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Reducing Costs in Full Depth Reclamation

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16. Abstract

Full depth reclamation (FDR) using emulsified asphalt or foamed asphalt continues to grow in usage throughout Texas. These mixtures typically use a cement additive in the mix design. The cement additive reportedly contributes to early strength gain, which can be particularly important for projects that require daily opening to heavy traffic. However, not all construction projects require daily opening to traffic, and some materials may provide adequate performance without the cement additive. Additionally, with potential cement supply shortages, design and construction of FDR layers using only asphalt treatments could save materials cost, reduce schedule risk, and increase daily productivity since one less step would be required in the treatment process. This project determined that without the cement additive, an additional three to four hours cure time could be required prior to opening to traffic. FDR mixes without the additive may be able to obtain similar strength and performance properties as long as they stay dry, but most common Texas materials for FDR require the cement additive to meet moisture conditioned strength requirements. If sourcing cement proves difficult, this project showed lime could be substituted 1:1 for the cement additive, although mixes with lime additive were less reliable in meeting moisture susceptibility criteria compared to mixes that used cement as the additive. In practice, emulsified or foamed asphalt-treated FDR mixes without additive could provide material cost savings, faster production, and user-delay savings, with the potential tradeoff of increased long-term performance risks due to their higher level of moisture susceptibility. Thus, no additive mixes are best considered on a case-by-case basis for low-risk areas, projects with logistical challenges for sourcing additives, or for projects where simply upgrading material properties is desired.

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Reducing Costs in Full Depth Reclamation

by

Jinho Kim
TTI Assistant Research Scientist
Texas A&M Transportation Institute

Stephen Sebesta
TTI Research Scientist
Texas A&M Transportation Institute

Kunhee Choi
Professor, Texas A&M University, and
TTI Research Scientist
Texas A&M Transportation Institute

and

Ross Taylor
Research Specialist V
Texas A&M Transportation Institute

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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 researcher in charge of the project was Stephen Sebesta.

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AADT	Annual average daily traffic
AC	Asphalt concrete
ACP	Asphalt concrete pavement
ADT	Average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AMPT	Asphalt mixture performance tester
ANOVA	Analysis of variance
AT	Ambient temperature
BRY	Bryan
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
CCPR	Cold Central Plant Recycling
CIR	Cold in-place recycling
CSJ	Control section job
CTD	Construction time determination
DCP	Dynamic cone penetrometer
E*	Dynamic modulus
EA	Emulsified asphalt
ESAL	Equivalent single axle load
ET	Emulsion-treated
ETB	Emulsified asphalt-treated base
FA	Foamed asphalt
FDR	Full depth reclamation
FHWA	Federal Highway Administration
FPS	Flexible Pavement Design System
FT	Foam-treated
FTB	Foamed asphalt-treated base
GNP	Graphene nanoplatelet
HMA	Hot mix asphalt
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
IDT	Indirect tensile strength
ITS	Indirect tensile strength
Mr	Resilient modulus
MT	Material temperature
ODA	Odessa
OMC	Optimum moisture content
PD	Permanent deformation
PI	Plasticity index
RH	Relative humidity
RUC	Road user cost
SGC	Superpave gyratory compactor
SJT	San Angelo

TSR	Tensile strength ratio
TxDOT	Texas Department of Transportation
TxME	Texas Mechanistic-Empirical Flexible Pavement Design and Analysis System
UCS	Unconfined compressive strength
UTM	Universal testing machine
α	Alpha
μ	Mu

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

Full depth reclamation (FDR) using emulsified asphalt (EA) or foamed asphalt (FA) continues to grow in usage throughout Texas. To date, almost all mixtures include a cement additive in the mix design. The cement additive contributes to early strength gain, which is particularly important for projects requiring daily opening to heavy traffic. However, not all projects demand such early opening, and some materials may perform adequately without cement. In addition, with potential cement supply shortages, designing and constructing FDR layers using only asphalt treatments could reduce material costs, lower schedule risk, and improve productivity by eliminating one step in the construction process.

The primary objective of this project is to evaluate the performance of asphalt-based FDR mixtures with and without a cement additive. The study investigates how removing the additive may affect both early traffic opening and long-term pavement performance. If foam-treated (FT) or emulsion-treated (ET) FDR mixtures can meet performance requirements without cement, projects could achieve cost savings and reduced construction time.

To support this goal, this project:

- Collected materials from five field projects across three Texas Department of Transportation (TxDOT) districts, representing a range of salvaged and new base proportions for lab testing.
- Characterized FDR mixtures with EA and FA, with and without cement or lime additive, to identify performance differences and conditions where the additive could be omitted.
- Evaluated the influence of aggregate and ambient temperature on indirect tensile strength (IDT), highlighting the role of environmental conditions in strength development.
- Developed an economic framework comparing costs, schedules, and traffic impacts of mixes with and without cement or lime, showing scenarios where omission can provide greater overall value.
- Used the Texas Mechanistic-Empirical Flexible Pavement Design and Analysis System (TxME) pavement design to model long-term performance of FDR bases under dry and wet conditions, emphasizing the strong influence of moisture and stabilization type on pavement behavior.

1.2. REPORT ORGANIZATION

This report is organized into nine chapters:

- Chapter 1 provides an overview of the project's background, motivation, and objectives, along with an outline of the report's organization.
- Chapter 2 reviews current literature and practice on FDR, with emphasis on the use of EA and FA, and the role of cement and lime additives.
- Chapter 3 describes the material collection process from five field projects across three TxDOT districts, providing details on the mix compositions and sampling procedures.

- Chapter 4 presents results from the comprehensive laboratory testing program, including strength and stiffness properties of FDR mixtures with and without additive under different asphalt treatments.
- Chapter 5 evaluates the influence of temperature on IDT development and discusses the implications of environmental conditions during mixing and curing.
- Chapter 6 quantifies project duration, user delay, construction cost, and traffic impacts for mixtures with and without additive for economic analysis and evaluates the effect of additive on the strength and stiffness of FDR mixtures at initial, intermediate, and final curing stages for structural analysis.
- Chapter 7 presents the overall conclusions and recommendations from the project, including scenarios where consideration could be given to eliminating additives.
- Chapter 8 presents the value of research from the project.
- Chapter 9 lists input variables used for the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS).

CHAPTER 2. LITERATURE REVIEW

This chapter reviews prior research and practices related to FDR using EA and FA with chemical additives. It examines the influence of cement and lime on strength, stiffness, and moisture resistance, as well as the curing behavior of FDR mixtures at early, intermediate, and final stages. Long-term performance findings, cost-effectiveness comparisons, and traffic opening considerations are also summarized to provide context for the laboratory in this project.

2.1. Foamed and Emulsified Asphalt Treatment with Chemical Additives in Pavement Strength and Flexibility

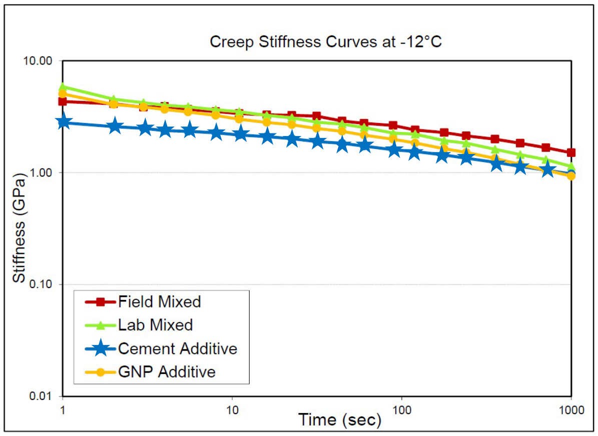
FDR recycles the entire flexible pavement structure creating a stronger, stabilized base course (1). FA treatment is used to improve the properties of base materials to enhance the performance and longevity of the pavement. By increasing the strength and reducing moisture sensitivity, the base materials can better support the weight of traffic and resist degradation due to weather and other external factors (2, 3).

Asphalt emulsion is a type of oil-in-water emulsion that is used to add asphalt binder to the road base during FDR. It consists of asphalt particles suspended in water with the help of an emulsifying agent, and typically contains 25–60 percent water, 40–75 percent bitumen, and 0.1–2.5 percent emulsifier (4). Emulsion used for FDR in Texas generally contains around 62 percent asphalt. Asphalt emulsion adds binder to road base during reclamation, creating an emulsion-treated base (ETB) that can be surfaced for traffic. Pavement strength determines early trafficking resistance (5).

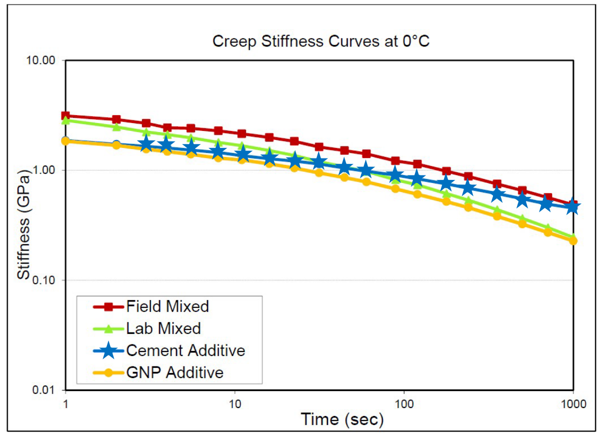
According to Hartman et al., four materials treated with asphalt emulsion (see Table 1) behave like viscoelastic materials, similar to asphalt mixtures, with creep stiffness dependent on temperature and loading time, as show in Figure 1 (6). The mixture that included 1 percent cement had the smallest creep stiffness slope, the lowest stiffness at the lowest temperature, and the highest stiffness at the highest temperature (6).

Table 1. Summary of Materials Tested (6).

Material Type	Sample ID	Additive	Mix Procedure
Field mixed	FL	3.6% emulsion	Field mixed, lab compacted
Lab mixed	LL	3.6% emulsion	Lab mixed, lab compacted
Cement additive	LLC	3.6% emulsion and 1% Portland cement	Lab mixed, lab compacted
Graphene nanoplatelet (GNP) additive	GNP	3.6% emulsion/graphene blend	Lab mixed, lab compacted



(a) −12°C



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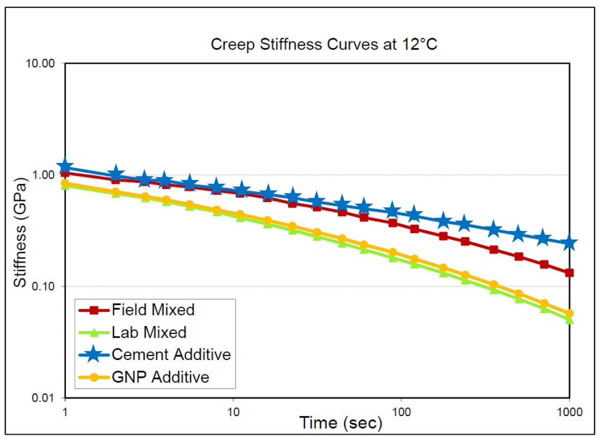


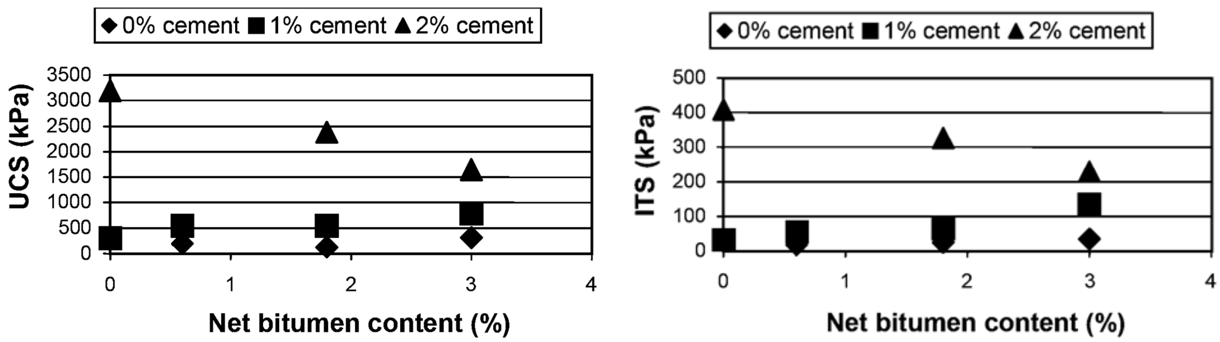
(c) 12°C

Figure 1. Creep Stiffness Curves at Different Temperatures (6).

According to Mallick et al., cement and lime additives improve the FDR layer's resistance to moisture damage. Cement-only mix and emulsion plus lime mix showed very high durability based on the rutting and resilient modulus test compared to other mixes such as emulsion, emulsion plus cement, and material with no additive (only water). Based on wet tensile strength, emulsion plus lime was the best additive (7).

The addition of cement to the FDR mix can increase the strength and modulus but also increases the critical cracking temperature and initial costs (6). The strength of the FDR layer may vary over time and be influenced by season, with bitumen-stabilized bases being more sensitive than cement-stabilized bases. Cement may improve FA curing and should be considered for improved performance, increased strength, and reduced temperature effects on moduli (8).

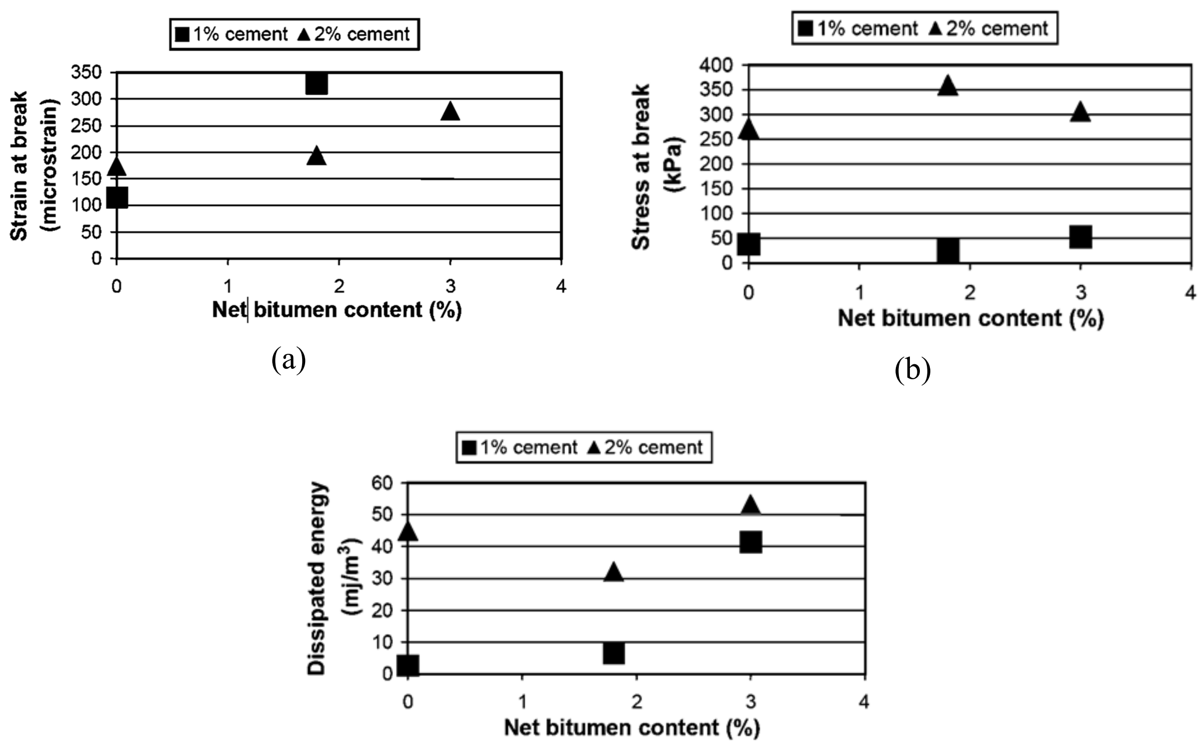
According to Liebenberg and Visser, mixes with 2 percent cement had decreased unconfined compressive strength (UCS) and IDT with increased emulsion (net bitumen) contents, while mixes with 1 percent cement or less had slightly increased UCS and IDT with increased bitumen content, as shown in Figure 2 (9).



(a) (b)

Figure 2. Influences of Cement and Emulsion (Net Bitumen) Contents on (a) UCS and (b) IDT (9).

Increased cement content significantly increases material strength and reduces flexibility, requiring more energy to break, as shown in Figure 3. Cement mostly contributes to material stiffness (9). An increase in the cement content therefore provides strength to the material, but the addition of too much will sacrifice flexibility. This should be borne in mind when UCS is specified in the mix design process, and the structural designer must bear this in mind when determining whether the objective is strength or flexibility (9).



(c)

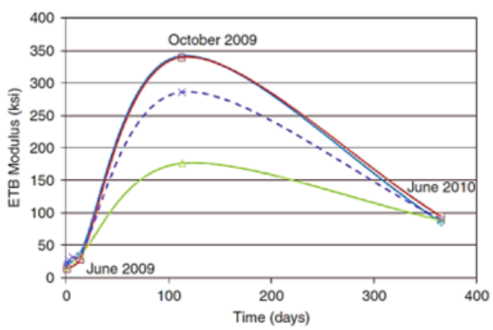
Figure 3. Influence of Cement and Emulsion (Net Bitumen) Contents on (a) Strain at Break, (b) Stress at Break, and (c) Dissipated Energy from Static Flexural Beam Test (9).

Optimum designs for FDR are often chosen based on minimum dry tensile strength and either a moisture conditioned or tensile strength ratio (TSR). Bang et al. found that 1 percent lime improved IDT and TSR for ET FDR. Lime also reduced air voids, potentially improving durability (10).

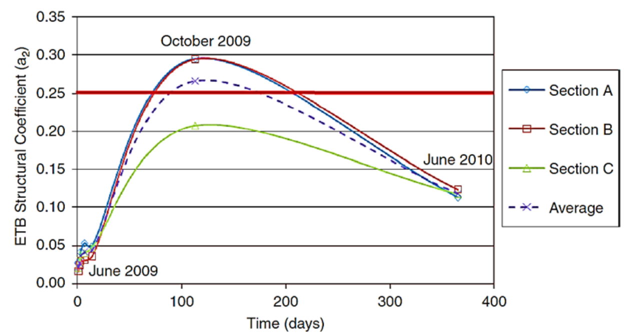
2.2. Properties in the Early, Intermediate, and Final Curing Stages

ETB layers typically have low initial strength due to the nature of uncured emulsion. However, research has shown that these layers can experience significant increases in resilient moduli during the first 28 days of curing. The duration of curing required to reach the desired strength of the FDR material may vary significantly, ranging from several weeks to several years, depending on the properties of the emulsion employed (4, 5, 11).

According to Quick and Guthrie, field-measured modulus values in three sections treated with only emulsion increased dramatically by four months after construction (see Figure 4a and b) but decreased considerably by one year, despite additional curing of the emulsion that may have occurred during this time (5). They recommended to not traffic materials similar to those studied during the first two weeks after construction (see Figure 4[c] and Figure 4[d]) due to reduced pavement capacity, which may lead to premature failure (5).



(a)



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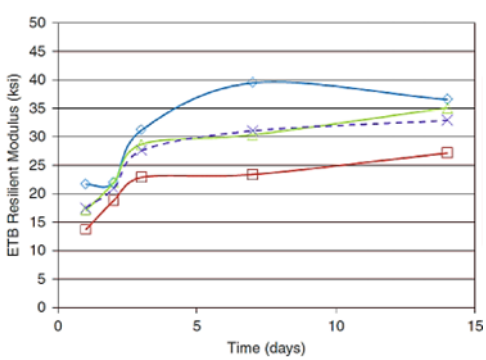

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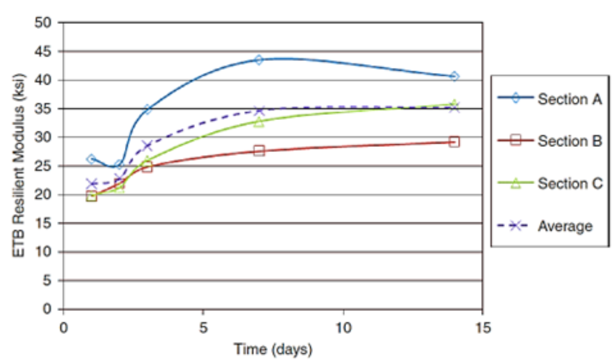


(d)

Figure 4. ETB Properties During First Year: (a) Resilient Modulus, (b) Layer Coefficients, (c) Portable Falling Weight Deflectometer Results, and (d) Dynamic Cone Penetrometer Results (5).

According to Budge and Wilde, the stiffness of ET FDR material significantly increases in the first two weeks after stabilization (12). As curing progresses, the dynamic cone penetrometer (DCP) index becomes more consistent, and different sites with different borrow materials converge to nearly identical DCP index values (Figure 5).

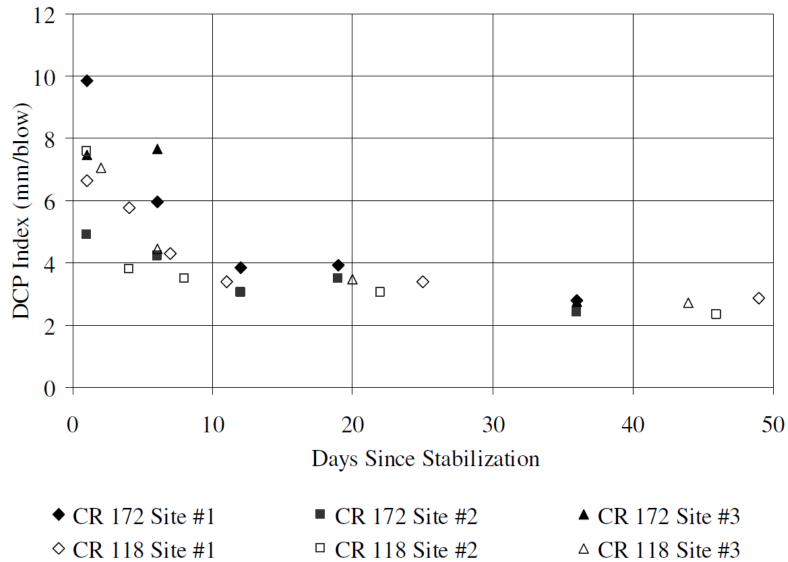


Figure 5. Variation of Average DCP Index with Time for Stabilized Material at Six Sites in Blue Earth County, Minnesota (12).

Allain et al. suggested that the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) may be sufficient for assessing the cracking resistance of FDR mixtures and predicting the potential for premature cracking in ET FDR mixtures. However, they recommended further research to confirm the findings and compare them to field data (13).

2.3. Long-Term Performance of Foamed and Emulsified Asphalt in FDR

Henrichs reported that emulsion stabilization leads to higher dynamic modulus values, indicating a stiffer sample than foam stabilization, and IDT testing highlights the variability and moisture susceptibility of FDR samples (1). Among sections constructed with cold in-place recycling (CIR) with FA and EA, and FDR sections constructed with FA and EA, FDR sections treated with emulsion plus 1 percent cement exhibited the most cracking. Allain et al. reported field performance of FDR with emulsion treatment was consistent with results from the IDEAL-CT, which showed that material had the lowest relative resistance to cracking (13).

Liebenberg and Visser used the repeated load four-point static beam test to determine the flexibility of materials, and their results showed that increasing the emulsion (net bitumen) content generally increased flexibility while having little impact on stress at break (9). For samples with lower cement contents, increasing the bitumen content increased the energy required to initiate failure (9).

According to Diefenderfer et al., the presence of chemical additives generally increased the dynamic modulus of cold-recycled mixtures —Cold Central Plant Recycling (CCPR), CIR, and

FDR— as shown in Table 2, but no significant trend existed (14). The presence of chemical additives generally reduced temperature dependency. This observation may be because the additives contain non-viscoelastic materials that play a role in the stiffness of the recycled layer beyond the initial curing. Figure 6 illustrates the range of dynamic modulus values with and without different additives (14).

Table 2. Comparisons of Stabilizing and Recycling Agent Combinations (14).

Test Temp.	Method	Emulsion Versus Foam	Emulsion Versus Emulsion + Cement	Emulsion Versus Emulsion + Lime	Emulsion + Cement Versus Foam + Cement	Foam Versus Foam + Cement	Cement Versus No Cement	Cement Versus Lime
4.4° C	CCPR	—	0.2873	—	—	—	0.2873	—
	CIR	0.7285	0.1862	0.2422	0.7151	0.8320	0.2055	**0.0042**
	FDR	**0.0016**	0.4958	—	**0.0016**	—	**0.0422**	—
21.1°C	CCPR	—	**0.0203**	—	—	—	**0.0203**	—
	CIR	0.7356	**0.0108**	**0.0000**	0.1496	0.0804	**0.0039**	0.1970
	FDR	0.7105	0.7840	—	0.7105	—	0.9558	—
37.8°C	CCPR	—	0.0513	—	—	—	0.0513	—
	CIR	0.0641	**0.0049**	**0.0068**	0.2183	0.3671	**0.0036**	0.0582
	FDR	0.9938	0.1466	—	0.9938	—	**0.0095**	—

Note: Significant statistical differences are highlighted with bold text; — = not available.

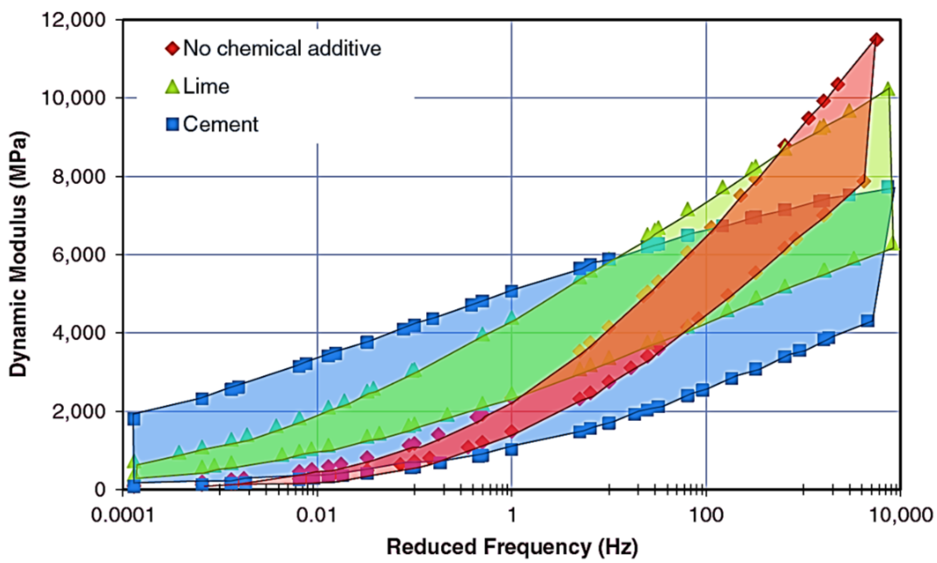


Figure 6. Dynamic Modulus Master Curve Data Envelopes for Mixtures with No Chemical Additive, Lime, and Cement (14).

According to Mallick et al., an FDR mix with 3.4 percent emulsion plus 2 percent lime showed a significantly higher layer coefficient compared to the mix with 2.2 percent emulsion (7). A comparison of cost per mile per 1,000-equivalent single axle load (ESAL) increase in life showed that recycling with 3.4 percent emulsion plus 2 percent lime was the most cost-effective option. Visual evaluation of recycled sections after one year showed no significant distress in any section except for moderate edge cracking (7).

Thomas and May found that mixtures with 1 percent cement had higher dynamic modulus (E*) values at lower frequencies. They also found that all cold-recycled asphalt cases performed well, with little variation due to mix composition, although the mixtures with 1 percent cement showed the least predicted distresses (15).

2.3.1. Field Evaluation

Jones, Wu, and Louw suggested that post-construction testing showed FDR materials with FA had satisfactory strengths, while FDR materials with emulsion had low strengths due to problems observed during construction, including excess emulsion. They also reported the FA section had significantly less rutting after similar load repetitions compared to no stabilization (16).

Amarh et al. found that both FA and asphalt emulsion treatments experience an increase in moduli up to six months after reclamation. Seasonal variations were observed, with the FA and asphalt emulsion sections having the highest and lowest moduli in the winter and summer, respectively. The bases treated with asphalt emulsion showed lower initial stiffness and a longer time to reach maximum strength compared to those stabilized with FA (8).

Johanneck and Dai reported that stabilized FDR systems, treated with engineered emulsion, have shown reduced horizontal tensile strain at the bottom of the hot mix asphalt (HMA) layer and improved pavement performance and service life compared to traditional HMA over granular base structures. In-field measurements also suggested that the FDR systems are performing well, with stable rutting except for a sharp increase due to material consolidation after opening to traffic (17).

2.3.2. Cost-Effectiveness of FDR and Traditional Methods

Hartman et al. evaluated FDR materials treated with 3.6 percent emulsion, 3.6 percent emulsion + 1 percent cement, and a 3.6 percent emulsion/graphene blend and reported that FDR with only emulsion provided the lowest annualized cost. The ET FDR mixture that included 1 percent cement had the smallest slope of the |E*| versus time curve (see Figure 7), indicating reduced relaxation capabilities. They reported the addition of cement reduced the predicted pavement life, and adding graphene nanoplatelet (GNP) to the emulsion treatment also reduced predicted life but improved cracking resistance (6).

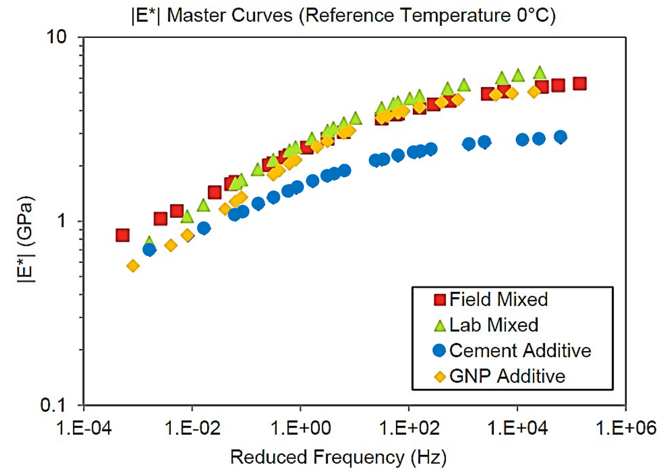


Figure 7. Fitted Dynamic Modulus Master Curves for All Materials (6).

2.3.3. Recommended Time to Traffic Opening

Traffic return times on the constructed FDR layer depend on various factors such as the specific materials and construction techniques used, the condition of the underlying pavement support, edge support, or confinement conditions, the expected loads and traffic counts that the road will be subjected to, and the rate of curing and strength gain of the FDR material in the environmental conditions at the site. Few studies have been found on traffic return times. One study by Hill and Braham investigated the timing for returning traffic to roads made by FDR using five different laboratory testing devices. The results showed that after 48 hours of curing, all five devices displayed expected trends such as an increase in the ability to withstand torque due to cohesion and a decrease in mass loss due to splitting. The asphalt emulsion FDR also showed higher resistance to potential raveling compared to the asphalt foam FDR at ambient temperature (18). However, this study did not specifically recommend a traffic return time for FDR roads.

Diefenderfer et al. (2016) recently proposed a short and long-pin raveling test to evaluate site conditions. They reported results from two sites (one CIR with FA plus cement, and one FDR with emulsion plus cement) where initial measurements were collected at 2 to 3 hours of cure time. They suggested both surfacing and trafficking should wait for additional tests over time to determine if additional cure time results in improved test results.

2.4. Summary for Literature Review

Literature supports the following:

- Additives (cement or lime) included in FDR mixes with EA or FA can improve the FDR materials' resistance to moisture damage and increase material strength and modulus.
- Too high additive rate can decrease material flexibility. The optimal FDR design should balance strength and flexibility.
- FDR materials treated with EA or FA may exhibit viscoelastic behavior and be influenced by temperature.
- FDR layers significantly increased in stiffness over the first two weeks. ET layers typically begin with low initial strength and gain significant strength over 28 days. Both

EA and FA can experience an increase in modulus up to at least six months after reclamation.

- Increasing asphalt content in the FDR mix increases flexibility with little impact on the stress at break.
- Chemical additives such as cement in mixes with EA or FA typically increase their dynamic modulus and reduce temperature dependency.
- Traffic return times can depend on many factors, including but not limited to the inclusion or exclusion of cement or lime additives in emulsion and foamed asphalt-treated FDR materials. Methods such as in-place stiffness, raveling, or shear tests may be useful to evaluate in-situ layer properties at early curing times after construction.

CHAPTER 3. SELECT AND COLLECT MATERIALS

This chapter documents the identification and collection of representative roadway materials from five TxDOT field projects selected for laboratory evaluation. Working closely with district personnel, the research team obtained untreated base materials from projects in the San Angelo, Odessa, and Bryan districts. The sampling process ensured that a range of roadway conditions and material sources were represented. These collected materials formed the basis for the laboratory testing program described in later tasks.

3.1. Location of the FDR Field Projects

Table 3 presents a list of the five field projects that were identified by the TxDOT team and selected for sampling. The information in Table 3 includes the roadway ID, the county where the field project is located, the control section job (CSJ) number, and the project limits. Figure 8 shows maps of the districts where these projects are located.

Table 3. FDR Projects.

District	Roadway	County	CSJ	Limits
San Angelo (SJT)	SH 137	Reagan	0494-10-017	From 11.5 miles south of Glasscock County line to RM 33
Odessa (ODA)	SL 338	Ector	2224-01-118	From US 385 to SH 191
Bryan (BRY)	FM 39	Madison	0639-02-034	From OSR to US 190
ODA	SH 18	Ward	0292-03-032	From Winkler County Line to BI 20-D
ODA	SH 128	Andrews	127-01-012	From New Mexico State Line to SH 115

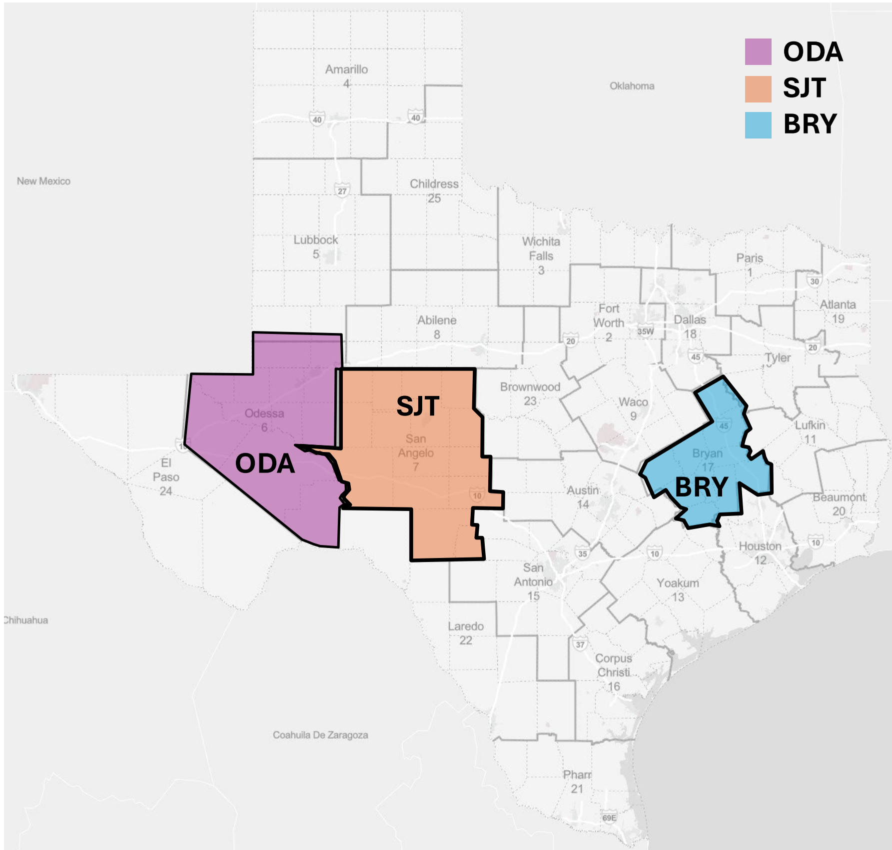
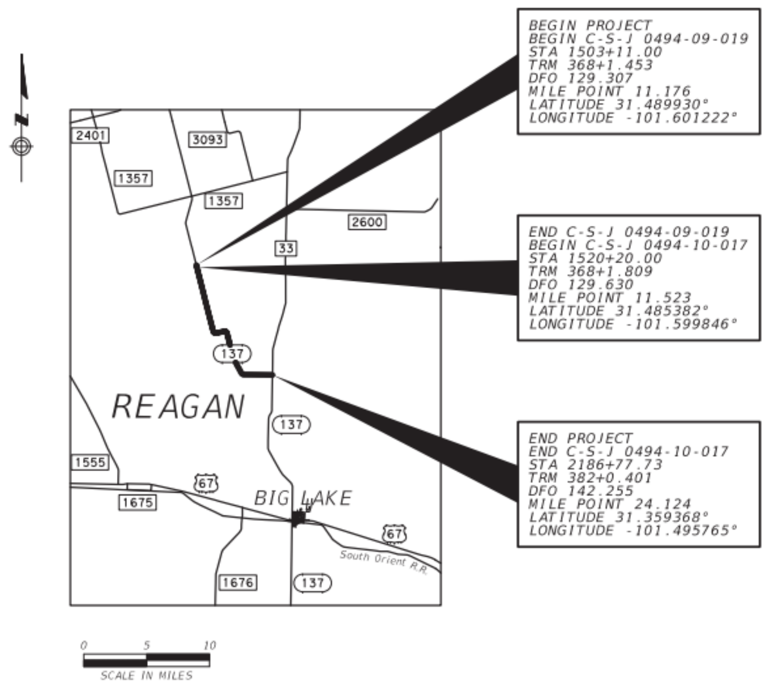


Figure 8. Location of the Selected FDR Field Projects Districts.

3.2. Collection of Representative Roadway Samples

The SH 137 project used a new base material for treatment, so that material was sampled from stockpile. For the other projects, sampling was performed directly behind the pavement reclaimer on untreated material without additives or treatments. The materials gathered were utilized in Tasks 4 and 5 of this research.

Figure 9 through Figure 13 show the project extents and representative materials from each of the selected projects. The research team coordinated with TxDOT to sample materials between July 2022 and October 2024. Based on needed quantities for the laboratory research test factorial, researchers collected around 4,500 lb of untreated materials from each field project.



(a)

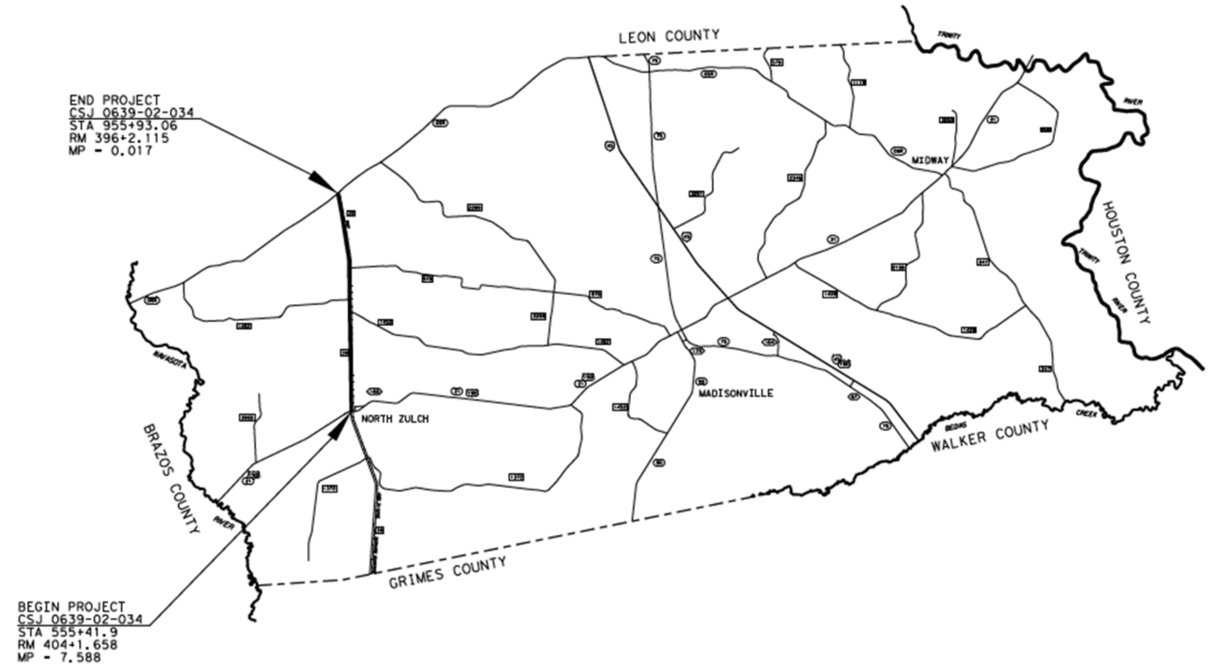
(b)

Figure 9. SJT SH 137 (a) Project Location and (b) Representative Materials.

(a)

(b)

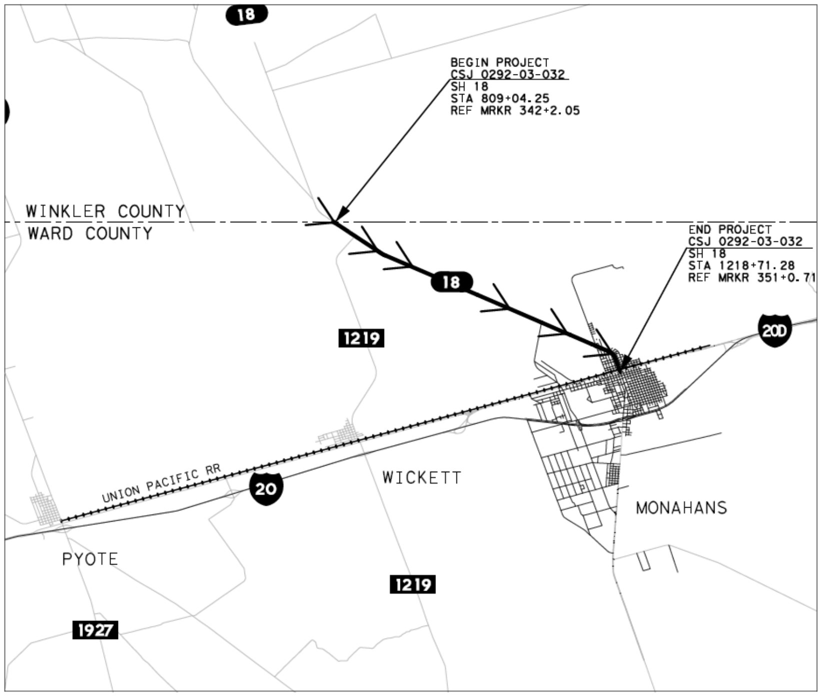
Figure 10. ODA SL 338 (a) Project Location and (b) Representative Materials.



(a)

(b)

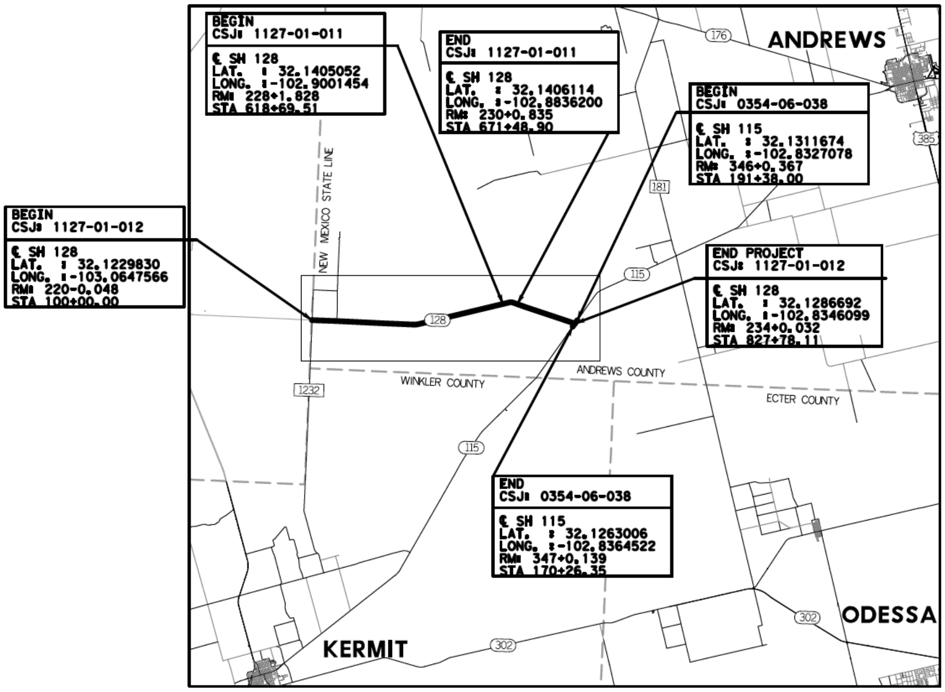
Figure 11. BRY FM 39 (a) Project Location and (b) Representative Materials.



(a)

(b)

Figure 12. ODA SH 18 (a) Project Location and (b) Representative Materials.



(a)

(b)

Figure 13. ODA SH 128 (a) Project Location and (b) Representative Materials.

3.3. FDR Project Information

- SH 137 (SJT): The material was collected in September 2022 for a project involving the highway improvement in Reagan County. The existing road configuration consisted of 1.5 to 3-inch surfacing and 2 to 10 inches of flexible base. The proposed section included widening and FDR with 6 to 9 inches of new flex base. The collected material consists of 100 percent new flexible base sourced from the Bedrock Pit. The project covers a 12.9-mile stretch from 11.5 miles south of Glasscock County line to RM 33.
- SL 338 (ODA): The material was collected in August 2023 for a project involving the construction and rehabilitation of existing roads in Ector County. The existing road configuration consisted of 1.5 to 2.5 inches of asphalt concrete pavement (ACP) over a 12-inch flexible base. The project spans a 7.6-mile stretch from US 385 to SH 191.
- FM 39 (BRY): The material was collected in January 2024 for a project involving the construction and rehabilitation of existing roads in Madison County. The existing road configuration consisted of two one-course surface treatments over a 16-inch compacted flexible base. The project spans a 7.6-mile stretch from OSR to US 190.
- SH 18 (ODA): The material was collected in December 2023 for a project involving the construction and rehabilitation of existing roads in Ward County. The existing road configuration consisted of 2 inches of ACP over a 10-inch flexible base. The project spans a 7.8-mile stretch from the Winkler County line to BI 20-D.
- SH 128 (ODA): The material was collected in October 2024 for a project involving the construction and rehabilitation of existing roads in Andrews County. The existing road configuration consisted of 1.5 inches of ACP over an 8-inch flexible base. The project spans a 14.2-mile stretch from the New Mexico state line to SH 115.

3.4. Summary of Materials Selection and Collection

Materials were collected between July 2022 and October 2024 from five roadway projects across three TxDOT districts. SH 137 involved only new base material, while the other four projects provided reclaimed base with varying asphalt and base layer thicknesses. Approximately 4,500 lb of untreated material were gathered from each site to support the laboratory testing program. These materials provided a representative dataset of Texas FDR conditions for subsequent structural and performance evaluations.

CHAPTER 4. COMPREHENSIVE LAB PROGRAM

This chapter outlines the laboratory evaluation framework used to characterize asphalt-stabilized FDR mixtures and to determine when a cement (or lime) additive is necessary. Materials from five TxDOT projects were used to execute a four-phase program:

- Fundamental material properties.
- Mix design (with/without additive).
- Time-strength behavior across curing stages.
- Time-performance behavior (modulus and permanent deformation).

Using SH 137 as the pilot, the initial test plan focused on mixes with and without cement and included IDT and UCS-based mixture design and early time-strength/performance checks. Insights from the pilot—along with agency input—led to a modified test plan:

1. Formally evaluate lime as a 1:1 cement substitute.
2. Remove wet UCS from mixture design to align with current Tex-122-E/Tex-134-E procedures.
3. Standardize curing to 68°F and 50 percent relative humidity (RH), and extend time points (4 hours, 24 hours, 3 days, 7 days, and 28 days) for time-strength and time-performance behavior.
4. Emphasize resilient modulus (Mr) and permanent deformation (PD) testing for time-dependent performance.

Under the modified plan, all four materials (SL 338, FM 39, SH 18, and SH 128) were designed with both emulsion and foam; time-dependent testing was performed on SL 338, FM 39, and SH 18 for both types of asphalt treatments, and on SH 128 only using emulsion treatment (due to material availability).

The results presented in this chapter provide the strength/stiffness development and rutting resistance trends needed for Task 6's mechanistic modeling and economic analyses, including traffic opening estimates and scenarios where the additive can be safely reduced or omitted.

4.1. Initial Lab Program

Researchers utilized materials collected from the projects shown in Table 3 to develop and execute a comprehensive laboratory program aimed at fully characterizing FDR mixes. Initially, the lab work focused only on mixes with and without cement additive. Table 4 summarizes the laboratory testing program, which consisted of four key phases:

- **Fundamental Materials Properties**: This phase focused on determining detailed fundamental properties of each FDR material to establish target densities and select dosage rates for subsequent mix design work.
- **Mix Design**: This phase evaluated the strength properties of FDR mixtures with and without additive to determine whether excluding the additive still allows the mix to meet minimum strength thresholds.

- **Time-Strength Properties**: This phase examined how FDR strength develops over time, evaluating the mixes at initial, intermediate, and final curing stages. This phase provides data that assesses time-dependent trade-offs, particularly for early traffic opening, with and without additive. Additionally, this phase provides a comparison of potential time-strength differences between EA and FA treatments.
- **Time-Performance Properties**: This phase focused on measuring the mechanistic-empirical load-carrying capacity of FDR mixes at different curing times. These tests provide insights into expected pavement performance and potential accumulated damage under traffic loads. This phase included modulus and PD properties under various stress conditions with repeated load. Given the emphasis on early traffic handling, this phase pays particular attention to PD risks. The results from this phase were incorporated into structural and economic analysis, where results will be used to evaluate expected FDR layer performance throughout the curing process.

Table 4. Initial Laboratory Testing Program.

<table>
<tr><th>Phase of Testing</th><th>Tests</th><th>Test Timing</th></tr>
<tr><td>Fundamental Materials Properties</td><td>Particle Size Analysis Including Percent Passing the No. 200 Sieve
Liquid Limit, Plastic Limit, Plasticity Index
Methylene Blue Value
Moisture-Density Relationship</td><td>In accordance with Test Methods
Tex-101-E, 110-E, 200-F
Tex-104-106-E
ASTM C1777
Tex-113-E</td></tr>
<tr><td>Mix Design</td><td>IDT
UCS</td><td>In accordance with Test Methods
Tex-122-E (EA) or
Tex-134-E (FA)</td></tr>
<tr><td>Time-Strength Properties</td><td>IDT
The current initial strength screening test used by the Receiving Agency
Triaxial Compression
Determines the cohesion and angle of internal friction; could be particularly meaningful to differentiate properties between FDR mixes with and without the cement additive</td><td rowspan="2">Initial Curing
Within 4–24 hr of compaction and within 0.5 percentage points of optimum moisture content
Intermediate Curing
Minimum 48 hr after compaction and within 2% below to 50% of optimum moisture content
Final Curing
Minimum 7 days after compaction and less than 50% of optimum moisture content</td></tr>
<tr><td>Time-Performance Properties</td><td>Repeated Load Triaxial
Determines stress-dependent resilient modulus value under repeated loading
PD
Determines rutting parameters
Dynamic Modulus
Determines frequency and temperature dependent modulus under repeated loading</td></tr>
</table>

Researchers used the lab program outlined in Table 4 to guide the testing of material sampled from SH 137. The curing stages defined in Table 4 were established using temperature- and humidity-controlled chambers. The following sections detail the lab results from the SH 137 material, which were then used to guide future testing, with adjustments to the test plan made based on Receiving Agency input.

4.1.1. Lab Results from SH 137 Material

4.1.1.1. Fundamental Material Properties

The SH 137 material was sourced from a stockpile because this project utilized a new base material for treatment. Table 5 and Table 6 shows the fundamental properties and particle size analysis of this material.

Table 5. Fundamental Material Properties for SH 137 Material.

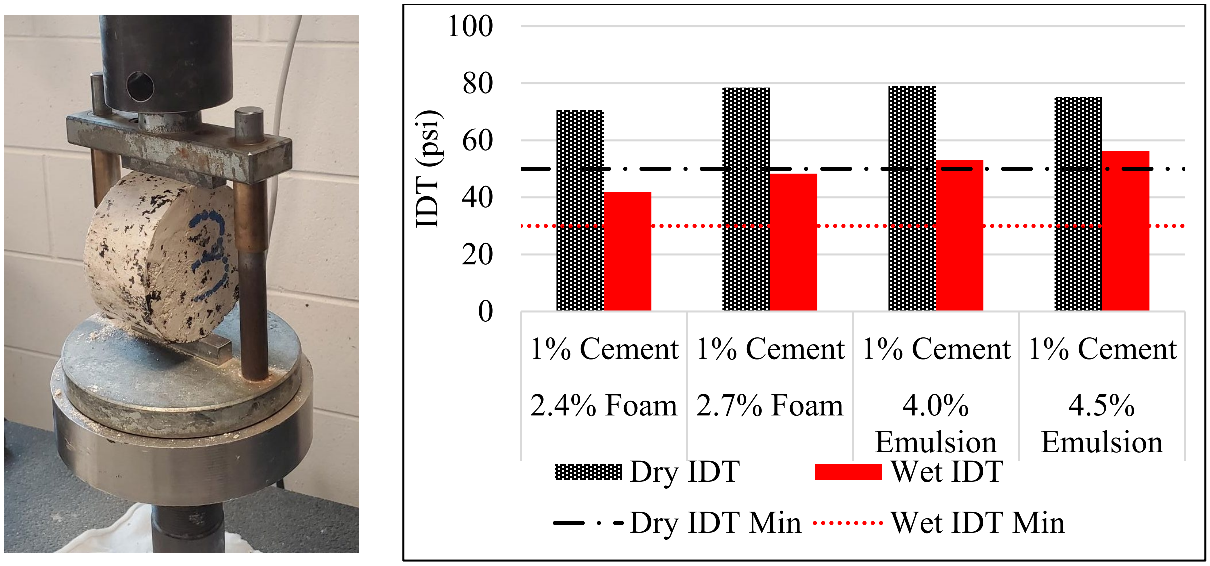
Test		Material Bedrock Caliche (SH 137 – SJT)
Atterberg Limits (Tex-104-6-E)	LL	16
	PL	12
	Plasticity Index	4
AASHTO Soil Classification		A-1-b
Methylene Blue Value (ASTM C1777)		12.7
Moisture-Density Relationship (Tex-113-E)	Max Dry Density (pcf)	132.7
	Optimum Moisture Content (%)	7.2

Table 6. Particle Size Analysis for SH 137 Material.

Test		Material Bedrock Caliche (SH 137 – SJT)
Particle Size Analysis (Tex-110-E/200-F)	Sieve Size	Cumulative Percent Passing (%)
	1 3/4"	100
	1 1/4"	97.9
	7/8"	92.4
	5/8"	83.2
	3/8"	69.5
	#4	54.8
	#40	29.4
	#100	23.3
	#200	19.8

4.1.1.2. Mix Design

Researchers prepared 4-inch diameter by 2-inch height samples and conducted IDT tests in accordance with Tex-122-E and Tex-134-E using EA and FA, respectively (Figure 14[a]). Figure 14(b) shows all mixes tested with 1 percent cement additive met the minimum strength requirements for dry and moisture conditioned (wet) IDT. These data also show that increasing emulsion content to 4.5 percent had minimal impact on IDT strength, while increasing the FA content from 2.4 percent to 2.7 percent resulted in increased both dry and wet IDT by about 7 psi. For construction on SH 137, a mix design of 1 percent cement + 2.4 percent FA was used.



(a) (b)

Figure 14. (a) IDT Test Setup and (b) IDT Mix Design Result for SH 137.

Figure 15 compares the dry and wet IDT for different alternate mix designs, including FT and ET mixtures with and without additive. During this research, questions arose whether lime could be substituted for the cement additive in FDR mixtures, so researchers tested the FA mix design selected for construction with lime substituted for cement. This substitution could help practitioners hedge against cement availability risks that occasionally occur in specific geographic regions.

The results in Figure 15 show the inclusion of the cement additive significantly increased both dry and wet IDT values, particularly in FT mixes. The results also suggest lime could potentially be used as a 1:1 substitute for cement and still produce a passing mix design.

With emulsion treatment, Figure 15 suggests ET mixes demonstrate higher moisture conditioned IDT strength than FT mixes without additive but still benefit from cement for added moisture resistance. Figure 15 shows that without the cement additive emulsion treatment came close to, but did not exceed, the 30-psi wet IDT minimum requirement.

Overall, the results from the SH 137 material indicate that FA treatments likely require cement or lime additive to meet the moisture conditioned strength requirements, whereas emulsion treatments may be more viable to produce a mixture design that meets both dry and wet strength requirements without an additive.

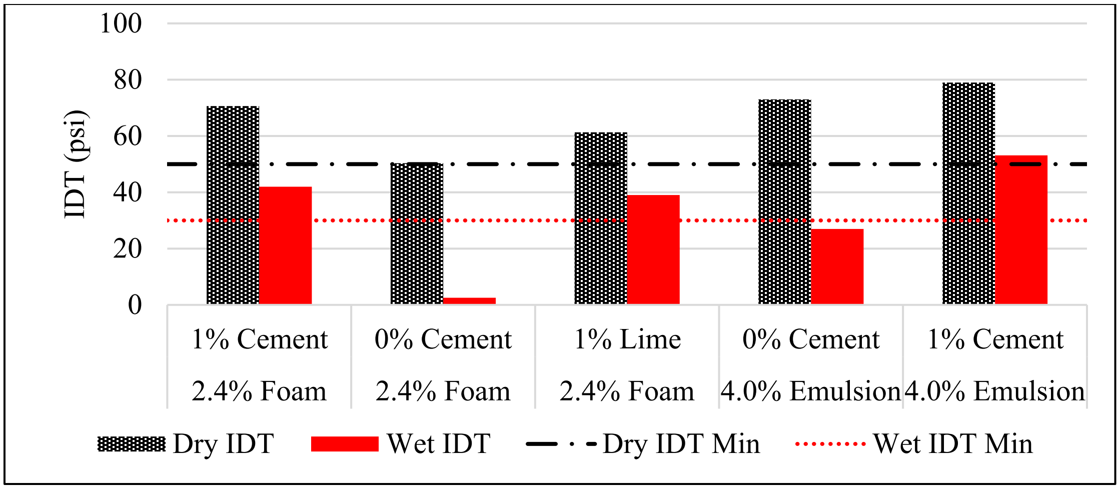
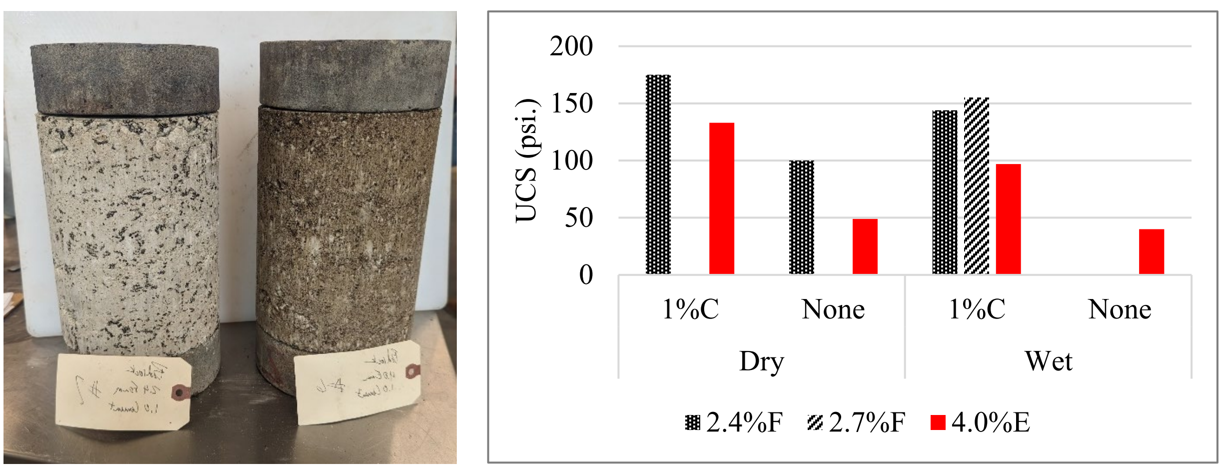


Figure 15. SH 137 Alternate Mix Design Results.

At the time of testing the SH 137 material, Tex-122 and Tex-134-E included wet UCS. Researchers conducted UCS, as shown in Figure 16(a). Without cement additive, no mixes tested met the 120-psi wet UCS minimum, as shown in Figure 16(b). Researchers did not test FA treatment for wet UCS without cement additive since the IDT results with that treatment already showed very low wet strength values. In dry conditions, FT samples exhibited significantly higher UCS values than ET samples.



(a) (b)

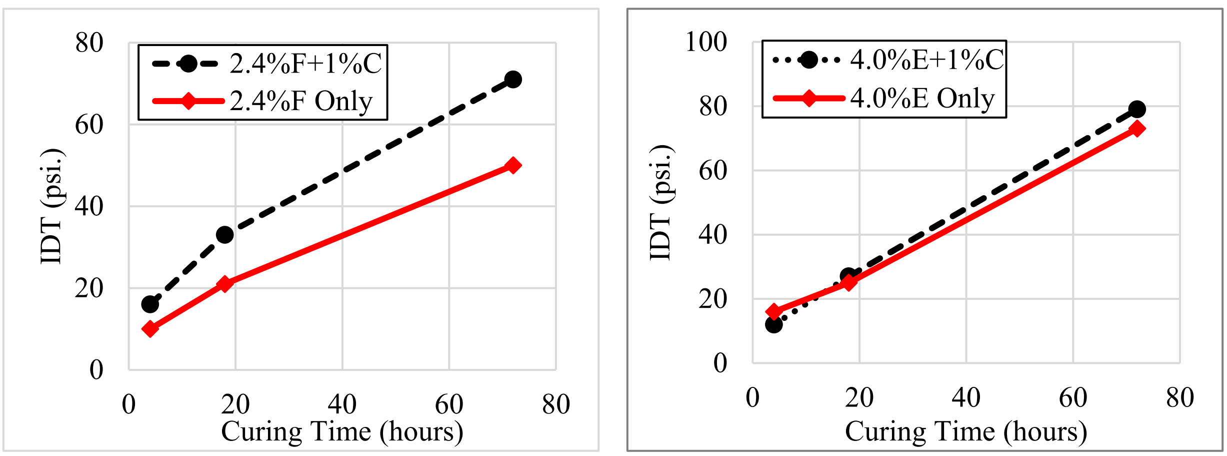
Figure 16. (a) Foam (left) and Emulsion (right) UCS Specimens and (b) UCS Results for SH 137.

Based on the IDT and UCS results, researchers selected 2.4 percent FA (the rate selected for construction) and 4.0 percent emulsion treatments (which should provide 2.4 percent residue) for further evaluation in time-strength and time-performance properties.

4.1.1.3. Time-Strength Properties

4.1.1.3.1 IDT Strength

Figure 17 shows time-strength properties of mixes with and without cement cured at 104°F and then tested for dry IDT. The results highlight a distinction between FA and EA treatments in their response to the inclusion of cement. For FT samples, the inclusion of cement increased the dry IDT by approximately 40 to 60 percent for a given curing time. In contrast, the inclusion of cement had minimal impact on the dry IDT of ET samples, where results were notably similar with or without cement for the dry condition. Additionally, all strength curves continued to rise, indicating ongoing strength gain even after 72 hours of curing. This suggests that the test duration for this experiment may need to extend beyond 72 hours, as the samples, while expected to reach "constant mass" by that time, still demonstrated ongoing strength development.



(a) Foam Treatment (b) Emulsion Treatment

Figure 17. Time-Strength IDT with SH 137 Material.

4.1.1.3.2 Triaxial Compression

For the untreated samples in the triaxial compression test, the testing followed Tex-117-E Part II. For the treated samples, materials were molded at their optimum moisture content (OMC) and then cured for 72 hours at 104°F without any moisture conditioning, as shown in Figure 18.

(a) Foam Treatment (b) Emulsion Treatment

Figure 18. (a) 2.4% Foam + 1% Cement Specimen and (b) 4.0% Emulsion + 1% Cement Specimens for the Triaxial Compression Test.

Table 7 shows that both foam and emulsion treatment with cement additive significantly increase strength compared to untreated material. The results also show sensitivity to confining pressure. FA treatment with cement showed the highest overall strength, exhibiting higher cohesion, the highest strengths under confinement, and nearly the same angle of internal friction as the untreated material. While emulsion treatment with cement also increased strength, it produced a lower internal angle of friction and lower maximum stress values than the FT mix. The original test plan included time-strength properties for these compressive tests, but other testing was pursued due to constraints on the quantity of available material.

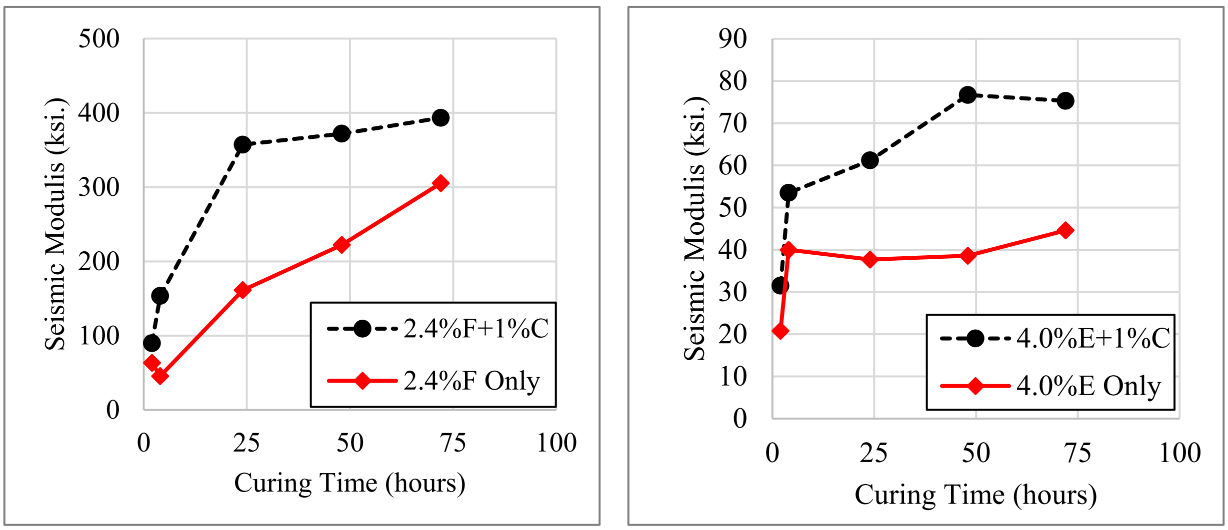
Table 7. Triaxial Compression Results from SH 137 Material.

Treatment	Confining Pressure (psi)	Average Corrected Stress (psi)	Internal Angle of Friction (degrees)	Cohesion (psi)
Untreated	0	37	54.8	6.5
	3	77		
	15	188		
2.4% F + 1% C	0	187	52.5	31.9
	3	219		
	15	315		
4.0% E + 1% C	0	145	47.7	28.6
	3	172		
	15	246		

4.1.1.4. Time-Performance Properties

Researchers utilized a seismic modulus test apparatus to evaluate time-performance properties with the material from SH 137. After fabricating test specimens to 6-inch diameter and 8-inch height, researchers cured the specimens at 104°F and measured the seismic modulus over a 72-hour period using two replicates per treatment.

The results in Figure 19 indicate that the inclusion of cement additive significantly accelerates early stiffness gain in both FT and ET samples. For FT samples, the measured modulus values align with field expectations, but the data do not clearly indicate whether the modulus values for samples with and without additive will converge, since the foam-only results were still increasing. In contrast, ET samples appear to have reached a plateau modulus by 72 hours, with the modulus values clearly higher when cement is included, and all the values well below the 200 ksi that is assumed in design of these layers. For ET samples, the modulus values, when viewed in context of the IDT strengths, seem unusually low, raising questions about a potential measurement error. Additionally, there was not enough material available to perform Mr, PD, or E* testing, limiting the ability to further validate or supplement the seismic modulus results.



(a) Foam Treatment (b) Emulsion Treatment

Figure 19. Seismic Modulus Over Time for SH 137 Material.

4.1.2. Observations from SH 137 Results

The use of lime (without mellowing) shows potential as a substitute for cement additive in FDR mix designs with FA or EA. With no additive in the FDR mix, mixtures met dry IDT requirements with both foam and emulsion treatments. However, the inclusion of cement additive significantly improved resistance to moisture as indicated by the wet IDT. Without cement, FT samples demonstrated poor strength after moisture conditioning, while ET samples performed better but still exhibited strength below the 30-psi wet IDT minimum.

The inclusion of cement additive resulted in faster initial stiffness gain. For FT samples, the data suggest the final modulus values may eventually converge with or without cement additive as time progresses. However, for ET samples, the data suggest the inclusion of cement additive produced higher stiffness over time, with no indication of convergence between treated and untreated samples. The observed strength and stiffness increases may not have fully plateaued by the time of final testing, suggesting that the curing process was still ongoing. Future testing should adjust the approach to better capture time-dependent property changes, ensuring more comprehensive evaluation of long-term performance.

4.1.3. Modifications to Task 4 Test Methods

Based on observations and experience from testing the material from SH 137, researchers modified the laboratory test plan with input from the Receiving Agency to improve alignment with project objectives. The lab testing modifications included:

- Revised the work plan to formally investigate whether lime could fully replace the cement additive on an equivalent basis with the remaining materials.
- Removed the moisture conditioned UCS from the mixture design phase, since during the performance time of this research project the UCS requirement was removed from the approved mix design procedures in Tex-122-E and Tex-134-E.
- Revised curing conditions to 68°F and 50 percent RH to prevent data concentration issues observed at 104°F when testing time-strength properties.
- Extending the curing time to 4 hours, 24 hours, 3 days, 7 days, and 28 days, allowing for a more comprehensive analysis when testing time-strength and time-performance properties.

4.2. Modified Lab Program

Table 8 presents the modified lab program which researchers used to guide testing the remaining materials. Materials from SL 338, FM 39, SH 18, and SH 128, were subjected to this modified lab program. Materials from all four locations were evaluated for both FA and EA mix designs as part of the mix design phase. However, for the time-dependent testing phases, including both time-strength and time-performance evaluations, only SL 338, FM 39, and SH 18 materials were tested under both FA and EA treatments. Material from SH 128 was evaluated exclusively using EA treatment due to material availability and prioritizing the treatment that was used in construction with that material.

Table 8. Modified Laboratory Testing Program.

Materials	Phase of Testing	Tests	Test Timing
SL 338 FM 39 SH 18 SH 128	Fundamental Materials Properties	Particle Size Analysis Including Percent Passing the No. 200 Sieve	In Accordance with Test Methods Tex-101-E, 110-E, 200-F
		Liquid Limit, Plastic Limit, Plasticity Index	Tex-104-106-E
		Methylene Blue Value	ASTM C1777
		Moisture-Density Relationship	Tex-113-E
	Mix Design	IDT	In Accordance with Test Methods Tex-122-E (EA) and Tex-134-E (FA)
	Time-Strength Properties	IDT	4 hours, 24 hours, 3 days, 7 days, and 28 days at 68°F and 50% RH
	Time-Performance Properties	Repeated Load Triaxial Resilient Modulus	
		PD	1 day, 3 days, 7 days, and 28 days at 68°F and 50% RH

4.2.1. Fundamental Materials Properties

Table 9 and Table 10 show the fundamental properties and particle size analysis of the untreated materials subjected to the modified lab testing program. Materials from SL 338, FM 39, and SH 18 are A-2-6, while SH 128 was classified as A-2-7 due to its higher plasticity. Methylene blue values and plasticity index (PI) indicated that the SH 128 material contained more active clay fines.

Table 9. Fundamental Materials Properties.

Test		SL 338	FM 39	SH 18	SH 128
Atterberg Limits (Tex-104-6-E)	**LL**	26	20	29	30
	PL	14	9	18	14
	PI	13	10	11	16
AASHTO Soil Classification		A-2-6	A-2-6	A-2-6	A-2-7
Methylene Blue Value (ASTM C1777)		13.6	15.6	11.9	20.0
Moisture-Density Relationship (Tex-113-E)	**Max Dry Density (pcf)**	127.5*	136.3*	123.2*	119.1*
	OMC (%)	7.5	6.6	9.8	9.4

* Determined without treatment.

Table 10. Particle Size Analysis for FDR Materials.

Test		SL 338	FM 39	SH 18	SH 128
Particle Size Analysis (Tex-110-E/200-F)	**Sieve Size**	**Cumulative Percent Passing (%)**			
	1 3/4"	100	100	100	100
	1 1/4"	98.8	96.3	89.4	100
	7/8"	96.5	89.7	79.4	96.8
	5/8"	91.7	81.4	71.2	92.4
	3/8"	78.8	68.7	61.0	83
	#4	58.4	55.4	50.5	67.5
	#40	29.1	38.1	34.9	39.8
	#200	17.3	15.8	15.0	16.9

4.2.2. Lab Mix Designs

Across the four different materials, type and rate of asphalt treatment, and type and rate of additive, researchers performed 43 different mixture designs.

4.2.2.1. SL 338 Mix Designs

Figure 20 illustrates the dry and wet IDT results for mixtures with SL 338 materials containing 1 percent cement, with varying asphalt binder types and contents. All three mixtures exceeded the minimum dry and wet IDT strength thresholds of 50 psi and 30 psi, respectively. The construction project used 1 percent cement with 2.4 percent FA. Based on these results, the research team selected 2.4 percent foam and 4.0 percent emulsion for subsequent alternative mixture design and performance-related testing.

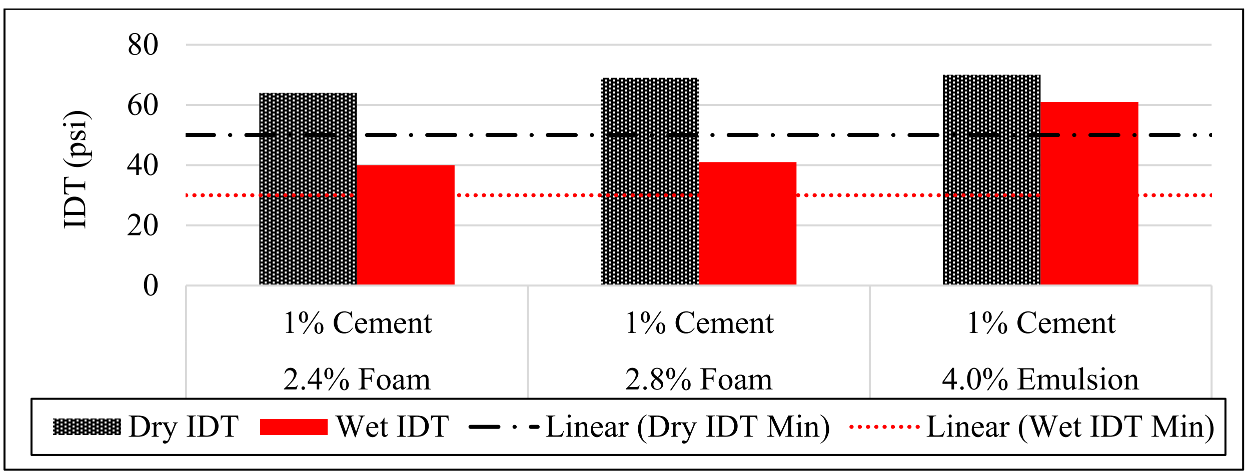


Figure 20. SL 338 Mix Design Results.

Figure 21 presents the alternative mix design results for SL 338. In the ET mixtures, both the cement and lime additive significantly enhanced dry and wet strength, with the lime additive producing the highest dry IDT (80 psi) and cement additive slightly outperforming lime in terms of wet strength (60 psi vs. 52 psi). The mixture without any additive met the wet strength requirement, indicating that emulsion alone may have potential to achieve adequate performance without the use of additives with this material.

Similar trends were observed in the FT mixtures. Results with cement and lime additive were similar and met all strength requirements, while the mixture at the design foam rate with no additive exhibited a substantial drop in wet IDT and fell well short of the 30-psi minimum. These results suggest that both the cement and lime additives are effective for enhancing strength and moisture resistance in FDR mixtures and provide further credibility to the potential use of lime as a 1:1 substitute for cement in asphalt-based FDR mix design. The results also suggest removing the additive from foamed asphalt-treated mixtures could be risky for operational environments where moisture sensitivity is a concern.

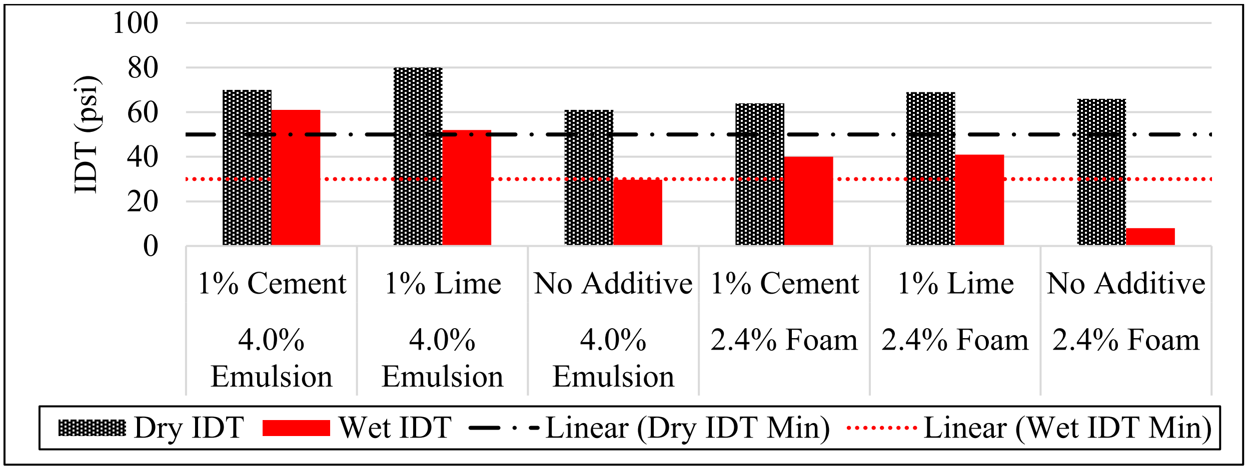


Figure 21. SL 338 Alternate Mix Design Results.

4.2.2.2. FM 39 Mix Designs

Figure 22 illustrates the mix design results from FM 39. All mixtures exceeded the minimum dry IDT strength threshold of 50 psi, while the mixtures containing 1 percent cement with 4.5 percent and 5.0 percent emulsion and all foam design marginally exceeded the wet IDT threshold of 30 psi. Based on these results, the mixtures containing 1 percent cement with 4.5 percent EA and 2.8 percent FA demonstrated the most balanced performance under both dry and wet conditions. Researchers used those asphalt rates for further tests. The construction project used 1 percent cement with 2.4 percent FA.

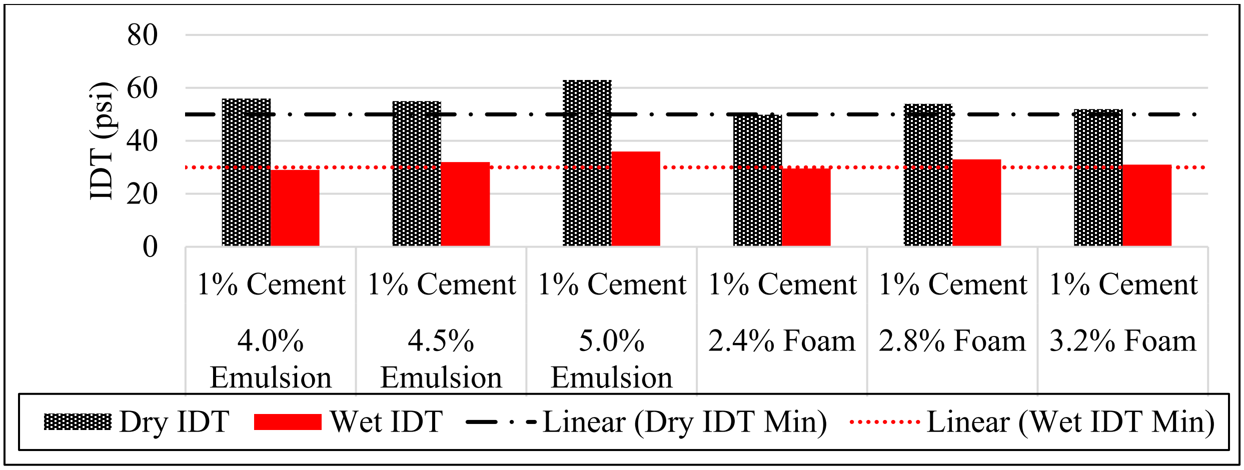


Figure 22. FM 39 Mix Design Results.

Figure 23 presents the IDT strength results for FM 39 with the alternative mix designs. In the ET mixtures, all combinations that included additive met minimum strength requirements with similar results. Without additive, the ET mix failed to meet the wet IDT criteria.

With FA treatment, both the cement and lime additives achieved similar dry strengths (52 to 53 psi), but only the mix with cement additive met the wet IDT minimum. The lime-additive mixture fell just below (24 psi), and the mixture without any additive showed poor wet strength (6 psi).

These results highlight the importance of running mixture designs with representative materials and proposed treatments. In this case, substituting lime for cement additive still produced a passing mix design with emulsion treatment, but not with FA treatment.

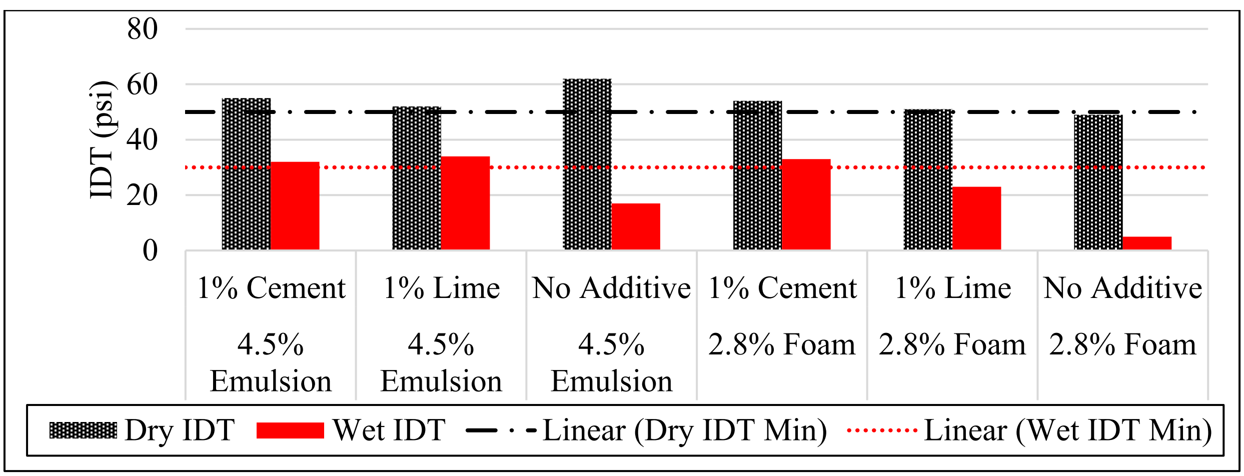


Figure 23. FM 39 Alternate Mix Design Results.

4.2.2.3. SH 18 Mix Designs

Figure 24 presents the mix design results with material from SH 18. All mixtures surpassed the minimum required strengths. Among these, the mixtures with 4.0 percent EA and 2.4 percent FA offered the most economical and well-balanced performance across both moisture conditions, making them the preferred candidates for further evaluation. The construction project was treated with emulsion and cement additive.

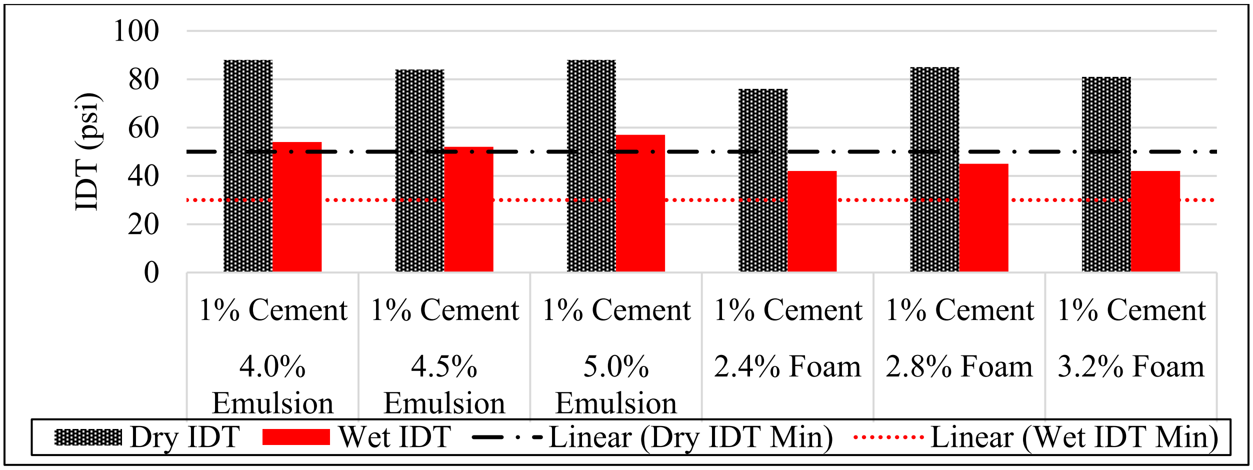


Figure 24. SH 18 Mix Design Results.

Figure 25 presents the alternate mix design results with the SH 18 material. With this material, the only mixtures meeting all strength criteria required the use of cement additive. The mixtures with lime or no additive displayed significantly lower dry and wet strengths. With no additive, regardless of emulsion or foam treatment, the results fell well below the minimum wet IDT.

Overall, these results highlight that for SH 18, a cement additive significantly enhanced strength and moisture susceptibility, while lime as an additive provided only moderate improvement.

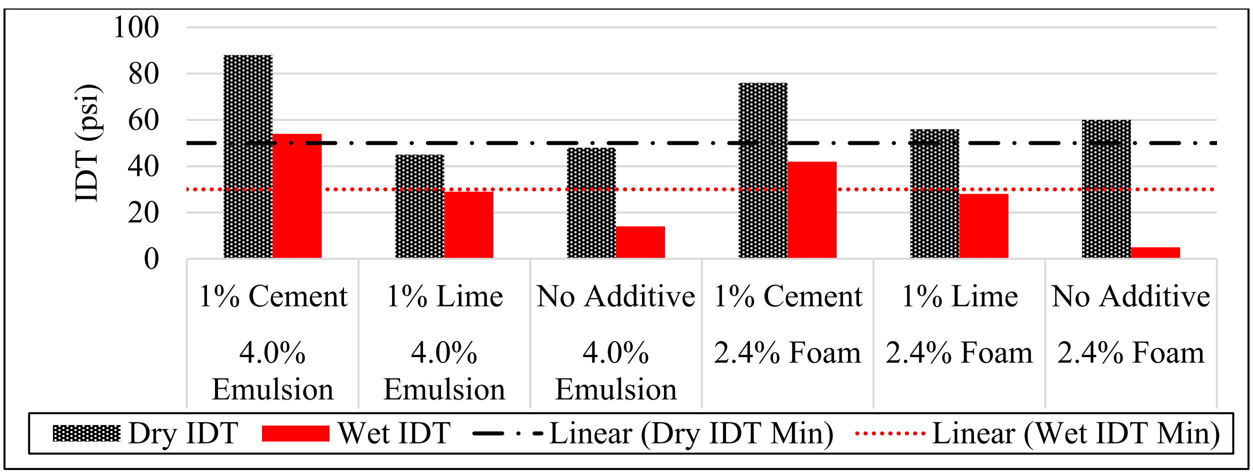


Figure 25. SH 18 Alternate Mix Design Results.

4.2.2.4. SH 128 Mix Designs

Figure 26 illustrates the mix design results from the SH 128 material. All mixtures exceeded the minimum dry IDT strength threshold of 50 psi. However, only those mixtures containing 4.0 percent emulsion and 2.4 percent FA exceeded the wet IDT threshold of 30 psi. Based on these results, the mixtures containing 1 percent cement with 4.0 percent EA and 2.4 percent FA were selected for subsequent alternative mixture design and performance-related testing. The construction project used 1 percent cement with 4.0 percent EA.

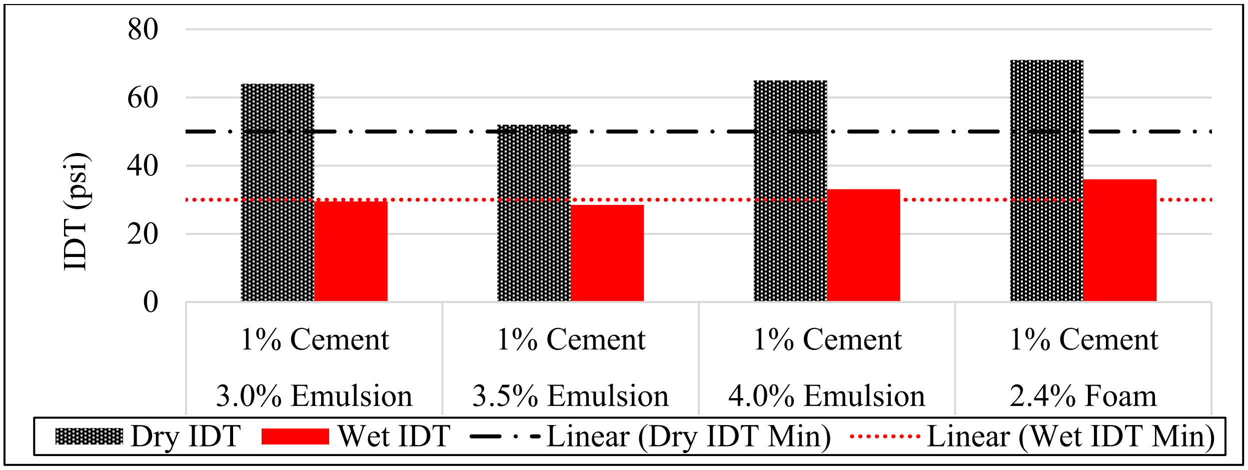


Figure 26. SH 128 Mix Design Results.

Figure 27 presents the IDT strength results for SH 128 material with alternate designs using 4.0 percent EA or 2.4 percent FA. With the ET mixtures, all combinations satisfied the dry IDT strength threshold of 50 psi. Compared to using cement additive, using lime additive with emulsion showed slightly lower dry and wet strengths but still met the minimum requirements. Despite achieving an acceptable dry strength, the mixture treated with emulsion without any additive showed a marked reduction in wet strength, falling well below the minimum 30-psi requirement.

With FA treatment, all three combinations exceeded the dry strength requirement, and substituting lime for cement still provided a mix that met all strength requirements. However, with no additive, FA treatment showed an extremely low wet IDT of only 2 psi. Overall, these results affirm the critical role cement and lime additives often play in enhancing the resilience of asphalt-based FDR mixtures in the presence of moisture.

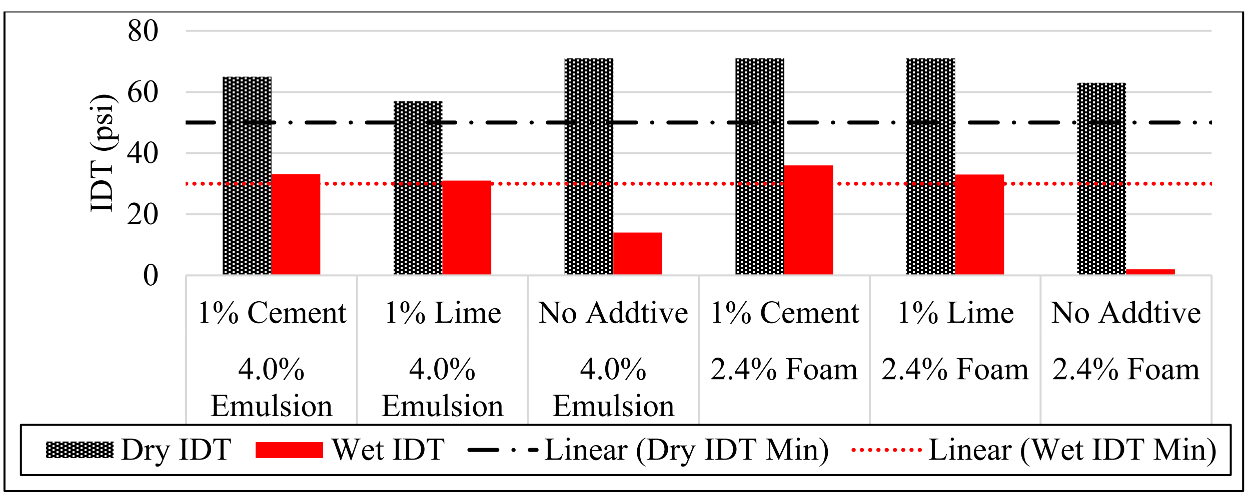
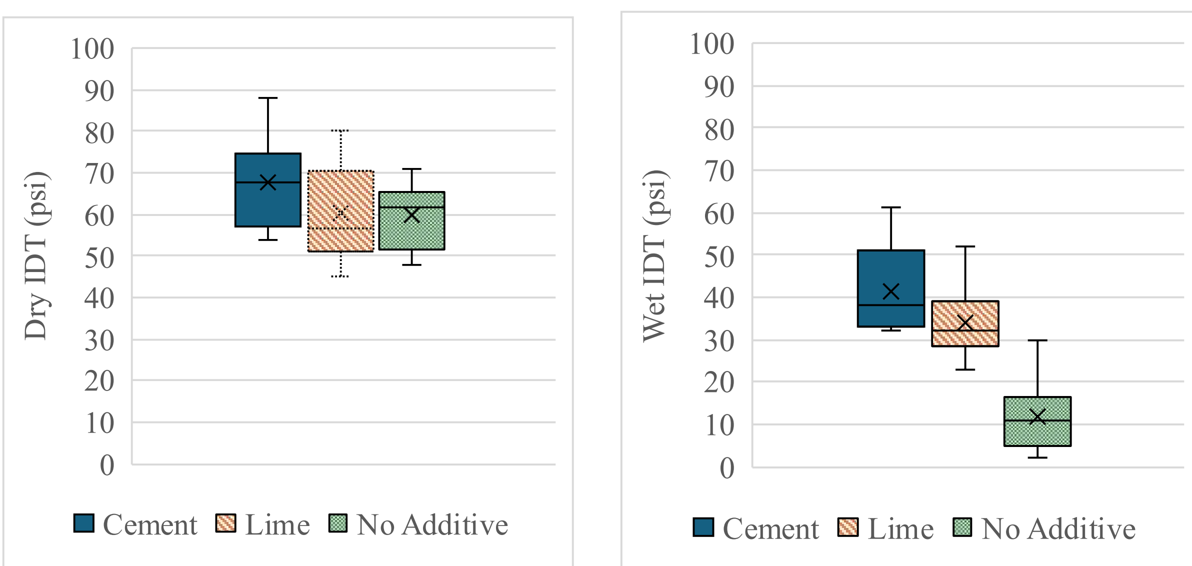


Figure 27. SH 128 Alternate Mix Design Results.

4.2.2.5. Conclusions from Mix Designs

Across all materials (SL 338, FM 39, SH 18, and SH 128), the inclusion of 1 percent cement consistently improved performance under both dry and wet IDT conditions. Dry strength usually met minimum requirements regardless of additive type. FA and EA with 1 percent cement additive mixtures reliably exceeded both the dry and wet strength thresholds, reaffirming cement's effectiveness as an additive. When lime was substituted to the same degree for cement, it also enhanced strength as compared to mixtures with no additive, but the wet strength of mixtures using lime as an additive sometimes failed to meet the minimum wet IDT criteria.

The box plots in Figure 28 illustrate the dry and wet mix design strength according to type of additive. Figure 28 illustrates that, regardless of additive or even the lack of additives, most materials will meet the 50-psi dry IDT minimum. However, the moisture conditioning typically governs whether a mix design will meet all strength requirements. Figure 28 illustrates that, for the materials tested, cement additive along with asphalt treatment provided the highest moisture conditioned strengths. Lime additive, although on average was able to produce mixtures that met the wet IDT minimum, did not produce mixes passing the wet IDT minimum as reliably as cement. When additive was totally removed, and materials treated with only EA or FA, most mixtures failed to meet the 30-psi wet IDT minimum, and the overall average wet IDT of these mixtures fell well short of the current minimum requirement.



(a) Dry IDT (b) Wet IDT

Figure 28. Box Plots for (a) Dry and (b) Wet IDT from Mix Designs.

The underlying data in Figure 28 can be further detailed as follows:

- Mixes that met both dry and wet IDT were achieved in 100 percent of the cases using asphalt (foam or emulsion) with cement additive.

- With lime additive, 88 percent of mixes met dry IDT requirements, and 62 percent of mixes met wet IDT requirements. Two of the mixes with lime additive that failed to meet the minimum wet IDT were within 2 psi of the minimum wet strength requirement.
- With no additive, 75 percent of mixes met the dry IDT minimum; however, only 12 percent of those mixes met the wet IDT minimum.

Figure 29 illustrates the overall dry and wet IDT mix design results by treatment type. Figure 29 illustrates that ET materials tend to have higher wet IDT values compared to materials treated with FA, regardless of the type of additive. Additionally, Figure 29 illustrates that when no additive is included, the wet IDT of ET materials is much higher than materials treated with FA and no additive. Thus, the results suggest that if additive cannot or will not be used with an FDR material, and moisture susceptibility is a concern for the operating environment, emulsion treatment would be preferred.

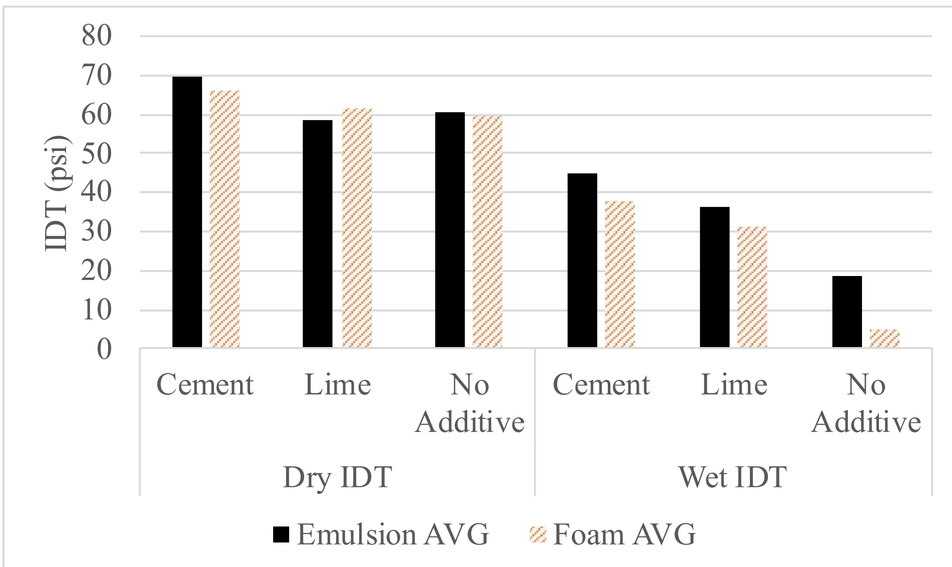


Figure 29. Dry and Wet IDT Averages by Additive and Asphalt Type.

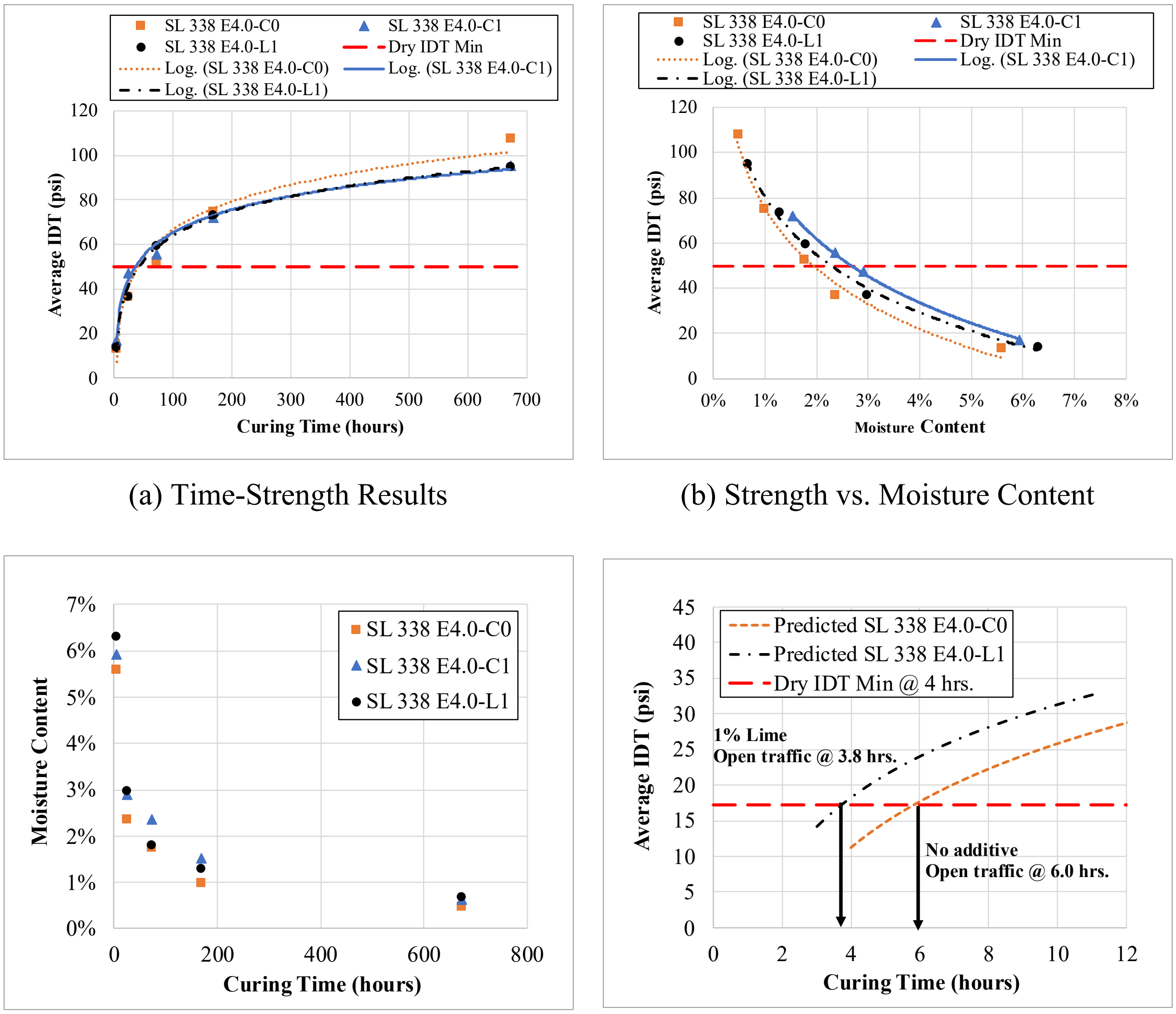
4.2.3. Time-Strength Properties

The time-strength testing program was designed to make optimal use of available laboratory resources while maintaining consistent environmental control. All specimens were cured under standardized conditions of 68°F and 50 percent RH to minimize variability from curing conditions. As part of the experimental protocol, four replicate specimens were prepared for each combination of mix design and additive condition. After reaching the designated curing duration (ranging from 4 hours to 28 days), IDT strength tests were conducted to evaluate the time-dependent strength development of the mixtures. Upon completion of the strength testing, the fractured specimens were placed in a 110°C oven for 24 hours to obtain their oven-dry weights. These measurements were used to calculate the moisture content at the time of testing, providing additional insight into the relationship between internal moisture loss and strength gain throughout the curing process.

4.2.3.1. Time-Strength Results

4.2.3.1.1 SL 338

Figure 30 presents the time-dependent strength development and moisture behavior of SL 338 mixtures treated with 4.0 percent EA under three additive conditions: 1 percent cement (C1), 1 percent lime (L1), and no additive (C0). As shown in Figure 30(a), all mixtures exhibited rapid strength gain within the first 72 hours, with the C1 and L1 mixtures demonstrating similar long-term IDT trends and slightly higher early strength than the C0 mixture, which eventually surpassed both after extended curing. Figure 30(b) confirms an inverse relationship between moisture content and IDT strength, with C1 and L1 maintaining higher strengths at a given moisture level; the C0 mixture initially lagged but ultimately converged at lower moisture contents. Figure 30(c) shows consistent moisture loss in all mixtures, with final values dropping below 2 percent within 7 days. As expected, each treatment lost moisture during the curing time, although variations in the rate of drying and absolute moisture content did exist between some of the treatments. Figure 30(d) illustrates early-age IDT strength projections, where the dry IDT of 18 psi after 4 hours of curing with the baseline mix design of 1 percent cement + 4.0 percent emulsion was used as the reference minimum strength before opening to traffic. Figure 30(d) indicates that the lime-additive mixture exceeded the dry IDT minimum (18 psi at 4 hours) in approximately 3.8 hours, while the non-additive mixture reached this level in about 6 hours. Figure 30(d) suggests that, with this material, the mix with lime additive plus emulsion could be opened to traffic just as rapidly as the mix with cement additive, while removing the additive entirely requires at least two additional hours of cure time.



(a) Time-Strength Results

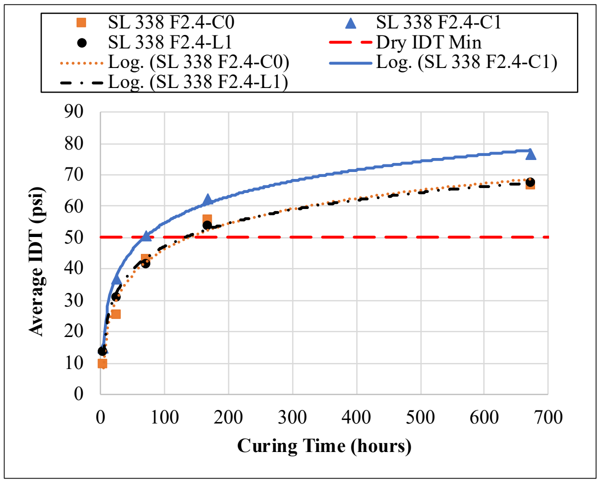
(b) Strength vs. Moisture Content

(c) Curing Time vs. Moisture Content

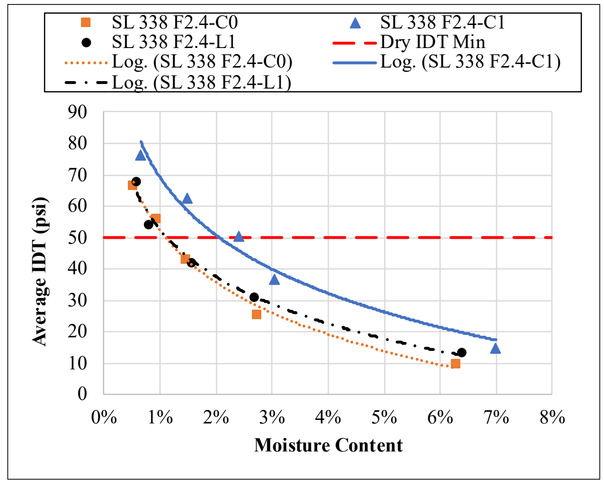
(d) Open Traffic Time for Alternative Design

Figure 30. Time-Strength Results for SL 338 with 4.0% Emulsion.

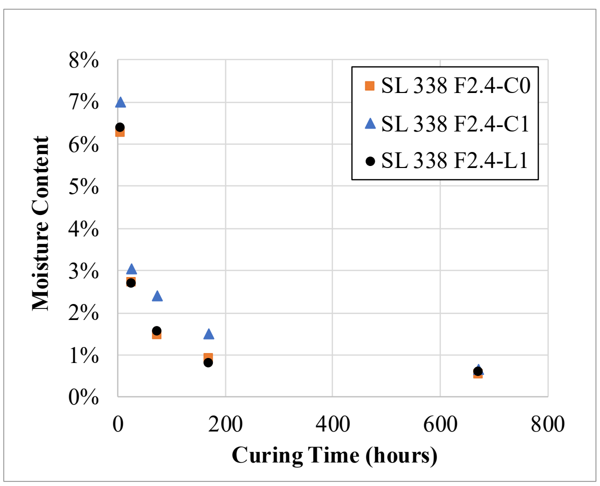
Figure 31 presents the time-dependent strength development and moisture behavior of SL 338 mixtures treated with 2.4 percent FA under three additive conditions: C1, L1, and C0. As shown in Figure 31(a), all mixtures exhibited rapid strength gain within the first 72 hours, with the C0 and L1 additive mixtures showing similar long-term IDT trends. The C1 mixture shows slightly higher early strength than the C0 mixture. Figure 31(b) confirms an inverse relationship between moisture content and IDT strength, with the C1 and L1 additive mixtures maintaining a higher strength at a given moisture level, while the C0 mixture initially lagged but ultimately approached the L1 additive curve at lower moisture contents. Figure 31(c) shows consistent moisture loss in all mixtures, with final values dropping below 2 percent within 7 days. Figure 31(d) presents the early-age IDT strength projections, indicating that the lime-additive mixture exceeded the dry IDT minimum (15 psi at 4 hours) in approximately 4.2 hours, while the non-additive mixture reached this level in about 7.2 hours. These results reasonably agree with results from this material treated with emulsion: with lime additive substituted for cement, similar times to traffic opening would be expected, while removing the additive altogether would require additional cure time.



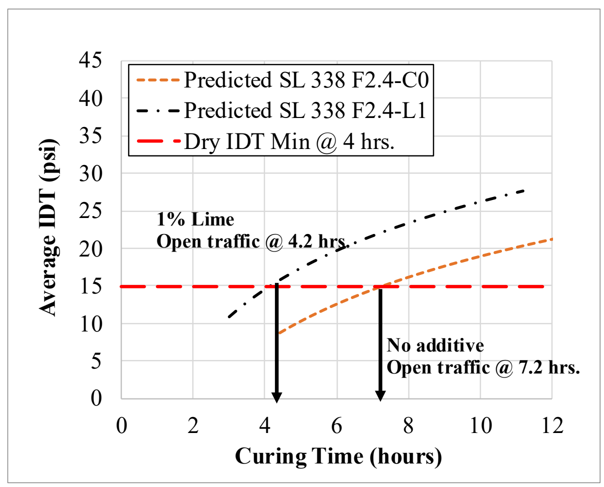
(a) Time-Strength Results



(b) Strength vs. Moisture Content



(c) Curing Time vs. Moisture Content

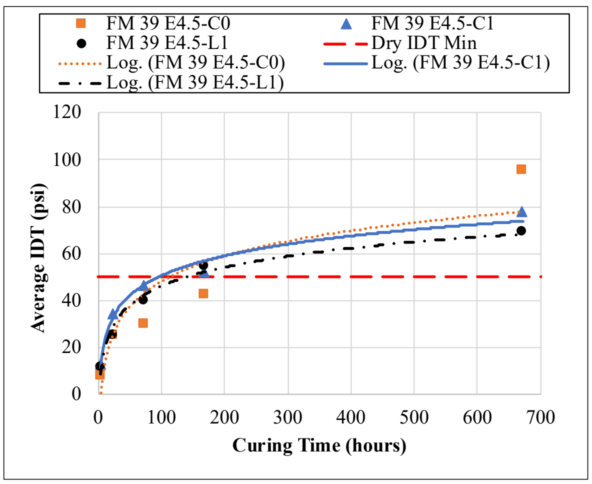


(d) Open Traffic Time for Alternative Design

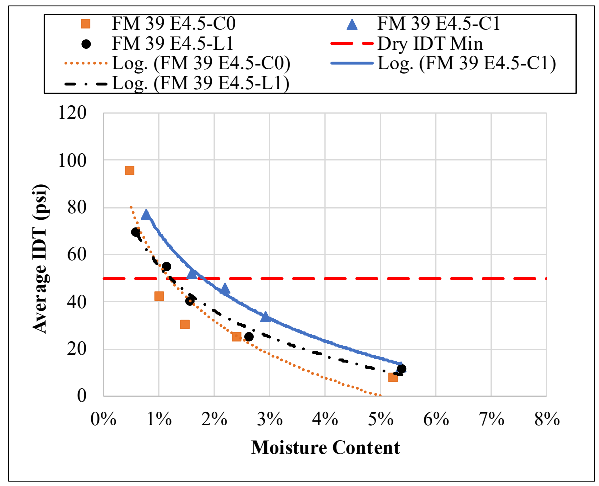
Figure 31. Time-Strength Results for SL 338 2.4% Foamed Asphalt-Treated Design.

4.2.3.1.2 FM 39

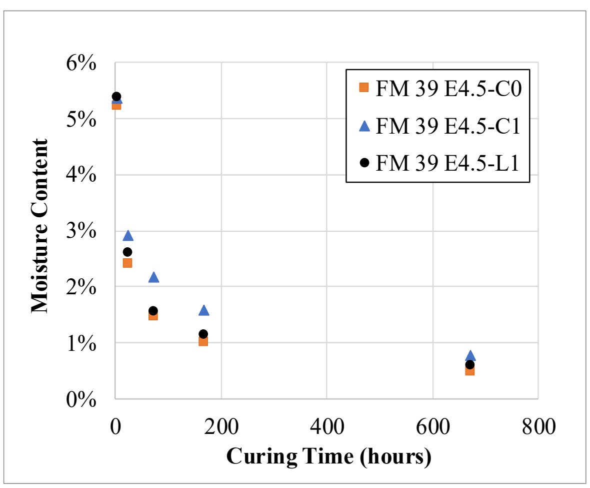
Figure 32 presents the time-dependent strength development and moisture behavior of FM 39 mixtures treated with 4.5 percent EA under three additive conditions: C1, L1, and C0. As shown in Figure 32(a), all mixtures exhibited rapid strength gain within the first 72 hours, with the C1 and L1 additive mixtures showing slightly higher early strength than the C0 mixture, which eventually matched the additive trends after prolonged curing. Figure 32(b) confirms an inverse relationship between moisture content and IDT strength, with the additive mixtures maintaining a higher strength at intermediate moisture levels. The non-additive mixture ultimately intersected with the additive curves as moisture decreased. Figure 32(c) shows moisture reduction across all mixtures, with final values falling below 2 percent within 7 days. As expected, each treatment lost moisture during the curing time, although variations in the rate of drying and absolute moisture content did exist between some of the treatments. Figure 32(d) presents early-age IDT strength projections, indicating that the lime-additive mixture exceeded the dry IDT minimum (12.5 psi at 4 hours) in approximately 3.8 hours, while the non-additive mixture required about 6.8 hours to reach the same threshold.



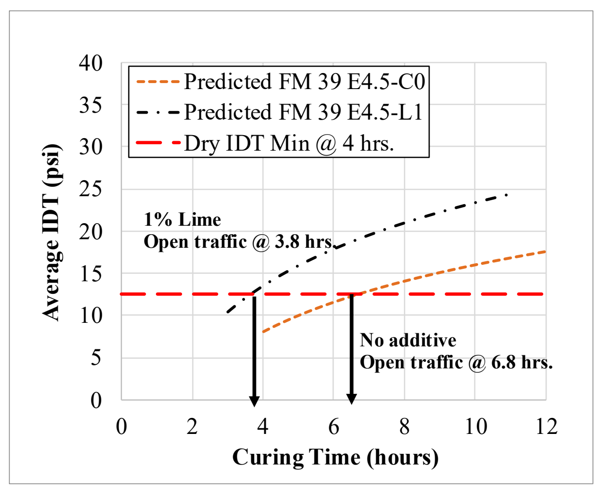
(a) Time-Strength Results



(b) Strength vs. Moisture Content



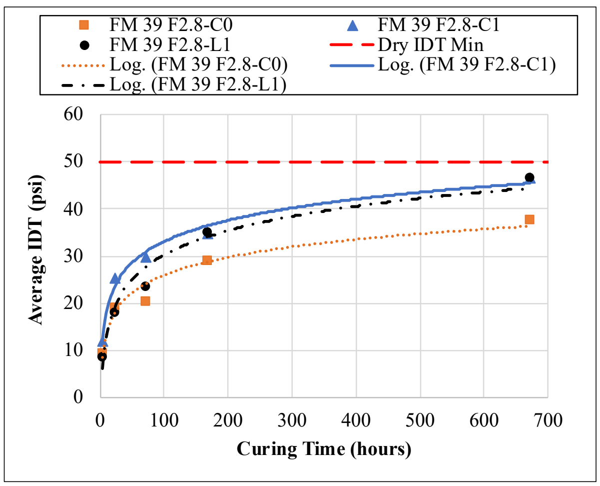
(c) Curing Time vs. Moisture Content



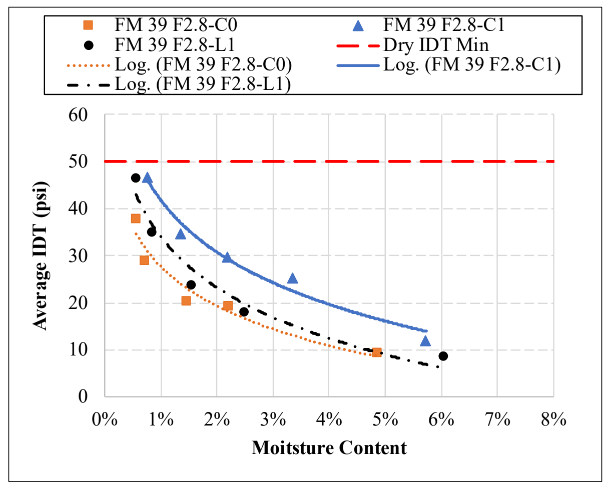
(d) Open Traffic Time for Alternative Design

Figure 32. Time-Strength Results for FM 39 4.5% Emulsified Asphalt-Treated Design.

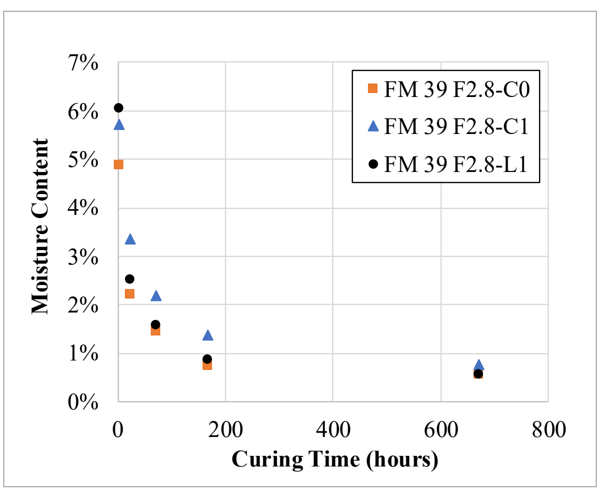
Figure 33 presents the time-dependent strength development and moisture behavior of FM 39 mixtures treated with 2.8 percent FA under three additive conditions: C1, L1, and C0. As shown in Figure 33(a), all mixtures demonstrated early strength gain, with the C1 mixture achieving the highest IDT values throughout most of the curing period. This was followed closely by the lime-additive mixture, which demonstrated almost the same IDT strength as the mix with cement additive at the end of the curing period, while the C0 mixture lagged in both early and long-term strength. Figure 33(b) shows a clear inverse relationship between moisture content and IDT strength, with the additive mixtures maintaining a higher strength at comparable moisture levels. Figure 33(c) illustrates steady moisture reduction across all cases, reaching below 2 percent within 7 days. As expected, each treatment lost moisture during the curing time, although variations in the rate of drying and absolute moisture content did exist between some of the treatments. Figure 33(d) presents the early-age IDT projections, showing that the lime-additive mixture reached the dry IDT threshold (12.5 psi at 4 hours) in approximately 3.6 hours, while the non-additive mixture required about 7.2 hours to meet the same condition.



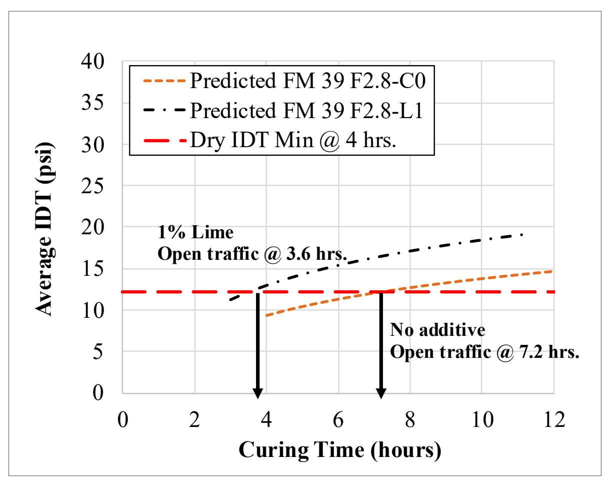
(a) Time-Strength Results



(b) Strength vs. Moisture Content



(c) Curing Time vs. Moisture Content

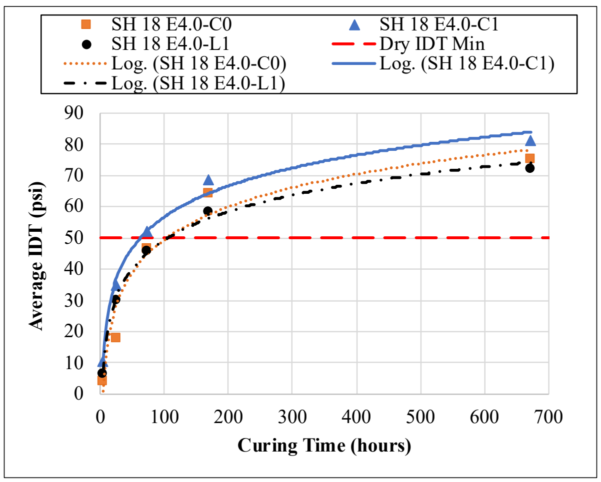


(d) Open Traffic Time for Alternative Design

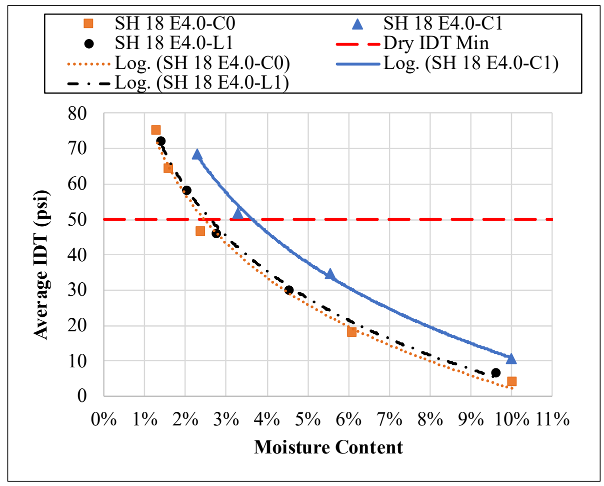
Figure 33. Time-Strength Results for FM 39 2.8% Foamed Asphalt-Treated Design.

4.2.3.1.3 SH 18

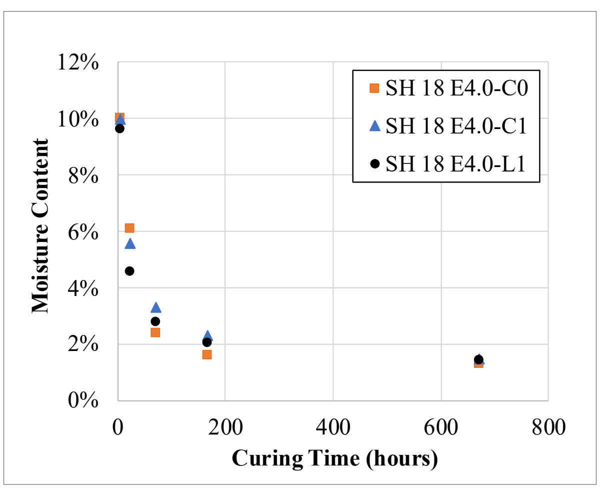
Figure 34 presents the time-dependent strength development and moisture behavior of SH 18 mixtures treated with 4.0 percent EA under three additive conditions: C1, L1, and C0. As shown in Figure 34(a), all mixtures exhibited rapid strength gain during early curing, with the C1 mixture consistently achieving the highest IDT values throughout. The C1 and L1 mixtures demonstrate similar IDT trends, with the C1 treatment higher in strength across all time intervals. Figure 34(b) confirms a strong inverse relationship between moisture content and IDT strength, with the cement additive mixture maintaining higher strength at any given moisture level as compared to the C0 and L1 mixture. Figure 34(c) shows that the moisture content steadily decreased for all mixtures, dropping below 2 percent within 7 days. Figure 34(d) presents the early-age IDT strength predictions and traffic opening estimates, showing that the lime-additive mixture reached the dry IDT minimum (11 psi at 4 hours) in approximately 4.4 hours, while the non-additive mixture required about 8.2 hours.



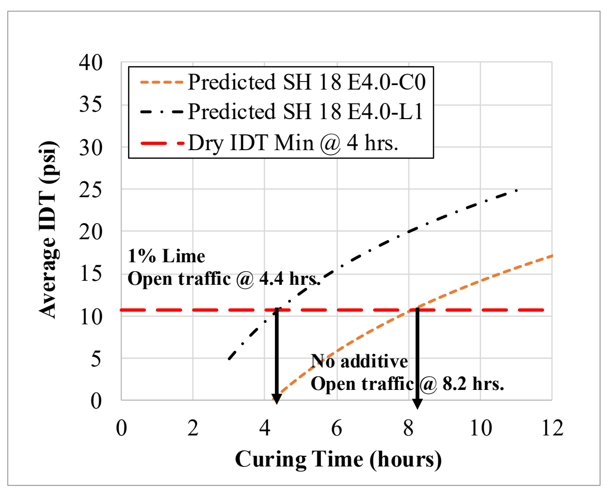
(a) Time-Strength Results



(b) Strength vs. Moisture Content



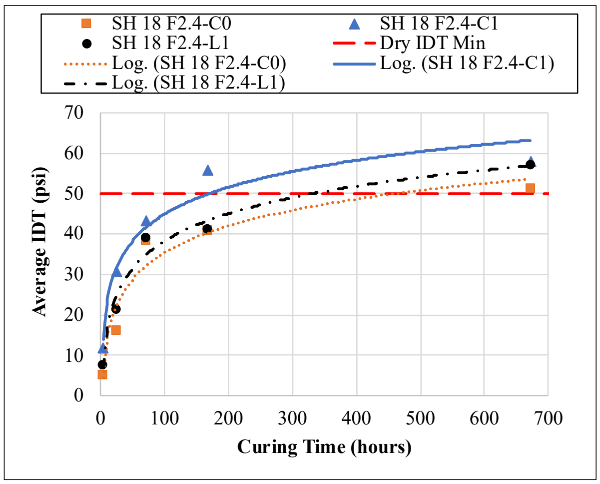
(c) Curing Time vs. Moisture Content



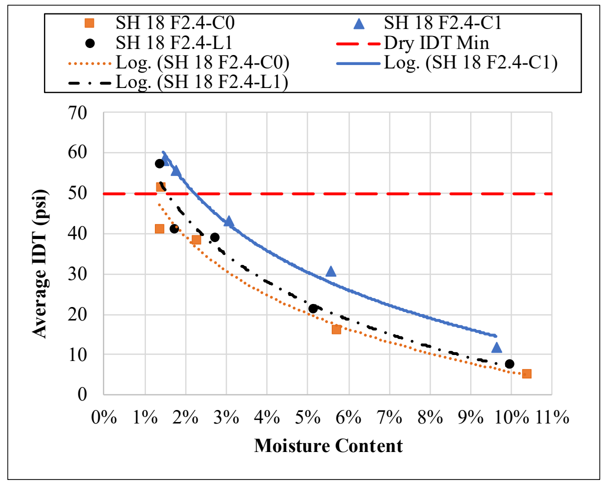
(d) Open Traffic Time for Alternative Design

Figure 34. Time-Strength Results for SH 18 4.0% Emulsified Asphalt-Treated Design.

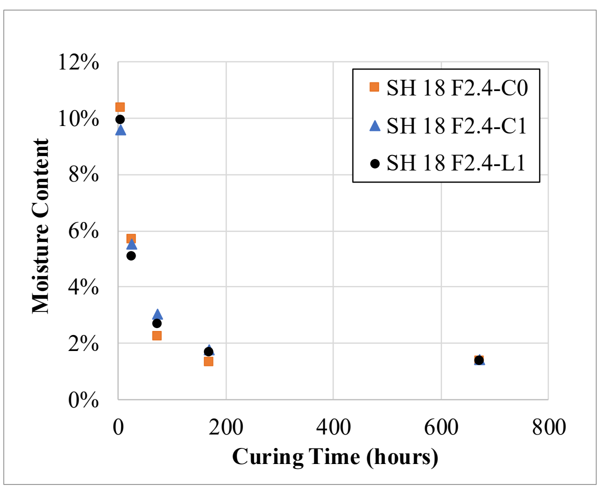
Figure 35 presents the time-dependent strength development and moisture behavior of SH 18 mixtures treated with 2.4 percent FA under three additive conditions: C1, L1, and C0. As shown in Figure 35(a), the C1 mixture demonstrated the highest early and long-term IDT strength, followed by the L1 mixture, while the non-additive mixture remained substantially lower than C1 throughout the curing period. Figure 35(b) confirms the inverse relationship between moisture content and IDT strength, with the C1 and L1 additive mixtures maintaining higher strengths than the C0 mix across varying moisture levels. In Figure 35(c), all mixtures showed a steady reduction in moisture content, reaching below 2 percent within 7 days. Figure 35(d) presents early-age IDT strength projections and traffic opening estimates. The lime-additive mixture reached the dry IDT minimum (12 psi at 4 hours) in approximately 3.2 hours, while the non-additive mixture required about 8.8 hours.



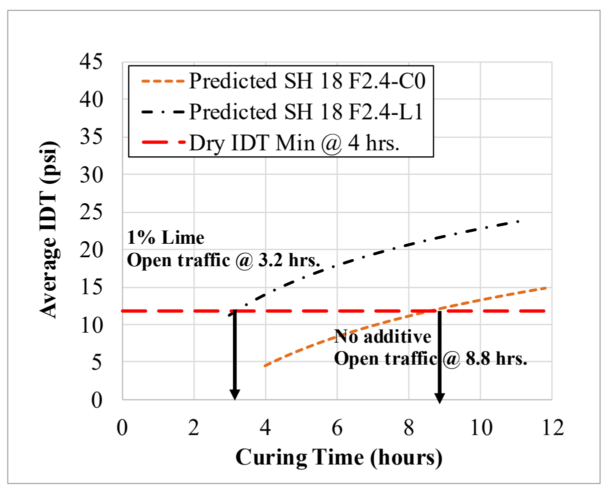
(a) Time-Strength Results



(b) Strength vs. Moisture Content



(c) Curing Time vs. Moisture Content

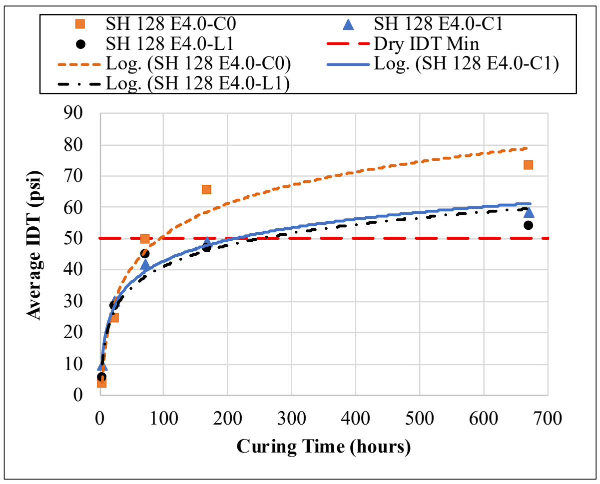


(d) Open Traffic Time for Alternative Design

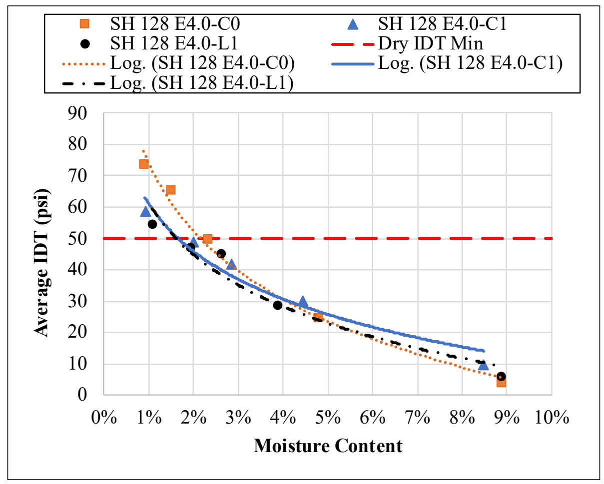
Figure 35. Time-Strength Results for SH 18 2.4% Foamed Asphalt-Treated Design.

4.2.3.1.4 SH 128

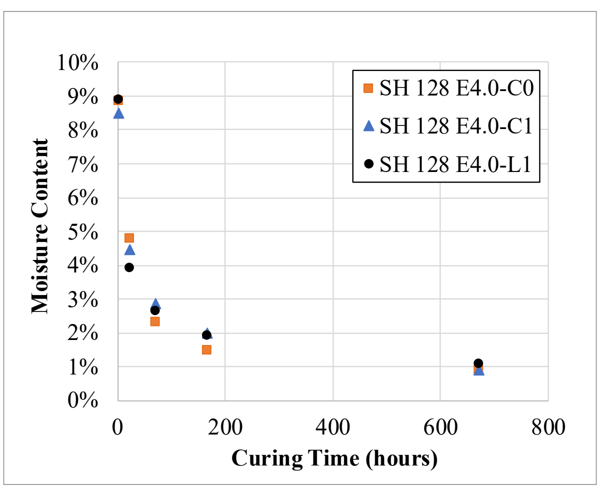
Figure 36 presents the time-dependent strength development and moisture behavior of SH 128 mixtures treated with 4.0 percent EA under three additive conditions: C1, L1, and C0. As shown in Figure 36(a), all mixtures showed rapid strength gain within the first 72 hours. The C1 and L1 additive mixtures exhibited similar long-term IDT trends, with slightly higher early strength than the non-additive mixture, though the C0 mixture eventually surpassed both additives after extended curing. Figure 36(b) confirms an inverse relationship between moisture content and IDT strength. The C0 mixture initially lagged but eventually intersected then surpassed the additive curves at lower moisture contents. Figure 36(c) shows consistent moisture reduction across all mixtures, with final values dropping below 2 percent within 7 days. Figure 36(d) presents the early-age IDT strength projections, showing that the lime-additive mixture surpassed the dry IDT minimum (10 psi at 4 hours) in approximately 3.2 hours, while the non-additive mixture reached this threshold in about 6 hours.



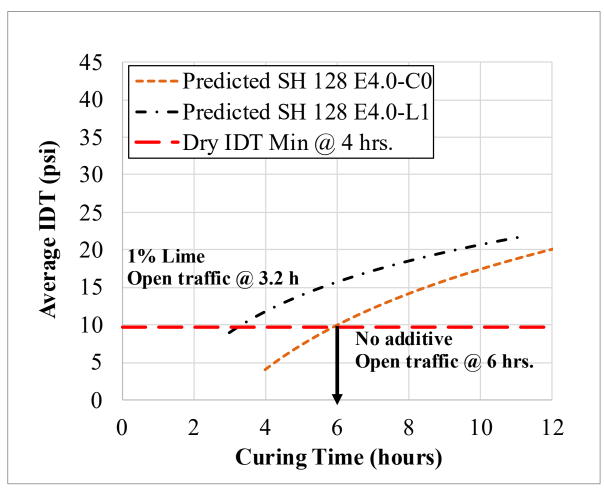
(a) Time-Strength Results



(b) Strength vs. Moisture Content



(c) Curing Time vs. Moisture Content



(d) Open Traffic Time for Alternative Design

Figure 36. Time-Strength Results for SH 128 4.0% Emulsified Asphalt-Treated Design.

4.2.3.2. Conclusions from Time-Strength Properties

Table 11 presents the estimated time required for the FDR mixtures with lime or no additive to reach the same IDT strength as the mixtures that included 1 percent cement additive after 4 hours. Since FDR mixtures with cement additive are routinely opened daily to traffic, researchers used that strength value as a metric for determining the cure time required with mixes that used lime or no additive. The lime-treated mixtures consistently reached an equivalent strength faster than mixes with no additive. Mixes with lime additive required approximately 3.2 to 4.4 hours across all materials. In contrast, mixtures with no additive needed substantially longer curing, ranging from 6.0 to 8.8 hours. On average, the lime-treated mixtures achieved cement-equivalent strength in about 4 hours, matching the expected time to trafficking as when cement additive is used. The mixtures with no additive required more time, approximately 7 hours when ET and about 8 hours when treated with FA. These results suggest when no additive is used, an additional 3 to 4 hours of curing is needed before opening sections to traffic. These results provide a basis for construction scheduling, user delay, and economic evaluations.

Table 11. Estimated Time to Traffic Opening Based on Early IDT Strength.

Material	**SL 338**		**FM 39**		**SH 18**		**SH 128**	**Avg.**	
Treatment	ET	FT	ET	FT	ET	FT	ET	ET	FT
1% cement	4	4	4	4	4	4	4	**4**	**4**
1% lime	3.8	4.2	3.8	3.6	4.4	3.2	3.2	**4**	**4**
Non-additive	6	7.2	6.8	7.2	8.2	8.8	6	**7**	**8**

Note: ET = emulsion-treated; FT = foam-treated.

4.2.4. Time-Performance Properties

Mr and PD tests were conducted to evaluate the time-performance behavior of the treated base materials. These tests were designed to capture the evolution of stiffness and deformation resistance over various curing durations, providing key insights into early-age performance and long-term structural integrity under traffic loading.

4.2.4.1. Resilient Modulus

The Mr characteristics of the base materials were assessed through a repeated load triaxial compression test, as shown in Figure 37. Testing was performed using either an asphalt mixture performance tester (AMPT) or universal testing machine (UTM), both equipped with closed-loop, servo-controlled loading systems. The system setup included a digital controller, load unit controller, data acquisition unit, and computer interface. Vertical deformations were measured using three linear variable differential transformers symmetrically positioned in the middle of each specimen. Axial loads were recorded using a load cell located within the triaxial chamber that enclosed the specimen during testing.

(a) AMPT (b) UTM

Figure 37. Repeated Load Test Setup: (a) AMPT and (b) UTM.

Each material type was tested at five different curing time intervals—4 hours, 1 day, 3 days, 7 days, and 28 days—to assess the progression of deformation resistance. The curing process was carried out under controlled environmental conditions of 68°F and 50 percent RH. For each curing interval, two replicate specimens were tested, with each test taking approximately 1.5 hours to complete. Additionally, researchers determined the Mr on specimens that were cured for 3 days at 104°F and then moisture conditioned by full submersion for 24 hours, which mirrors the protocol for wet strength determination in the current approved mix design procedures.

The Mr test protocol included 16 sequences: a preconditioning stage designed for granular base and subbase materials of 500 to 1,000 cycles, and 15 loading phases of 100 cycles, as outlined in American Association of State Highway and Transportation Officials (AASHTO) T 307 (19). Testing was terminated either after completion of the specified load sequences or when the specimen exhibited 5 percent vertical permanent strain, whichever occurred first. The test loading parameters for both sequences are summarized in Table 12.

Table 12. Mr Testing Sequences for Base/Subbase Material (19).

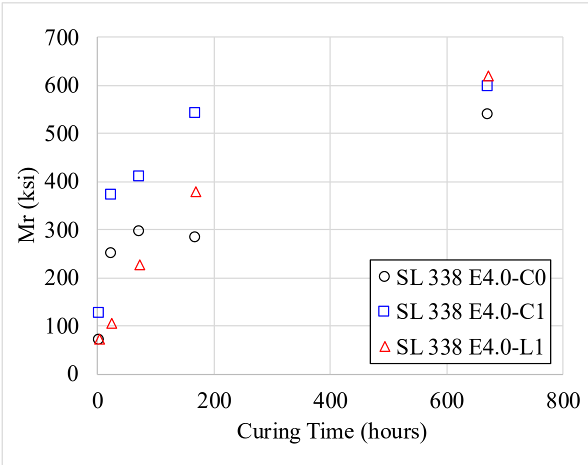
Sequence No.	Confining Pressure		Max. Axial Stress		Cyclic Stress		Constant Stress		No. of Load Applications
	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)	
0	103.4	15	103.4	15	93.1	13.5	10.3	1.5	500 to 1000
1	20.7	3	20.7	3	18.6	2.7	2.1	0.3	100
2	20.7	3	41.4	6	37.3	5.4	4.1	0.6	100
3	20.7	3	62.1	9	55.9	8.1	6.2	0.9	100
4	34.5	5	34.5	5	31	4.5	3.4	0.5	100
5	34.5	5	68.9	10	62	9	6.9	1	100
6	68.9	10	103.4	15	93.1	13.5	10.3	1.5	100
7	68.9	10	68.9	10	62	9	6.9	1	100
8	68.9	10	137.9	20	124.1	18	13.8	2	100
9	103.4	15	206.8	30	186.1	27	20.7	3	100
10	103.4	15	68.9	10	62	9	6.9	1	100
11	103.4	15	103.4	15	93.1	13.5	10.3	1.5	100
12	137.9	20	206.8	30	186.1	27	20.7	3	100
13	137.9	20	103.4	15	93.1	13.5	10.3	1.5	100
14	137.9	20	137.9	20	124.1	18	13.8	2	100
15	137.9	20	275.8	40	248.2	36	27.6	4	100

Testing was primarily conducted using an AMPT. The Mr was experimentally determined by applying a repeated axial load to a material specimen placed inside a triaxial cell. It was calculated as the ratio of the maximum cyclic stress (σ_{cyc}) to the recoverable elastic strain (ε_r), as shown below:

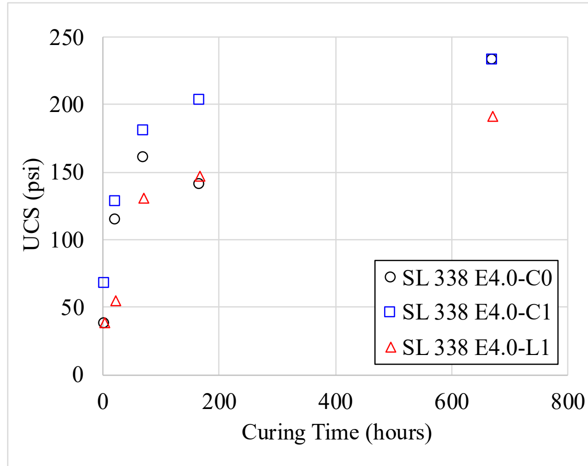
$$M_r = \frac{\sigma_{cyc}}{\varepsilon_r} \quad (1)$$

At the conclusion of the Mr tests, researchers immediately performed a UCS test on the specimens and then measured their moisture content by oven drying.

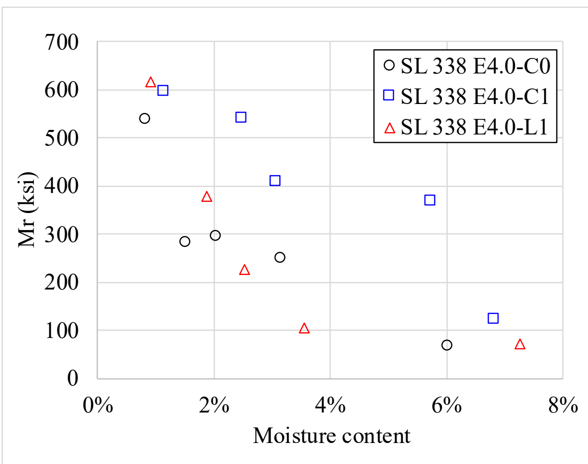
Figure 38 presents the resilient modulus results for the SL 338 mixtures treated with 4.0 percent EA under three additive conditions—C1, L1, and C0—evaluated across different curing durations. Figure 38(a) shows all mixtures exhibited an increasing Mr with time, with C1 showing the highest values, especially at cure times of 1 week or less. L1 and C0 demonstrated lower values than C1 but still exceeded 200 ksi after 7 days of curing. Figure 38(b) presents the UCS trends, which mirrored the Mr results. C1 consistently outperformed C0 and L1, with all mixtures showing notable UCS growth between 3 and 7 days. Figure 38(c) confirms an inverse relationship between moisture content and Mr. Figure 38(d) shows C0 experienced a large drop in Mr after moisture conditioning, highlighting the improved moisture susceptibility offered by the inclusion of additive in the mix.



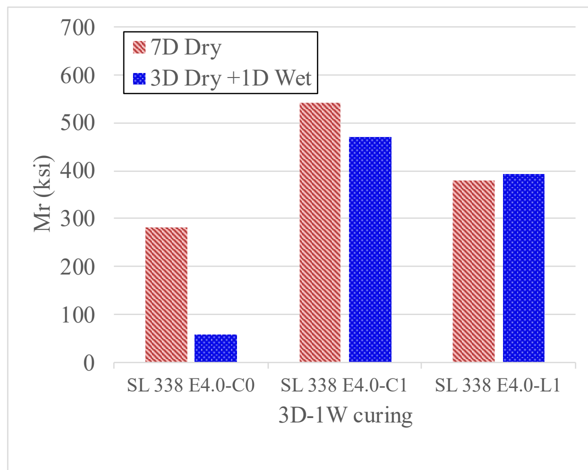
(a) Mr vs. Curing Time



(b) UCS vs. Curing Time



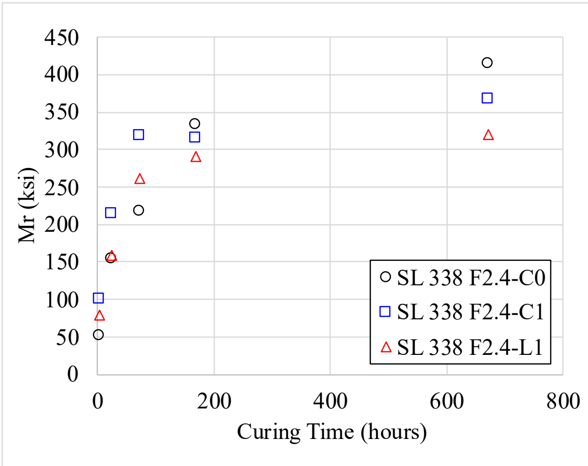
(c) Mr vs. Moisture Content



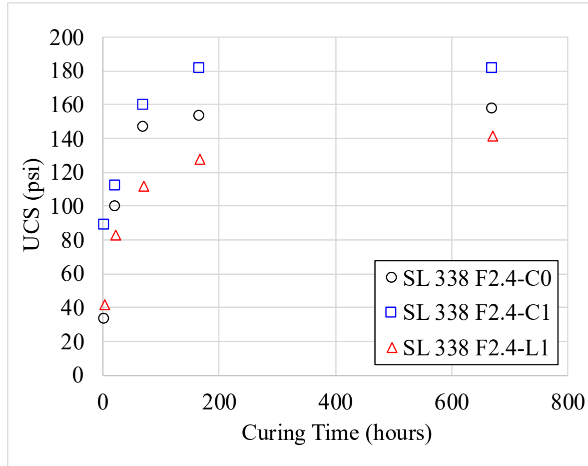
(d) Mr Comparison: 3D–1W Curing vs. Dry Condition

Figure 38. Resilient Modulus Test Results for SL 338 Emulsified Asphalt Mixtures.

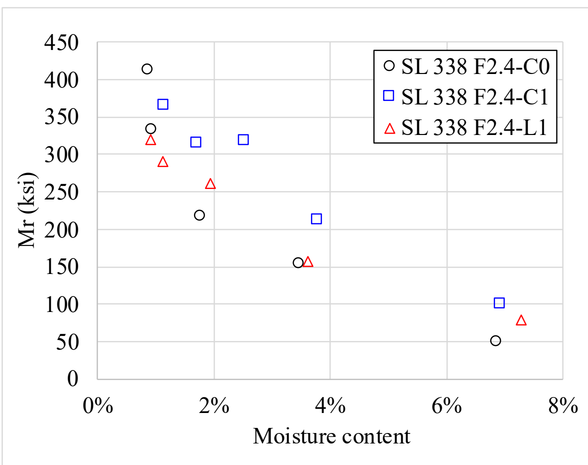
Figure 39 presents the resilient modulus and strength development of the SL 338 mixtures treated with 2.4 percent FA under three additive conditions—C1, L1, and C0—evaluated across various curing durations and moisture states. Figure 39(a) shows all mixtures demonstrated an increasing Mr with curing time, with C1 showing the greatest improvement from 4 hours to 3 days. L1 showed moderate modulus gains, while C0 started from a significantly lower modulus. Figure 39(b) shows the UCS trends paralleling the Mr results, with C1 consistently outperforming the other groups. All mixtures experienced substantial UCS growth between 1 and 7 days. Figure 39(c) illustrates an inverse relationship between moisture content and Mr. As moisture content decreased, Mr increased, with C1 exhibiting the highest modulus at each level. Figure 39(d) shows that all mixtures showed reduced modulus after moisture conditioning, most notably C0, where the Mr value dropped to below 50 ksi. The C1 and L1 mixtures retained their modulus value better, reaffirming their better performance in the presence of moisture that was observed in mix design tests.



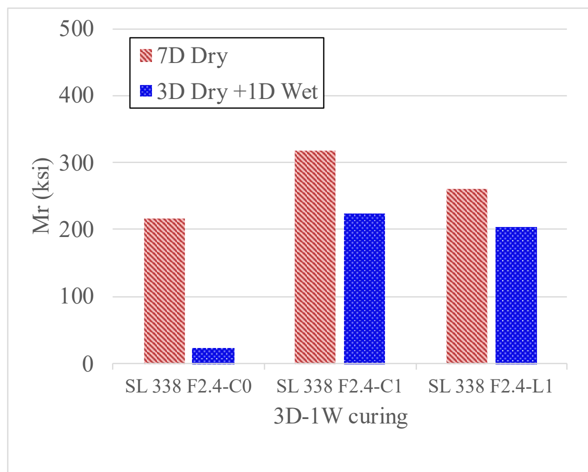
(a) Mr vs. Curing Time



(b) UCS vs. Curing Time



(c) Mr vs. Moisture Content



(d) Mr Comparison: 3D–1W Curing vs. Dry Condition

Figure 39. Resilient Modulus Test Results for SL 338 Foamed Asphalt Mixtures.

Table 13 through Table 17 highlight the significant effects of curing time, additive type, and asphalt type on the mechanical properties of foamed or EA-treated base materials. In general, both Mr and UCS increased consistently with curing time, with the most rapid gains occurring within the first 7 days—especially in cement-treated EA and FA mixes, which showed higher modulus and strength than lime or no-additive mixes at early ages. However, long-term results show several cases where lime-treated or untreated mixtures exhibit Mr values comparable to or even exceeding those of cement-treated mixtures at the same curing time.

Additive type played a critical role in mixture performance. Mixtures with cement additive achieved the highest strength and stiffness, followed by lime-additive mixtures, which also showed consistent improvement over mixtures with no additive. Mixtures with no additive generally exhibited the lowest modulus and strength values, especially when treated with FA, and were highly sensitive to moisture exposure. This moisture susceptibility was evident in the

3-day dry plus 1-day wet curing condition, where mixtures with no additive displayed significant reductions in modulus and strength.

Table 13. Resilient Modulus, Moisture Content, and UCS Results for SL 338 with Foam.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
SL 338 F2.4-C0	4 Hours	51	6.9%	33
	24 Hours	154	3.5%	100
	3 Days	217	1.8%	147
	7 Days	334	0.9%	153
	28 Days	414	0.9%	157
	3D-1W	23	9.3%	11
SL 338 F2.4-C1	4 Hours	101	6.9%	89
	24 Hours	213	3.8%	112
	3 Days	319	2.5%	160
	7 Days	316	1.7%	181
	28 Days	366	1.2%	181
	3D-1W	225	8.9%	154
SL 338 F2.4-L1	4 Hours	79	7.3%	42
	24 Hours	158	3.6%	83
	3 Days	261	1.9%	112
	7 Days	291	1.1%	128
	28 Days	320	0.9%	142
	3D-1W	203	8.9%	102

Table 14. Resilient Modulus, Moisture Content, and UCS for SL 338 with Emulsion.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
SL 338 E4.0-C0	4 Hours	69	6.0%	38
	24 Hours	250	3.2%	114
	3 Days	295	2.0%	160
	7 Days	283	1.5%	141
	28 Days	538	0.8%	233
	3D-1W	58	7.2%	43
SL 338 E4.0-C1	4 Hours	125	6.8%	68
	24 Hours	370	5.7%	128
	3 Days	408	3.1%	180
	7 Days	542	2.5%	203
	28 Days	596	1.1%	233
	3D-1W	469	8.2%	175
SL 338 E4.0-L1	4 Hours	72	7.3%	38
	24 Hours	106	3.6%	54
	3 Days	228	2.5%	131
	7 Days	379	1.9%	147
	28 Days	618	0.9%	192
	3D-1W	393	7.0%	130

Table 15. Resilient Modulus, Moisture Content, and UCS for FM 39 with Foam.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
FM 39 F2.8-C0	4 Hours	31	6.1%	32
	24 Hours	150	2.8%	99
	3 Days	269	1.7%	122
	7 Days	331	1.1%	143
	28 Days	498	0.5%	231
	3D-1W	Exceeded strain limit	6.5%	16
FM 39 F2.8-C1	4 Hours	105	5.6%	103
	24 Hours	239	3.7%	144
	3 Days	233	2.8%	173
	7 Days	306	1.8%	179
	28 Days	354	0.9%	231
	3D-1W	151	7.3%	112
FM 39 F2.8-L1	4 Hours	100	6.1%	60
	24 Hours	154	3.3%	79
	3 Days	261	2.0%	114
	7 Days	282	1.2%	126
	28 Days	471	0.6%	173
	3D-1W	92	6.2%	94

Table 16. Resilient Modulus, Moisture Content, and UCS for FM 39 with Emulsion.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
FM 39 E4.5-C0	4 Hours	55	5.9%	34
	24 Hours	130	3.4%	88
	3 Days	243	1.9%	129
	7 Days	341	1.3%	157
	28 Days	621	0.5%	263
	3D-1W	42	3.8%	62
FM 39 E4.5-C1	4 Hours	98	5.3%	95
	24 Hours	159	3.4%	136
	3 Days	239	3.1%	174
	7 Days	331	2.2%	197
	28 Days	445	1.0%	294
	3D-1W	166	5.2%	147
FM 39 E4.5-L1	4 Hours	98	5.4%	53
	24 Hours	241	3.2%	94
	3 Days	193	2.3%	136
	7 Days	297	1.5%	162
	28 Days	444	0.6%	225
	3D-1W	175	5.7%	103

Table 17. Resilient Modulus, Moisture Content, and UCS for SH 18 with Emulsion.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
SH 18 4.0E-C0	4 Hours	30	10.2%	23
	24 Hours	96	4.7%	131
	3 Days	216	2.7%	214
	7 Days	259	1.9%	250
	28 Days	406	1.3%	330
	3D-1W	25	8.1%	42
SH 18 4.0E-C1	4 Hours	40	10.2%	77
	24 Hours	109	6.2%	174
	3 Days	242	4.0%	212
	7 Days	365	2.6%	339
	28 Days	365	1.5%	355
	3D-1W	128	10.4%	95
SH 18 4.0E-L1	4 Hours	51	10.4%	30
	24 Hours	137	5.3%	90
	3 Days	159	3.4%	146
	7 Days	255	2.1%	231
	28 Days	384	1.4%	268
	3D-1W	119	9.5%	94

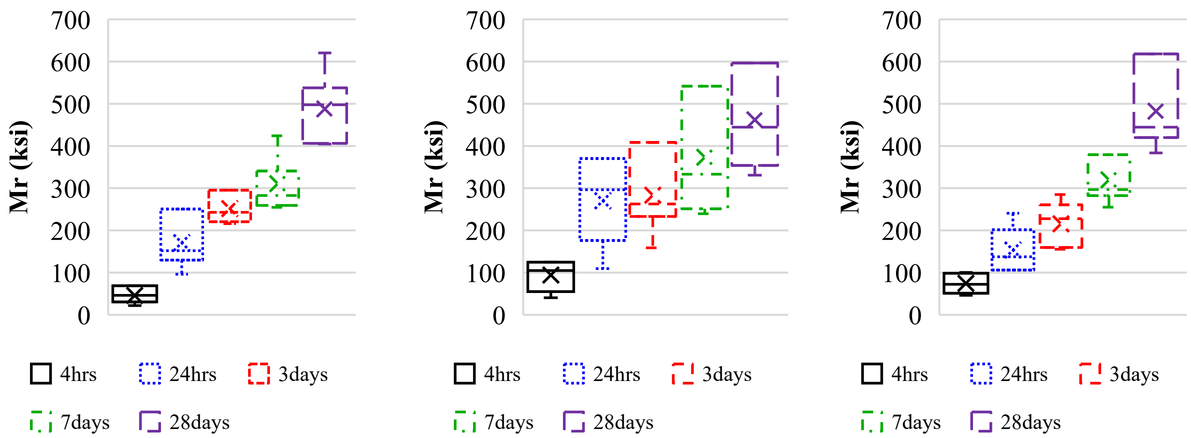
Table 18. Resilient Modulus, Moisture Content, and UCS for SH 18 with Foam.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
SH 18 2.4F-C0	4 Hours	22	9.8%	30
	24 Hours	152	4.6%	103
	3 Days	222	2.8%	189
	7 Days	424	1.5%	133
	28 Days	405	1.2%	199
	3D-1W	Fail		
SH 18 2.4F-C1	4 Hours	55	9.7%	68
	24 Hours	176	6.2%	113
	3 Days	263	3.5%	78
	7 Days	401	2.4%	213
	28 Days	546	1.4%	207
	3D-1W	75	10.6%	112
SH 18 2.4F-L1	4 Hours	46	9.8%	27
	24 Hours	128	6.1%	81
	3 Days	155	3.2%	138
	7 Days	288	1.8%	109
	28 Days	421	1.3%	164
	3D-1W	127	10.4%	93

Table 19. Resilient Modulus, Moisture Content, and UCS for SH 128 with Emulsion.

ID	Curing Time	Mr (ksi)	MC Avg.	UCS Avg.
SH 128 E4.0-C0	4 Hours	46	8.5%	35
	24 Hours	169	3.8%	141
	3 Days	221	2.7%	191
	7 Days	255	1.8%	229
	28 Days	410	0.9%	293
	3D-1W	79	6.6%	73
SH 128 E4.0-C1	4 Hours	112	7.9%	79
	24 Hours	271	4.9%	137
	3 Days	333	3.6%	212
	7 Days	296	2.5%	231
	28 Days	331	1.4%	350
	3D-1W	181	8.6%	137
SH 128 E4.0-L1	4 Hours	81	8.1%	49
	24 Hours	202	4.5%	106
	3 Days	285	2.8%	170
	7 Days	358	2.1%	202
	28 Days	420	1.2%	260
	3D-1W	241	8.6%	120

As shown in Figure 40(a), a clear and consistent trend of increasing Mr values was observed across all three conditions as the curing time progressed from 4 hours to 28 days. At the initial 4-hour mark, all samples generally exhibited low Mr values below 125 ksi, indicating minimal early-age stiffness. As curing advanced to 24 hours and 3 days, a steady gain in stiffness was observed in all samples. By 7 days, the median Mr values for all conditions approached or exceeded 300 ksi. At 28 days, the materials showed significant strengthening, with median Mr values reaching the 450 to 500 ksi range. While all samples followed a similar upward trend, the cement additive mixture displayed a slightly higher mean Mr value and wider range at 28 days.



(a) No additive (b) Cement (c) Lime

Figure 40. Mr Strength in Accordance with the Curing Time and Different Additives Under Dry Conditions.

Figure 41 presents the data obtained from specimens cured under a combined condition of 3-day dry followed by 1-day wet curing. This curing and conditioning protocol mimics the protocol for determining wet IDT strength during the mix design. Figure 41 shows that after moisture conditioning, both the lime and cement additives significantly improved the Mr of the mixtures, as compared to the non-additive condition. The boxplot includes several key components. The X mark indicates the mean value, while the horizontal bar inside each box represents the median. The box itself shows the interquartile range from the 25th to the 75th percentile, and the whiskers extend to the minimum and maximum values, excluding outliers. Dots beyond the whiskers denote outliers such as the approximately 460 ksi value in the lime group and 400 ksi value in the cement group.

In Figure 41 the non-additive group exhibited the lowest and least variable Mr values, indicating limited stiffness. Lime-added samples showed a higher median Mr and relatively consistent performance, though one outlier was observed. Cement-added samples achieved the highest overall Mr range but demonstrated greater variability. These results suggest that while both additives enhanced stiffness, lime provided more uniform improvements, whereas cement could lead to higher but less predictable gains.

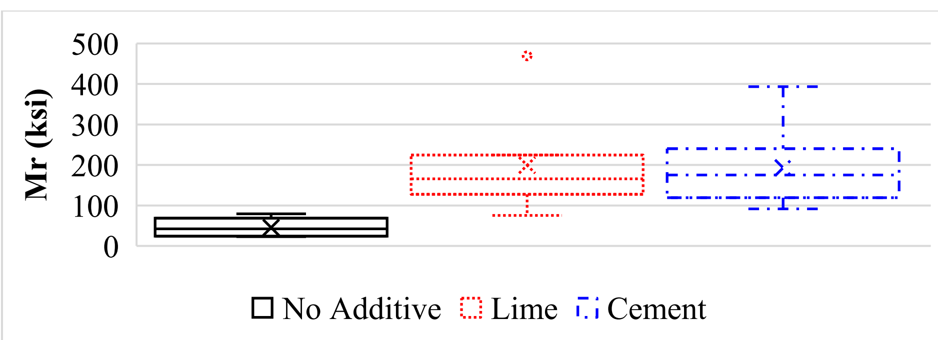
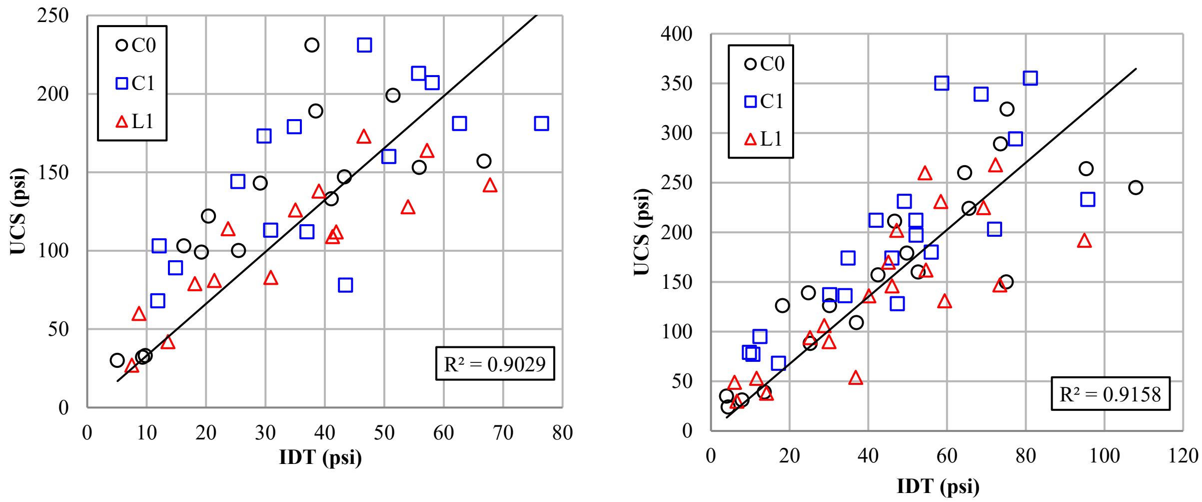


Figure 41. Mr Results After 3-Day Dry and 1-Day Wet Curing.

4.2.4.1.1 Simplified Regression Framework for Correlating IDT with UCS and MR

Figure 42 illustrates the relationship between IDT and UCS for the FA and EA mixtures under dry conditions. Based on the regression equations used herein, the mixture designed to achieve the IDT-required strength of 50 psi corresponded to an estimated UCS of approximately 165 psi for the FA and 169 psi for the EA. The data reveal a strong linear correlation between IDT and UCS, indicating that IDT strength can serve as a reliable predictor of compressive behavior.



(a) Foamed asphalt-treated base (FTB) mixtures

(b) ETB mixtures

Figure 42. UCS versus IDT by Type of Additive.

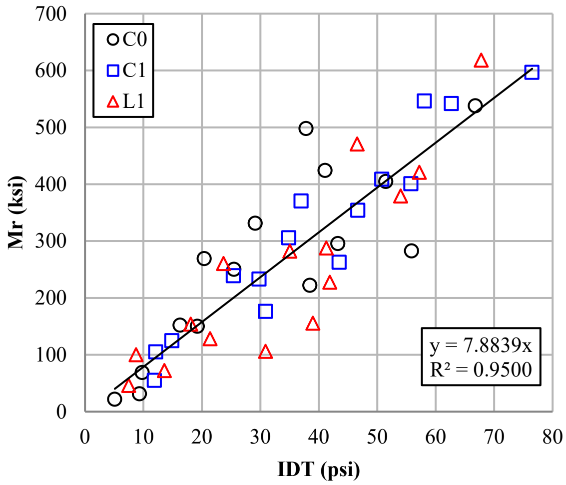
Equations (2) and (3) represent the linear relationship between UCS and IDT strength; to simplify the expression, the intercept was fixed to zero, resulting in the form as UCS = a × IDT. Derived from the regression analysis, this model enables UCS estimation using IDT results to a high level of fit ($R^2 > 0.90$). It offers a practical and cost-effective alternative to direct UCS testing, making it valuable for performance-based pavement design.

$$\text{UCS (FTB)} = \text{IDT (FTB)} \times 3.309 \quad (2)$$

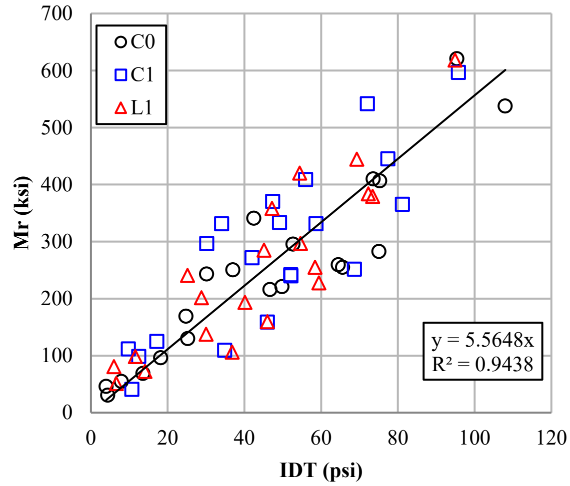
$$\text{UCS (ETB)} = \text{IDT (ETB)} \times 3.376 \quad (3)$$

4.2.4.1.2 Relationship Between IDT and Mr

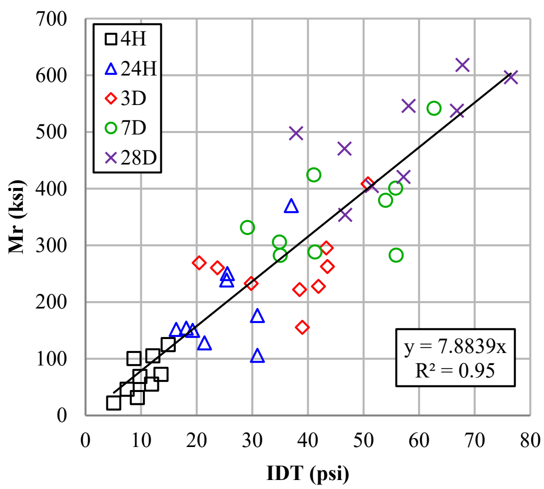
Figure 43 presents the relationship between IDT and Mr for FTB and ETB mixtures under dry conditions for (a, b) additive type and (c, d) curing time. Across all cases, a strong linear correlation was observed between IDT strength and Mr, reaffirming the predictive capability of IDT values for structural stiffness in ETB and FTB mixtures. Based on the regression equations used herein, the mixture designed to achieve the IDT-required strength of 50 psi corresponds to an estimated Mr of approximately 390 ksi for FA treatment and 280 ksi for EA treatment. This experimental finding suggests that at a given tensile strength level, FA mixtures tend to develop greater stiffness and structural capacity than do EA mixtures when in dry condition.



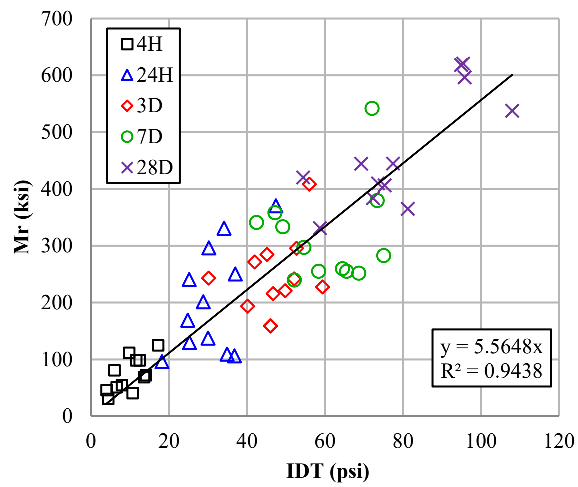
(a) Correlation between IDT and Mr values of FTB mixtures with various additives



(b) Correlation between IDT and Mr values of ETB mixtures with various additives



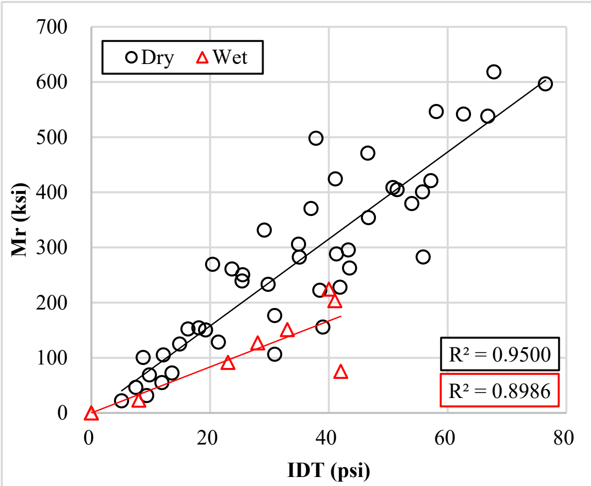
(c) Correlation between IDT and Mr values of FTB mixtures with various curing times



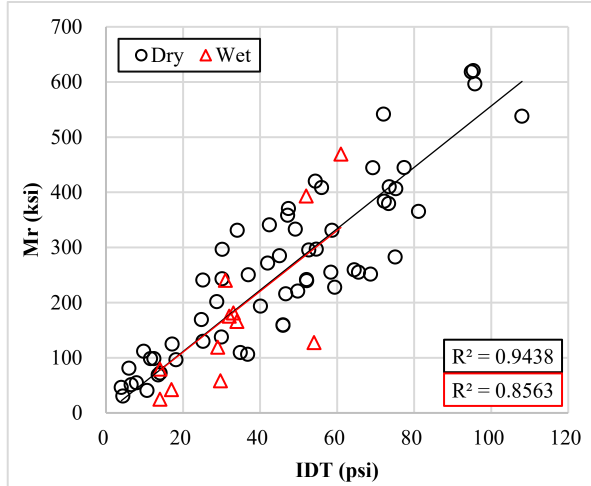
(d) Correlation between IDT and Mr values of ETB mixtures with various curing times

Figure 43. Relationship Between IDT Strength and Mr Under Various Additives and Curing Times.

Figure 44 presents the relationship between IDT and Mr under dry and wet (after submersion) conditions for (a) FA and (b) EA mixtures. In both cases, a positive linear correlation between the IDT and Mr values can be observed. These observations confirm that IDT strength remains a strong predictor of stiffness, even after moisture conditioning. However, a notable difference emerges when comparing the slopes of the regression lines in Equations (4) through (7) between FTB and ETB and the dry and wet conditions.



(a) FTB mixtures



(b) ETB mixtures

Figure 44. Relationship Between IDT Strength and Mr for FTB and ETB Under Dry and Wet Conditions.

$$\text{Mr (FTB, Dry)} = \text{IDT (FTB, Dry)} \times 7.88 \tag{4}$$

$$\text{Mr (FTB, Wet)} = \text{IDT (FTB, Wet)} \times 4.17 \tag{5}$$

$$\text{Mr (ETB, Dry)} = \text{IDT (ETB, Dry)} \times 5.57 \tag{6}$$

$$\text{Mr (ETB, Wet)} = \text{IDT (ETB, Wet)} \times 5.51 \tag{7}$$

According to Equations (4) and (5), the slope of the Mr–IDT relationship for the FA mixtures decreased significantly from 7.88 (dry condition) to 4.17 (wet condition). This result indicates that the moisture exposure for FTB substantially reduced stiffness relative to tensile strength. In contrast, the results for the EA mixtures described by Equations (6) and (7) indicate that ETB maintained a more consistent relationship, with the slope decreasing negligibly from 5.57 to 5.51 between the dry and wet conditions. This suggests that emulsified mixtures exhibit a more stable modulus performance under wet conditions than foamed mixtures.

These findings highlight a key distinction in moisture sensitivity between the two binder systems. While FA designs can achieve high stiffness under dry conditions, their performance is more susceptible to degradation in wet environments. Although ETB provides less stiffness than FTB in dry conditions, it maintains more reliable stiffness levels under both dry and wet conditions, offering improved durability when moisture exposure is a concern. If the current dry design requirement of 50 psi is met, the estimated Mr values are approximately 394 ksi for FA and 278 ksi for EA mixtures. Furthermore, if the current wet design requirement of 30 psi IDT strength is met, the estimated Mr values are approximately 124 ksi for FA and 165 ksi for EA mixtures.

In both binder systems, the regression models derived from the data yield high coefficients of determination, indicating a consistent mechanical response across mixture types and curing conditions. This can be advantageous when designing for load-bearing capacity in moisture-controlled environments. Furthermore, the IDT–Mr correlation holds consistently across varying curing times, implying that the relationship is robust against time-dependent changes in material properties. These findings collectively suggest that IDT testing can be used as a reliable surrogate for estimating modulus performance, especially during early-stage quality control and field assessment of base stabilization treatments.

4.2.4.2. Permanent Deformation

The PD characteristics of base materials were assessed through either the AMPT or UTM, as shown in Figure 37. Each material type was tested at four different curing time intervals—1D, 3D, 7D, and 28D—to assess the progression of deformation resistance. The curing process was carried out under controlled environmental conditions of 68°F and 50 percent RH. For each curing interval, two replicate specimens were tested, with each test taking approximately 3 hours to complete. The test protocol included two sequences: a preconditioning stage of 100 cycles, and a primary loading phase of up to 10,000 cycles, or until the specimen reached a vertical permanent strain of 5 percent, whichever occurred first (20). The test loading parameters for both sequences are summarized in Table 20.

Table 20. PD Sequence for Granular Base and Subbase (20).

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		N_{rep}
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	cycles
Preconditioning	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
Permanent Deformation	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	10,000

In the context of PD testing for pavement materials, the parameters alpha (α) and mu (μ) serve as key indicators of a mixture's long-term deformation characteristics and rutting resistance. The α parameter reflects the slope behavior of the permanent strain curve in a log-log scale and represents the material's rate of strain accumulation. A higher α value indicates a steeper growth of sharper strain with repeated loading, suggesting a higher susceptibility to rutting overtime. Conversely, a lower α suggests slower strain accumulation and better resistance to long-term deformation.

The μ parameter is defined as a combination of the intercept and slope of the strain curve, with the resilient strain measured at a specific loading cycle (typically the 200th cycle). Mu provides a normalized measure of rutting resistance, capturing both the initial deformation potential and stiffness of the material. A higher μ suggests more permanent strain per unit resilient strain, implying poorer deformation resistance.

In PD testing, the cumulative axial permanent strain is plotted against the number of load cycles, as shown in Figure 45. The cumulative axial and resilient strains (ε_r) are calculated at the 200th loading cycle. The linear portion of the log-log plot of the data is used to extract the PD parameters: intercept (a) and slope (b). Using these values, the rutting resistance parameters are calculated as:

$$\alpha = 1 - b \tag{8}$$

$$\mu = \frac{ab}{\varepsilon_r} \tag{9}$$

These metrics provided a quantifiable means of comparing the PD resistance across the different curing conditions and additive combinations. These rutting parameters are also used in pavement mechanistic-empirical models to analyze expected pavement performance.

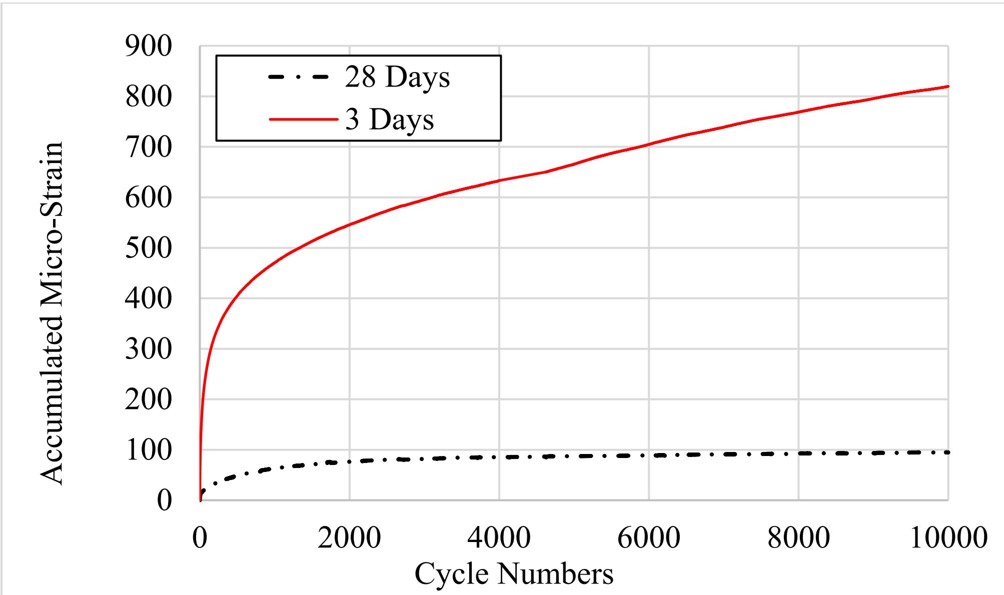


Figure 45. Example PD Test Data: FM 39 with 4.5%E-1C.

The comprehensive dataset in Table 21 through Table 25 provides valuable insights into the time-dependent mechanical behavior of treated base mixtures across the materials, treatments, additive conditions, and curing durations. The results particularly focused on the evolution of key rutting resistance parameters—α and μ —alongside the modulus values derived from the PD and Mr tests.

Table 21. PD and Modulus Properties of SL 338 with 2.4% Foamed Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
F 2.4% – C 0%	24hrs	0.865	0.254	140.383	214	154
	3days	0.842	0.245	85.717	350	217
	7days	0.824	0.151	65.033	462	334
	28days	0.397	0.045	55.467	541	414
F 2.4% – C 1%	24hrs	0.850	0.231	83.183	361	213
	3days	0.790	0.199	74.600	402	319
	7days	0.726	0.176	72.967	411	316
	28days	0.446	0.013	67.500	445	366
F 2.4% – L 1%	24hrs	0.899	0.176	120.883	248	158
	3days	0.853	0.197	88.333	340	261
	7days	0.932	0.108	88.833	338	291
	28days	0.692	0.040	83.567	359	320

Table 22. PD and Modulus Properties of SL 338 with 4.0% Emulsified Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
E 4.0% − C 0%	24hrs	0.801	0.276	126.750	237	250
	3days	0.776	0.242	80.233	374	295
	7days	0.758	0.120	53.883	557	283
	28days	0.769	0.115	42.383	708	538
E 4.0% − C 1%	24hrs	0.824	0.159	96.250	312	370
	3days	0.745	0.189	64.233	467	408
	7days	0.713	0.175	64.400	466	542
	28days	0.631	0.086	48.583	618	596
E 4.0% − L 1%	24hrs	0.889	0.379	111.100	270	106
	3days	0.799	0.271	74.033	406	305
	7days	0.693	0.151	56.033	536	302
	28days	0.767	0.068	50.583	594	618

Table 23. PD and Modulus Properties of FM 39 with 2.8% Foamed Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
F 2.8% − C 0%	24hrs	0.883	0.685	167.917	179	150
	3days	0.825	0.244	90.050	333	269
	7days	0.891	0.221	95.717	314	331
	28days	0.881	0.225	84.050	357	498
F 2.8% − C 1%	24hrs	0.928	0.541	129.250	232	239
	3days	0.909	0.212	100.283	299	233
	7days	0.818	0.383	84.483	355	306
	28days	0.916	0.311	62.150	483	354
F 2.8% − L 1%	24hrs	0.916	0.299	116.933	257	154
	3days	0.840	0.157	90.917	330	261
	7days	0.912	0.223	94.367	318	282
	28days	0.792	0.183	57.867	519	471

Table 24. PD and Modulus Properties of FM 39 with 4.5% Emulsified Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
E 4.5% − C 0%	24hrs	0.863	0.364	133.950	224	130
	3days	0.829	0.310	111.367	270	243
	7days	0.826	0.233	100.433	299	341
	28days	0.858	0.067	41.550	723	621
E 4.5% − C 1%	24hrs	0.914	0.747	136.100	221	159
	3days	0.799	0.265	71.400	420	239
	7days	0.833	0.157	68.283	440	331
	28days	0.778	0.132	46.133	651	445
E 4.5% − L 1%	24hrs	0.873	0.403	103.633	290	241
	3days	0.804	0.231	67.633	444	193
	7days	0.912	0.142	82.200	365	297
	28days	0.873	0.116	48.533	619	444

Table 25. PD and Modulus Properties of SH 18 with 2.4% Foamed Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
F 2.4% − C 0%	24hrs	0.878	0.338	170.400	176	150
	3days	0.889	0.290	113.650	264	269
	7days	0.885	0.155	95.983	313	331
	28days	0.864	0.091	89.450	336	498
F 2.4% − C 1%	24hrs	0.864	0.306	135.000	222	239
	3days	0.787	0.157	133.533	225	233
	7days	0.914	0.162	123.283	244	306
	28days	0.835	0.118	103.650	290	354
F 2.4% − L 1%	24hrs	0.786	0.127	165.217	182	154
	3days	0.934	0.135	140.933	213	261
	7days	0.885	0.149	95.267	315	282
	28days	0.790	0.109	98.200	306	471

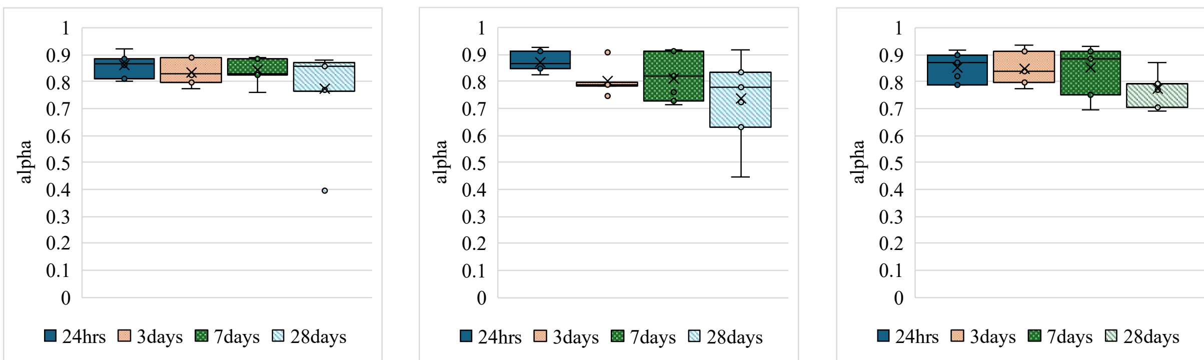
Table 26. PD and Modulus Properties of SH 18 with 4.0% Emulsified Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
E 4.0% − C 0%	24hrs	0.923	0.426	230.067	130	150
	3days	0.889	0.290	113.650	264	269
	7days	0.885	0.155	95.983	313	331
	28days	0.872	0.092	89.450	336	498
E 4.0% − C 1%	24hrs	0.865	0.305	135.000	222	239
	3days	0.787	0.157	133.533	225	233
	7days	0.915	0.161	123.283	244	306
	28days	0.835	0.118	103.650	290	354
E 4.0% − L 1%	24hrs	0.789	0.127	165.217	182	154
	3days	0.914	0.162	140.933	213	261
	7days	0.886	0.149	95.267	315	282
	28days	0.790	0.109	98.200	306	471

Table 27. PD and Modulus Properties of SH 128 with 4.0% Emulsified Asphalt.

Mix Design	Specimen Label	α	μ	Epsilon (r200)	Modulus (PD)	Modulus (Mr)
E 4.0% − C 0%	24hrs	0.810	0.365	281.900	107	150
	3days	0.799	0.330	163.550	184	269
	7days	0.829	0.367	128.883	233	331
	28days	0.766	0.150	77.733	386	498
E 4.0% − C 1%	24hrs	0.848	0.589	185.300	162	239
	3days	0.781	0.212	105.483	285	233
	7days	0.762	0.123	91.750	327	306
	28days	0.721	0.070	80.250	374	354
E 4.0% − L 1%	24hrs	0.821	0.321	197.000	152	154
	3days	0.776	0.204	103.517	290	261
	7days	0.751	0.131	83.850	358	282
	28days	0.703	0.109	80.583	373	471

Figure 46 presents the evolution of the α parameter over time for three different FDR mixture scenarios, corresponding to no additive, 1 percent cement, and 1 percent lime additive. For reference, in the TxME, the default α parameter for base material is 0.87. Figure 46 shows that across all additive types, α generally decreases with curing time, indicating improved resistance PD as stiffness develops. As shown in Figure 46(a), average α values in mixes with no additive changed little with time. Mixes with cement additive showed a notable and consistent decrease in α with curing time, as Figure 46(b) shows, reflecting enhanced rutting resistance with cure time. Figure 46(c) shows mixes with lime additive had a stable α value up through 7 days of curing, after which time the α value decreased. These trends highlight that cement is the most effective additive for accelerating rut resistance, while lime additive takes slightly longer for this rut resistance to develop. Mixes with no additive showed mixed results with less clear improvements as compared to the default base course α value of 0.87.

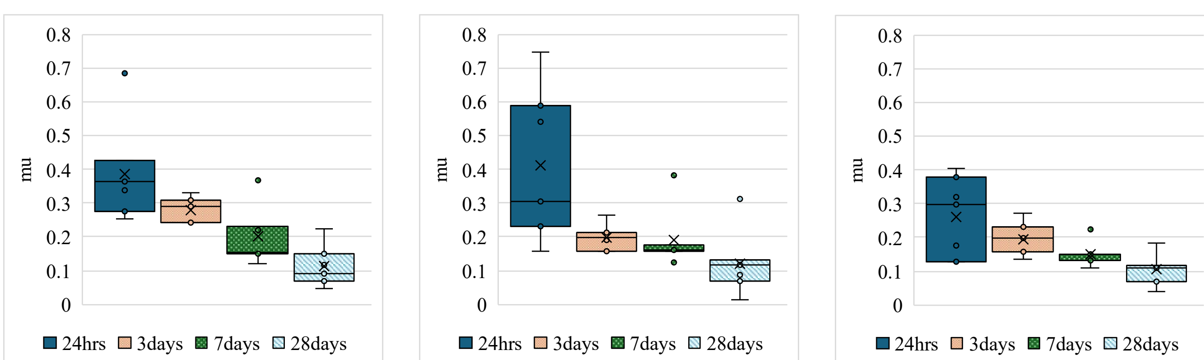


(a) No Additive (b) Cement Additive (c) Lime Additive

Figure 46. Alpha Value on PD Test on Different Curing Time.

Figure 47 shows all mixtures exhibit a consistent decrease in μ with curing time, indicating improved rutting resistance over time. There is a slight tendency for the mixtures with additives (cement or lime) to show lower μ values at 24 hours and 3 days' time compared to mixtures with no additive, indicating a modest early benefit in rutting resistance from additive inclusion.

While some variability is observed at the 24-hour mark, particularly in mixtures with cement additive, the overall trend converges by 28 days, with all μ values falling to about 0.1. For reference, the default μ value in the TxME for base material is 0.0981.



(a) No Additive (b) Cement Additive (c) Lime Additive

Figure 47. Mu Value on PD Test on Different Curing Time.

Figure 48 illustrates an example of the accumulated micro-strain over repeated loading cycles. The results show after 24 hours of curing, the mixture with no additive experienced significantly more accumulated strain compared to the mixes with additive. These results illustrate that in the initial curing time the inclusion of cement or lime additive substantially improves rutting resistance with FT or ET FDR mixtures.

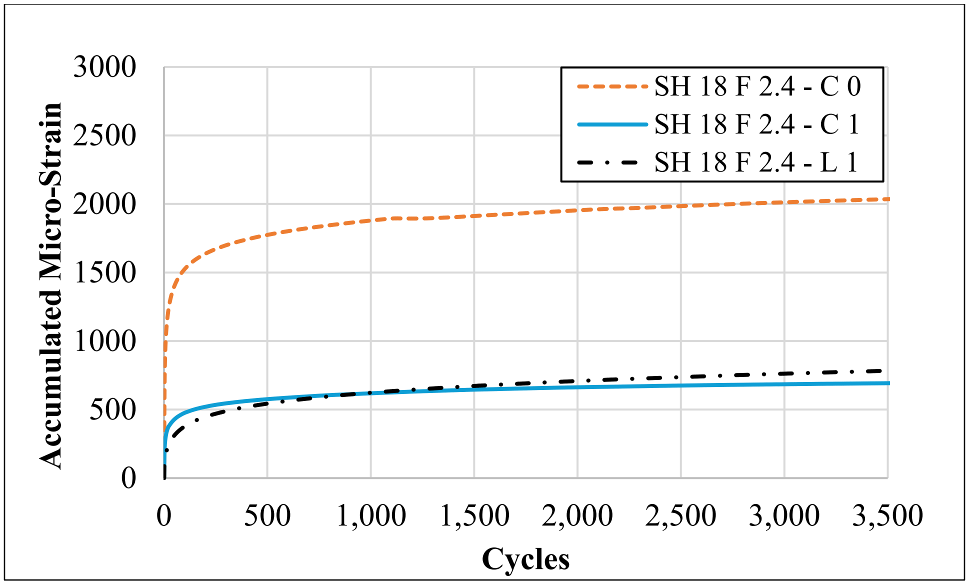


Figure 48. Example PD Curve for After 1 Day Curing.

4.3. Summary of Conclusions for Comprehensive Lab Program

Based on the results, the following conclusions can be drawn from the data developed in the comprehensive laboratory evaluation of FDR mixtures:

- FDR mix designs that meet current TxDOT strength requirements without any additive are rarely viable with FA treatment, and occasionally viable with emulsion treatment. Meeting the wet strength requirement is the limiting factor when removing the additive.
- Using lime (with no mellowing) as a replacement for cement additive is promising but also failed to meet current wet strength mix design minimums about 40 percent of the time.
- Mixture designs using lime additive should be able to be opened to traffic in a similar time frame as mixes using cement additive. Mixes with no additive may require an extra 3 to 4 hours of curing before opening to traffic.
- Across all tested materials and binder systems, the inclusion of 1 percent cement additive consistently yielded the highest strength and stiffness performance.
- FDR mixtures that included lime additive also improved performance, offering adequate performance in many cases as indicated by strength, modulus, and PD properties. These results suggest lime might serve as a viable substitute in regions where cement is difficult to source as an additive with asphalt-based FDR mixtures.
- Mixtures treated with emulsion were more moisture tolerant than their FA counterparts. However, mixes treated with FA showed faster early-age modulus growth and higher

cohesion in triaxial testing, making foam a competitive option if moisture exposure can be controlled.

- Strength and stiffness evolved significantly with curing, particularly within the first 7 days. Mixtures with cement additive showed the fastest development, while mixtures with no additive lagged in strength and stiffness and often failed to meet minimum design values when fully moisture conditioned. This study's inclusion of 3-day dry + 1-day wet regimes revealed pronounced vulnerabilities in FDR mixtures with no additive, further emphasizing the value of hydraulic additives if moisture susceptibility is a concern.
- Under dry conditions, mixtures targeting the IDT design strength minimum of 50 psi corresponded with lab-measured Mr values of ~390 ksi for FA and ~280 ksi for ET mixtures. Under wet conditions with IDT design strength minimums of 30 psi, those estimates shifted to ~124 ksi and ~165 ksi, respectively. These findings highlight some potential differences of expected behavior between foam and emulsion treatments and offer critical insights for pavement design considerations.
- The decline in α values and corresponding μ behavior over time served as effective indicators of rutting resistance evolution with curing. Mixtures with cement additive consistently showed steeper reductions in α and μ, reinforcing their greater long-term structural integrity. While lime-additive mixtures did not exhibit reductions as pronounced as those observed in the cement additive mixtures, mixtures with lime additive still demonstrated notable improvements in rutting resistance.
- Mixtures without any additive generally failed the wet performance (fully moisture conditioned) criteria in mix design and demonstrated slower modulus gain and higher rutting susceptibility, particularly at earlier cure times. Successful use of FDR mixtures with no additive will rely in part on keeping water out of the material, identifying and using appropriate assumptions in pavement design, and identifying locations where construction staging and traffic levels can allow sufficient cure time before opening.
- Chapter 6 presents additional analysis of these results, where the results directly inform the cost-benefit analysis and decision-making framework to further determine where and when removal of the additive could be considered for FDR.

CHAPTER 5. TEMPERATURE INFLUENCE ON FDR

This research included a task focused on evaluating the influence of temperature on the mechanical behavior of FDR materials. Materials from SL 338 and SH 128 were selected for a comprehensive two-factor experimental program. To minimize the influence of ambient humidity on the curing process, RH was controlled during curing. The IDT of each mixture was evaluated at multiple curing intervals: 4 hours, 24 hours, 72 hours, 7 days, and 28 days after compaction. Thus, this task allowed researchers to investigate the time-dependent strength development under varying material and ambient temperatures, with comparisons being made between EA and FA treatments across multiple curing intervals.

5.1. Properties of Materials

5.1.1. Materials Collection and Preparation

Materials from SL 338 and SH 128 were collected and used to evaluate the temperature influence. Figure 49 shows the untreated materials, with additional details of their sampling and associated construction projects in Chapter 3.

(a) (b)

Figure 49. Representative Materials: (a) ODA SL 338 and (b) ODA SH 128.

5.1.2. Fundamental Material Properties

The two materials, SL 338 and SH 128, exhibit distinct geotechnical characteristics. Table 28 and Table 29 show that the SL 338 material is a coarser material with lower plasticity (PI = 4), higher maximum dry density (132.7 pcf), and lower OMC (7.2 percent). In contrast, the material from SH 128 contains more fine particles and clay, as reflected in its higher PI (16), higher methylene blue value (20.0), and lower dry density (119.1 pcf). The SL 338 material is classified as A-2-6 by AASHTO Soil Classification, indicating a sandy or gravelly material with low plasticity fines, while the material from SH 128 is classified as A-2-7.

Table 28. Fundamental Properties of Materials for Temperature Influence Test.

Test		SL 338	SH 128
Atterberg Limits (Tex-104-6-E)	LL	16	30
	PL	12	14
	PI	4	16
AASHTO Soil Classification		A-2-6	A-2-7
Methylene Blue Value (ASTM C 1777)		13.6	20.0
Moisture-Density Relationship (Tex-113-E)	Max Dry Density (pcf)	132.7*	119.1*
	OMC (%)	7.2	9.4

* Non-treated moisture-density curve.

Table 29. Particle Size Analysis for SL 338 and SH 128.

Test		SL 338	SH 128
Particle Size Analysis (Tex-110-E/200-F)	Sieve Size	Cumulative Percent Passing (%)	
	1 3/4"	100	100
	1 1/4"	98.8	100
	7/8"	96.5	96.8
	5/8"	91.7	92.4
	3/8"	78.8	83
	#4	58.4	67.5
	#40	29.1	39.8
	#200	17.3	16.9

5.2. Baseline Mix Design

Researchers prepared cylindrical specimens measuring 4 inches in diameter and 2 inches in height, fabricating three replicate samples for each testing condition. IDT tests were conducted in accordance with Tex-122-E and Tex-134-E, which evaluate both dry (cured) and moisture conditioned (wet) IDT strength. All specimens were compacted using a Superpave gyratory compactor (SGC) and then tested, as illustrated in Figure 50.

(a) A fabricated sample using SGC

(b) IDT test

Figure 50. Specimen Compaction and IDT Testing.

Figure 51 shows that with the material from SL 338 all mixtures tested exceeded the minimum strength thresholds. For the SL 338 project, CSJ 2224-01-118, Ector County, from US 385 to SH 191, the actual treatment used in construction was 2.4 percent FA with 1 percent cement. This treatment rate was applied in the laboratory for FA testing. To maintain consistency in actual binder content for comparison, 4.0 percent emulsion was selected for EA mixtures.

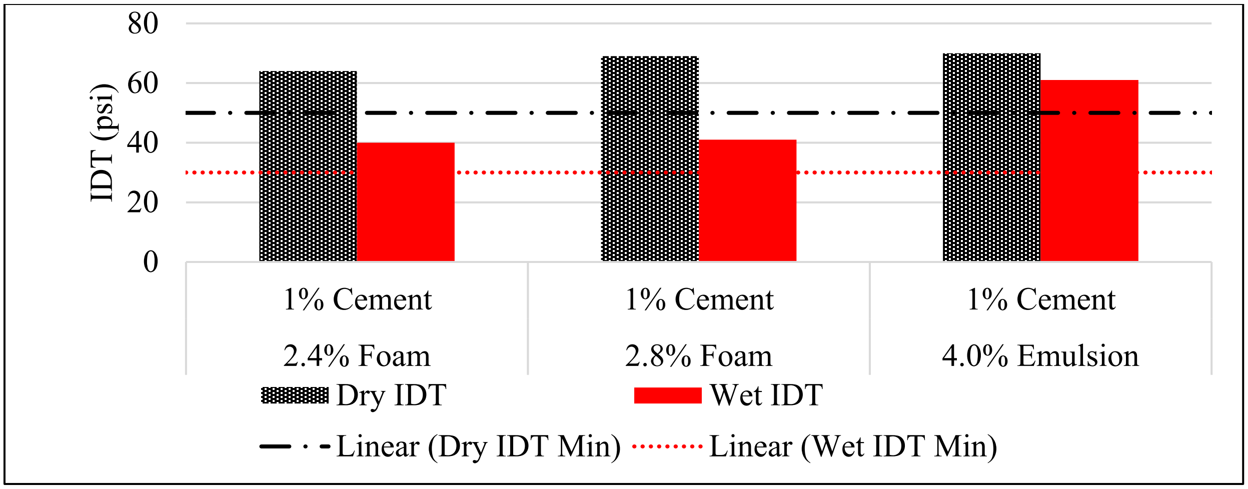


Figure 51. SL 338 Mix Design Results.

Figure 52 illustrates the IDT mix design results for material from SH 128. All mixtures exceeded the minimum dry IDT strength thresholds. For the SH 128 project, CSJ 127-01-012, Andrews County, from the New Mexico state line to SH 115, the actual treatment used in construction was 4.0 percent EA with 1 percent cement.

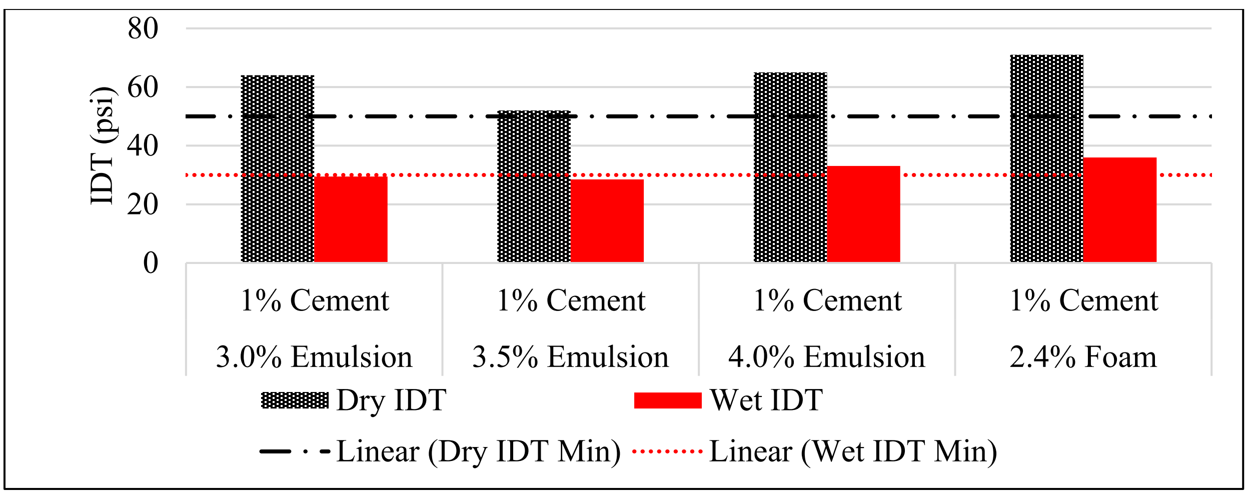


Figure 52. SH 128 Mix Design Results.

Based on the results in Figure 51 and Figure 52, researchers used 1 percent cement with either 4.0 percent EA or 2.4 percent FA for further evaluation of temperature influence for both the SL 338 and SH 128 materials.

5.3. Temperature Influence on IDT Strength

Table 30 presents the test factorial matrix developed to evaluate the influence of temperature. The controlled material temperature (MT) is the target temperature of the aggregate at the time of mixing in the cement and asphalt. The ambient temperature (AT) is the temperature during curing of the treated, compacted test specimens.

Table 30. Temperature Influence Test for Two-Factor Experimental Program.

Mix Design	Controlled Material and AT		Curing Time
SL338 F 2.4%-C 1%	Case 1	MT 72°F- AT 72°F	4 hours, 24 hours, 72 hours, 7 days, and 28 days
SL338 E 4.0%-C 1%	Case 2	MT 72°F- AT 50°F	
SH128 F 2.4%-C 1%	Case 3	MT 40°F- AT 72°F	
SH128 E 4.0%-C 1%	Case 4	MT 40°F- AT 50°F	

As part of this experimental program, the researchers prepared four replicate specimens for each combination of treatment rate, temperature case (both MT and AT), and curing duration. After the designated curing period, IDT strength tests were conducted on all specimens. Following IDT testing, the fractured specimens were placed in a 110°C oven for 24 hours to determine their oven-dry weights.

Figure 54 illustrates the effects of MT, AT, and moisture content on the IDT strength development of the SH 128 material treated with FA. Figure 54 indicates that the mixture experienced rapid strength gain during the first 7 days, with the MT 72°F–AT 72°F condition achieving the fastest development. In contrast, the MT 40°F–AT 50°F condition showed delayed early strength but ultimately reached comparable long-term values and still exceeded the 50 psi minimum design criteria. However, Figure 54 shows that after 28 days curing none of the MT and AT conditions produced results that equaled the 71-psi value measured in the original mixture design.

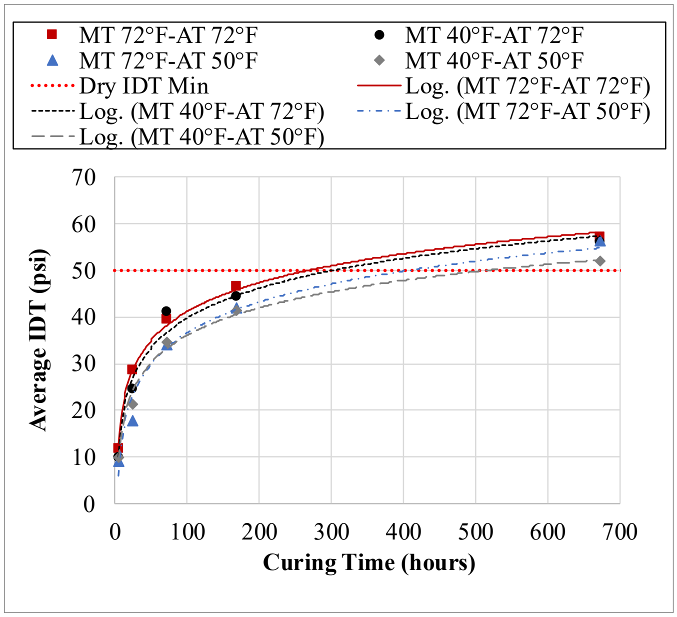
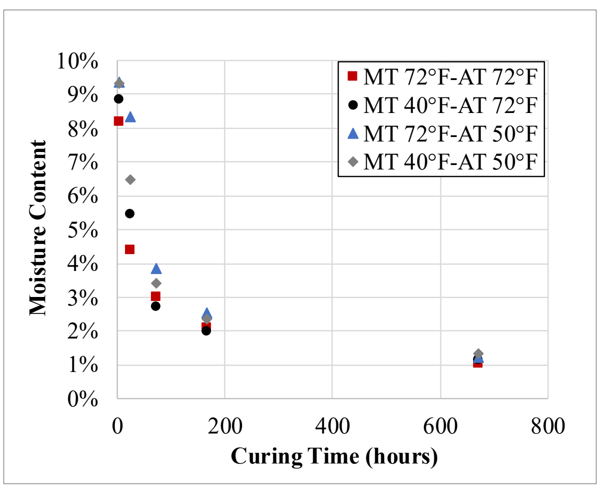
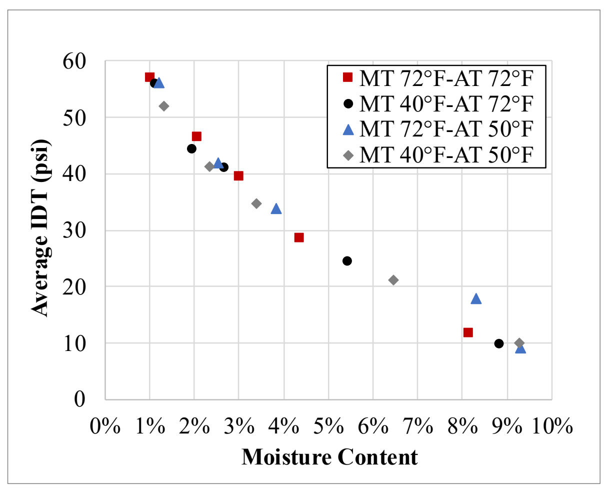


Figure 53. IDT versus Curing Time Results from SH 128 Foam Design for Different MT and AT Conditions.

From the measured moisture content of the specimens after IDT testing, Figure 54(a) shows a steady reduction in moisture content over time for all MT and AT conditions. Specimens cured under higher ATs (72°F) maintained slightly lower moisture contents throughout the curing period. Figure 54(b) shows that IDT strength consistently increased with decreasing moisture content regardless of MT and AT conditions.



(a) Moisture Content



(b) IDT Strength

Figure 54. Effect of Curing Temperature on Moisture Loss and IDT Strength for SH 128 (2.4%F-1%C).

Figure 55 illustrates the effects of MT and AT on the IDT strength development of SH 128 mixtures stabilized with EA. All curing conditions showed rapid strength gain within the first 7 days. Contrasted with the SH 128 results with FA, lower temperature conditions (MT 40°F and/or AT 50°F) exhibited higher long-term strengths, with the MT 40°F–AT 72°F and MT 40°F–AT 50°F cases achieving the highest IDT strengths by the end of the 28-day curing period. The achieved values were close to or surpassed the original mix design dry strength of 65 psi, except for the MT 72°F–AT 40°F case after 28-days curing.

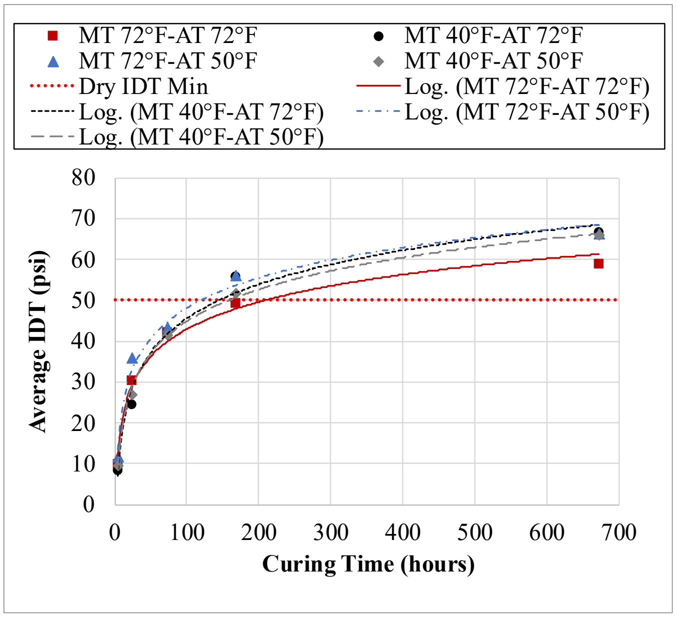
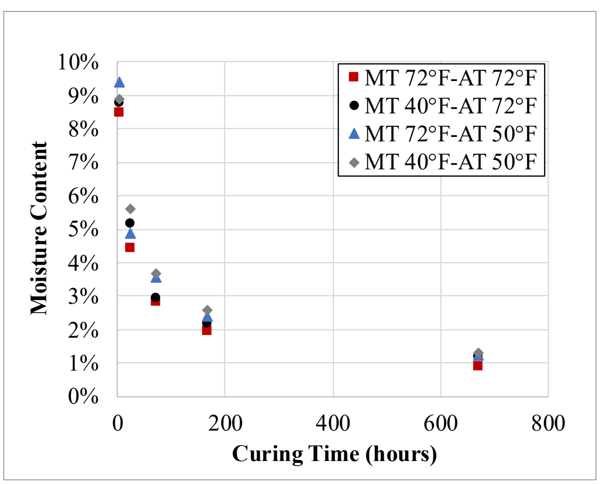
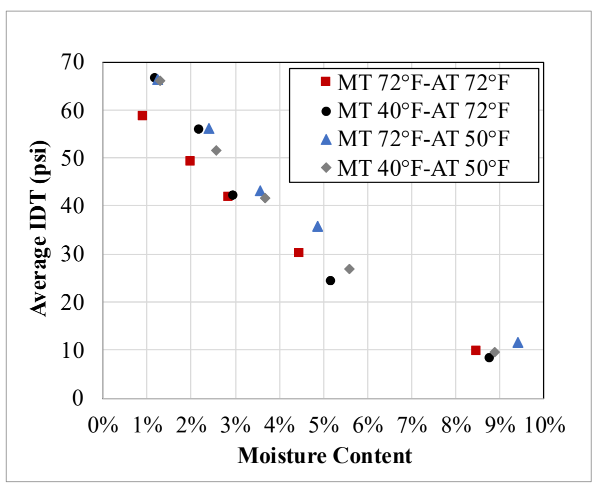


Figure 55. IDT versus Curing Time Results from SH 128 Emulsion Design for Different MT and AT Conditions.

Figure 56(a) shows a consistent reduction in moisture content across all curing conditions. Specimens cured under higher ATs (72°F) maintained slightly lower moisture contents throughout the curing period. As shown in Figure 56(b), IDT strength decreased with increasing moisture content under all curing conditions, with specimens cured at lower ATs (50°F) generally achieving higher strength at comparable moisture levels.



(a) Moisture Content



(b) IDT Strength

Figure 56. Effect of Curing Temperature on Moisture Loss and IDT Strength for SH 128 (4.0%E-1%C).

Figure 57 illustrates the influence of temperature on the time-strength behavior of the SL 338 material treated with 2.4 percent foam and 1 percent cement. Figure 57 shows that the mixtures exhibited rapid early strength development, particularly within the first 7 days. The MT 72°F–AT 72°F scenario yielded the highest overall strength, while the MT 40°F–AT 50°F condition showed slower initial gain but steady strength progression over time.

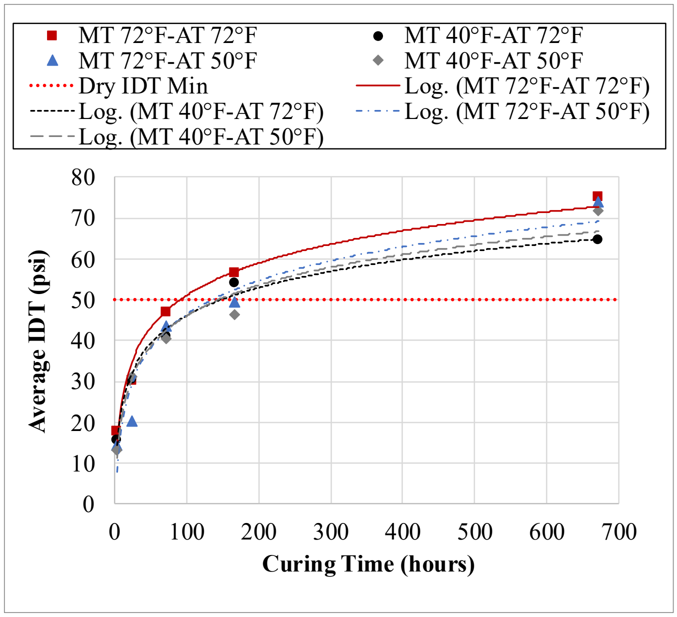
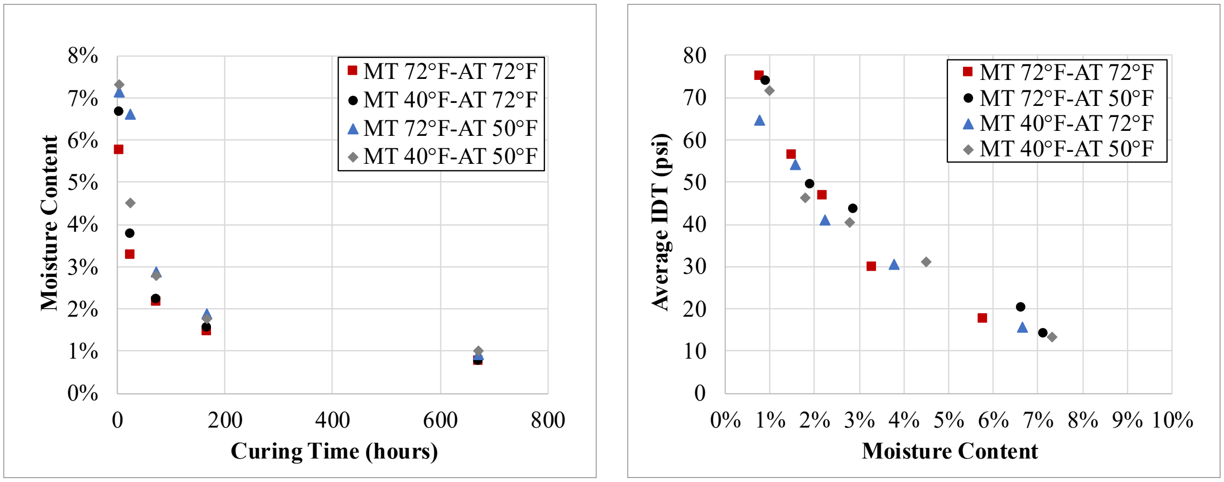


Figure 57. IDT versus Curing Time Results from SL 338 Foam Design for Different MT and AT Conditions.

Figure 58(a) presents the moisture content reduction over time, with all curing conditions showing a consistent drying trend. Specimens cured under higher MTs and ATs (MT 72°F–AT 72°F) generally exhibited slightly lower moisture contents at each time point, indicating that elevated temperatures may accelerate the drying process during curing. As shown in Figure 58(b), IDT strength decreased with increasing moisture content under all curing conditions, following a consistent trend across scenarios.



(a) Moisture Content (b) IDT Strength

Figure 58. Effect of Curing Temperature on Moisture Loss and IDT Strength for SL 338 (2.4%F-1%C).

Figure 59 illustrates the influence of temperature on the time-strength behavior of the SL 338 material treated with 4.0 percent emulsion and 1 percent cement. Figure 59 shows that all specimens experienced rapid strength gain within the first 7 days. The results indicate that AT and MT conditions did not have a notable impact on long-term strength performance, while higher temperatures influenced strength development during the early curing stage.

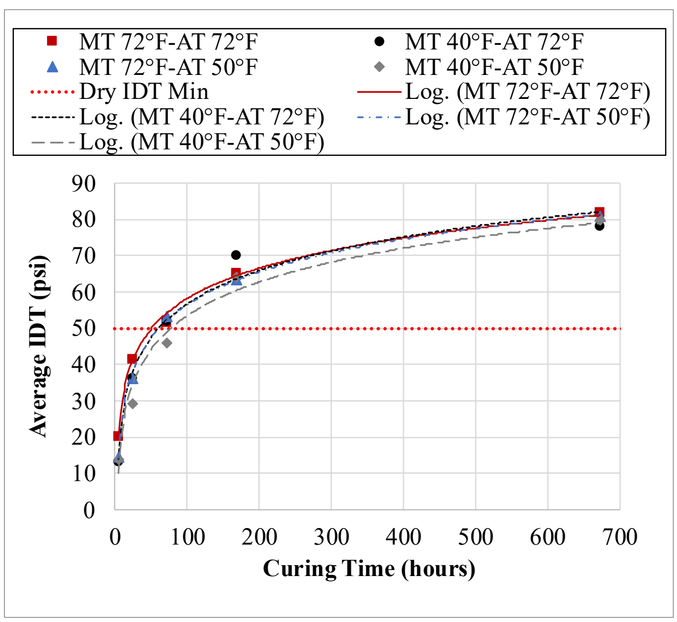
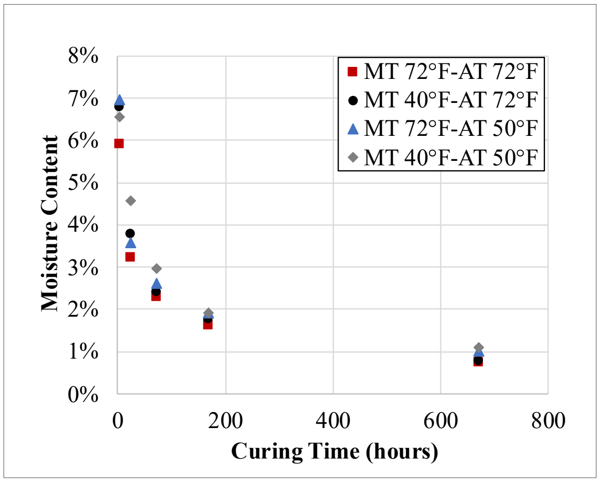
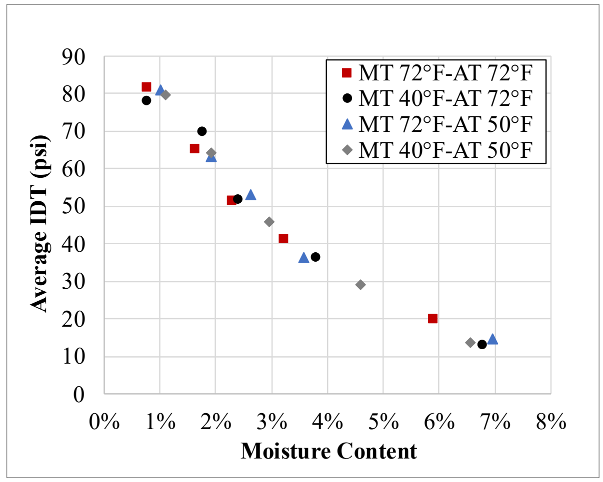


Figure 59. IDT versus Curing Time Results from SL 338 Emulsion Design for Different MT and AT Conditions.

Figure 60(a) illustrates the reduction in moisture content over time. Specimens cured under higher MTs and ATs (MT 72°F–AT 72°F) maintained slightly lower moisture contents throughout the curing period, indicating that elevated temperatures accelerate the drying process and may enhance early-age strength gain. As shown in Figure 60(b), IDT strength consistently increased with decreasing moisture content regardless of MT and AT conditions.



(a) Moisture Content



(b) IDT Strength

Figure 60. Effect of Curing Temperature on Moisture Loss and IDT Strength for SL 338 (4.0%E-1%C).

Table 31 summarizes the results of the analysis of variance (ANOVA) conducted to assess the effects of MT, AT, and their interaction (MT × AT) on the IDT strength of SH 128 and SL 338 materials under various curing durations and temperature conditions. The ANOVA is a statistical method used to determine whether there are significant differences between the means of multiple groups. In the context of this study, ANOVA was used to assess the individual and interactive effects of MT, AT, and cure time on the IDT results of each FDR mixture. A p-value less than 0.05 was considered statistically significant, indicating that the corresponding factor had a measurable influence on strength development.

Table 31. Analysis of ANOVA on SH 128 and SL 338 Material.

Curing Time	Temperature/Material	p-value			
		SH 128 Foam	SH 128 Emulsion	SL 338 Foam	SL 338 Emulsion
4H	**MT**	**0.00050**	**0.19440**	**0.03040**	**0.00016**
	AT	**0.00200**	**0.01110**	**0.00050**	**0.00719**
	MT × AT	0.49651	0.05202	**0.00295**	**0.00067**
24H	**MT**	**0.00003**	0.74840	**0.00810**	**< 0.0001**
	AT	**0.00410**	**< 0.0001**	**0.02380**	**< 0.0001**
	MT × AT	**0.03741**	**0.00201**	0.68652	**0.00346**
3D	**MT**	0.77060	0.56606	**0.01173**	0.19104
	AT	0.89050	**0.01046**	0.21322	0.54117
	MT × AT	0.87532	0.12658	0.05325	0.13063
7D	**MT**	0.65221	0.55810	0.12268	0.28743
	AT	0.56941	0.11272	**0.00109**	0.14845
	MT × AT	0.48512	0.10018	**0.01429**	0.69460
28D	**MT**	0.25900	0.30578	**0.04274**	0.47569
	AT	0.29310	0.35924	0.30896	0.90777
	MT × AT	0.12211	0.05739	0.40306	0.60943

Note: Significant statistical differences are highlighted with bold text.

From Table 31, at early curing times (4 and 24 hours), both MT and AT exhibited statistically significant effects on most mixtures, and two of the four materials tested showed interaction effects between MT and AT. This indicates that initial environmental and material conditions are crucial in determining the immediate (short term) strength properties of the FT and ET materials.

At intermediate curing durations (3 and 7 days), the significance of temperature effects diminished, as indicated by most p-values exceeding 0.05. Nevertheless, notable exceptions remained: The SL 338 material treated with FA continued to exhibit a statistically significant response to ambient temperature at 7 days and displayed a significant interaction effect between MT and AT; the SH 128 material treated with emulsion displayed a significant AT effect at 3 days.

By 28 days of curing, temperature effects were largely insignificant across all mixtures. The only exception was the SL 338 material treated with FA, which maintained a significant sensitivity to MT. Overall, the findings suggest that temperature conditions are most impactful during early-age curing but become progressively less influential as mixtures mature and intrinsic material properties dominate strength development.

5.4. Discussion

The experimental results clearly demonstrate that MT and AT influence the strength development of FDR mixtures; however, further analysis revealed that this effect is not governed by temperature alone.

5.4.1. Influence of Temperature and Humidity on Moisture Evaporation and Strength Development in FDR Mixtures

Although lower curing temperatures have been shown to delay strength development in FDR mixtures in the early curing time, this effect cannot be attributed to temperature alone. The primary mechanism is the influence of temperature on moisture evaporation. Since FDR strength gains in mixtures treated with EA or FA relies on moisture loss, slower evaporation under cold conditions hinders early strength development. However, evaporation is not governed by temperature alone. In cold but dry environments, a high vapor pressure deficit may still promote moisture loss, allowing for adequate strength gain. This highlights the importance of both temperature and humidity in curing.

Engineering decisions regarding curing protocols should therefore account for environmental moisture conditions, not just temperature. In cold and humid environments, careful monitoring for moisture content may be necessary before opening to traffic. Ultimately, the interaction between temperature and humidity governs evaporation rates and strength development, emphasizing the importance of site-specific curing strategies.

5.4.2. Limitations in Controlling MT During FDR Specimen Preparation

In this experiment, the target MT for the cold condition was 40°F. However, after mixing with treatment and preparing the specimens for compaction, the actual treated FDR mixture temperature rose to nearly 60°F, and after molding was about 68°F. Figure 61 shows the cold aggregate material quickly warmed up to near room temperature during mixing, reducing the intended effect of MT. To better assess the impact of MT, future studies should focus on maintaining the target temperature throughout the preparation process by using insulated containers or temperature-controlled environments during mixing and compaction.

(a) After 24 hours of temperature conditioning of material (40.6°C)

(b) Measured before molding: during material weighing (58.8°C)

(c) Immediately after molding: surface temperature (67.8°C)

(d) After molding: internal temperature of specimen (65.5°C)

Figure 61. Material and Specimen Temperature Measurements at Different Stages of Sample Preparation.

Despite these limitations, the experimental results demonstrate that moisture content has a strong influence on strength development. Reduced MT and AT significantly delay moisture loss during the early curing stages, with differences in moisture content across temperature conditions most pronounced within the first 30 hours of curing.

5.5. Conclusions for Temperature Influence on FDR

This study evaluated the effects of MT at the time of mixing and AT during curing on the strength development of FDR mixtures treated with EA or FA. The findings demonstrate that higher curing temperatures generally led to faster strength gain and lower residual moisture content at each curing interval. In contrast, mixtures cured under lower temperatures exhibited slower strength development in the early stages but were still capable of reaching comparable long-term strength, as shown in Table 32. While initial IDT strength varied with temperature conditions, the 28-day results showed no strong correlation between temperature and final strength, indicating that long-term performance is less sensitive to early thermal conditions.

Table 32. IDT Strength at 28 Days Under Varying Temperature Conditions.

Material Temp. (°F)	Ambient Temp. (°F)	SH 128 Foam (psi)	SH 128 Emulsion (psi)	SL 338 Foam (psi)	SL 338 Emulsion (psi)
72	72	59	57	75	82
72	50	66	56	74	81
40	72	67	56	65	78
40	50	66	52	72	80

Further analysis revealed that these temperature-related effects were primarily driven by their influence on moisture evaporation. Since the strength of the FDR mixtures was highly dependent on moisture loss, slower evaporation rates under colder conditions delayed strength gain. This observation underscores the role of not only temperature but also ambient humidity and vapor pressure deficit when designing curing protocols. The results also indicate that moisture content retained in the specimens had a more significant impact on strength development than did MT itself, as shown by the strong inverse correlation between moisture and strength across all conditions.

ANOVA results confirmed temperature effects were most significant during early curing, within 4 to 24 hours after compaction, but generally diminished by 7 to 28 days. Mixtures cured under cooler ambient conditions (50°F) still achieved sufficient long-term strength, provided that extended curing times were allowed. These observations suggest that temperature impacts on early strength could impact stability when opening to traffic; weather restrictions in the current specifications help address this potential risk.

In summary, while temperature affects the pace of strength gain, moisture content and its rate of evaporation are the primary drivers of strength gain in FDR mixtures treated with FA or EA. The guidance derived from this study can help agencies optimize curing protocols for varying environmental conditions, reducing premature opening risks, and improving the reliability of stabilized base performance.

CHAPTER 6. ECONOMIC AND STRUCTURAL ANALYSIS

This chapter presents economic and structural analyses of FDR layers with and without additive, combining laboratory-derived curing data with realistic traffic and construction parameters. The economic analysis quantifies benefits and trade-offs in project duration, user delay, construction costs, and traffic impacts, based on lab-determined strength and stiffness gains across the curing timeline to ensure practical and implementable outcomes. The structural analysis evaluates load-carrying performance at early- and long-term curing stages under varying traffic levels.

6.1. ECONOMIC ANALYSIS

6.1.1. Economic Analysis Summary

FDR is a sustainable pavement rehabilitation treatment that involves recycling existing asphalt pavements and a portion of the base layer to create a new base for roadways. FDR has emerged as a widely adopted pavement rehabilitation strategy that enhances structural integrity while preserving existing roadway materials. However, the economic valuation of FDR mix design alternatives, particularly when evaluating the inclusion or exclusion of cement and lime additives, remains insufficiently researched in both academic and agency-level studies. Most prior studies have emphasized technical performance and lifecycle behavior, with limited attention paid to the monetary implications of reduced construction time, traffic delay costs, and road user cost (RUC) savings associated with various mix configurations.

This analysis addresses the critical gap by integrating three key economic influential dimensions—construction schedule, material costs, and traffic mobility impacts—into a comprehensive framework. It examines the impact of using or omitting 1 percent cement or lime in EA and FA mix designs on total project costs. While cement is traditionally added to ensure early strength and moisture resistance, its cost and construction complexity warrant reevaluation, especially under traffic conditions where faster construction may yield more substantial monetary benefits to motorists.

The study was geared to assist the Receiving Agency in determining the cost-effectiveness of the six FDR lab mix design alternatives shown in Table 33.

Table 33. FDR Mix Designs.

Mix Design	FDR Stabilizing Agents
Design 1: EA-1%C	Emulsified Asphalt with 1% Cement
Design 2: EA-1%L	Emulsified Asphalt with 1% Lime
Design 3: EA-NA	Emulsified Asphalt Only (No additive)
Design 4: FA-1%C	Foamed Asphalt with 1% Cement
Design 5: FA-1%L	Foamed Asphalt with 1% Lime
Design 6: FA-NA	Foamed Asphalt Only (No additive)

The primary objective was to estimate the monetary trade-offs of including or omitting cement or lime additives in EA and FA mixes based on:

- Total construction material and labor costs.
- Schedule acceleration and reduced lane closure durations.
- Traffic delays and road user delay costs with varying annual average daily traffic (AADT) volumes.

The significance of this work lies in its practical alignment with TxDOT's growing focus on cost-efficient, sustainable pavement design and reduced user-delay impacts, particularly in urban corridors and freight-reliant regions.

6.1.1.1. Methodological Framework for Economic Valuation

To accurately assess the economic implications of six FDR lab mix design alternatives, this study adopted an integrated three-step methodology. The framework explicitly evaluates how variations in material configuration (i.e., the inclusion or exclusion of 1 percent cement or lime additives in EA and FA mixes) affect total construction cost, construction duration, and road user delay costs. The three key components of the methodology include construction schedule analysis, construction cost estimation, and mobility impact assessment.

6.1.1.1.1 Construction Schedule Analysis: Estimating Production Rates and Contract Time

The first step in the methodology involved estimating the required construction windows and total contract time for each mix design alternative. Using the Federal Highway Administration (FHWA)-endorsed CA4PRS software, researchers simulated daily production scenarios based on realistic work windows, material handling constraints, and traffic management strategies.

To support the modeling, project-specific geometric and operational data were gathered from four real-world TxDOT demonstration sites: SL 338, FM 39, SH 18, and SH 128. These roadway segments varied in size (15.2 to 30.4 lane-miles), traffic volumes (AADT ranging from 4,044 to 19,400), and typical cross-section designs, providing a diverse basis for evaluation.

Key modeling assumptions included:

- Lane Closure Strategy: A "half closure with partial completion" was applied, where one lane in each direction remains open to minimize traffic disruptions.
- Daily Working Window: FDR operations were assumed to occur between 6:00 a.m. and 6:00–8:00 p.m. on weekdays.
- Construction Duration: Completion time was based on mix-specific production rates and curing requirements.

Production rate inputs varied by mix design:

- EA with additive and all FA options: 0.75 lane-miles per day.
- EA without additives: 0.94 lane-miles/day (due to longer working windows and fewer processing steps).

The traffic reopening time was estimated using laboratory curing and strength gain data from the laboratory phase of this research project. For non-additive options, traffic reopening was delayed until the treated base achieved a strength equivalent to the 1 percent cement benchmark. EA-NA required an additional 3 hours of curing, while FA-NA required 4 extra hours. These inputs enabled researchers to determine the number of construction days (windows) needed for each site and design alternative, a critical input into the subsequent cost and mobility analysis.

6.1.1.1.2 Construction Cost Estimation: Material Quantity Takeoffs and Unit Pricing

The second step involved conducting a manual, bottom-up cost estimation of construction materials and operations. This process utilized detailed quantity takeoffs for each site and mix configuration, supported by current (2024) pricing data drawn from:

- RSMeans Cost Manual.
- TxDOT bid price database.
- FHWA cost estimation guidelines.

Inputs included:

- Material densities, layer depths, and treated area widths for HMA and FDR sections.
- Unit prices for key materials, such as:
  - Cement: $268.87/ton
  - Lime: $370.24/ton
  - FA: $597.55/ton
  - EA: $3.1/gallon
  - EA and FA treatments: $0.56–$0.61/sq yd/in
  - HMA: $125/ton

Quantity estimates were developed for each of the six mix design scenarios. This enabled precise comparisons of material costs by scenario.

Key findings from this stage included:

- Eliminating additives reduced FDR material costs by 5.8 percent (EA) and 9.2 percent (FA) on average.
- Substituting lime for cement increased material costs by 2.2 percent (EA) and 3.5 percent (FA) on average.
- Total material cost estimates across projects ranged from $2.64 million to $6.74 million, depending on the treatment type and site characteristics.

Construction cost calculations were then combined with schedule data to generate complete project cost estimates (FDR + HMA), forming the cost foundation for the final total economic valuation.

6.1.1.1.3 Mobility Impact Assessment: Estimating RUCs

The final step evaluated RUCs associated with traffic delays caused by construction staging. Using input parameters such as AADT, truck percentage, lane closure durations, and detour assumptions, researchers estimated:

- Lane closure lengths per working day.
- Speed reductions (e.g., from 70–75 mph to 45 mph).
- Hourly delay durations for each mix design scenario.
- RUCs for passenger cars and trucks, based on TxDOT's 2024 vehicle cost assumptions:
  - $37.20/hr for passenger cars.
  - $52.75/hr for trucks.

Additional assumptions included:

- Detour Rate: 20 percent of vehicles detoured, with an added delay of 20 minutes.
- Work Zone Lengths: Varied by project site and construction scenario.
- Closure Duration:
  - 11 hours/day for additive scenarios.
  - 13 hours/day for non-additive scenarios (due to curing delays).

This analysis revealed that EA-NA scenarios consistently reduced RUCs due to shorter project durations enabled by higher production rates. Conversely, FA-NA scenarios often increased RUCs, despite lower material costs due to longer daily closures and unchanged productivity.

On high-traffic corridors such as SL 338 (AADT 19,400), RUC savings under EA-NA reached 24.9 percent, demonstrating the nonlinear and convex relationship between delay impacts and traffic volumes.

Results from all three steps were synthesized to compute the total upfront cost of each FDR mix design alternative, incorporating:

- Direct construction material and labor costs.
- Project duration and associated overhead.
- Mobility costs from user delays.

This integrative methodology enables scenario-specific insights, informed by traffic volume, project size, and environmental or material considerations. It also enables weighing trade-offs between performance, cost, and mobility in a unified framework. By combining scheduling simulation, cost engineering, and traffic impact modeling, this approach offers a comprehensive economic evaluation that is both data-driven and directly applicable to operational planning and mix design specification decisions.

6.1.1.2. Results and Findings

The integrated economic valuation yielded a clear comparative understanding of how different FDR mix designs perform in terms of construction schedule, cost efficiency, and mobility impacts. The analysis covered four representative rehabilitation projects—SL 338, FM 39, SH 18, and SH 128—spanning a range of traffic conditions, project sizes, and cross-section profiles.

6.1.1.2.1 Construction Time and Production Rate Impacts

The results revealed the following key findings regarding the impacts of additive-free FDR on construction time and production rate:

- EA without additives achieved the highest production rate (0.94 lane-miles/day), outperforming all other designs, which were limited to 0.75 lane-miles/day.
- This 25 percent increase in productivity significantly reduced the number of construction days required—by as much as 8 days on SL 338, a high-traffic corridor.

6.1.1.2.2 Construction Cost Reduction

The results revealed the following impact of removing additive on construction costs:

- Removing the 1 percent cement additive resulted in material cost savings of 5.8 percent (EA) and 9.2 percent (FA) on average.
- Substituting lime for cement increased material costs by approximately 2.2 percent (EA) and 3.5 percent (FA).

6.1.1.2.3 RUC Savings

The results revealed the following impacts on RUC from removal of the additive:

- EA without additives consistently produced the lowest RUC, achieving a 20.2 percent average reduction across all four projects compared to the benchmark (EA with cement).
- The benefit was most pronounced on SL 338 (AADT 19,400), where RUC savings reached nearly 25 percent, due to accelerated project completion.

6.1.1.2.4 Total Cost Efficiency

The results showed the overall cost implications of additive removal are as follows:

- EA without additives demonstrated the greatest total cost reduction, averaging 6.2 percent across all projects, with a peak of 12.5 percent on SL 338.
- FA without additives, though lower in material cost, failed to yield similar mobility savings due to unchanged production rates and longer curing time, resulting in increased daily closure durations.

6.1.1.2.5 Performance Caveat

While EA-NA consistently ranked as the most cost-effective in the short term, laboratory performance testing from Chapter 4 indicated that non-additive mixes may fail to meet current moisture conditioned strength requirements under certain environmental conditions. This raises potential durability concerns in wet climates or for projects requiring high early strength.

Strictly from a cost perspective, Figure 62 illustrates the impact of alternative designs on component materials, construction, user delay, and overall total project costs. The heatmap clearly shows that EA-NA provides the most balanced and significant economic benefits across all cost categories, including substantial savings in road user delay costs. For the Receiving Agency, this means that on-time, on-budget-sensitive projects with high AADT could greatly reduce both agency and user costs, as long as performance criteria are met. Conversely, FA-NA has the highest user-delay cost because it maintains the same daily production rate and total project duration as the FA additive options but requires longer closure duration (i.e., 13 hours versus 11 hours) before reopening to traffic. This extended daily closure adds delay hours without reducing the number of workdays, resulting in increased user-delay costs. As a result, even though FA-NA has a 9.2 percent reduction in materials cost, FA-NA shows a +16.7 percent increase in user-delay cost and an overall total cost savings of only 1.4 percent compared to the FA-1%C baseline.

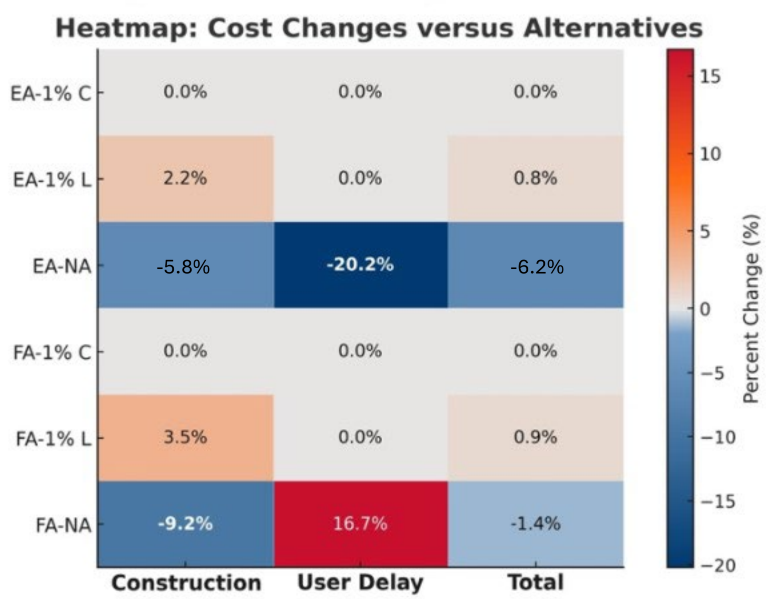


Figure 62. Results of Comparative Economic Valuations.

6.1.1.3. Key Takeaways

This analysis provides quantitative evidence that can guide the Receiving Agency in selecting FDR strategies aligned with project-specific goals. In high-traffic or time-sensitive corridors, eliminating additives, particularly in EA mixes, can substantially lower total project costs by reducing both material inputs and user-delay impacts.

In low-AADT environments, where user delays are less impactful, FA-NA offers a cost-effective solution due to lower material costs. Caution is advised, however; while FA non-additive mixes offer strong economic advantages, current laboratory strength data suggest potential performance risks under wet conditions or in projects requiring high early strength. Therefore, project specifications must be carefully considered, and relaxed strength criteria or favorable environmental conditions may be needed to justify the use of non-additive FDR designs. The Receiving Agency could mitigate the higher user-delay cost through strategies that either shorten the daily closure or reduce the number of closure days. The best strategies for pursuing FA-NA include:

- Optimize work scheduling: Shift to nighttime closures or off-peak hours, especially on higher-AADT roadways, to reduce traffic delays even if curing remains lengthy. This approach directly lowers road user delay costs without changing the mix.
- Increase daily production rate: Minimize mobilization and demobilization times (e.g., for equipment, crews, or processes) to complete more lane-miles per day, thereby reducing the total number of construction days and cumulative delay exposure.
- Target FA-NA to low-traffic corridors: On low-AADT facilities, user-delay costs contribute minimally to the overall cost, so FA-NA's high material savings could significantly improve economic outcomes.
- Integrate with staged or phased construction: In high-traffic areas, combine FA-NA with staging that maintains at least partial lane access during curing to reduce total lane closure times.

This analysis sets a precedent for integrating time, cost, and user delay into FDR economic evaluations. It contributes to TxDOT's broader goals of performance-based design and cost-conscious decision-making while advancing academic literature on the multi-dimensional valuation of pavement rehabilitation strategies. The approach and findings may inform revisions to specifications, pilot testing of non-additive EA designs, and guidelines for maximizing economic efficiency on future FDR projects.

6.1.2. Project Information and Traffic

The Performing Agency team conducted an economic analysis of four projects: SL 338, FM 39, SH 18, and SH 128. The SL 338 project involved a 30.4 lane-mile rehabilitation, with two lanes in each direction (northbound and southbound), spanning 7.6 centerline miles per direction. The highway section also includes two 10-foot-wide shoulders. Figure 63 illustrates the typical cross-section of the rehabilitated roadway, which features a 26-foot-wide treated section composed of 10 inches of FTB, topped with a 1.5-inch SMAR-F bonding course. This route handles an AADT of 19,400 vehicles, with 9 percent truck traffic and a growth rate of 2.28 percent.

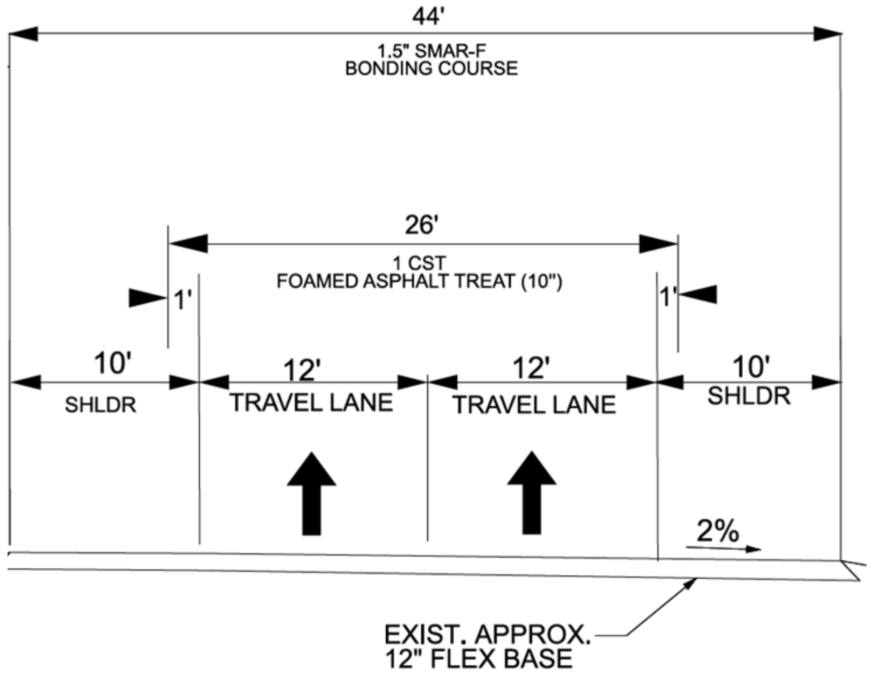


Figure 63. Proposed Lane Configuration of SL 338.

The FM 39 project involved a 15.2 lane-mile rehabilitation, covering 7.6 centerline miles. The highway section also features two 10-foot-wide shoulders. The cross-section includes two 12-foot travel lanes, two 8-foot shoulders, and a total width of 40 feet. The pavement structure includes a 3-inch HMA surface (Item 3077), a bonding course (Item 3084), a prime coat (Item 316), an 8-inch FTB, and a 6-inch cement-treated existing base (see Figure 64). This route supports an AADT of 4,400 vehicles, with 10.6 percent trucks and a traffic growth rate of 0.87 percent.

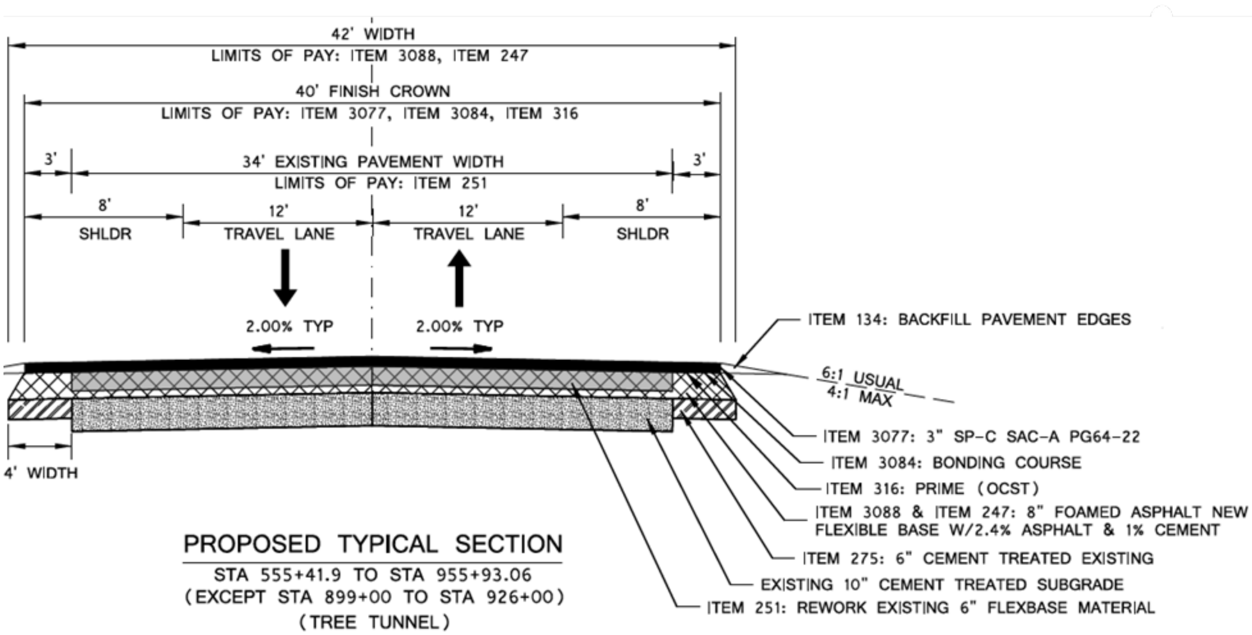


Figure 64. Proposed Lane Configuration of FM 39.

The SH 18 project involved a 23.4 lane-mile rehabilitation, featuring a typical section with three 12-foot travel lanes and two 10-foot shoulders, totaling a 56-foot-wide roadway (see Figure 65). The pavement structure includes a 2-inch SMAR-F surface, one course surface treatment (CST), a 4-inch SP-B HMA layer, and a prime coat. Below the asphalt, the base consists of 7 inches of ET flexible base material. This route serves an AADT of 8,200 vehicles, with 27.8 percent truck traffic and a growth rate of 2.02 percent.

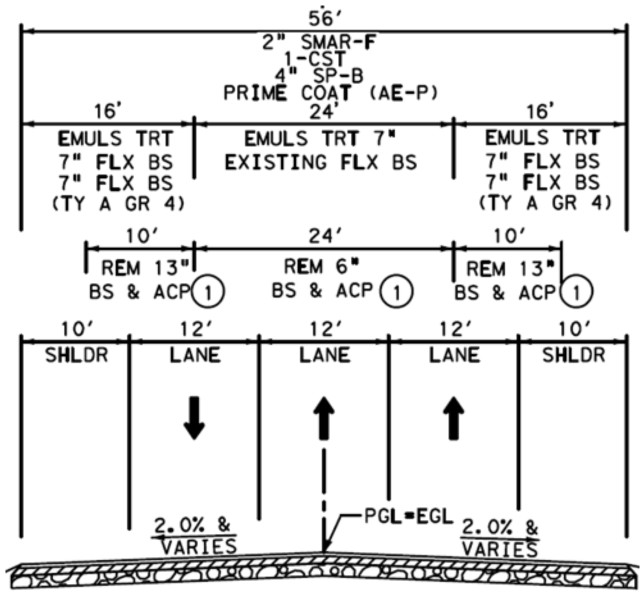


Figure 65. Proposed Lane Configuration of SH 18.

The SH 128 project involved a 28.4 lane-mile rehabilitation. The typical section includes two 12-foot travel lanes and two 10-foot shoulders, resulting in a total paved width of 44 feet, as shown in Figure 66. The pavement structure consists of a 2-inch SMAR-F surface course, underseal, and a 4-inch SP-B layer over a prime coat. Below the asphalt layers, the base section includes 8 inches of ETB. The emulsion treatment is applied across the entire 28-foot-wide reworked base area. The outside 10-foot shoulder sections are constructed with an 8-inch flexible base, which also was emulsion treated. This route accommodates an AADT of 4,044 vehicles, with 42.3 percent of truck traffic and a growth rate of 1.69 percent.

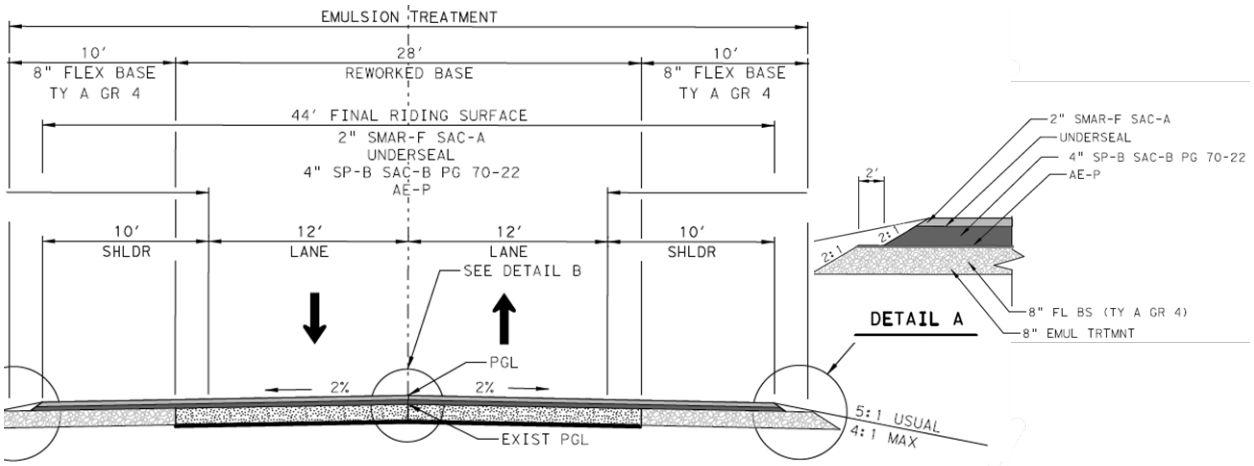


Figure 66. Proposed Lane Configuration of SH 128.

6.1.3. Data Collection and Research Methods

Figure 67 shows how input data related to construction staging and mix design options were collected and analyzed. Unit cost data came from the latest 2024 RSMeans Cost Manual and the TxDOT bid price database. Other input data include road section profiles, average daily traffic volumes, truck percentages specific to each demonstration project, traffic opening timelines for each FDR mix design scenario, the duration of the FDR construction window, FDR and HMA production rates, FDR operation costs, and more. A full list of the input data used in the analysis is available in the Chapter 9.

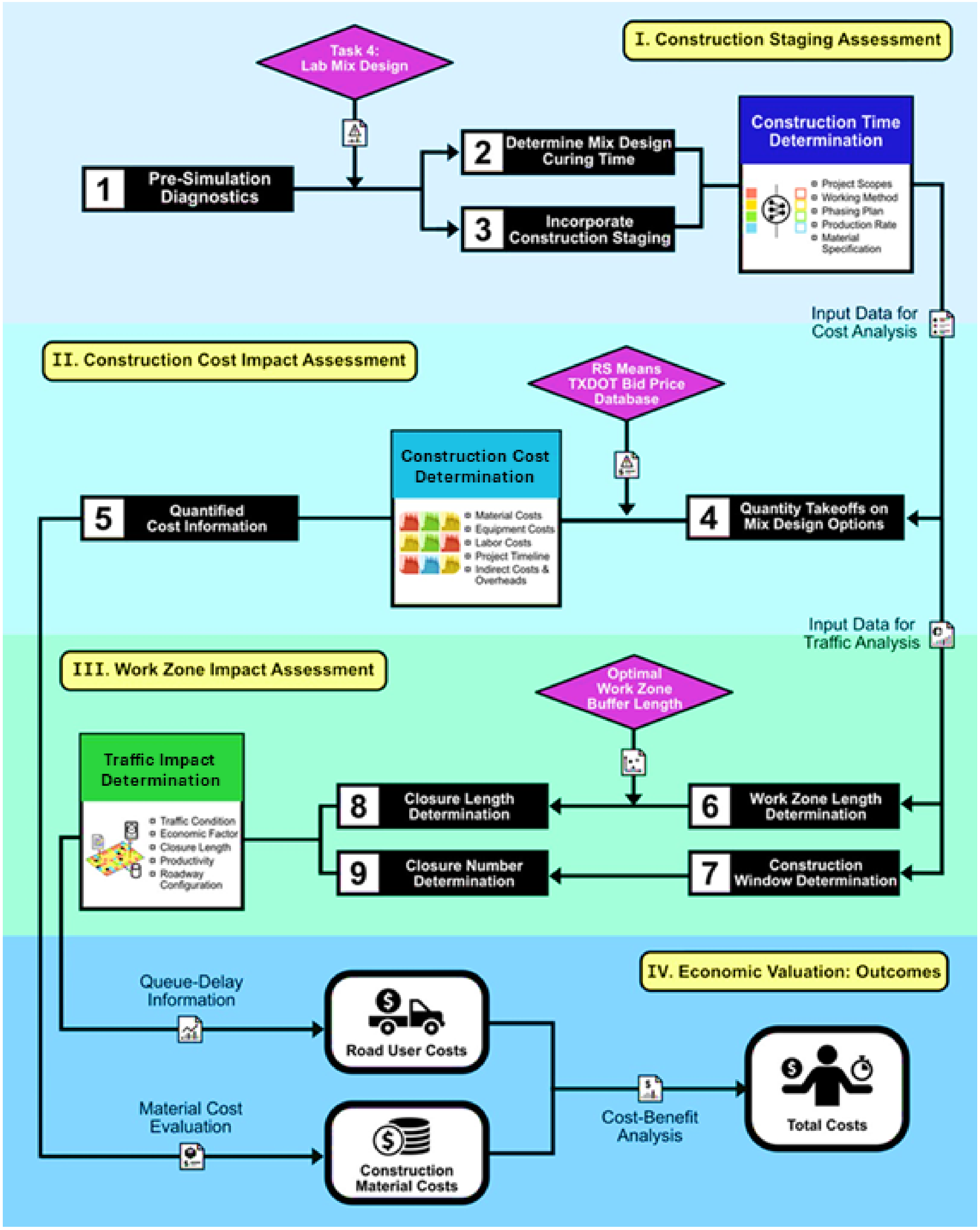


Figure 67. Economic Valuation Flow Chart.

Figure 67 illustrates that the integrative three-step procedure begins with a construction time determination (CTD), evaluating the effect of each mix design alternative on the overall project duration. The CTD analysis simulates various construction scenarios using specialized software, incorporating key factors such as production rates, lane closure strategies, and traffic opening timelines.

The second step focuses on accurate cost estimation, where construction material costs are calculated manually through detailed quantity takeoffs. These estimates are derived from current market prices for materials, construction operations, and equipment usage, ensuring accuracy and relevance.

The final step assesses the mobility impact of the six mix design options shown in Table 33. The mobility impact assessment requires a detailed analysis of existing traffic patterns, including AADT volumes, truck percentages, and lane configurations specific to each project. Using these data, the research team calculated daily RUCs by considering reduced speed limits during construction, lane closures, and estimated queue delays in work zones.

This comprehensive approach allows for a well-rounded analysis that integrates time, cost, and traffic considerations into a cohesive framework. The integrative procedure helps optimize construction staging for the best possible outcomes by evaluating trade-offs between different mix design alternatives.

6.1.4. Construction Time Assessment

As shown in Figure 67, the research team quantified construction contract times based on the FDR mix design production rates, taking into account project resource constraints. The assumption of same-day working hours on weekdays from 6:00 a.m. to 6–8:00 p.m. aligns with the traditional practices provided by the Receiving Agency technical team and was incorporated into the analysis.

The selected approach for each designated construction window involved a half closure with partial completion. This lane closure strategy maintains one open lane in each direction while closing the other for construction operations, reflecting a conventional approach to lane closures. This approach enables continuous traffic flow and minimizes disruption to motorists, allowing for efficient and safe rehabilitation work. The production rates were defined as follows: the typical FDR process was set at 0.75 lane-miles per day, while the HMA process was assigned a rate of 0.9 lane-miles per day, based on industry data. Typically, the FDR process is followed by approximately 4 hours of finishing work (mobilization and demobilization times were assumed to both be 1 hour), after which the road can be reopened to traffic.

In this analysis, traffic opening times were determined based on the strength and curing time results obtained from the lab study presented in Chapter 4. In standard FDR construction practices, 1 percent cement is typically incorporated into the mix, regardless of whether EA or FA is used, since this low level of cement promotes early strength gain and mitigates strength degradation under wet conditions. Under such typical conditions, traffic can generally be reopened approximately 4 hours after completion of the FDR process, following routine finishing operations, without compromising pavement performance.

To evaluate alternative mix designs without cement, including those with lime or no additives, the traffic opening schedules were estimated based on the time required to reach equivalent strength to the 1 percent cement-treated design. These estimates were derived by analyzing trends in strength development, particularly for non-cement mixtures, and aligning them with traffic reopening criteria. Using this analytical framework, traffic opening times for all mix design alternatives were established and are summarized in Table 34.

Table 34. Estimated Traffic Opening Times Equivalent to 1% Cement Design Strength.

Time Equivalent to FDR with 1% Cement Strength	Emulsion	Foam
1% cement	4 Hours	4 Hours
1% lime	4 Hours	4 Hours
Non-additive	7 Hours	8 Hours

Another critical input for construction staging was the roadway's cross-section design. Table 35 summarizes key input variables for the four project sites. The total lane mileage ranges from 15.2 to 30.4 lane-miles, with roadway lengths varying between 7.6 and 14.2 miles. The width of FDR-treated sections varies from 26 to 56 feet, and FDR depths range from 7 to 8 inches across all the projects.

Table 35. Cross-Section Key Profile.

Input Variables	SL 338	FM 39	SH 18	SH 128
Total Lane Miles (lane-mile)	30.4	15.2	23.4	28.4
Total Centerline Miles (mi)	7.6	7.6	7.8	14.2
Lane Width (ft)	12	11	12	12
Number of Lanes	4	2	3	2
Shoulder Width (ft)	10	6	10	10
Depth of 1st HMA (inch)	1.5 SMAR-F	3 SP-C	2 SMAR-F	2 SMAR-F
Depth of 2nd HMA (inch)	NA	NA	4 SP-B	4 SP-B
Total Width of FDR (ft)	26	42	56	48
Depth of FDR (inch)	8	8	7	8

The construction window scenarios consider three distinct FDR design approaches: (1) EA and FA designs with additive, (2) EA design without additive, and (3) FA design without additive, as shown in Figure 68. Each scenario outlines a full-day construction sequence, highlighting differences in production rates and traffic reopening times.

- In the EA and FA designs with additive, the application of additive is followed by 4 hours of FDR operations, resulting in a production rate of 0.75 lane-miles per day. Since no curing delay is required, finishing can be completed by 6:00 p.m., allowing same-day traffic reopening.
- In contrast, EA design without an additive achieves the highest production rate of 0.94 lane-miles per day by allowing 5 continuous hours of FDR operations. However, this scenario requires a 3-hour additional curing period, delaying the reopening of traffic until 8:00 p.m.
- Similarly, FA design without an additive involves 4 hours of FDR work, yielding a production rate of 0.75 lane-miles per day. Due to a longer additional curing requirement of 4 hours, traffic is also reopened at 8 p.m., despite the job being completed by 4:00 p.m.

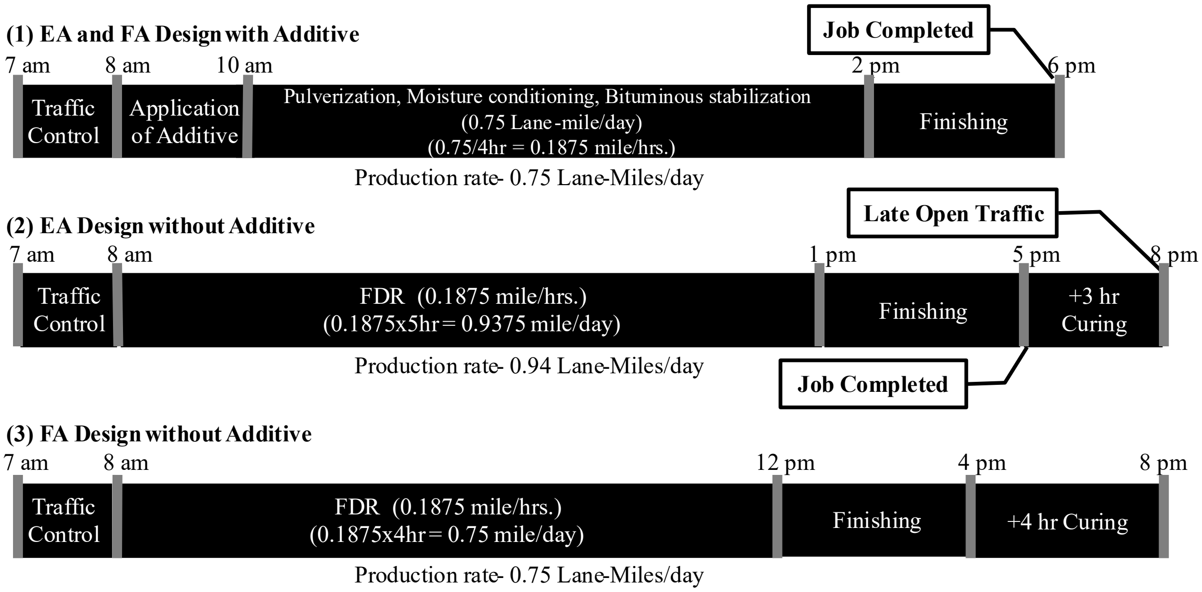


Figure 68. Construction Window Scenario for FDR.

These differences in daily production and traffic opening times are primarily influenced by the inclusion of additives, which reduce curing time, and the total duration allocated for FDR operations within the daily construction window. The results of the schedule analysis for the FDR component of the construction time are recorded in Table 36. Table 37 presents the construction time for the surface layer(s) as applicable to the four projects.

Table 36. Results of the Construction Staging Assessment for FDR.

Working Scenario	Production Rate per Construction Window (Lane-Miles)	Number of Construction Windows Needed (days)			
		SL 338	FM 39	SH 18	SH 128
EA with 1% Cement	0.75	41	21	32	38
EA with 1% Lime	0.75	41	21	32	38
EA without Additives	0.94	33	17	25	31
FA with 1% Cement	0.75	41	21	32	38
FA with 1% Lime	0.75	41	21	32	38
FA without Additives	0.75	41	21	32	38

Table 37. Results of the Construction Staging Assessment for HMA.

Working Scenario	Production Rate per Construction Window (Lane-Miles)	Number of Construction Windows Needed			
		SL 338	FM 39	SH 18	SH 128
HMA 1st	0.9	34	17	26	32
HMA 2nd	0.9	NA	NA	26	32

6.1.5. Construction Cost Assessment

Construction materials costs were calculated manually based on published market values and specifications. Specifically, the average prices for Texas bid items are as follows:

- Cement: $268.87 per ton (special specification 3089-6002).
- Lime (hydrated lime dry): $370.24 per ton (special specification 260-6001).
- EA: $3.10 per gallon (special specification 3088-6004).
- FA: $597.55 per ton (special specification 3088-6007).
- EA Treatment: $0.61 per square yard/in (special specification 3089-6004).
- FA Treatment: $0.56 per square yard/in (special specification 3088-6007).
- HMA: $125/ton.

Based on the project length, width, typical sections, and mix design options, the estimates of the various construction material quantities and costs are summarized for each of the four projects in Table 38 to Table 40. The data in Table 44 show that the project savings in materials cost from eliminating the additive in the FDR mix range from approximately 5.8 percent ($0.21M–$0.38M) for EA designs to approximately 9.2 percent ($0.27M–$0.39M) for FA designs.

Table 38. Material Quantity Estimates.

Project Parameters	SL 338	FM 39	SH 18	SH 128
Total Lane Length (mi)	30.4	15.2	23.4	28.4
Total Length (mi)	7.6	7.6	7.8	14.2
Direction	2	1	1	1
Depth of HMA (inch)	1.5	3	6	6
Depth of FDR (inch)	8	8	7	8
Total Width of HMA (ft)	26	40	56	44
Total Width of FDR (ft)	26	42	56	48
HMA Density (lb/ft^3)	145	145	145	145
FDR Density (lb/ft^3)	127.5	136.3	123.2	119.1
HMA Surface Area (square yard)	231,851	178,347	256,256	366,549
FDR Surface Area (square yard)	231,851	187,264	256,256	399,872
FDR Quantity (ton)	88,683	76,572	82,873	142,874
1% Additives Quantity (ton)	887	766	829	1429
HMA Quantity (ton)	18,910	29,093	83,604	119,587

Table 39. Material Unit Cost Estimates.

Unit Cost Items	SL 338	FM 39	SH 18	SH 128
HMA Cost ($/Ton)	$125	$125	$125	$125
Emulsion Cost ($/SY)	$14.2	$17.1	$9.6	$10.6
Foam Cost ($/SY)	$6.9	$8.6	$4.6	$5.1
Cement Cost ($/SY)	$1.29	$1.37	$0.87	$0.96
Lime Cost ($/SY)	$1.77	$1.89	$1.20	$1.32
Emulsion Treat Cost ($/SY)	$6.14	$6.14	$4.30	$4.91
Foam Treat Cost ($/SY)	$5.55	$5.55	$3.89	$4.44
Construction Cost (EA+C+ET) $/SY	$21.62	$24.59	$14.77	$16.48
Construction Cost (EA+L+ET) $/SY	$22.11	$25.11	$15.10	$16.84
Construction Cost (EA+ET) $/SY	$20.34	$23.22	$13.90	$15.52
Construction Cost (FA+C+FT) $/SY	$13.69	$15.48	$9.39	$10.53
Construction Cost (FA+L+FT) $/SY	$14.18	$16.00	$9.72	$10.89
Construction Cost (FA+FT) $/SY	$12.41	$14.10	$8.52	$9.57

Table 40. Total Material Cost Estimates.

Cost Items	SL 338	FM 39	SH 18	SH 128
HMA	$2.37M	$3.64M	$10.45M	$14.95M
FDR Cost (EA+C+ET) $/SY	$5.01M	$4.60M	$3.79M	$6.59M
FDR Cost (EA+L+ET) $/SY	$5.13M	$4.70M	$3.87M	$6.74M
FDR Cost (EA+ET) $/SY	$4.72M	$4.35M	$3.56M	$6.21M
FDR Cost (FA+C+FT) $/SY	$3.18M	$2.90M	$2.41M	$4.21M
FDR Cost (FA+L+FT) $/SY	$3.29M	$3.00M	$2.49M	$4.35M
FDR Cost (FA+FT) $/SY	$2.88M	$2.64M	$2.18M	$3.83M

6.1.6. Mobility Impact Assessment

The mobility impact assessment aimed to quantify the effects of construction on traffic mobility and the traveling public. The evaluation included estimates of daily and total RUCs derived from simulated delay times due to the work zone impacts on traffic for each FDR mix design alternative. The research team first gathered essential information about the work zones, including lane width, number of lanes, direction of travel, traffic patterns, volume, and speed limits. The project phasing, duration, and lane closure plans were then reviewed. Based on the compiled information, hourly traffic volume, truck percentage, lane width, and lane closure options, the anticipated traffic delay times around the work zones for each identified mix design alternative were simulated and recorded. Finally, total road user delay costs were calculated based on the project duration, traffic demand, and estimated delays.

The AADT ranged from 4,044 to 19,400 vehicles, with truck traffic percentages varying from 9 percent to 42.3 percent across the four projects, as summarized in Chapter 9. Under normal conditions, speed limits were up to 75 mph but are reduced to 45 mph during lane closures. Across all projects, a 5 percent no-show rate was assumed during construction, with 20 percent of vehicles detouring and an average additional detour time of 20 minutes.

The lane closure length was determined by adding the buffer work zone length (0.5 miles) to the work zone length. Table 41 presents the lane closure lengths and operation hours applied in the assessment.

Table 41. Closure Length per Working Day for FDR Mix Designs.

Working Scenario	Closure Length (Lane-miles)				Operation Hours			
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128
EA with 1% Cement	1.25	1.25	1.25	1.25	11	11	11	11
EA with 1% Lime	1.25	1.25	1.25	1.25	11	11	11	11
EA without Additives	1.44	1.44	1.44	1.44	13	13	13	13
FA with 1% Cement	1.25	1.25	1.25	1.25	11	11	11	11
FA with 1% Lime	1.25	1.25	1.25	1.25	11	11	11	11
FA without Additives	1.25	1.25	1.25	1.25	13	13	13	13

*11 or 13 working hours per day were assumed.

The closure duration for FDR with additives was 11 out of 24 hours, representing approximately 0.46 for a full day. In contrast, FDR without additives required a closure duration of 13 out of 24 hours, or 0.54 for a full day (see Figure 68). The number of impacted closures was determined based on the results from the previous stage of the construction time assessment. According to TxDOT, the estimated traveler's time value for 2024 is $37.20 per hour for passenger cars and $52.75 per hour for trucks. The final results of the work zone impact assessment are presented in Table 42 and Table 43.

Table 42. Calculated RUCs During FDR for Alternative Mix Designs.

Materials	Working Scenario	RUC			
		SL 338	FM 39	SH 18	SH 128
EA	EA with 1% Cement	2.78M	0.32M	1.15M	0.61M
	EA with 1% Lime	2.78M	0.32M	1.15M	0.61M
	EA without Additives	2.25M	0.26M	0.81M	0.49M
FA	FA with 1% Cement	2.78M	0.32M	1.15M	0.61M
	FA with 1% Lime	2.78M	0.32M	1.15M	0.61M
	FA without Additives	3.26M	0.39M	1.24M	0.73M

Table 43. Calculated RUCs on Project for FDR+HMA.

Materials	Working Scenario	RUC			
		SL 338	FM 39	SH 18	SH 128
EA	EA with 1% Cement	5.08M	0.58M	3.53M	1.62M
	EA with 1% Lime	5.08M	0.58M	3.53M	1.62M
	EA without Additives	3.81M	0.47M	2.82M	1.35M
FA	FA with 1% Cement	5.08M	0.58M	3.53M	1.62M
	FA with 1% Lime	5.08M	0.58M	3.53M	1.62M
	FA without Additives	5.28M	0.62M	3.75M	1.72M

6.1.7. Results

The study utilized CA4PRS to quantify the monetary impacts of the various FDR mixture designs on construction time, material costs, and mobility. The results were obtained by synthesizing the outcomes of all three-step assessments. The economic valuation of six FDR mix design alternatives, comparing EA and FA with and without 1 percent cement and lime additives, reveals that non-additive options provide the lowest overall upfront cost.

6.1.7.1. Construction Costs

Eliminating additives in EA and FA mixes resulted in approximately 5.8 percent and 9.2 percent cost reductions in materials, respectively. In contrast, substituting cement with lime increased materials costs by about 2.2 percent in EA and 3.5 percent in FA, as shown in Table 44. The cost differences between EA and FA mixtures are consistent with industry trends, with EA generally being more expensive than FA.

Table 44. Construction Costs Impacts for FDR.

FDR Mix Design Options	Construction Costs				Cost Difference (%)				
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128	Avg.
EA-1% C	$5.01M	$4.60M	$3.79M	$6.59M	(Benchmark)				
EA-1% L	$5.13M	$4.70M	$3.87M	$6.74M	2.2%	2.1%	2.2%	2.2%	**2.2%**
EA-NA	$4.72M	$4.35M	$3.56M	$6.21M	−5.9%	−5.6%	−5.9%	−5.8%	**−5.8%**
FA-1% C	$3.18M	$2.90M	$2.41M	$4.21M	(Benchmark)				
FA-1% L	$3.29M	$3.00M	$2.49M	$4.35M	3.5%	3.3%	3.5%	3.4%	**3.5%**
FA-NA	$2.88M	$2.64M	$2.18M	$3.83M	−9.4%	−8.9%	−9.3%	−9.1%	**−9.2%**

Table 45 shows that the total cost of construction materials is reduced by approximately 2.6 percent to 3.3 percent on average when the additive is removed from EA or FA mixes, respectively. Substituting cement with lime increased average costs by about 1.0 percent in EA and 1.2 percent in FA. Contrasting Table 45 with Table 44 shows that since HMA is such a significant driver of construction costs, the cost implications from alternative FDR designs start to become masked in the overall total project costs once the HMA component is included.

Table 45. Construction Costs and Cost Saving Effect for HMA and FDR.

FDR Mix Design Options	Construction Costs				Cost Difference (%)				
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128	Avg.
EA-1% C	$7.37M	$8.24M	$14.24M	$21.54M	(Benchmark)				
EA-1% L	$7.49M	$8.34M	$14.32M	$21.69M	1.6%	1.2%	0.6%	0.7%	**1.0%**
EA-NA	$7.08M	$7.99M	$14.01M	$21.16M	−3.9%	−3.0%	−1.6%	−1.8%	**−2.6%**
FA-1% C	$5.54M	$6.54M	$12.86M	$19.16M	(Benchmark)				
FA-1% L	$5.65M	$6.64M	$12.94M	$19.30M	2.0%	1.5%	0.6%	0.7%	**1.2%**
FA-NA	$5.24M	$6.28M	$12.63M	$18.78M	−5.4%	−4.0%	−1.8%	−2.0%	**−3.3%**

6.1.7.2. Mobility Costs

Among the six mix design alternatives, EA without additives exhibits the highest production rate at 0.94 lane-miles per day, while the other five designs, including those with cement or lime additives, maintain a lower, consistent production rate of 0.75 lane-miles per day. This represents a 25 percent increase in daily productivity for the EA non-additive option. As a result, the faster construction progress achieved with this design directly contributes to reduced user-delay costs, which are particularly significant for high-traffic corridors. In scenarios with heavy traffic volumes, this improvement in production rate can lead to user cost savings for the entire project exceeding $1M, as shown in Table 46 and Table 47, depending on traffic composition and closure durations.

Table 46. Calculated Road User Delay Costs for FDR.

FDR Mix Design Options	Road User Delay Costs ($)				Cost Difference (%)				
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128	Avg.
EA-1% C	2.78M	0.32M	1.15M	0.61M	(Benchmark)				
EA-1% L	2.78M	0.32M	1.15M	0.61M	0%	0%	0%	0%	**0%**
EA-NA	2.25M	0.26M	0.81M	0.53M	−19.1%	−18.7%-	−29.6%	−13.1%	**−20.1%**
FA-1% C	2.78M	0.32M	1.15M	0.61M	(Benchmark)				
FA-1% L	2.78M	0.32M	1.15M	0.61M	0%	0%	0%	0%	**0%**
FA-NA	3.26M	0.39M	1.24M	0.73M	17.3%	21.9%	7.8%	19.7%	**16.7%**

Table 47. Calculated Road User Delay Costs for HMA and FDR.

FDR Mix Design Options	Road User Delay Costs ($)				Cost Difference (%)				
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128	Avg.
EA-1% C	5.08M	0.58M	3.53M	1.62M	(Benchmark)				
EA-1% L	5.08M	0.58M	3.53M	1.62M	0%	0%	0%	0%	0%
EA-NA	3.81M	0.47M	2.82M	1.35M	−24.9%	−19.0%	−20.1%	−16.7%	**−20.2%**
FA-1% C	5.08M	0.58M	3.53M	1.62M	(Benchmark)				
FA-1% L	5.08M	0.58M	3.53M	1.62M	0%	0%	0%	0%	0%
FA-NA	5.28M	0.62M	3.75M	1.72M	3.9%	6.9%	6.2%	8.6%	**13.4%**

More specifically, the findings reveal that the EA mix without additives consistently achieves the most substantial reduction in RUC, particularly in high-traffic corridors such as SL 338, which has the highest AADT of 19,400. This outcome can be directly attributed to the elevated production rate of the EA non-additive design (0.94 lane-miles/day), which represents a 25 percent improvement over the additive-based alternatives (0.75 lane-miles/day). Such increases in production rate proportionally reduce the number of required construction windows and total closure days, an effect that is magnified in high-AADT environments where delay costs are non-linearly correlated with traffic volume and closure duration.

Moreover, the mobility cost function is convex in traffic flow, meaning that time savings under high-demand conditions yield disproportionately large user cost savings. In contrast, the FA non-additive design fails to realize similar benefits despite eliminating additives. This is because the FA-NA configuration maintains the same daily production rate as its additive counterparts (0.75 lane-miles/day), yet it incurs an extended curing time (4 hours), resulting in longer daily lane closures (13 hours vs. 11 hours). The result is an increase in user delay duration without any compensatory reduction in project duration, thereby increasing total RUC.

6.1.7.3. *Total Costs*

Figure 69 through Figure 72 illustrate the results of the economic valuation for each of the six FDR mix designs and each of the four real-world project situations analyzed. These figures demonstrate that the use or absence of additives in FDR mixtures can significantly affect construction time, material costs, and mobility costs, ultimately impacting the overall upfront total project costs.

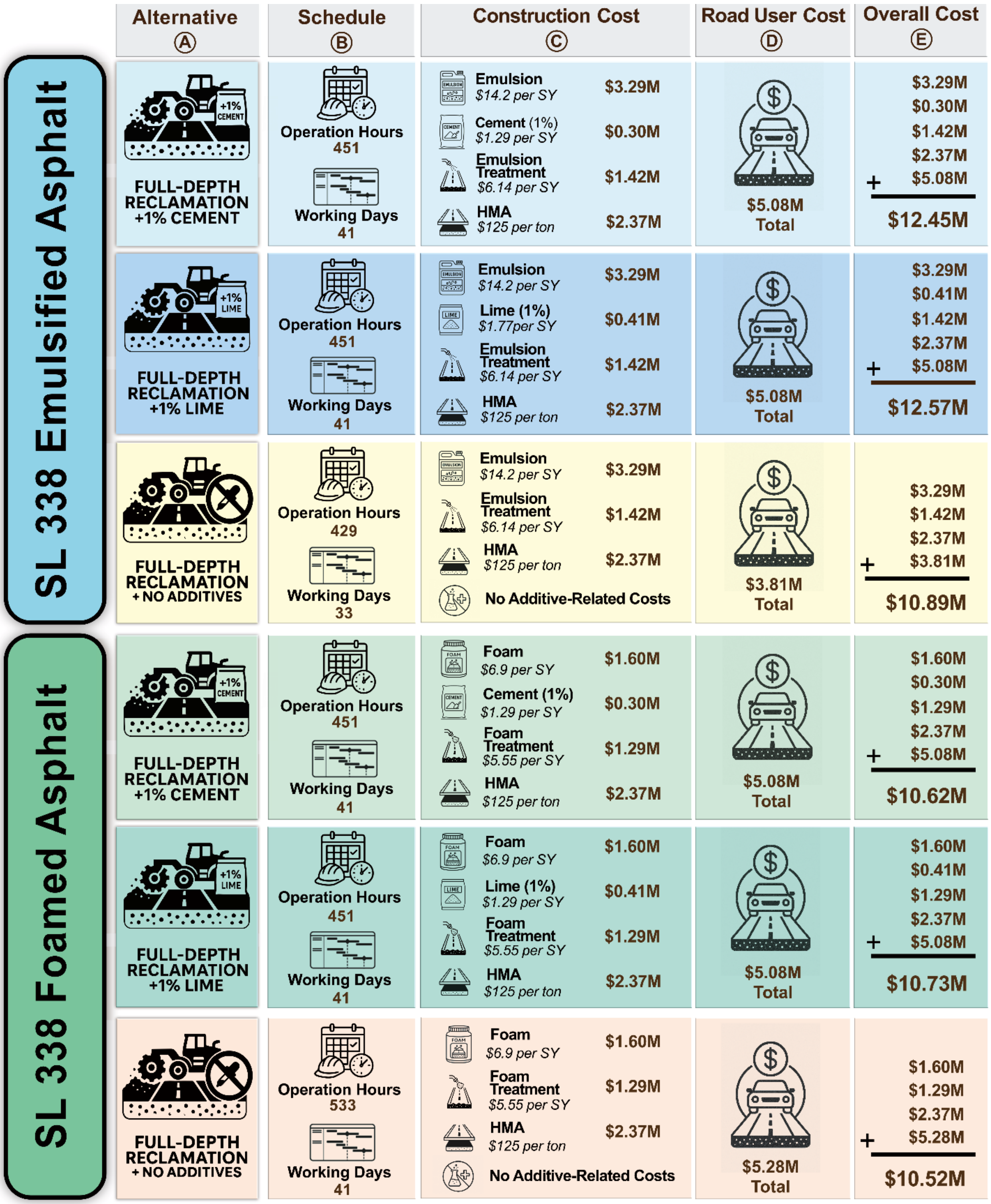


Figure 69. Results of the Three-Step Economic Valuation Assessments for SL 338.

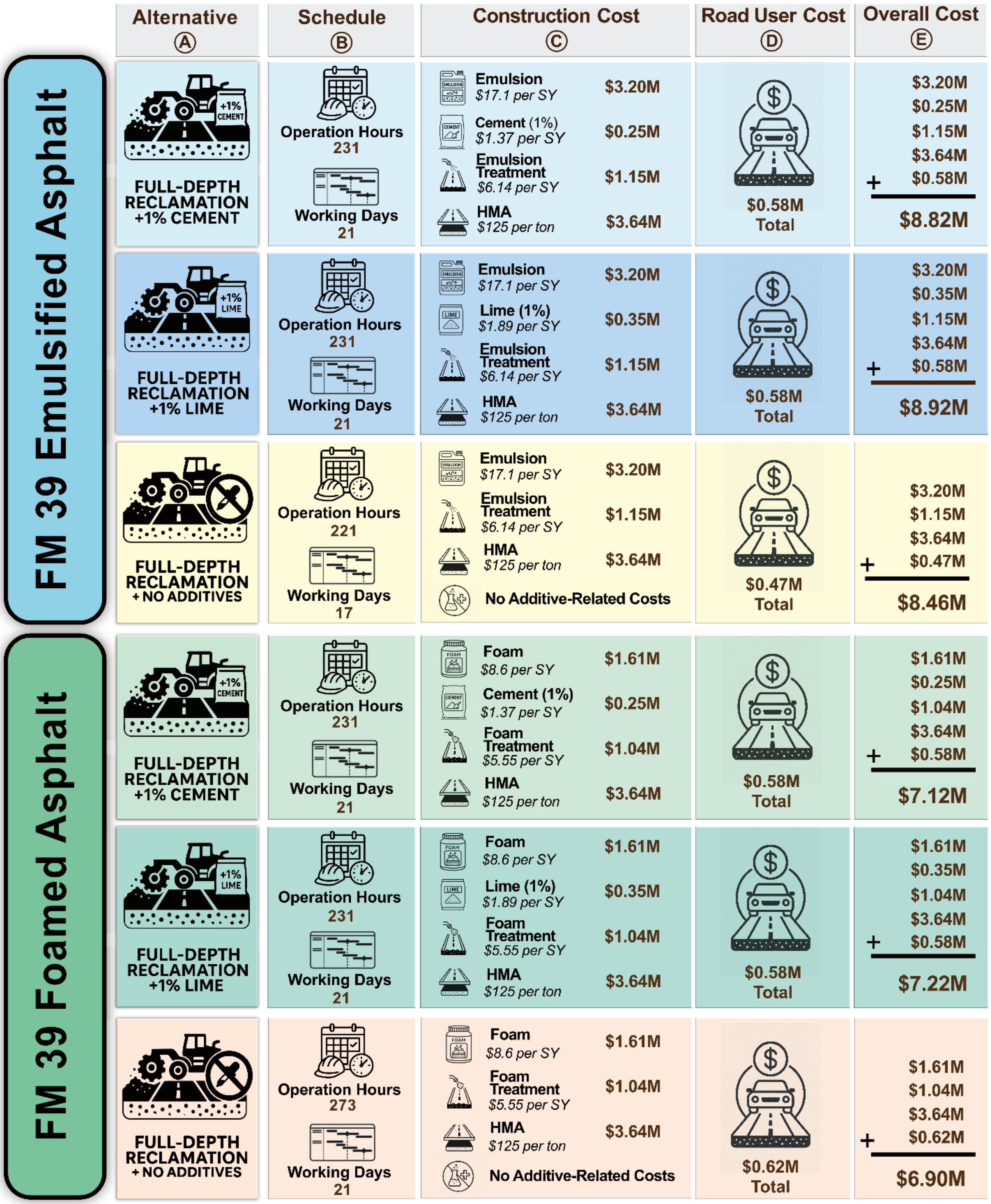


Figure 70. Results of the Three-Step Economic Valuation Assessments for FM 39.

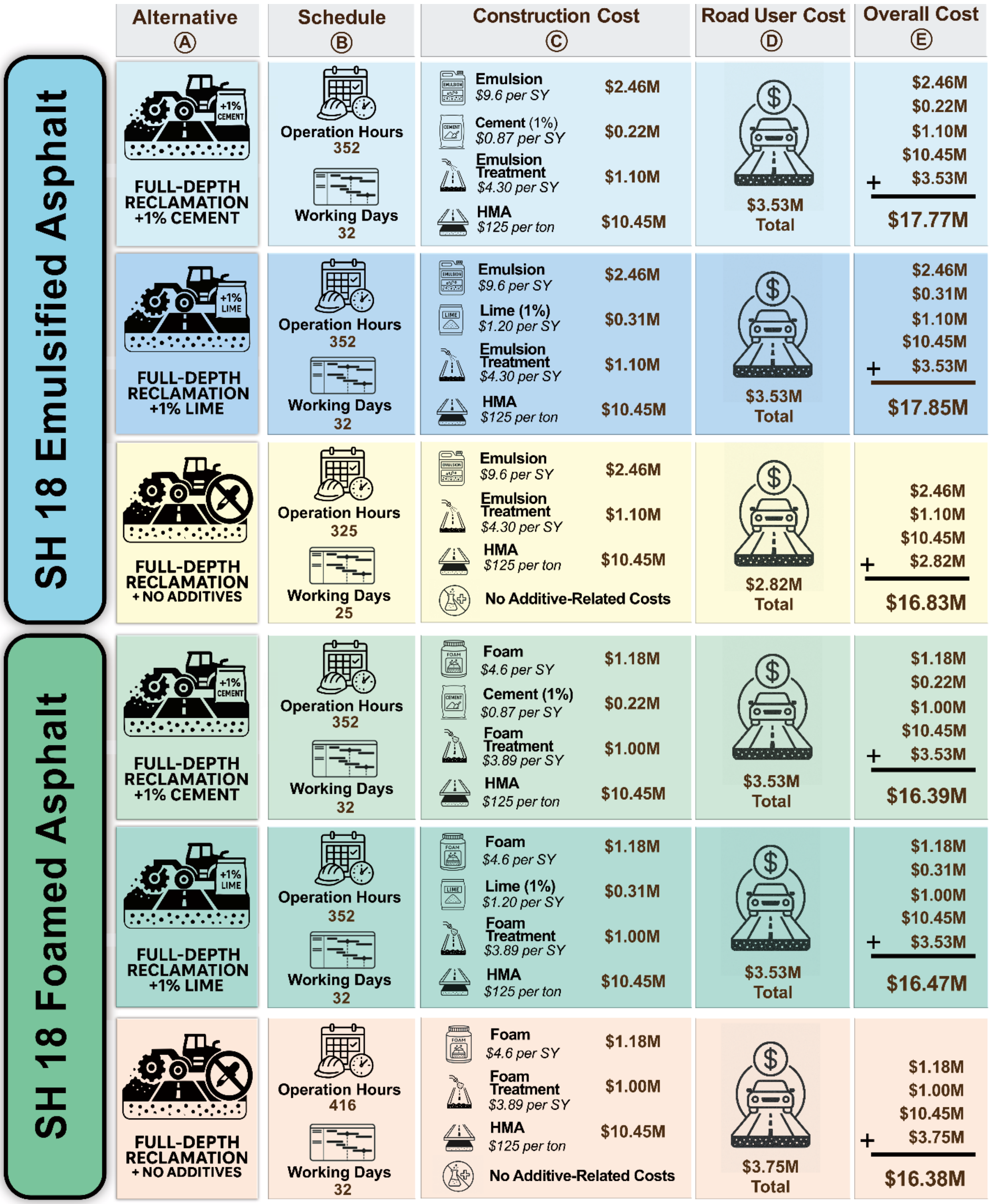


Figure 71. Results of the Three-Step Economic Valuation Assessments for SH 18.

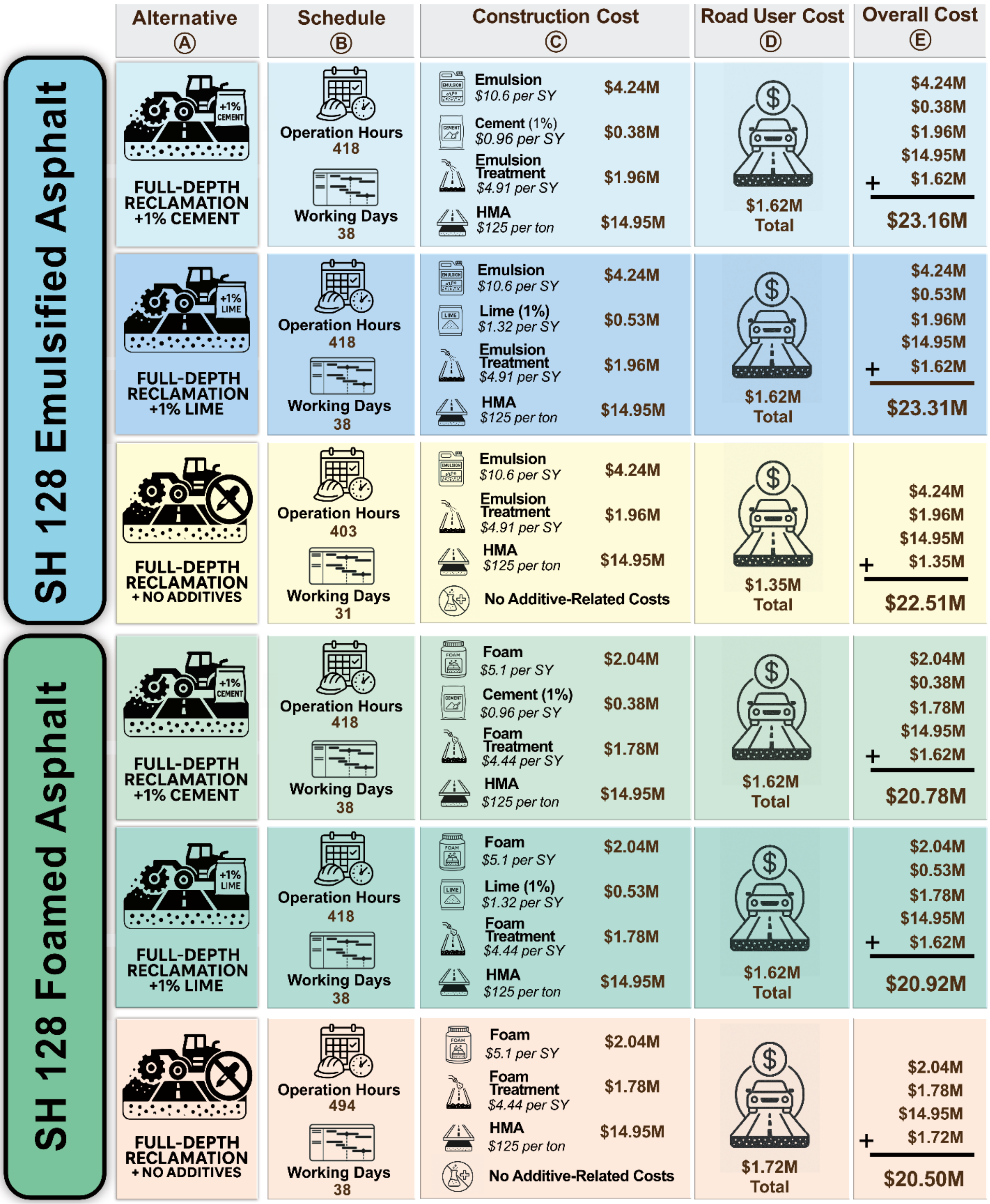


Figure 72. Results of the Three-Step Economic Valuation Assessments for SH 128.

Table 48 shows the cumulative impact of the cost implications of the FDR mix design options. Table 48 shows that the use of EA without an additive could provide a meaningful reduction in initial upfront costs. The overall savings are comprised of both material cost savings, where the elimination of the additive results in one less material, and a mobility component, where a higher daily production rate allows for fewer mobility impacts during construction.

Table 48. Total Overall Costs and Cost Saving Effect.

FDR Mix Design Options	Total Project Cost ($)				Cost Difference (%)				
	SL 338	FM 39	SH 18	SH 128	SL 338	FM 39	SH 18	SH 128	Avg.
EA-1% C	12.45M	8.82M	17.77M	23.16M	(Benchmark)				
EA-1% L	12.57M	8.92M	17.85M	23.31M	1.0%	1.1%	0.5%	0.6%	**0.8%**
EA-NA	10.89M	8.46M	16.83M	22.51M	−12.5%	−4.1%	−5.3%	−2.8%	**−6.2%**
FA-1% C	10.62M	7.12M	16.39M	20.78M	(Benchmark)				
FA-1% L	10.73M	7.22M	16.47M	20.92M	1.0%	1.4%	0.5%	0.7%	**0.9%**
FA-NA	10.52M	6.90M	16.38M	20.50M	−1.0%	−3.1%	−0.1%	−1.3%	**−1.4%**

These findings underscore the significant cost implications of using additives like cement and lime. Although these materials are known for enhancing the pavement's structural integrity and early strength, their use increases material costs, which is a driver of the higher total project costs observed. The additional expense is not only due to the direct cost of the additives themselves but also the increased labor, time, and construction sequences required to integrate them into the mix.

Moreover, the economic advantage of employing EA without additives becomes particularly pronounced in high traffic volume scenarios, exemplified by projects such as SL 338 (see Table 46 and Table 47). In such cases, the rapid construction pace achievable with EA non-additive designs substantially reduces mobility costs due to minimized road user delays; the user-delay savings clearly outweigh material cost savings.

Conversely, in low-AADT scenarios, such as FM 39 or SH 128, the benefit from reduced mobility impacts is less evident, and material costs primarily dictate overall economic efficiency. Consequently, FA-based options, owing to their inherently lower material expenses, remain the lowest cost in these contexts.

In high-traffic scenarios, user delay represents a dominant component of total project costs, allowing the accelerated construction process of EA non-additive mixtures to effectively offset their relatively higher material costs compared to FA options. In contrast, for projects characterized by lower traffic volumes, the economic influence of mobility savings diminishes considerably. Under such conditions, construction speed contributes marginally to total savings, making material costs the decisive factor.

Nevertheless, when considering the elimination of additives in FDR mixes, from a purely cost perspective, EA without additives remains the most suitable choice overall due to its combination of high productivity, reduced construction complexity, and mitigation of construction-related uncertainties. Eliminating additives simplifies construction operations by reducing the number of required steps and materials, thus enhancing the reliability and consistency of the construction process. Furthermore, this streamlined approach minimizes susceptibility to supply-chain disruptions that may be associated with additives, potentially accelerating project completion and improving resource allocation efficiency. Collectively, these operational benefits underscore EA without additives as the most viable additive-free FDR solution, particularly in rehabilitation projects where both mobility costs and construction efficiency critically influence overall project success.

6.1.8. Conclusions for Economic Analysis

Across the four projects evaluated, the non-additive EA option consistently provided the greatest overall savings, making it the most economically advantageous alternative under the modeled conditions, particularly in high-AADT corridors where minimizing total costs and user delays is critical. The analysis shows that EA-NA achieves balanced benefits across material, construction, and user-delay categories, with reductions in mobility costs of up to almost 25 percent on the busiest roadway modeled. These benefits stem primarily from EA-NA's higher daily production rate, which reduces the total number of construction windows and shortens closure durations, resulting in both agency cost savings and significant reductions in RUCs.

By contrast, the non-additive FA option achieved the highest material cost savings of all alternatives but also incurred the highest user-delay cost (+16.7 percent relative to the FA-1%C baseline). This outcome reflects two combined factors: FA-NA maintained the same daily production rate as additive-based FA designs and required a longer daily closure period before opening to traffic due to longer curing times. The longer closure hours per day amplified mobility costs without any offsetting reduction in total project duration.

Although non-additive EA designs present compelling economic advantages, laboratory performance testing highlights potential risks under wet conditions or in applications requiring high early strength. These risks indicate that EA-NA should be deployed selectively, in contexts where environmental conditions, project specifications, or relaxed wet strength criteria permit. Similarly, FA-NA may be best suited for low-AADT corridors where user-delay costs are less impactful and material savings dominate total cost outcomes.

When FA-NA is considered for higher-volume roads, the Receiving Agency can lower user-delay costs by adopting targeted strategies such as improving moisture management, scheduling work during nighttime or off-peak hours, increasing daily production through better crew and equipment utilization, and implementing staged construction to maintain partial lane access during curing. These measures address FA-NA's main drawback without diminishing its material cost advantage.

This economic analysis demonstrates the value of integrating construction time, direct costs, and user-delay costs into the economic evaluation of FDR mix design alternatives. By capturing the full cost implications of materials and schedule and mobility impacts, the methodology aligns with performance-based, cost-effective decision-making.

6.2. Structural Analysis

The results from the laboratory study were analyzed to determine the impact of the additive on the short- and long-term expected pavement performance. The material properties obtained from the lab study were incorporated into pavement analysis and design software to estimate the accumulated damage in the FDR layer over time, considering variations in assumed traffic levels and opening times to traffic.

6.2.1. TxME Analysis on the Alternative Additive on FDR Material

FDR is an established pavement rehabilitation technique that recycles existing materials in place to create a stabilized base, often with the addition of cement, lime, or asphalt binders. Its cost-effectiveness and sustainability advantages have led to its increasing application across highway agencies. However, the performance of FDR layers depends strongly on structural configuration, material properties, environmental conditions, and traffic loading. In particular, the presence or absence of chemical additives may substantially influence the long-term mechanistic response of FDR bases under varying climate conditions. To address these considerations, this analysis combined laboratory testing with TxME analyses to evaluate the rutting and fatigue performance of pavements constructed using FDR base layers with cement, lime, and no additive.

6.2.1.1. Structure Input

Figure 73 shows the pavement structure input screen in TxME, where users define key parameters including pavement type and project location, layer materials, pavement structure, and detailed material properties. This interface allows integration of structural configuration with material-specific inputs such as modulus, gradation, and binder type for mechanistic pavement analysis.

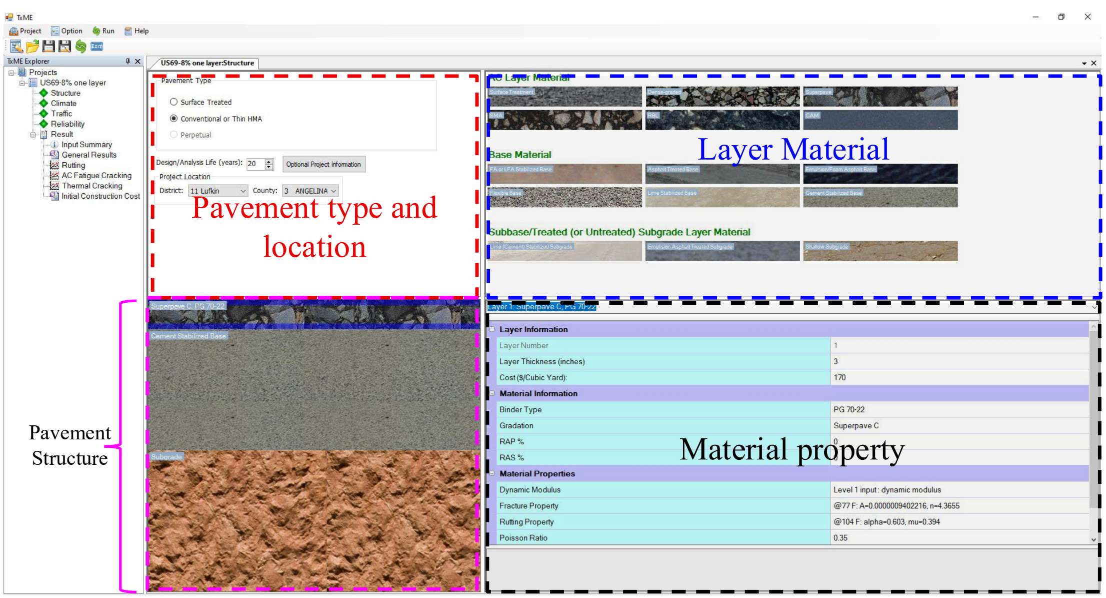


Figure 73. Pavement Structure Information Screen in TxME.

The TxME program was employed to evaluate the performance of FDR base layers incorporating cement, lime, and no additive. The asphalt concrete (AC) layer, flexible base materials, and section thickness were modeled based on actual field conditions corresponding to the projects participating in this research. In order to examine the effect of different additives within the FDR layer, assumptions were made regarding the default modulus values of the existing AC, flexible base, and subgrade layers. The pavement structure, material types, and assumed modulus values are summarized in Table 49. Although these assumptions do not fully replicate in-situ conditions, they were adopted to enable a clear visualization of the influence of additive type on the performance of the FDR layer.

As summarized in Table 49, the roadway sections considered included SL 338, FM 39, SH 18, and SH 128. AC surface layers ranged from 1.5 to 3 inches in thickness, with binder grades varying between PG 64-22, PG 70-22, and PG 76-22 depending on the section. For base layers, SL 338 and FM 39 employed foamed asphalt-treated bases, whereas SH 18 and SH 128 were stabilized with emulsion, in some cases overlying additional flexible base layers (up to 6 inches thick). Subgrade stiffness also varied across the sections, with assumed moduli of 8 to 20 ksi, reflecting differences in underlying support conditions applicable to the specific site locations. These variations provided a representative set of structural configurations for evaluating the impact of additive type in the FDR layer.

Table 49. Pavement Layer Property Input.

Material	Roadway	SL 338	FM 39	SH 18	SH 128
Asphalt Concrete	1st Material	SMAR-F	SP-C	SMAR-F	SMAR-F
	Binder Grade	PG 76-22	PG 64-22	PG 76-22	PG 76-22
	1st Thickness (inch)	1.5	3	2	2
	2nd Material	—	—	SP-B	SP-B
	Binder Grade	—	—	PG 70-22	PG 70-22
	2nd Thickness (inch)	—	—	4	4
Base	Treated Base Material	Foam	Foam	Emulsion	Emulsion
	Treated Base Thickness (inch)	8	8	7	8
	Flex Base Material	—	—	Flexible	Flexible
	Flex Base Thickness (inch)	—	—	6	1.5
Subgrade	Modulus (ksi)	20	8	20	16

Figure 74 displays the pavement structure modeled for SL 338. The section was represented in TxME as a single asphalt surface layer (SMA-D), an emulsion/foam asphalt-treated base, and a subgrade. The total thickness of the asphalt layer was taken from project plans, while the stabilized base was modeled as the primary structural layer beneath the surface. This configuration was used to evaluate the performance of the FDR base with different additive conditions under the representative roadway environment.

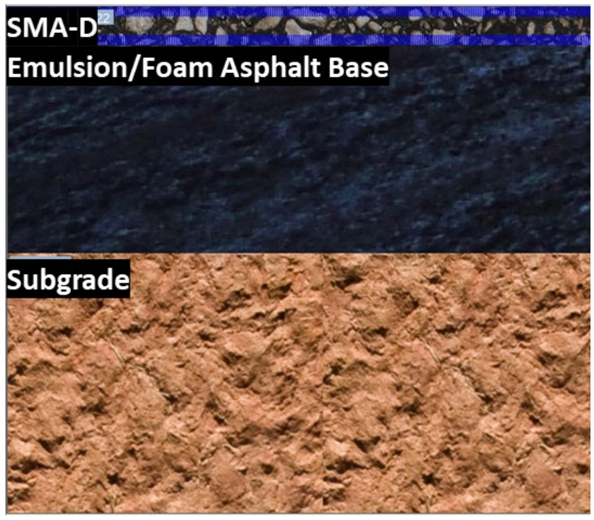


Figure 74. Example of Pavement Structures on SL 338.

6.2.1.2. Material Properties

The TxME analysis requires the input of material properties, specifically fracture properties and rutting properties, to accurately predict the pavement's performance in terms of cracking and rutting.

6.2.1.2.1 Input Properties of AC Layers

Table 50 presents the mechanistic properties assigned to the AC layers used in the TxME analyses. For each mixture type, fracture and rutting parameters were defined through the coefficients A, n, α, and μ, which characterize the material's cracking resistance and PD behavior. In this study, these parameter values were not derived from laboratory testing but instead assigned as default values based on the binder type and grade information available in the plan map, consistent with standard TxME input practices.

Table 50. Input Properties of AC Layers.

Roadway	Fracture Property		Rutting Property		Poisson Ratio	Thermal Coefficient of Expansion (1e-6 in/in/F)
	A	n	α	μ		
SMAR-F (PG76-22)	6.0576E-8	5.1166	0.7106	0.8004	0.35	13.5
SP-C (PG64-22)	6.0544E-6	3.8541	0.7168	0.6459	0.35	13.5
SP-B (PG70-22)	6.4359E-6	3.8374	0.7326	0.6314	0.35	13.5

6.2.1.2.2 Input Properties of FDR/Base Layers

Table 51 summarizes the modulus, rutting parameter (α), and PD coefficient (μ) at 28-day dry curing for FDR base layers evaluated on four roadway sections (SL 338, FM 39, SH 18, and SH 128) as part of Task 4. Each section was assessed under three additive conditions: C1, C0, and L1. The values presented in Table 51 were subsequently used as input for the TxME analysis. Overall, the resilient modulus values ranged from approximately 320 ksi to nearly 500 ksi, with FM 39 showing the highest stiffness under the no additive condition (498 ksi). Rutting parameter (a) values indicated notable variation among additive types, with cement-stabilized mixtures (C1) generally producing lower (a) values, suggesting improved resistance to PD. The PD coefficient (μ) followed a similar trend, where lime- and cement-treated sections often exhibited lower values compared to untreated mixtures.

Table 51. Rutting Property Inputs for Dry Condition.

Roadway	SL 338			FM 39			SH 18			SH 128		
	C1	**C0**	**L1**	**C1**	**C0**	**L1**	**C1**	**C0**	**L1**	**C1**	**C0**	**L1**
Modulus (ksi)	366	414	320	354	498	471	365	406	384	331	410	420
Rutting (a)	0.446	0.397	0.692	0.916	0.881	0.792	0.835	0.872	0.79	0.721	0.766	0.703
μ	0.013	0.045	0.04	0.311	0.225	0.183	0.118	0.092	0.109	0.07	0.15	0.109

Table 52 summarizes the rutting property inputs under wet conditions for FDR base layers. The resilient modulus showed wide variability, ranging from as low as 5 ksi (exceeded strain limit) for the no additive mixture on FM 39 to as high as 241 ksi for the lime-stabilized mixture on SH 128. Overall, mixtures stabilized with cement or lime exhibited significantly higher stiffness compared to no additive mixtures. This trend was particularly pronounced for FM 39 and SH 18, where the no additive condition resulted in substantially reduced modulus values. For all cases, the rutting parameter (a) and the PD coefficient (μ) were not directly measured and were assigned default values of 0.8706 and 0.0981, respectively.

Table 52. Rutting Property Inputs for Wet Condition.

Roadway	SL 338			FM 39			SH 18			SH 128		
	C1	**C0**	**L1**	**C1**	**C0**	**L1**	**C1**	**C0**	**L1**	**C1**	**C0**	**L1**
Modulus (ksi)	225	23	203	151	5*	92	128	25	119	181	79	241
Rutting (a)	0.8706											
μ	0.0981											

* Exceeded strain limit.

6.2.1.3. Climate

Environmental conditions are a critical factor in pavement performance because they govern the seasonal fluctuations of temperature and moisture that directly affect the load-carrying capacity of unbound materials. In TxME, climate information can be introduced either by selecting a representative weather station or through interpolation based on geographic coordinates. Table 53 provides the climate input data applied in this analysis, including mean annual temperature and precipitation, number of wet days, freeze-thaw characteristics, and representative monthly temperature values. These data were incorporated into the Enhanced Integrated Climatic Model within TxME to simulate the temperature and moisture profiles of the pavement structure and subgrade.

Table 53. Climate Input Data.

ID	SL 338	FM 39	SH 18	SH 128
Mean annual temperature (°F)	65.1	68.2	65.1	65.1
Mean annual precipitation (inch)	11.0	62.2	11.0	11.0
Number of wet days	85.2	143.1	85.2	85.2
Freezing index (°F-days)	185.3	49.8	185.3	185.3
Average annual number of freeze/thaw cycles	33.7	12.6	33.7	33.7
January (°F)	46.8	52.3	46.8	46.8
February (°F)	49.6	54.5	49.6	49.6
March (°F)	56.1	60.4	56.1	56.1
April (°F)	67.0	68.1	67.0	67.0
May (°F)	75.7	75.8	75.7	75.7
June (°F)	81.0	81.0	81.0	81.0
July (°F)	83.6	83.5	83.6	83.6
August (°F)	82.8	83.5	82.8	82.8
September (°F)	76.2	79.2	76.2	76.2
October (°F)	64.8	69.9	64.8	64.8
November (°F)	53.0	59.7	53.0	53.0
December (°F)	44.8	50.9	44.8	44.8

6.2.1.4. Traffic Inputs

In TxME, traffic inputs are classified into two levels: Level 1 requires load spectra input, while Level 2 uses ESAL input. For this analysis, the researchers adopted the Level 2 input approach. The traffic data were obtained from the Texas Statewide Planning Map, which provided estimates of average daily traffic (ADT), truck percentages, and projected ESALs over a 20-year period. By incorporating this traffic information into TxME, the long-term effects of traffic loading on pavement performance could be simulated and evaluated.

Table 54 summarizes the traffic input used to calculate the 20-year ESAL values for each roadway section considered in this analysis. Beginning ADT values ranged from 4,044 (SH 128) to 19,400 (SL 338), with ending ADT values increasing to between 5,662 and 30,500 over the 20-year horizon. Truck percentages varied widely across the roadways, from as low as 9 percent on SL 338 to as high as 42.3 percent on SH 128. Correspondingly, the 20-year cumulative ESALs ranged from 3.1M (FM 39) to 13.6M (SH 18), reflecting both traffic volumes and truck proportions.

Table 54. Traffic Inputs—ESAL Values Based on the Growth Rate.

Traffic Inputs	SL 338	FM 39	SH 18	SH 128
ADT Begin	19400	4400	8200	4044
ADT End	30500	5230	15000	5662
% of Truck	9	10.6	27.8	42.3
20-YR ESALs (Millions)	10.7	3.1	13.6	9.9

6.2.2. Impact of Cement Additive on Long-Term Pavement Performance

Based on the properties of the FDR layer (with and without additive) at the final curing stage, researchers determined the impact of including or excluding the additive on the expected long-term pavement performance under the traffic levels and design life. Using TxME's predictive capabilities, the analyses were conducted at a 95 percent reliability level. This approach enabled researchers to assess the expected long-term pavement performance of scenarios incorporating FDR base with or without additives.

Figure 75 illustrates the predicted total rut depth of the asphalt pavements at four projects. In all cases, the simulated rutting performance remained well below the TxME analysis limit of 0.5 inches throughout the 20-year design period. The overall trends show that the rut depth increases most rapidly in the early service years and then stabilizes with time. Among the sites, FM 39 exhibited the highest accumulation of rutting, reaching approximately 0.3–0.35 inches by the end of the analysis period. In contrast, the other three locations (SL 338, SH 18, and SH 128) showed relatively low rut depths, generally not exceeding 0.2 inches. The differences among cement, lime, and no additive conditions were negligible when the FDR base layer properties are input using values from the 28-day dry conditions, with predicted pavement performance curves overlapping almost completely for each site regardless of additive treatment.

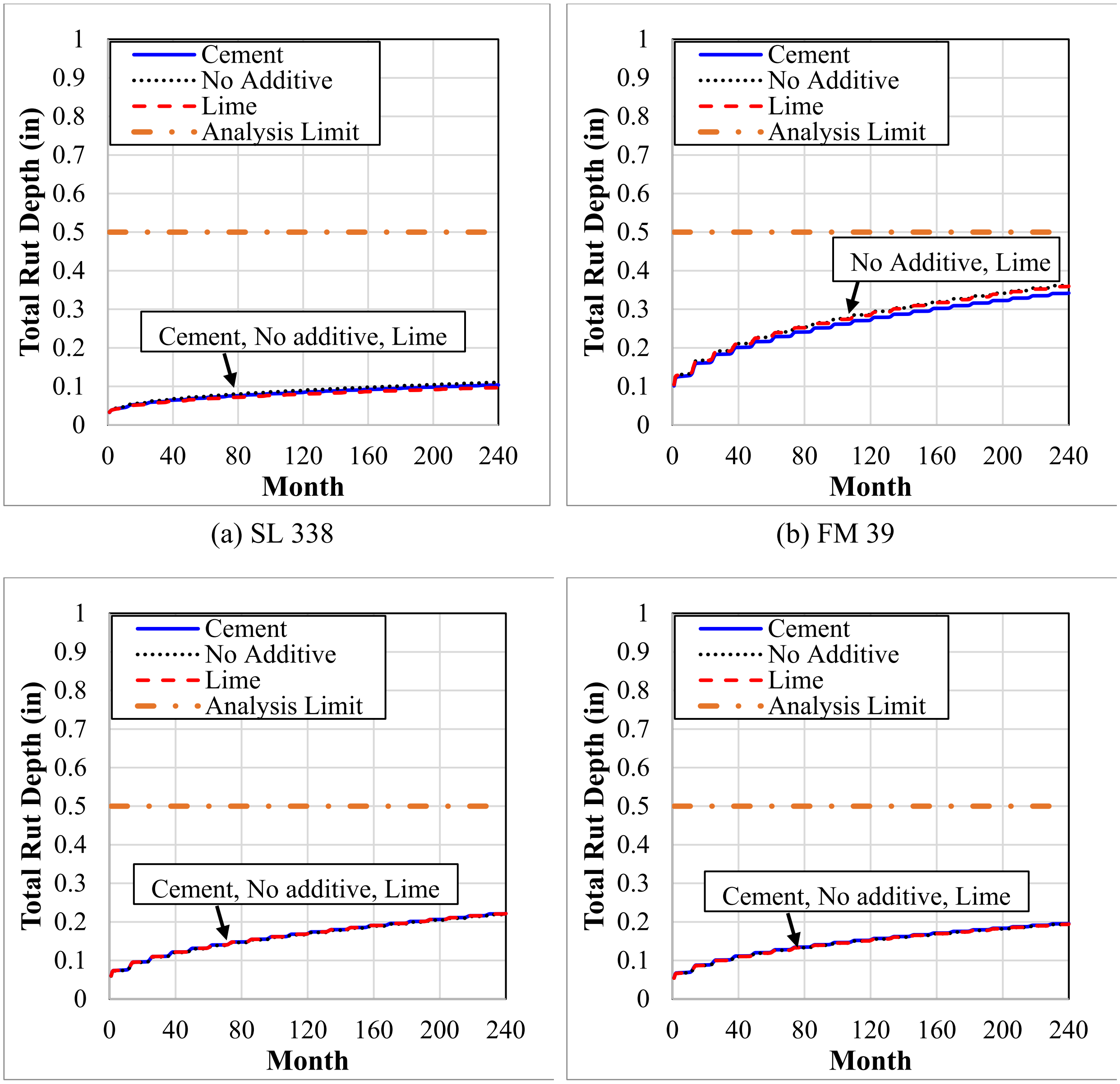


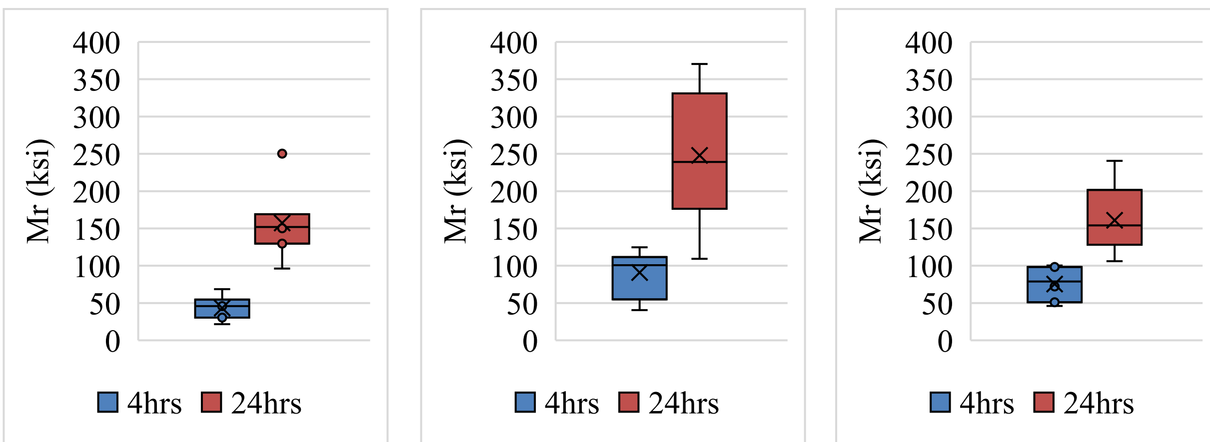
Figure 75. Total Rut Depth Results on TxME Analysis—28 Days Dry Condition.

6.2.3. Traffic Capacity of FDR Layers and Influence of Early Traffic Opening

Field experience has shown that when traffic is opened immediately after construction, rutting may occur. This has motivated research on determining what level of traffic the FDR layer (with or without additive) can withstand based on the expected rate of gain in strength and stiffness, and on analyzing how the timing of opening to traffic impacts pavement performance.

This section aims to determine the level of traffic that the FDR layer, with or without cement additive, can sustain based on the rate of strength and stiffness development, and to assess how the timing of traffic opening affects pavement performance during the early and intermediate curing stages. To support this evaluation, researchers used the IDT and Mr tests from curing times of 4 hours and 24 hours presented in Chapter 4, which showed that both IDT and Mr were highly sensitive to moisture content, with strength and stiffness increasing as moisture levels decreased.

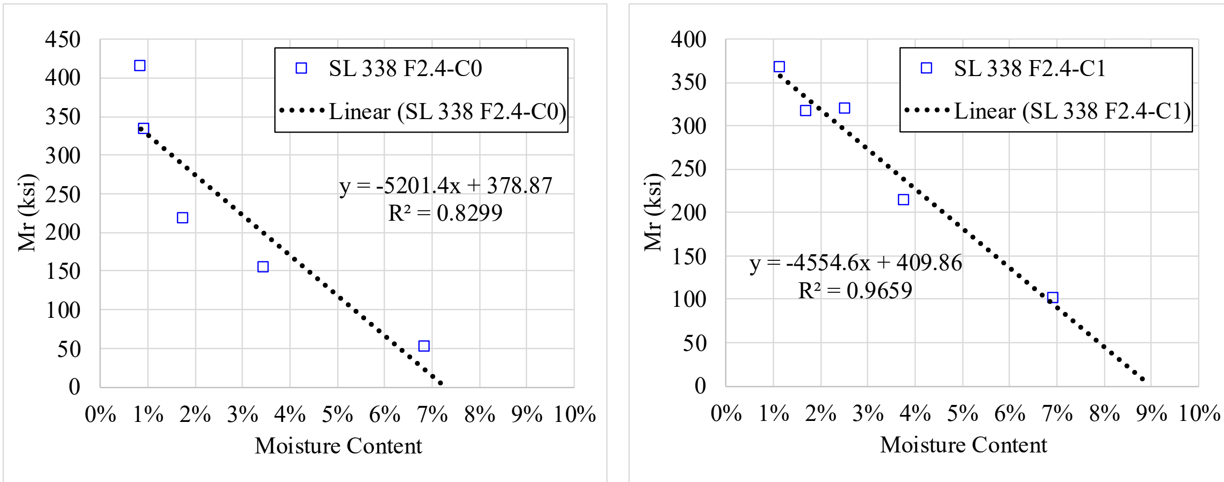
As shown in Figure 76, the 4- and 24-hour Mr values remained relatively low across all mixtures, reflecting the high moisture conditions immediately after compaction. For the no additive mixture (Figure 76[a]), average Mr values after 4 hours were around 50 ksi, showing limited stiffness development at this early stage. The cement additive mixture (Figure 76[b]) exhibited slightly higher Mr values at 4 hours, averaging around 100 ksi, suggesting an initial contribution from cement hydration even at this short curing time. The lime-additive mixture (Figure 76[c]) showed Mr values in the range of 70–100 ksi at 4 hours, comparable to or slightly higher than the no additive case.



(a) No additive (b) Cement (c) Lime

Figure 76. Mr Result Early Curing Stage.

Assuming traffic is opened 4 hours after completing FDR construction, the TxME analysis using the worst-case modulus input of 21 ksi (no additive) for the SL 338 mixture indicates an average laboratory-measured moisture content of 6.88 percent after 4 hours of curing. Based on this moisture condition, the interpreted FDR resilient modulus of approximately 21 ksi, as shown in Figure 77(a), suggests that severe rutting is unlikely to occur in the very short term, as illustrated in Figure 78. For comparison, the SL 338 mixture with additive exhibited an average laboratory-measured moisture content of 7 percent after 4 hours of curing, and based on this moisture condition, the interpreted FDR resilient modulus, as shown in Figure 77(b), was approximately 91 ksi.



(a) Without additive (b) With additive

Figure 77. Moisture Content versus Resilient Modulus (MC–Mr) Relationship on SL 338.

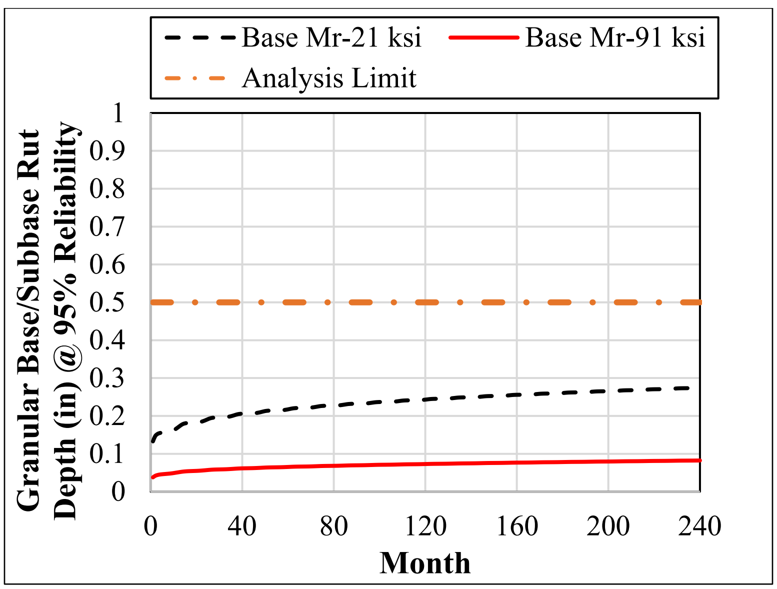
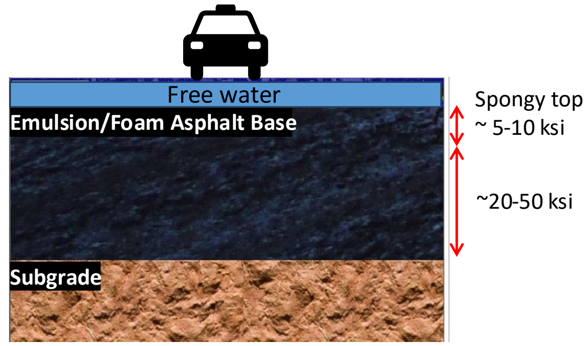


Figure 78. TxME Analyses with Early Curing Stage Inputs.

Researchers suggest that observed rutting in the field may not be primarily attributable to the initial traffic opening time or traffic volume (since analyses using the 4-hour data did not predict severe failures), but rather to excess moisture generated during compaction. As illustrated in Figure 79(a), materials with higher OMC often exhibit free water on the surface of laboratory-prepared specimens. If this pavement surface is assumed to extend infinitely, then, as shown in Figure 79(b), water would remain on the pavement surface and the moisture content in the upper portion of the base layer would exceed the OMC.

(a) Free water on the surface of laboratory-prepared specimens



(b) Free water on the surface of field (OMC for SL 338-7.5%)

Figure 79. Potential Problem from Free Water on the Surface.

In TxME, the total analysis period is fixed at 240 months (20 years), with the smallest reporting interval limited to one month. This constraint prevents direct evaluation of the very early curing conditions that are of particular interest in this study, such as 4 hours and 24 hours after construction. To address this limitation, the researchers first extracted the traffic volume corresponding to a single month from TxME and then proportionally adjusted these values to represent a shorter analysis period. The resulting modified traffic inputs were subsequently used to assess pavement behavior during the critical early stages of the first month, as summarized in Table 55. Furthermore, because TxME incorporates seasonal variations in temperature that can influence material performance, the temperature dataset was normalized to a constant reference value of 77°F. This adjustment ensured that the short-term behavioral analyses reflected only the effects of traffic and curing, without confounding seasonal temperature effects. In addition, to evaluate how different traffic levels influence early-age performance, analyses were conducted not only for the typical 10 million ESALs case (representative of the SL 338 site) but also across a broader range from 1 to 20 million ESALs.

Table 55. Adjusted Analysis Traffic ESALs Input.

Input Traffic ESALs for 20 YR (millions)	Cumulative Traffic ESALs for One Month	Adjusted Analysis ESALs Input for 20 YR (millions)
1	3,359	0.0034
5	16,794	0.017
10*	33,589	0.034
20	67,178	0.068

Note — 10M represents the typical traffic level for the actual site (SL 338).

From Task 4, the moisture content versus resilient modulus (MC–Mr) relationship (Figure 77[b]) was used to estimate the Mr value when specimens were subjected to water immersion. At a moisture content of 8.9 percent, the calculated Mr was around 4.5 ksi.

For comparison, two analysis scenarios were considered:

- Composite section consisting of 2 inches of 4.5 ksi material, representing the condition at 4 hours with moisture above OMC, over 6 inches of 21 ksi material, representing the worst case without cement at 4 hours.
- Uniform section consisting of 8 inches of 21 ksi base material.

Figure 80 presents the results of these analyses.

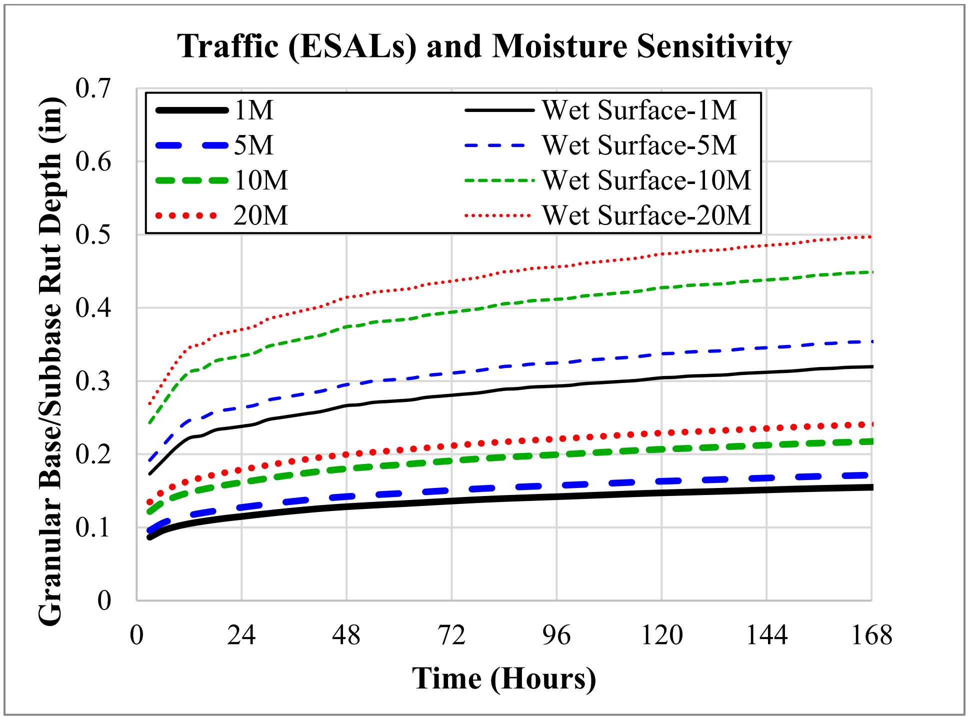


Figure 80. Effect of Traffic Levels and Surface Moisture on Predicted Rut Depths in Granular Base/Subbase.

As shown in Figure 80, the TxME-predicted rutting response clearly differentiates between the dry condition—represented by a single FDR layer with a 21 ksi modulus—and the wet-surface condition, modeled as a two-layer system with a weakened upper layer (4.5 ksi) over a dry lower layer (21 ksi), across various traffic levels. For the dry cases (solid lines), rut depths remained moderate, increasing gradually with higher ESALs (approximately 0.17 to 0.24 inches after 168 hours [7 days]). These values suggest that under controlled moisture conditions, even relatively high traffic levels can be accommodated without significant rutting in the short term.

In contrast, when excessive moisture is present, as modeled in Figure 80 by the dashed lines, rut depths increase dramatically. After one week, these cases produced rut depths of about 0.32 to 0.5 inches, roughly double the values observed under dry conditions. This trend underscores the significant sensitivity of early-age performance to excess moisture. The mechanism is consistent with field observations: water expelled during compaction tends to migrate upward, creating a moisture-rich zone at the surface that weakens the upper portion of the base layer, thereby accelerating rutting under traffic loads. Problems in the field have also been documented when materials are worked and compacted wet of optimum or when excessive water has been applied through sprinkling during finishing operations.

These results demonstrate that while early traffic opening may be structurally acceptable when based solely on laboratory modulus measurements, the presence of excess moisture can substantially reduce effective stiffness and lead to premature rutting. Accordingly, traffic should only be permitted once the surface has dried sufficiently to mitigate this moisture-induced performance risk.

6.2.4. Timing of Heavy Load Acceptability on FDR Layers

The data in Chapter 4 showed that FDR layers gradually gain stiffness as moisture dissipates after compaction, making the presence and removal of moisture a critical factor in early performance. In practice, FDR mixtures are usually adjusted to an appropriate moisture content prior to compaction; however, water generated and redistributed during the compaction process can delay strength development. Laboratory data show that this water often migrates toward the surface and escapes, which explains why specimens tested after 4 hours sometimes exhibit no rutting despite their early age. Not all FDR projects show this moisture migration at 4 hours, but when it occurs in the field, unlike in the laboratory, the water may remain trapped near the material surface, significantly reducing the observed strength. Consequently, field engineers should not rely solely on a predetermined traffic opening schedule but should instead monitor the actual moisture condition of the FDR layer and permit traffic only after sufficient drying has taken place to ensure structural integrity. According to the TxME analysis shown in Figure 80, if strength reduction due to excess surface moisture does not occur, traffic opening as early as 4 hours after construction would be structurally acceptable.

6.2.5. Effect of Moisture Damage on Short and Long-Term Performance

Figure 81 presents the TxME-predicted rutting response of the granular base/subbase layer under a 10M 20-yr ESAL traffic level during the initial 10-day period. Four cases were modeled to represent two moisture conditions. The gray-shaded region corresponds to the dry condition, assuming higher stiffness values (50 to 100 ksi), whereas the red-dotted region represents the wet condition with substantially reduced stiffness (4.5 to 21 ksi) due to moisture.

Under the ideal condition, rutting developed gradually, beginning near 0.05 inches and stabilizing at approximately 0.12 inches by the end of the analysis period (10 days), indicating sufficient stiffness and structural stability during early trafficking. In contrast, under the worst-case condition, the presence of excess moisture accelerated PD, producing rut depths nearly twice those of the ideal case. This behavior further illustrates the detrimental impact of excessive moisture and its impact on the effective modulus of the FDR layer in early traffic situations.

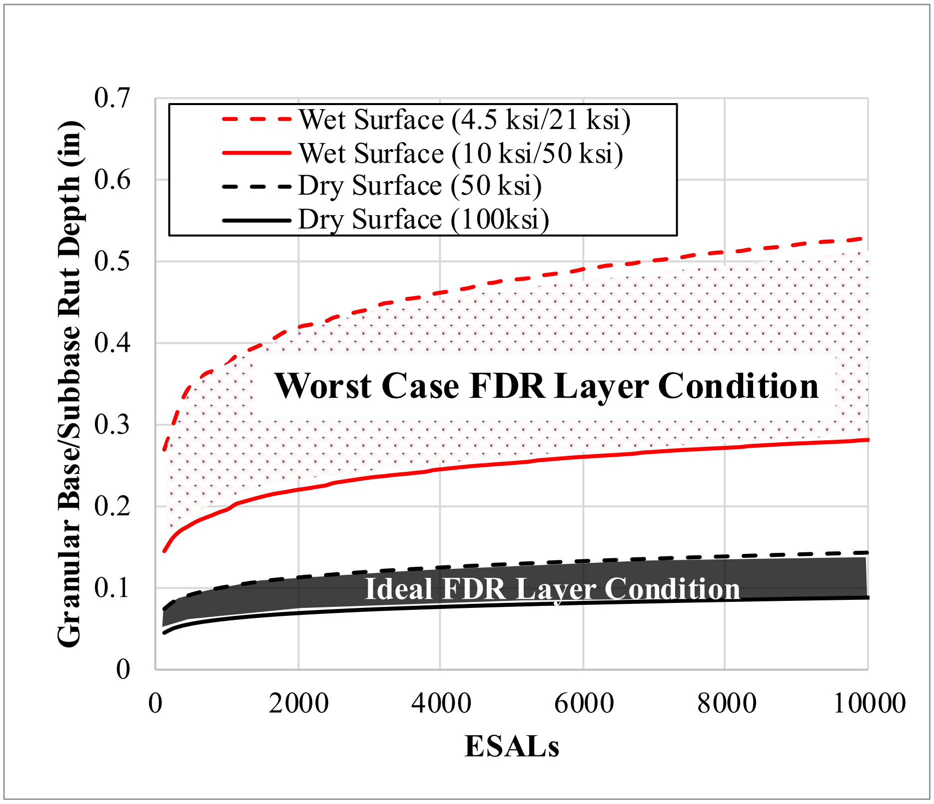
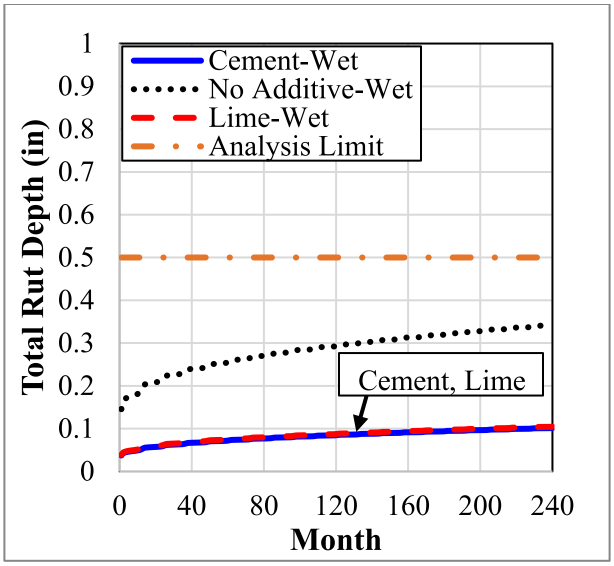
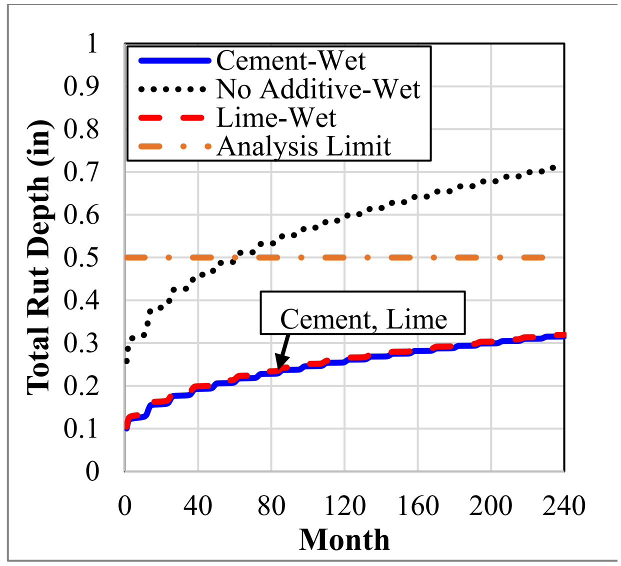


Figure 81. Short-Term TxME-Predicted Rut Depths.

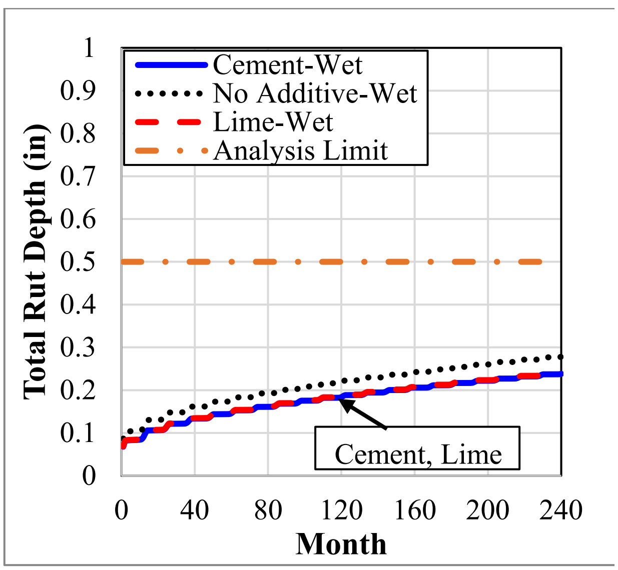
From a long-term pavement performance perspective to evaluate the resilience of FDR layers in the presence of moisture, Figure 82 illustrates the predicted total rut depth of asphalt pavements at four project sites under wet conditions, where the FDR layer modulus values used in the modeling were derived in lab from material fully cured then soaked in water for 24 hours. Under dry conditions as shown in Figure 75, rutting was minimal at all locations, with little distinction among bases treated with cement, lime, or left untreated. In contrast, the wet condition analyses illustrated in Figure 82 showed pronounced rut accumulation in some scenarios, in some cases approaching or exceeding the TxME analysis limit. The effects of cement and lime additive were clearly demonstrated, since both additives significantly suppressed rut progression and kept performance within acceptable bounds. These findings highlight that although additive benefits may appear negligible under dry conditions, they are critical in reducing rutting risk when pavements are exposed to moisture.



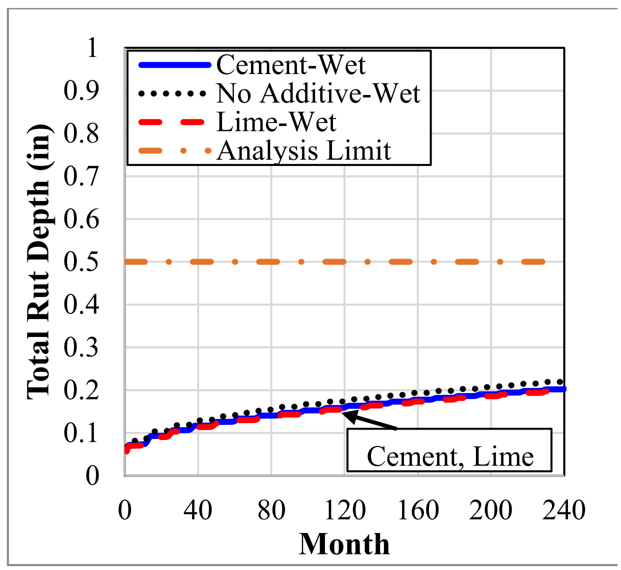
(a) SL 338



(b) FM 39



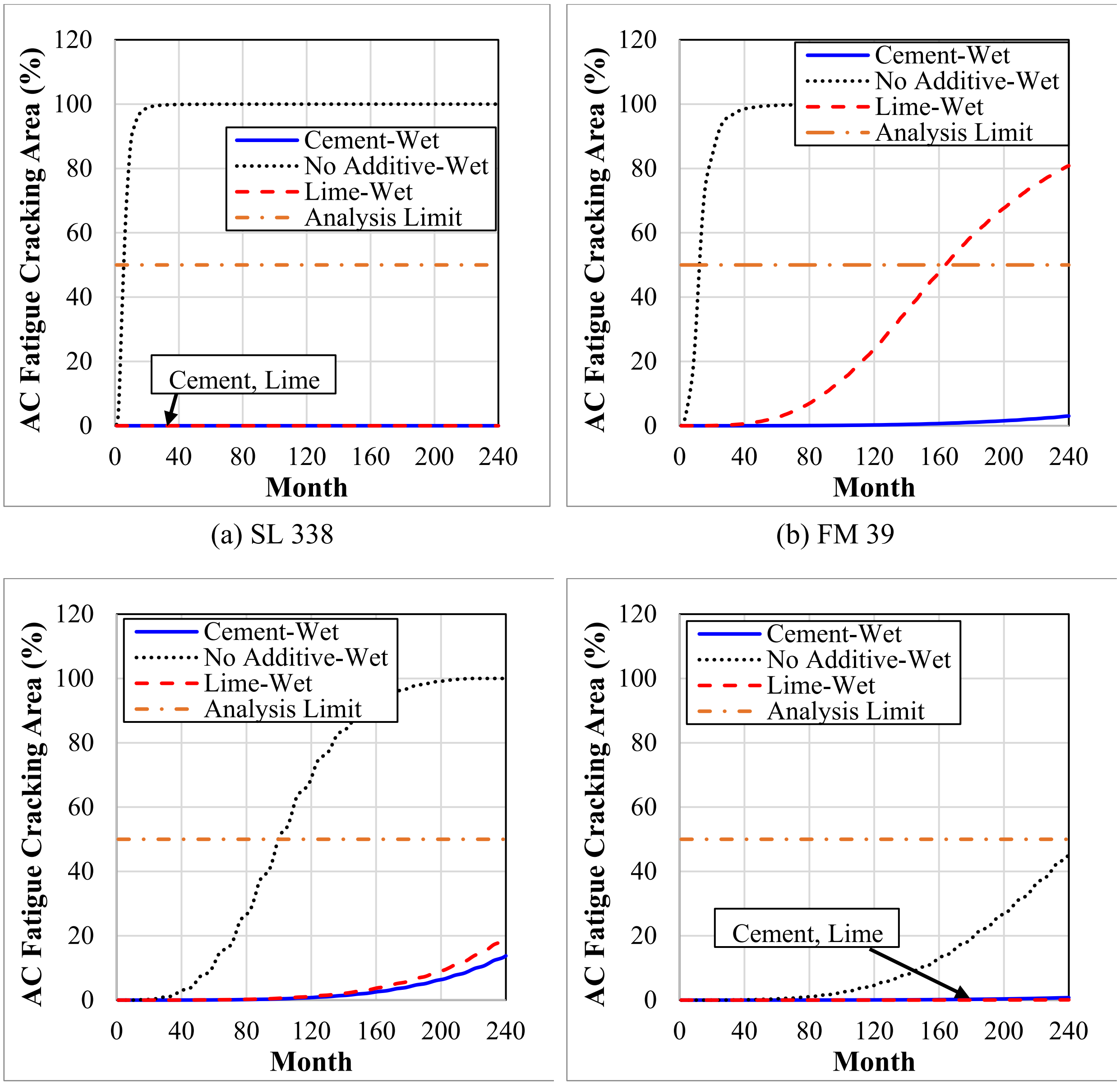
(c) SH 18



(d) SH 128

Figure 82. Total Rut Depth Results on TxME Analysis—Wet.

Figure 83 presents the predicted AC fatigue cracking area with FDR layer modulus assumed under wet conditions. The results demonstrate a pronounced effect of moisture on fatigue performance compared with the dry condition, where no cracking was observed across any site or additive type. Under wet conditions, the no additive case exhibited more rapid and severe deterioration across all project scenarios, with SL 338 and FM 39 reaching nearly 100 percent fatigue cracking within the first 60 months, and SH 18 also surpassing the TxME analysis limit of 50 percent before the end of the analysis period. These findings indicate that FDR bases without additives, which are generally more susceptible to moisture damage, will result in premature fatigue failure if exposed to significant moisture. However, the case of SH 128 shows that under certain material and environmental conditions, traffic levels, and pavement cross-section, FDR bases without additive that receive significant moisture exposure may still maintain acceptable performance over the 20-year design life.



(a) SL 338

(b) FM 39

(c) SH 18

(d) SH 128

Figure 83. AC Fatigue Cracking Area on TxME Analysis—Wet.

6.2.6. Conclusions from Structural Analysis

The structural analysis using lab-derived mechanistic-empirical properties, actual pavement cross sections and traffic levels from the four projects participating in this research, and a focus on short- and long-term expected pavement performance, reveals the following conclusions:

- Additives are most critical in FDR mix performance under wet conditions. At 28-day dry curing, performance differences among cement, lime, and no additive mixtures are minor. Under wet conditions, no additive FDR material experiences significant reduction in resilience and thus shows vulnerability to rutting and AC fatigue. Mixes with cement and lime additive provide more resilience in the presence of moisture, limiting rut progression and nearly eliminating fatigue cracking.
- Moisture is the dominant factor in early traffic performance. Excess water in the FDR material after compaction significantly lowers effective Mr and accelerates early rutting. Under dry or near-optimal moisture conditions, rutting remains substantially lower for the same traffic levels, regardless of presence or lack of additive.
- Traffic opening should be governed by moisture, not time. If surface water is present, the risk of rapid rutting is high. The moisture control requirements in the current specs need to be enforced to minimize risk of damage under same-day traffic.
- In early traffic pavement performance modeling, rut depth increased steadily with increasing ESALs. However, moisture has an even larger impact than traffic level on early performance. Rut depth growth rates under wet conditions were nearly double those of dry conditions.
- Consideration should be given to developing and incorporating an early traffic performance module into the TxME. The structural analysis presented required rescaling traffic to shorter durations to capture early behavior and focus on the desired inference space.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the results and findings from literature, material collection, laboratory testing, temperature evaluation, and economic and structural analyses. Together, these results provide a comprehensive understanding of FDR performance with and without additives, the role of curing and environmental conditions, and the economic trade-offs relevant to TxDOT projects.

7.1. LITERATURE REVIEW

The findings from the literature review included:

- Cement and lime additives in FDR mixes improve strength, stiffness, and moisture resistance but reduce flexibility when overused.
- FA shows higher dry stiffness; EA is more reliable at providing higher strengths in wet conditions.
- Most strength and modulus gains occur within the first 2–4 weeks, although strength and modulus gain can continue for months. The long-term durability depends on treatment type and additive.

7.2. SELECT AND COLLECT MATERIALS

The material collection resulted in the following findings:

- Materials collected from five different projects captured both new and reclaimed bases and should reasonably represent a cross-section of materials.
- The dataset reflects a wide range of Texas FDR conditions, ensuring representative laboratory evaluation.

7.3. COMPREHENSIVE LAB PROGRAM

The researchers found the following from the results of the laboratory testing:

- Strength gain in all FDR mixtures was strongly governed by moisture removal during curing. Most mixes reached approximately 2 percent or less moisture after 72 hours under the tested curing conditions.
- Cement additive produced the highest and most consistent strength across all conditions, while lime showed potential as a replacement for cement additive but was not as reliable at producing mixes that met wet strength criteria.
- Mixes without additive generally met minimum dry strength requirements but were slower to develop strength and frequently failed to meet wet strength criteria.
- Non-additive mixtures may require an additional 3–4 hours of curing before traffic opening compared to mixes with additives.
- FA generally performed better under dry conditions, while EA exhibited more resilience under wet conditions, reflecting binder-specific moisture sensitivity characteristics.

- Mixtures with additives showed higher early-age (≤ 24 hr) resilient modulus values. With extended curing, the modulus of non-additive mixes approached those of the mixes with additive.
- Moisture conditioning has a more detrimental impact on non-additive mixtures.
- After long-term curing, all mixtures exhibited rutting parameters comparable to TxME default base material values. Additive-treated mixtures reached these values more rapidly than untreated ones.
- Strong correlations among IDT, UCS, and Mr were observed, supporting simplified approaches for predicting mixture performance based on key strength indicators.

7.4. TEMPERATURE INFLUENCE ON FDR

From the temperature evaluation, the researchers concluded:

- Temperature mainly affects the rate of early strength gain, particularly before 3 days.
- Warmer curing temperatures accelerated drying and strength; cooler curing temperatures delayed early gains.
- Moisture evaporation, governed by both temperature and humidity, was the key driver of strength development.

7.5. ECONOMIC AND STRUCTURAL ANALYSIS RESULTS

The economic and structural analyses resulted in the following:

- EA without additive offers up to approximately 25 percent higher daily production, which can shorten construction duration and accelerate project delivery.
- Eliminating additives reduced material costs by roughly 6–10 percent, representing a substantial direct cost saving. Conversely, substituting lime for cement increased total mixture cost by approximately 3 percent.
- On high-traffic roadways, user-delay costs were identified as a dominant component of total project expense. The faster production achievable with EA without additive yielded up to 25 percent reduction in user-delay costs.
- Non-additive mixtures generally performed adequately after full curing but carried higher risks under wet or early-strength-sensitive conditions.
- Pavement performance modeling using early-age properties indicated a potential for unacceptable rutting if traffic was applied before sufficient moisture removal.
- The primary driver of early damage appears to be excess moisture rather than inherent material weakness, emphasizing the importance of proper moisture control during construction and finishing operations, and proof-rolling prior to traffic opening.
- After long-term curing, all mixtures exhibited rutting parameters similar to TxME default base material values. Additive-treated mixes reached these stabilized performance levels more rapidly, while untreated mixes required additional time to achieve equivalent stiffness and resistance to PD.
- From a purely cost perspective, EA with no additive remains the most cost-effective and schedule-efficient option when moisture is well managed, while FA with no additive provides greater material savings but is more suitable for low-AADT corridors. Selective

use of non-additive options could balance cost and schedule benefits with acceptable performance risks.

7.6. RECOMMENDED TEST PROCEDURE AND SPECIFICATION UPDATES

Based on the findings from this study, the following recommendations are proposed to guide future design and use of asphalt-based FDR mixtures:

- Conduct asphalt-based FDR mix designs both with and without additives to assess the potential for reducing cost and construction time while maintaining performance. If cement sourcing becomes problematic, consider testing a 1:1 replacement of cement with lime, applied as either a hydrated or slurry form.
- Avoid incorporating any treatment—whether additive or non-additive—when the base material is excessively wet. This practice is critical for ensuring stability and becomes even more influential in non-additive mixtures.
- Utilize CA4PRS to quantify schedule, cost, and user-delay impacts associated with additive selection and curing requirements. When removing additives, recognize that this approach involves key trade-offs: the wet strength requirement may need to be waived, and mixtures may require an additional 3–4 hours of curing prior to opening to traffic.
- Reassess the design modulus values used in Flexible Pavement Design System (FPS) and TxME analyses. Current FPS defaults are based on in-service pavements constructed with additives. Although lab data suggest that, with adequate curing, the final values should be similar with additive and non-additive mixes, field data are needed to confirm those values.
- Incorporate or develop an early traffic performance module within TxME to better represent early-traffic scenarios. This enhancement would allow evaluation of short-term performance impacts when FDR layers are opened before full curing.

7.7. RECOMMENDED FUTURE WORK

Future research should further evaluate the selective use of non-additive FDR mixtures under control and low-risk conditions. While additive-treated mixtures generally offer more reliable early strength and moisture resistance, the results from this study indicate that non-additive options may still be viable on a case-by-case basis, particularly where project-specific or logistical constraints exist.

Recommended areas of focus include:

- Application in low-risk environments, such as low-AADT routes or areas where risk of exposure to moisture is low.
- Assessment of logistical and supply challenges, including cases where additive delivery, blending, or scheduling limitations restrict construction continuity.
- Evaluation by regional crews to verify field constructability and performance consistency under varying local practices and climatic conditions.
- Exploration of non-additive treatment for marginal base materials to determine whether improvements in gradation control, compaction, or curing management can yield acceptable performance without the need for inclusion of chemical additives.

CHAPTER 8. VALUE OF RESEARCH

Table 56 presents value areas and a description of these value areas in context to the project.

Table 56. Benefit Areas of Research.

Value Area	Description
Level of Knowledge	Advances understanding of FDR mixture behavior with and without additives, including curing, temperature sensitivity, and long-term performance.
Management and Policy	Informs TxDOT specifications and decision-making by identifying when cement or lime is necessary versus when non-additive designs may be sufficient; supports cost-effective, performance-based design policies.
Quality of Life	Reduces construction duration and traffic disruptions, minimizing driver delays and improving safety during rehabilitation projects.
Customer Satisfaction and Environmental Sustainability	Encourages sustainable practices through recycling in-place materials, reducing cement demand, lowering emissions, and addressing potential supply shortages; enhances public satisfaction through faster, less disruptive construction.
Service Life, Traffic and Congestion Reduction, Reduced Maintenance Costs, Materials and Pavements, and Infrastructure Condition	Optimizes mix designs for durability and identifies conditions where additives extend service life while reducing maintenance and lifecycle costs.

Under a conservative assumption, it is estimated that approximately 10 percent of all emulsion projects could be constructed without any additive, corresponding to about a 12 percent probability of meeting the wet strength requirement observed in this study. Considering that the average annual budget of construction rehabilitation projects using ET FDR layers, including asphalt surface, was approximately $140M across calendar years 2022 and 2023, the average yearly non-additive projects can be estimated at $14M.

Based on the results from this research, performing FDR without additives yields an average material and construction cost reduction of 2.6 percent of the total project letting cost. Although user-delay costs vary by traffic volume and location, data from four representative sites in this research indicate that user delay is about 26 percent of total construction costs, and performing FDR without additive yields an average user-delay savings of about 20 percent. Accordingly, the user-delay component is estimated at around $3M. Thus, the potential annual user-delay savings for FDR projects without additive are approximately $0.71M, and material and construction savings are about $0.36M per year, resulting in total annual cost savings of $1.07M.

When a 7 percent discount rate is applied, the cumulative net present value of these combined material and user-delay savings over a 10-year analysis period is estimated to be approximately $6.5M.

CHAPTER 9. APPENDIX: INPUT VARIABLES USED FOR CA4PRS

The complete list of input variables used for CA4PRS simulations is summarized in Table 57.

Table 57. Input Variables Applied to CA4PRS Simulations.

Input Variables	SL 338	FM 39	SH 18	SH 128
Project Scope—Total Lane Miles (lane-mile)	30.4	15.2	23.4	28.4
Project Scope—Total Length (mi)	7.6	7.6	7.8	14.2
Project Scope—Lane Width (ft)	12	11	12	12
Project Scope—Number of Lanes	4	2	3	2
Project Scope—Shoulder Width (ft)	10	6	10	10
Section Profile—Depth of 1st HMA (inch)	1.5 SMAR-F	3 SP-C	2 SMAR-F	2 SMAR-F
Section Profile—Depth of 1st HMA (inch)	-	-	4 SP-B	4 SP-B
Section Profile—Total Width of FDR (ft)	26	42	56	48
Section Profile—Depth of FDR (inch)	8	8	7	8
Daily Mobilization Time	1 Hour			
Daily Demobilization Time	1 Hour			
Daily Construction Window	Same Day Opening on Weekdays			
Duration for One Construction Window (From 07:00 a.m. to 06:00 p.m.)	11 Hours—EA and FA with Additives 13 Hours—EA and FA without Additives			
Batch Plant Capacity (Ton/Hour)	440.9			
Number of Batch Plants	1			
Paver's Non-Paving Travel Speed	18.6 Miles per Hour			
HMA Delivery Truck Capacity	26.5 Ton			
Trucks per Hour for HMA Delivery	15			
Packing Efficiency for HMA Delivery Trucks	1			
FDR Production Rate	0.75 Lane-Miles per Day—EA with Additives, FA with and without Additives 0.94 Lane-Miles per Day—EA without Additives			
HMA Production Rate	0.9 Lane-Miles per Day			
HMA Cooling Time	2 Hours			
Shoulder Overlay	Pre-paved Shoulder			
Working Method	Half Closure/Partial Completion			
Type of Traffic Condition	Rural	Rural	Rural	Rural
Speed Limits-No Construction (Miles per Hour)	75	70	70	65
Speed Limits-Under Construction (Miles per Hour)	45			
Construction Year	2022	2022	2022	2023

Closure Length	See Table 9			
Per Closure Duration—with Additives	0.458 per Day (or 11 Hours per Day)			
Per Closure Duration—without Additives	0.542 per Day (or 13 Hours per Day)			
Number of Impacted Closures in Each Direction	Half of the Number of Construction Windows Needed			
Roadway Capacity Before Construction—Single Lane Open (Passenger Cars per Hour per Lane)	1739			
Roadway Capacity Before Construction—Multiple Lane Open (Passenger Cars per Hour per Lane)	2126			
Roadway Capacity During Construction—Single Lane Open (Passenger Cars per Hour per Lane)	1148			
Roadway Capacity During Construction—Multiple Lane Open (Passenger Cars per Hour per Lane)	1627			
Vehicle Cost—Passenger Car	$37.20 per Hour			
Vehicle Cost—Truck	$52.75 per Hour			
Percentage of Trucks on Road	9%	10.6%	27.8%	42.3%
Traffic Year	2020	2022	2022	2020
Growth Rate	2.28%	0.87%	2.02%	1.69%
Average Annual Daily Traffic	19400	4400	8200	4044
Percentage of No-Show-Up Vehicles	5%	5%	5%	5%
Percentage of Vehicles Taking Detour	20%	20%	20%	20%
Additional Travel Time for Vehicles Taking Detours	5 Minutes			

CHAPTER 10. REFERENCES

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