.2 Fill the container to approximately ½ to 1 in. above the top of the specimens with tap water in a manner that does not disturb and contact the specimens.

8.5.3 Soak each specimen in the container at a water temperature of 72 ± 5 °F for 24-hrs ± 15 minutes.

8.5.4 Remove each specimen from the container and use an absorptive cloth or paper towel to remove free water on the surface of the specimen.

8.5.5 Proceed to Section 8.6 for IDT strength testing.

8.6 ***IDT Strength Testing***

8.6.1 Measure and record the surface temperature of the test specimen using a thermometer from Section 2.8. Temperature of each test specimen must be 72 ± 5 °F.

8.6.2 Measure and record the IDT strength of the moisture conditioned and the unconditioned test specimens following Sections 4.5 to 4.11 of Tex-226-F using the appropriate loading strips for 4 in. diameter test specimens.

8.6.3 When the test results do not meet specifications, modify the mixture design as deemed necessary.

8.6.3.1 When adjusting the percent asphalt or additive content proceed to Section 8.2. A new M-D curve is not required.

8.6.3.2 When adjusting the percentages of reclaimed base, RAP, and when applicable, additional material of flexible base or choosing to add additional material of flexible base proceed to Section 7. A new M-D curve is required.

8.7 Proceed to Section 10 when the test results meet specifications.

9. CALCULATIONS

9.1 Use the following equation to calculate the moisture content of the sample when using additive or foamed asphalt contents that are different from the Moisture-Density (M-D) curve from Section 7.

$$MC = OMC + (0.25 \times (ADTV_1 - ADTV_0))$$

Where:

MC = moisture content of the sample.

OMC = Optimum Moisture Content, % from M-D curve.

$ADTV_1$ = New additive content (%).

$ADTV_0$ = Additive content (%) used in the M-D curve.

0.25 = Adjustment factor from Tex-120-E, Section 8.1.

9.2 Use the following equation to calculate the corrected weight of material for a compacted specimen when the height is less or more than the target height.

$$Corrected\ Weight = Target\ Height \times \left(\frac{Weight}{Height}\right)$$

Where:

Target Height = 2.0 in. for an IDT sample or 8.000 in. for a M-D curve sample;

Weight = Weight of compacted sample, lbs.; and

Height = Height of compacted sample, in.

10. TEST REPORT

10.1 Report the type of asphalt binder and when applicable, the type of additive.

10.2 Report the laboratory foaming system verification results.

10.3 Report the following information to the nearest 0.1:

- Additive content, when applicable;
- Design foamed asphalt binder content;

- Gradation of aggregate blend;
- Maximum dry density;
- Optimum foaming water percentage; and
- Optimum moisture content.

10.4 Report the following information to the nearest whole number:

- Average IDT strength for unconditioned test specimens;
- Average IDT strength for moisture conditioned test specimens;
- Foamed asphalt properties, half-life and expansion ratio;
- Optimum foaming temperature;
- Percent of additional material when applicable; and
- Percent of existing material.