Accelerating the Mix Design for Cement-Treated Bases

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16. Abstract

Cement treatment of roadway or stockpile materials enhances the strength and stiffness properties of pavement base layers to meet structural requirements in a cost-effective and sustainable manner. Historically, cement stabilization mixture design criteria relied on compressive strength test results; depending on the treatment and test method, tests could take nearly a month to complete. In this project, researchers developed an accelerated design procedure for cement-treated base materials with a focus on rapid test turnaround times, lab curing techniques that quickly simulate cured field conditions, inclusion of moisture susceptibility in the mix design, and performance-related design criteria. The accelerated procedure uses 4-inch diameter, 2-inch tall specimens to measure the indirect tensile strength after an accelerated cure. This accelerated procedure produces strength results 4 days after molding specimens. The results from this accelerated procedure can also estimate the resilient modulus and modulus of rupture for use in pavement analysis and design checks.

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ACCELERATING THE MIX DESIGN FOR CEMENT-TREATED BASES

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DISCLAIMER

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This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Stephen Sebesta.

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

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
ATL	Atlanta
AVG	Average
BMT	Beaumont
BP	Backpressure
BRY	Bryan
BS	British standard
C	Percent cement
CTB	Cement-treated base
EB	Eastbound
EN	European standard
ESAL	Equivalent single axle load
FDR	Full depth recycling
FPS 21	Flexible Pavement Design System 21
FTW	Fort Worth
FWD	Falling weight deflectometer
GPR	Ground penetrating radar
HMA	Hot mix asphalt
IDT	Indirect tensile
MBV	Methylene blue value
MEPDG	Mechanistic-Empirical Pavement Design Guide
MoR	Modulus of rupture
Mr	Resilient modulus
N	Number of gyrations
ODA	Odessa
P200	Percent passing the #200 sieve
PCA	Portland Cement Association
PI	Plasticity index
RAP	Reclaimed asphalt pavement
SGC	Superpave gyratory compactor
TLT	Transportation laboratory testing
TST	Tube suction testing
TxDOT	Texas Department of Transportation
UCS	Unconfined compressive strength
WB	Westbound

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND OBJECTIVES

Treatment of base materials can improve how the base layer contributes to a pavement's performance. Treatment can increase the strength of the base layer to provide long-term support for the pavement structure, enable the pavement design to meet its design life with a reduced thickness, reduce the moisture susceptibility of materials, and/or allow for the upgrade of marginal local materials to provide satisfactory performance (Texas Department of Transportation, 2019). Base material treatments may include lime, cement, fly ash, emulsified asphalt, or foamed asphalt. In Texas, cement remains the most common treatment used for base materials. Pending Texas Department of Transportation (TxDOT) mix design procedures for emulsified or foamed asphalt treatments use the indirect tensile (IDT) strengths of 4-inch diameter, 2-inch tall specimens and produce strength results 4 days after molding. However, procedures for cement treatment currently only allow 6-inch diameter, 8-inch tall specimens and require at least 7 days from the time of molding for strength results.

This project aimed to streamline the mix design process for cement-treated base materials by developing a harmonized and accelerated procedure. Researchers primarily focused on enhancing test turnaround times, reducing the quantity of materials required, and incorporating moisture conditioning aspects. This research project's deliverables included recommended standardized test methodologies, relevant specification modifications, and developed outreach content. The primary goals of this project were to:

- Develop new test procedures.
- Modify specifications.
- Conduct workshops or training activities.
- Initiate demonstration projects with performance monitoring.

1.2. REPORT ORGANIZATION

This report is organized into the following seven chapters:

- Chapter 1 provides a brief overview of the project's background and objectives, along with an outline of the report's organization.
- Chapter 2 presents a synthesis of existing practices for mixture designs and research findings geared toward enhancing test turnaround times and incorporating the influence of moisture on mix design specimens for cement-treated materials.
- Chapter 3 summarizes coordination with TxDOT districts to identify and sample different materials for use in the lab testing program.
- Chapter 4 presents comprehensive lab evaluation methods and results for eight distinct materials under varying curing conditions and durations. The outcomes highlighted the basis for a rapid mix design procedure for cement-treated bases using IDT strengths and a potential association between the IDT strength and the modulus of rupture (MoR) and resilient modulus (Mr) of cement-treated bases.
- Chapter 5 includes demonstration project recommendations and findings.

- Chapter 6 describes how results from the rapid mix design procedure may be used to perform a cement-treated base mechanistic check.
- Chapter 7 presents conclusions and recommendations.
- Chapter 8 presents value of research from the project.

CHAPTER 2. LITERATURE REVIEW

This chapter synthesizes existing practices for mixture designs and research findings related to test turnaround times and moisture effects on the mix design of cement-treated bases.

2.1. NATIONAL PROCEDURES

The American Association of State Highway and Transportation Officials' AASHTO-T135 standard presents a procedure for preparing soil-cement specimens, including mixing, compacting, and curing methods (American Association of State Highway and Transportation Officials, 2017). Although specimens from this AASHTO standard procedure are intended for use in determining soil-cement losses, moisture changes, and volume changes, the curing process resembles the process outlined in the TxDOT Tex-120-E standard procedure (Texas Department of Transportation, 2022)—the compacted specimens cure in a moist room for 7 days without capillary wetting or a surcharge.

Similarly, ASTM International provides a standard test procedure (ASTM D1633) to determine the compressive strength of soil-cement molded cylindrical specimens. This standard recommends curing the compacted soil-cement specimen in the molds in a moist room for 7 days. At the end of the curing period, the specimens should be immersed in water for 4 hours before compressive strength testing (ASTM International, 2017).

For concrete rather than soil-cement mixtures, ASTM C684 provides different types of accelerated curing methods to prepare compression test specimens. This standard recommends the following four procedures for curing concrete specimens under conditions intended to accelerate the development of strength (ASTM International, 2003):

1. **Warm water method**. Immediately after concrete specimens are molded, the specimens in the molds are immersed in a water bath maintained at 95°F (35°C) throughout the curing period of 23.5 hours. The strength gain is mainly attributed to the heat of the cement hydration, with the water bath acting as an insulator. While this curing method is simple, fast, and safe, the compressive strength gained is lower compared with specimens cured at normal conditions (Baghdadi, 1982).
2. **Boiling water method**. The molded specimens are placed in storage for 23 hours at 70°F (21°C) for initial curing. Then, the specimens are immersed in boiling water for 3.5 hours and allowed to cool at room temperature for at least 1 hour prior to strength testing.
3. **Autogenous method**. The molded specimens are placed in a plastic bag and cured for 48 hours in an insulated container in which the elevated curing temperature is obtained from the heat of the cement hydration.
4. **High temperature and pressure method**. The compacted specimens in the molds are cured in a curing apparatus maintaining a pressure of 1,500 psi (10.3 MPa) for 5 hours. During the first 3 hours, the temperature should be at 300°F (150°C). After the first 3 hours, the heating element should be turned off for the remainder of the curing period.

2.2. STATE DEPARTMENTS OF TRANSPORTATION

State departments of transportation (DOTs) provide a variety of different test procedures for cement-treated materials. Most states use 7-day curing in a moisture room prior to unconfined compressive strength (UCS) testing. Variations among state test procedures arise when comparing the sample dimensions, compaction methods, target cement contents, and minimum and maximum unconfined compressive strengths.

Table 1 compares state DOT procedures and specifications. South Carolina provides a different procedure than most other states. Their method calls for 6-inch diameter, 12-inch tall specimens molded with a vibratory compactor. With a curing time of 7 days in a moisture room followed by 1-day immersion in water, their method was also the lengthiest procedure reviewed.

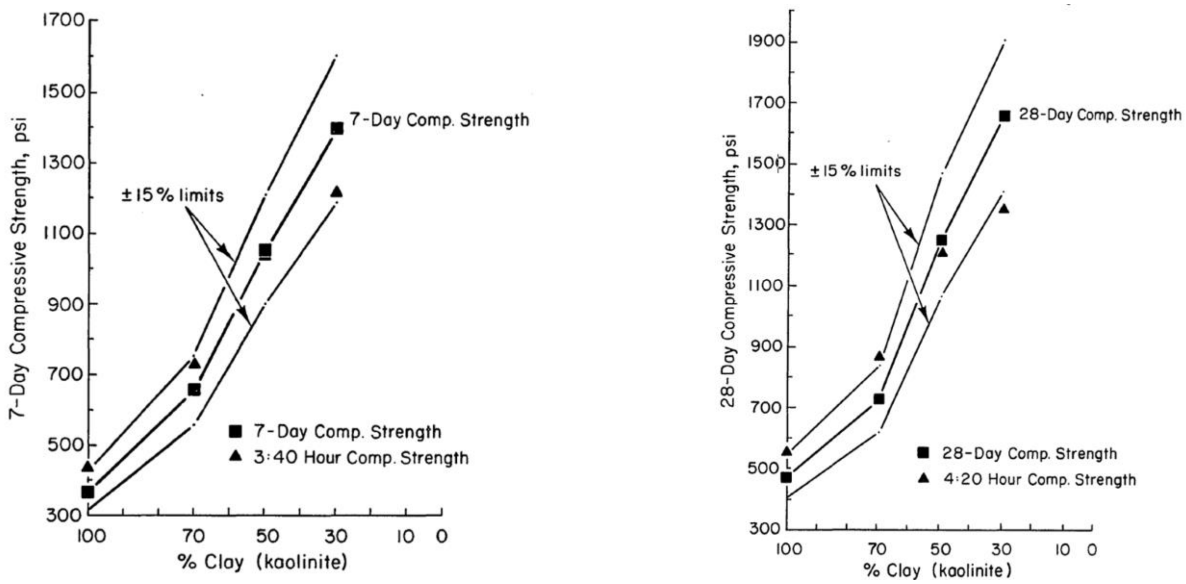
Table 1. Comparison of State DOT Procedures and Specifications for Cement-Stabilized Bases.

DOT	Minimum Strength (psi)	Maximum Strength (psi)	Curing Time	Sample Dimension (d×h inch)	Compaction Method	Design Cement Range or Target	Test Procedure	Specification Number	Notes
Alabama	300	400	7-day moisture cure	4×4.584	Manual: 5.5-lb hammer, 12-inch drop	3, 5, 7%	ALDOT 416	Section 302	
Arizona	500	-	7-day moisture cure, final 24-hour immersion in saturated lime water	4×4.584	Automatic or manual: 5.5-lb hammer, 12-inch drop	165 lb cement/yd^3 minimum	ARIZ 220a	Section 304	
Arkansas	400	-	7-day moisture cure			3–8%		Section 308	Class 7 aggregate
California	750	-	7-day room temperature cure	4×4	Manual: 30 blows by rod then 50 blows by 6-lb hammer, 6-inch drop	5%	CTM 312	Section 27	
Georgia-Design	300	-	7-day moisture cure	4×4.6	Automatic or manual: 5.5-lb hammer, 12-inch drop	3, 4, 5%	GDT 65	Section 301	
Illinois	500	-	7-day moisture cure, 4-hour immersion					Section 352.12	
Indiana	300*	-	7-day moisture cure	4×4.584 or 6×4.584	Automatic: 10-lb hammer, 18-inch drop	4–6% (minimum 3 contents)	ITM 595	Section 307	*300–500 minimum depending on hot mix asphalt (HMA) overlay rate
Kansas	650	1600	7-day moisture cure	6×6	Automatic or manual: 5.5-lb hammer, 12-inch drop		KT 37	Section 306	
Louisiana	150	-	7-day moisture cure	6×6	Automatic or manual: 5.5-lb hammer, 12-inch drop	6, 9, 12, 15%	DOTD TR 432	Section 303	
Maryland	750	-	7-day moisture cure, cap on 6th day, 4-hour immersion	6×8	Automatic: 10-lb hammer	3.25–4.75%	MSMT 321	Section 501/502	

DOT	Minimum Strength (psi)	Maximum Strength (psi)	Curing Time	Sample Dimension (d×h inch)	Compaction Method	Design Cement Range or Target	Test Procedure	Specification Number	Notes
Montana	500	1500	7-day moisture cure, 1st day in mold	4×4.584	Automatic or manual: 5.5-lb hammer, 12-inch drop	4.5% minimum	MT 261	Section 304	AASHTO T135 and T136 (14%)
Nevada	750	-	6-day moisture cure+ 1-day immersion	4×4	Manual: 30 blows by rod then 50 blows by 6-lb hammer, 4-inch drop	0.5% increments up to 4.5%	T236B 239B	Section 304	
Oklahoma	600	1200	7-day moisture cure, 1st day in mold, 4-hour immersion omitted from AASHTO T22	6×6	Automatic or manual: 5.5-lb hammer, 12-inch drop	3–5%	OHD L-53	Section 317	
Pennsylvania	650	-	7-day moisture cure, 4-hour immersion					Section 321	Durability test PTM 111 (14% loss)
South Carolina	600	-	7-day moisture cure, 1st day in mold, 1 day immersion (8 days total)	6×12	Vibratory: ASTM C1435	3.50%	SCT 142	SC-M-308_1015	
Texas	300*	-	7-day moisture cure	6×8	Automatic: 10-lb hammer, 18-inch drop	4, 6, 8, 10%	Tex-120-E	Item 275-276	*300 class M minimum, 500 class L minimum, class N "as shown on plans"
Kansas	650	1600	7-day moisture cure	6×6	Automatic or manual: 5.5-lb hammer, 12-inch drop		KT 37	Section 306	

2.3. RESEARCH LITERATURE

Baghdadi (1982) investigated an accelerated curing method to estimate the compressive strengths of soil-cement mixes cured for 7 and 28 days at 72°F and 100 percent humidity. The accelerated curing procedure was a modified boiling water method from ASTM C684, where soil-cement specimens were boiled for certain periods of time and then soaked in distilled water for 24 hours after a 30-minute cooling period at room temperature. In this study, specimens were boiled for periods of 1, 1.5, 2, 2.5, 3, 3.5, 4, and 5 hours. The accelerated compressive strengths were compared to the strengths of a duplicate set of specimens cured at normal conditions. Test results indicated that the accelerated cured specimens had higher strengths with longer boiling times and higher cement contents. Specimens boiled for 3 hours and 40 minutes predicted the 7-day strength within ±15 percent, while an average boiling time of 4 hours and 20 minutes predicted the 28-day strength within ±15 percent, as shown in Figure 1.



(a) 7-day normal vs. 3-hour 40-minute accelerated cure (b) 28-day normal vs. 4-hour 20-minute accelerated cure

Figure 1. Comparison of Compressive Strengths (Baghdadi, 1982).

In TxDOT research project 0-5569, completed in 2009, researchers evaluated tube suction testing (TST), backpressure (BP)conditioning, submergence, and vacuum conditioning to explore accelerated test methods for treating subgrade soil (Celaya et al., 2009). They evaluated a soil-cement mixture (Wichita Falls sandy soil treated with 3 percent cement). Because Tex-120-E did not include procedures for moisture conditioning, specimens were prepared and subjected to moisture conditioning according to Tex-121-E, resulting in a *modified Tex-120-E* (Veisi et al., 2010). Figure 2 shows that the modified Tex-120-E and TST procedures produced comparable results. The backpressure and vacuum methods generated similar compressive strengths that were smaller than those obtained with the Tex-120. The alternative moisture conditioning methods resulted in lower strengths than the Tex-120-E procedures due to the longer curing time imposed in the Tex-120-E procedures (Veisi et al., 2010).

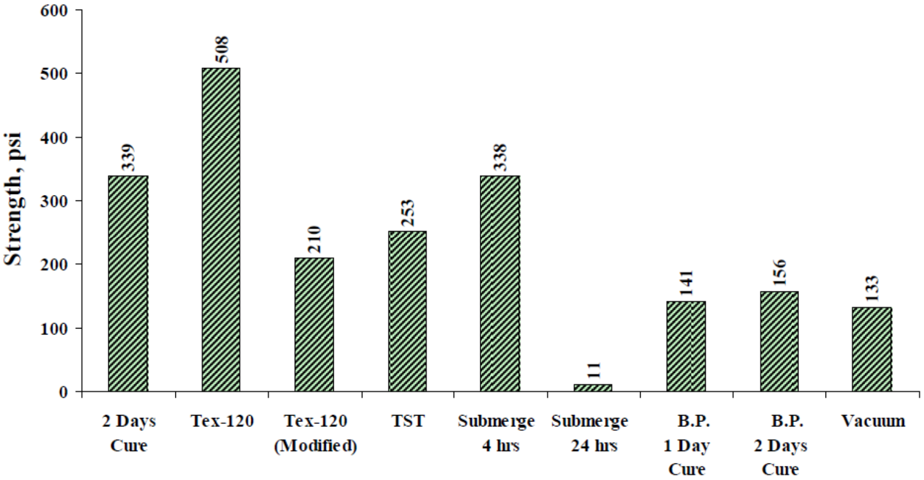
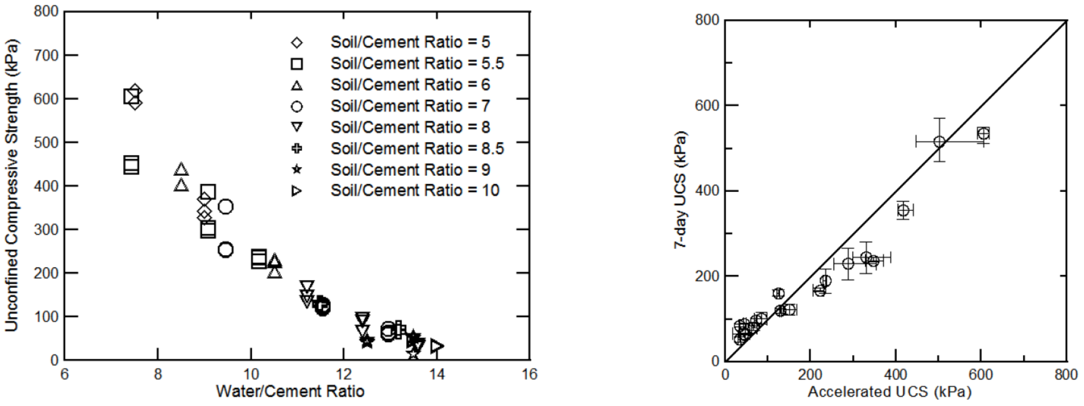


Figure 2. Strength Results by Curing Method (Veisi et al., 2010).

In 2011, another accelerated testing procedure was proposed by Lu et al. (2011) for curing cement-stabilized dredged Singapore marine clay, generated by dredging to maintain harbors and channels. Like other studies on accelerated curing procedures, Lu et al. (2011) investigated the applicability of the accelerated testing technique using elevated curing temperatures. With different soil/cement ratios, specimens arising from the same batch of mixture were separately cured under two different curing conditions: (1) normal curing for 7 days at room temperature (22°C) and (2) accelerated curing for 24 hours in a water bath maintained at 60°C. After 24-hour curing in the water bath, the specimens were allowed to cool gradually in the water to avoid thermal shock (i.e., a sudden drop in temperature that may cause damage to the specimens), resulting in a total accelerated curing time of 30 hours. From these test results, the following conclusions were drawn, as illustrated in Figure 3:

- The mixtures' soil/cement or water/cement ratio governs the strength under both normal and accelerated curing conditions [Figure 3(a)].
- The accelerated compressive strengths after 30-hour curing can be used to predict 7-day strengths, although it may overpredict by 20 percent [Figure 3(b)].



(a) Accelerated UCS vs. soil/cement ratio

(b) Accelerated UCS vs. 7-day UCS

Figure 3. Comparisons of Accelerated Compressive Strengths (Lu et al., 2011).

2.4. INTERNATIONAL AGENCIES

In Japan, Komiya et al. (2015) examined the effects of accelerated curing time, temperature, and pressure on the strength of soil-cement mixtures. In this study, the compacted soil-cement specimens were cured under either standard or accelerated curing conditions in molds. The specimens were cured in water at 20°C for 28 days for the standard condition. A commercial pressure cooker was used to manipulate pressure for the accelerated curing. The internal pressure in the pressure cooker was approximately 0.1 MPa (14.5 psi) when the water began to boil. A pressure regulator or safety valve was activated at >98 kPa. Therefore, a maximum pressure of 0.1 MPa was applied in the pressure cooker during curing. For the accelerated curing, the pressure cooker—filled with water and compacted soil-cement specimens—was stored in an oven maintained at 80, 90, and 100°C for 20, 24, 28, 48, and 72 hours. Figure 4 shows the standard and accelerated curing methods, respectively. The test results indicated that the compressive strengths and strength ratios ($\text{UCS}_{\text{accelerated}}/\text{UCS}_{\text{standard}}$) increased between 24 and 48 hours. Also, although increased curing temperatures did not contribute to strength gain, increased curing pressures did slightly increase strength.


(a) Standard curing in water
(b) Accelerated curing in pressure cooker and oven

Figure 4. Standard and Accelerated Curing Methods (Komiya et al., 2015).

European standard (EN) 13286-50 provides the standard curing process of soil-cement mixtures. The standard recommends curing soil-cement specimens in a water basin at 20°C for 28 days (Lund & Hansen, 2014).

British standard (BS) 1881-112 provides for accelerated curing at different temperatures but limits these procedures to the preparation of concrete specimens. This standard recommends immersing the concrete specimens in a curing tank maintained at 35, 56, or 82°C for a period of 24, 20, or 14 hours, respectively (British Standards Institute, 1983).

The *Transportation Laboratory Testing (TLT) Manual 501*, published by the Alberta Ministry of Transportation, provides specimen preparation procedures for mix designs of soil-cement mixtures. The TLT-501 recommends curing compacted specimens in a moisture room maintained at 21°C and 95–100 percent humidity for 7 days. After curing in the moisture room, each specimen should be immersed in water for not less than 4 hours before compressive strength testing (Alberta Ministry of Transportation, 2002).

Table 2 compares all curing procedures reviewed above for mixtures treated with cement. Some highlights from the information for mixtures treated with cement include the following:

- Accelerated testing methods with turnaround times ranging from 1 to 3 days could be viable.
- Accelerated curing methods in the literature have generally used sealed curing at elevated temperatures in a water bath, similar to some existing methods for concrete.
- Accepted standards using moisture conditioning generally use full submersion for 4 hours but have used up to 24 hours submersion.

Table 2. Comparison of Curing Procedures for Soil-Cement Mixtures.

Procedure Source		**Curing**			**Immersing/Soaking**			**Notes**
		Time	**Temperature**	**Condition**	**Time**	**Temperature**	**Condition**	
Tex-120-E		7 days	Room	In damp room				
AASHTO T135		7 days	Room	In damp room				
ASTM D1633		7 days	Room	In damp room	4 hours	Room	Immersed in water	
ASTM C684	Warm water	23.5 hours	95°F	In water bath				
	Boiling water	23 hours	70°F	In storage	3.5 hours	Boiled water	Immersed	Cool 1 hour before testing
	Autogenous	48 hours	-	In insulated container				
	High temperature and pressure	5 hours	300°F	Under pressure of 1500 psi				After first 3 hours, heating element should be turned off
Baghdadi (1982)	Normal	7, 28 days	72°F	In 100% relative humidity room	24 hours	Room	Soaked in water	
	Accelerated	1–5 hours	Boiled water	In boiled water bath	24 hours	Room	Soaked in water	
Celaya et al. (2009)	Submerge	2 days	104°F		4/24 hours	Room	Submerged in water bath	
	Tube suction	2 days	104°F		8 days	Room	Capillary saturation	6-hour oven dry at room temperature before capillary saturation
	Backpressure conditioning	2 days	104°F		4–6 hours	Room	Conditioned in backpressure device	10 psi confining pressure and 5 psi backpressure
Lu et al. (2011)	Normal	7 days	Room					
	Accelerated	1 day	60°C	In water bath				Cool 6 hours before testing
Komiya et al. (2015)	Standard	28 days	20°C	In water bath				
	Accelerated	20, 24, 28, 48, 72 hours	80, 90, 100°C	In pressure cooker in oven				
EN 13286-50		28 days	20°C	In water bath				
BS 1881-112		24, 20, 14 hours	35, 56, 82°C	In curing tank				
TLT-501		7 days	21°C	In 95–100% relative humidity room	4 hours	Room	Immersed in water	

2.5. SUMMARY AND CONCLUSIONS FROM THE LITERATURE REVIEW

Standard methods consistently use a 7-day moist-cured compressive strength for mixture design with cement treatment. The literature review indicated that accelerating cure methods could be viable with cure times as little as 1 to 3 days. Most of these methods have adapted existing concrete test procedures and accelerated the rate of curing by using elevated temperatures with specimens in full submersion. The literature review showed that, while interest remains in accelerated methods for mixture design, proposed accelerated methods have generally not migrated into practice.

From the literature review and discussion with the TxDOT project team, this research project will focus on accelerating the mix design procedure for cement-treated bases by researching the following curing conditions:

- Curing specimens for 7 days in an environment with a minimum humidity of 95 percent, according to the current Tex-120-E curing method. This method served as the reference curing condition.
- Curing for 72 hours with specimens sealed in bags at 104 °F.
- Curing for 30 hours with specimens fully submersed in water at 140°F for 24 hours followed by a 6-hour cooldown. This method represented the most accelerated approach identified in the literature.
- Curing for 30 hours with specimens sealed in bags at 104 °F.

CHAPTER 3. MATERIALS SAMPLING

This chapter presents the results of coordination efforts with TxDOT districts to identify and sample different materials for use in lab testing. Each of the materials sampled were evaluated for cement treatment in upcoming construction projects. Researchers coordinated with TxDOT districts to sample the materials presented in Table 3. Figure 5 through Figure 10 show the materials.

Table 3. Participating Districts and Materials Sampled.

District	Pavement	Date Sampled	Material Sampled
Beaumont (BMT)	FM 1746	May 7, 2020	Roadway salvage consisting of reclaimed asphalt pavement (RAP) and flexible base
		June 2, 2020	Type A, grade 1–2 flexible base from stockpile (Gulf Coast-Texas Materials, Jasper, Texas)
Bryan (BRY)	FM 1155	March 10, 2020	Crushed concrete (Knife River-Riverbend pit)
Odessa (ODA)	SH 18	October 1, 2020	Roadway salvage flexible base
Atlanta (ATL)	US 259	August 11–13, 2021 (roadway) September 21, 2021 (RAP from stockpile)	Roadway salvage and Queen City RAP for 50/50 RAP/salvage blend
ODA	FM 2594	January 17–19, 2022	Roadway salvage and subgrade for 63/37 subgrade/salvage base blend
Fort Worth (FTW)	FM 205	January 25, 2022	Roadway salvage (station 365+83)
			Type A, grade 1–2 flexible base from stockpile 4

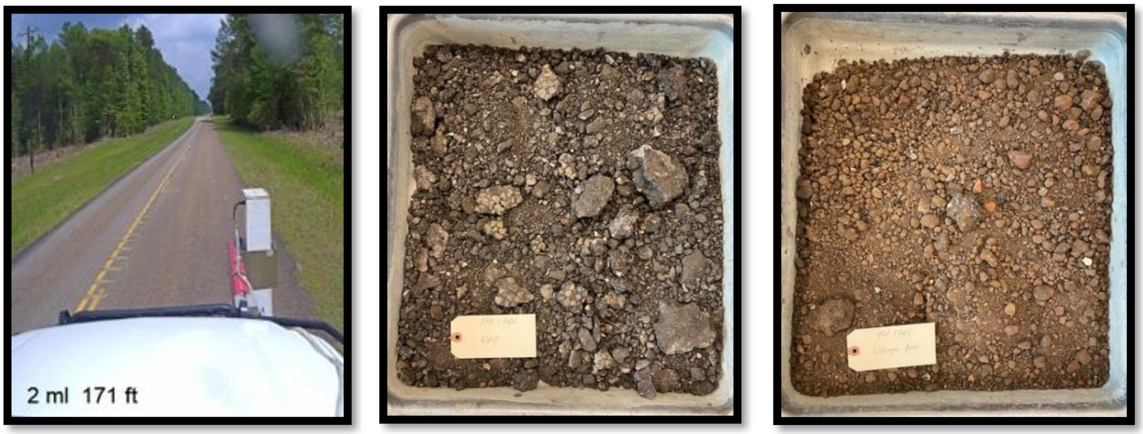


Figure 5. FM 1746 Roadway Sample Location (Left), RAP (Center) and Salvage Flexible Base (Right).

Figure 6. FM 1746 Type A, Grade 1–2 Flexible Base (Left) and FM 1155 Crushed Concrete (Right) Materials Sampled from Stockpile.

Figure 7. SH 18 Roadway Sample Location (Left) and Salvage Flexible Base (Right).

Figure 8. US 259 Roadway Sample Location (Left) and RAP and Salvage Base (Right).

Figure 9. FM 2594 Roadway Sample Location (Left) and Representative Materials (Right).

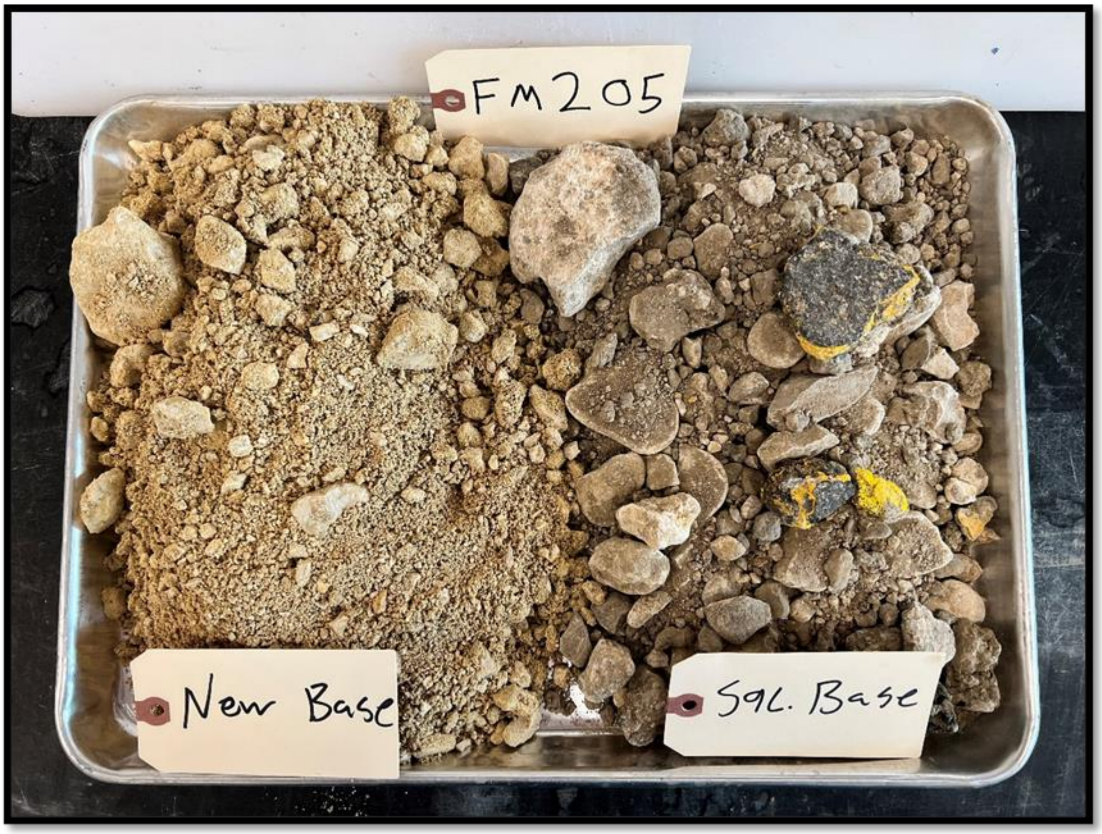


Figure 10. FM 205 Materials from Stockpile (Left) and Roadway (Right).

CHAPTER 4. LABORATORY EVALUATION

Researchers evaluated a total of eight different materials using various curing conditions and durations. Promising results from the initial four materials helped to identify specific conditions that could be harmonized with cement treatment and other curing methods to expedite IDT test turnaround times. These promising initial findings led researchers to conduct further laboratory testing on additional materials. This chapter summarizes the methods and results from the initial materials tested and then, building upon these initial results, describes the methods and findings from analysis of the additional materials.

4.1. CURING AND TESTING METHODS FOR INITIAL MATERIALS

In coordination with TxDOT districts, researchers initially selected four base materials for analysis. Each of these materials represented materials intended for cement treatment in an upcoming construction project. After characterizing each materials' basic properties including particle size distribution (Tex-110-E), plasticity index (Tex-104–106-E), and moisture-density relationship (Tex-113-E), researchers determined the optimum cement treatment level based on the 7-day moist-cured UCS in accordance with Tex-120-E (Texas Department of Transportation, 2022). Next, researchers fabricated IDT test specimens at 2, 3, 4, and 6 percent Portland Type I/II cement by weight, molding 4-inch diameter, 2-inch tall specimens in the Superpave gyratory compactor (SGC) to the target height. Researchers fabricated and tested the IDT mix designs using four different curing methods identified in the literature as follows:

- **Curing Method A:** 7-day moist cure of specimens. This curing condition represented the standard curing time and environment used by TxDOT in the Tex-120-E test methods.
- **Curing Method B:** 72-hour cure at 104°F with specimens sealed in bags. This curing time and temperature harmonized with the Tex-122-E and Tex-134-E draft test methods used for emulsion and foamed asphalt mixture designs, respectively (Texas Department of Transportation, 2023a and Texas Department of Transportation, 2023b). For cement treatment, the curing condition included sealing specimens in bags to preserve molding moisture and allow for continued cement hydration and reaction product development during the cure time.
- **Curing Method C:** 30-hour cure at 140°F for the first 24 hours followed by a 6-hour cooldown with specimens submerged in water. This method represented the most accelerated approach identified in the literature.
- **Curing Method D:** 30-hour cure at 104°F with specimens sealed in bags. This curing method combined the most accelerated cure time from method C with the more broadly accepted curing practice of maintaining specimens in sealed bags (to preserve compaction moisture) and the more broadly accepted accelerated curing temperature of 104°F.

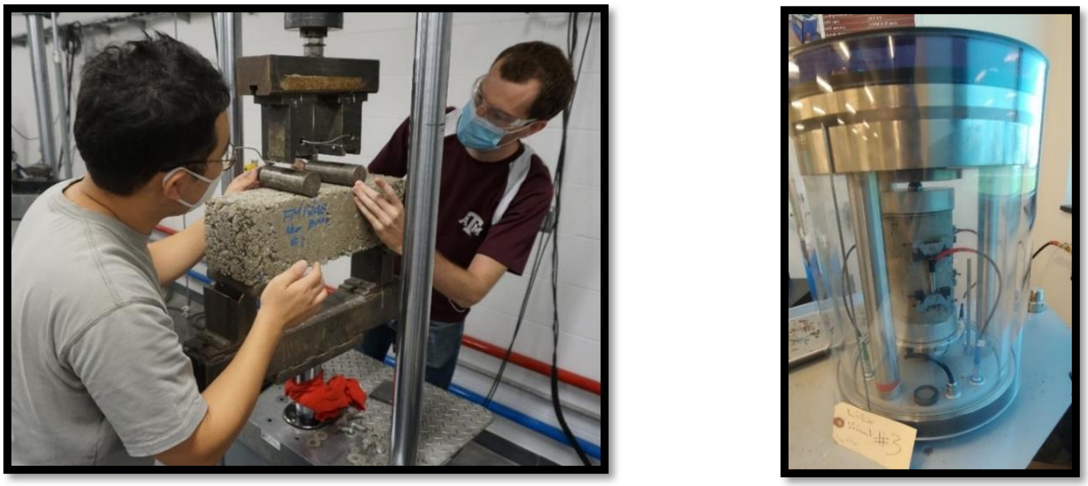
Except for method C, which only produced moisture-conditioned specimens, researchers fabricated six IDT test specimens at each cement content level. After curing, researchers measured IDT strengths on three specimens to determine dry strengths. The remaining three specimens were moisture conditioned after curing (submerged in water for 24 hours at 72±4°F).

Researchers then measured IDT strengths to determine wet strengths. All IDT strength measurements represented averages from triplicate test specimens.

Finally, researchers fabricated and tested specimens of each material at each cement content level in triplicate for MoR testing in accordance with AASHTO T97 and Mr testing in accordance with AASHTO T307 (American Association of State Highway and Transportation Officials, 2003 and American Association of State Highway and Transportation Officials, 2018). This initial laboratory testing program in total included 48 UCS test specimens, 336 IDT test specimens, 48 MoR test beams, and 48 Mr test specimens. Figure 11 illustrates these tests.

(a) UCS Test Specimens

(b) IDT Testing



(c) Preparation for MoR Testing

(d) Mr Testing

Figure 11. Key Tests in Laboratory Program: (a) UCS, (b) IDT, (c) MoR, and (d) Mr.

4.2. LAB TEST RESULTS FOR INITIAL MATERIALS

4.2.1. Material Characterization

Table 4 shows the materials used and their key properties. The materials represented two stockpile materials and two roadway salvage materials. This range of materials aligned well with practice; base treatments may include plant-mix or roadway-mix applications.

Table 4. Basic Properties of Initial Materials.

Material	**FM 1155** Crushed Concrete from Stockpile	**FM 1746** Roadway Salvage with RAP/Flexible Base Blend	**FM 1746** Type A, Grade 1–2 Base from Stockpile	**SH 18** Roadway Salvage Flexible Base
AASHTO Soil Classification	A-2-6	A-2-4	A-2-6	A-2-6
Master Grading (Percent Passing)	*This space intentionally left blank*			
1¾ inch	100.0	100.0	100.0	100.0
1¼ inch	96.2	93.2	89.8	98.6
7/8 inch	90.6	87.0	73.8	90.1
5/8 inch	84.9	80.9	63.1	83.0
3/8 inch	72.1	67.9	48.0	72.0
#4	54.6	50.9	33.9	60.4
#40	22.8	25.0	15.0	36.1
#100	9.2	12.7	11.8	20.5
#200	4.9	8.9	9.6	15.3
Liquid Limit (%)	27	18	23	25
Plasticity Index (%)	11	10	13	11
Maximum Density (pcf)*	120.5	130.2	142.7	116.3
Optimum Moisture Content (%)*	10.9	6.7	6.8	11.8

*Determined with a 3 percent cement content.

4.2.2. Strength, MoR, and Mr Test Results

Table 5 shows the results from the lab testing program for each material and cement content level. Given the range of materials and cement contents used, measured UCS values ranged from about 200 to almost 900 psi. For context, many TxDOT districts currently use a UCS target of 300 psi, and historically have used UCS values from 175 up to 500 psi (Texas Department of Transportation 2004, 2014). The range of values measured in this study reasonably covers the range of UCS values TxDOT has applied in practice.

Dry IDT strength measurements ranged from 24 to over 160 psi, while wet IDT strengths ranged from 15 to over 160 psi. The MoR and Mr test results also covered a wide range, with measured MoR values from about 30 to almost 200 psi and Mr values from about 300 to 2,500 ksi.

Table 5. Lab Testing Results for Initial Materials.

Test		**Tex-120-E UCS (psi)**	**IDT (psi)**							**MoR (psi)**	**Mr (ksi)**
Curing Method		A	A		B		C	D		A	A
Conditioning		Dry	Dry	Wet	Dry	Wet	Wet	Dry	Wet	Dry	Dry
FM 1155 Crushed Concrete	2%	230	43	32	48	60	42	50	50	31	374
	3%	303	58	41	64	60	44	55	59	28	498
	4%	317	68	54	74	84	48	58	62	70	629
	6%	569	71	65	128	104	41	82	83	96	918
FM 1746 Salvage Mixture	2%	196	50	44	41	46	29	28	31	48	660
	3%	260	62	64	68	69	33	34	55	71	937
	4%	387	99	92	85	95	25	60	64	118	1100
	6%	524	137	121	100	112	25	60	81	174	1488
FM 1746 New Base	2%	377	48	44	46	55	-	39	43	76	934
	3%	506	88	75	94	88	-	65	64	138	1586
	4%	648	105	91	124	111	66	77	91	196	2005
	6%	887	161	131	161	165	47	133	155	290	2555
SH 18 Salvage Base	2%	424	61	68	75	68	44	24	26	128	711
	3%	408	62	61	90	82	56	32	38	188	712
	4%	503	72	66	87	81	19	58	61	192	1045
	6%	626	96	103	87	112	15	77	78	225	1303

-Not available. Specimens were not in testable condition after the soaking period.

Curing method C presented many challenges. Although this method showed promise in the literature, researchers believe this method is too harsh for typical cement-treated base materials in Texas. During the elevated temperature, soaked curing conditions, specimens often deteriorated and in two cases were not even testable. Figure 12 illustrates the harshness of curing method C.

(a) Deteriorated specimens during soaking (b) Significant deterioration of testable specimens

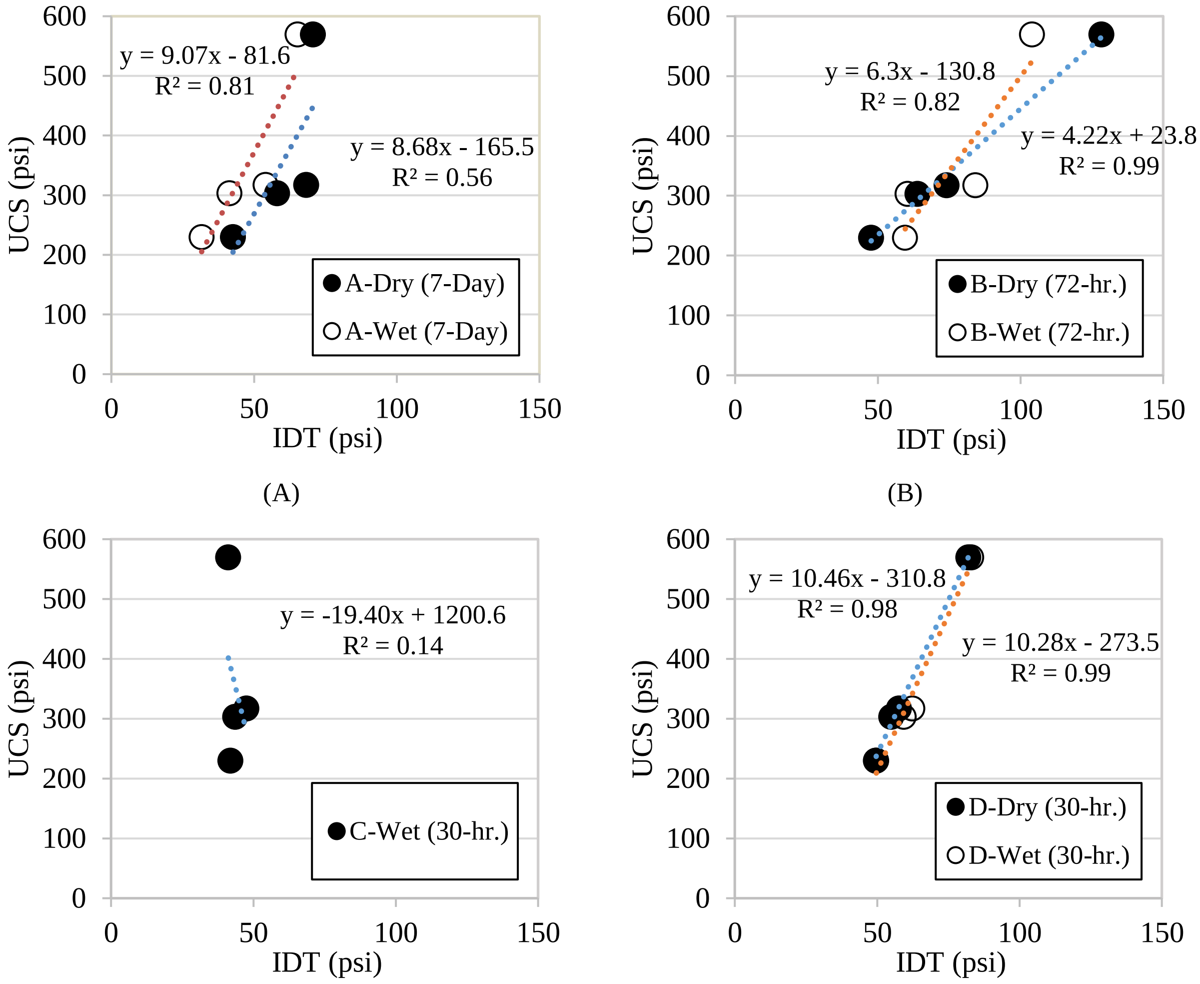
Figure 12. Harshness of Curing Method C for Texas Cement-Treated Bases

4.3. ANALYSIS OF INITIAL MATERIALS

Researchers focused initial analyses on determining which, if any, of the IDT test methods best correlate with UCS test methods and whether moisture conditioning influences the overall results. Researchers evaluated potential material-specific factors that may impact the IDT-UCS test method relationship and also analyzed whether any of the different curing methods improved test precision. Additionally, given the importance of the MoR and Mr in performance analysis and design of cement-treated bases and the significant effort required to perform these tests, researchers also evaluated if these data further validated or could be used to update IDT tests to MoR models identified in the literature and if the IDT tests could be used to estimate the resilient modulus.

4.3.1. Relationship Between IDT and UCS Test Methods

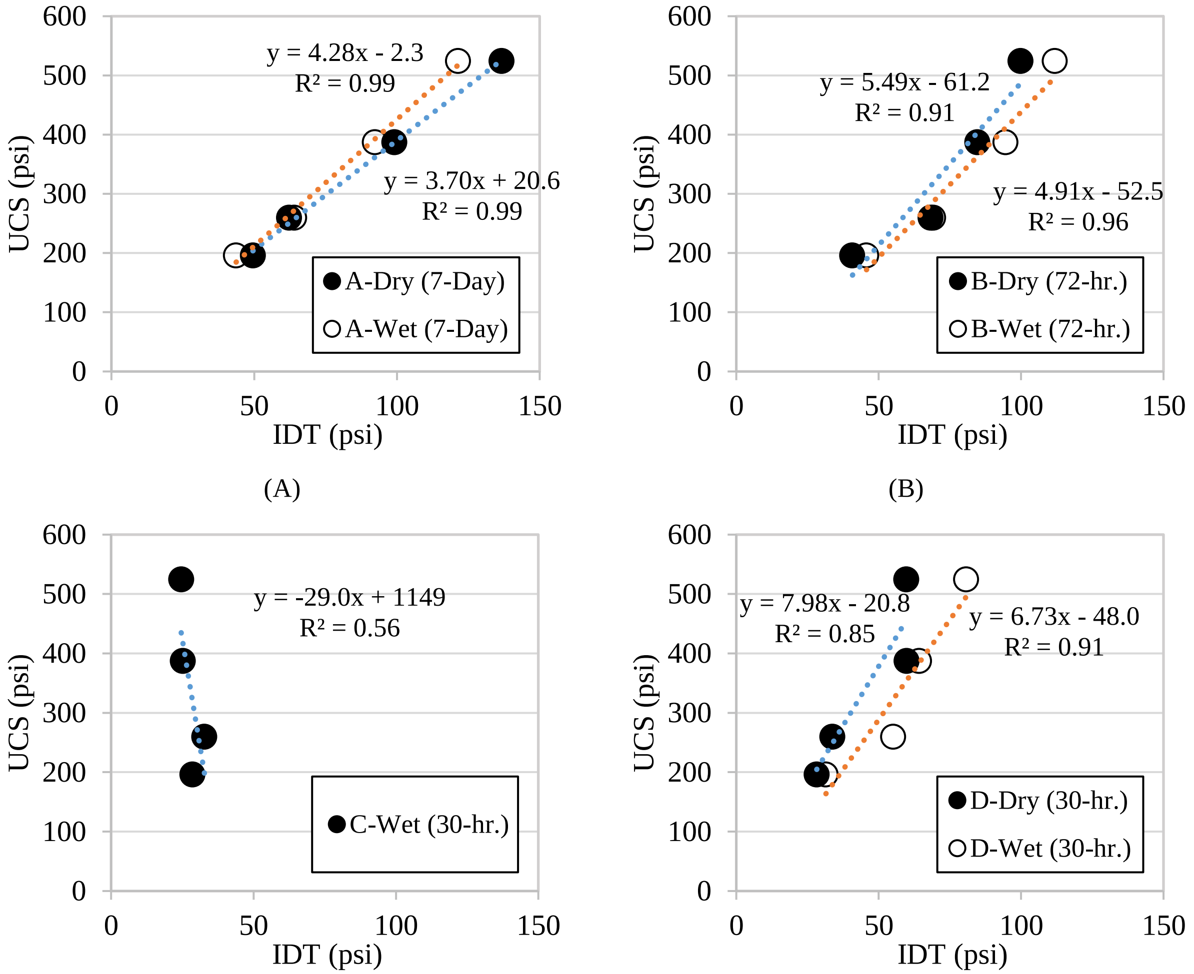
Figure 13 through Figure 16 present the results of the Tex-120-E UCS and IDT tests for each material. These results showed that, except for curing method C, strong correlations usually existed between IDT strength and UCS. Thus, accelerated cure options of 72 hours (curing method B) and even 30 hours (curing method D) could be viable for mix design purposes.



(A) (B)

(C) (D)

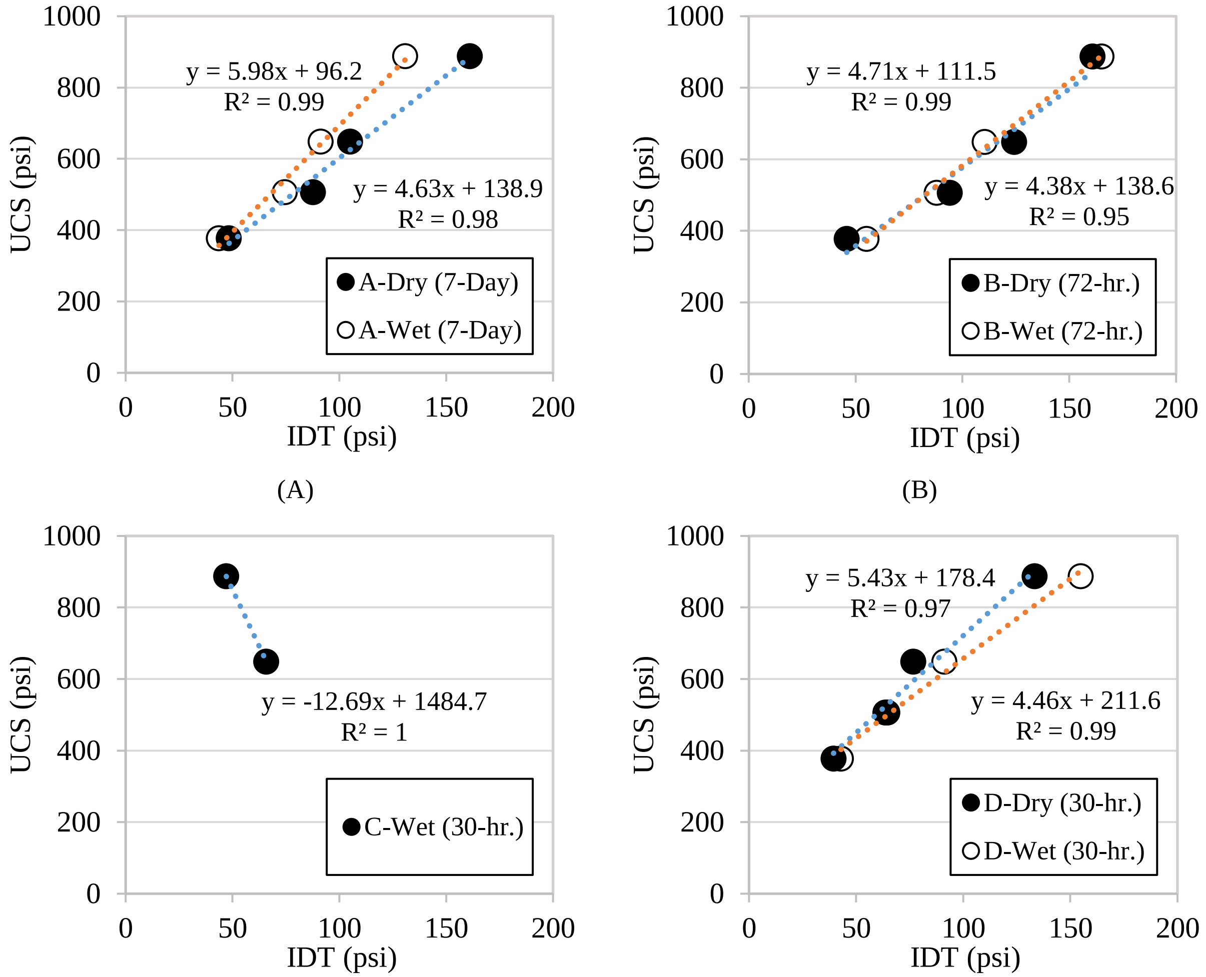
Figure 13. UCS vs. IDT Strength for FM 1155 by Curing Method A, B, C, and D.



(A) (B)

(C) (D)

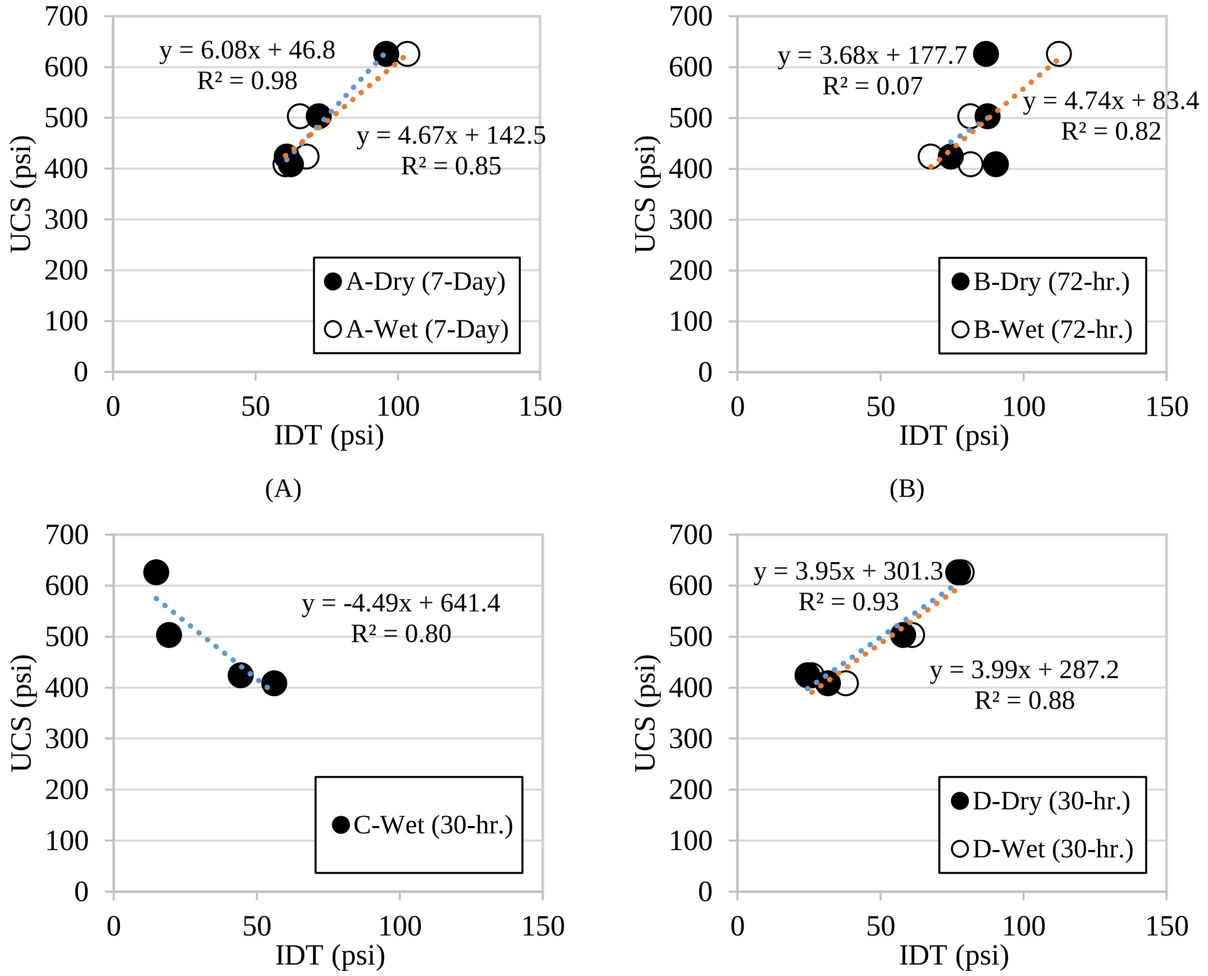
Figure 14. UCS vs. IDT Strength for FM 1746 Salvage Mix by Curing Methods A, B, C, and D.



(A) (B)

(C) (D)

Figure 15. UCS vs. IDT Strength for FM 1746 New Base by Curing Methods A, B, C, and D.

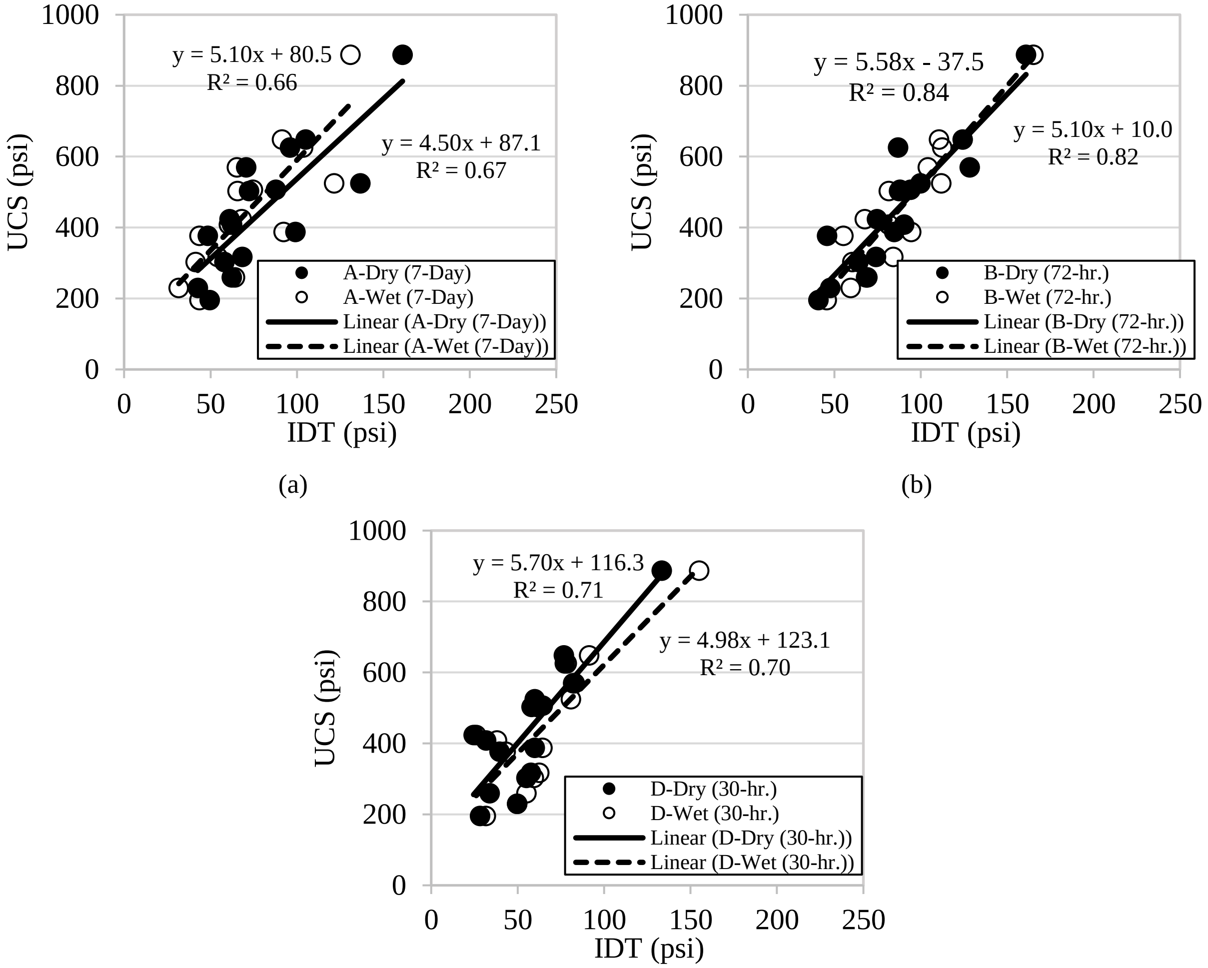


(A) (B)

(C) (D)

Figure 16. UCS vs. IDT Strength for SH 18 Salvage Base by Curing Methods A, B, C, and D.

Based on observations from Figure 13 through Figure 16, curing method C was eliminated from further consideration, and additional analyses focused on evaluating the relationship between UCS and IDT strength for the cross section of data with all four materials and curing methods A, B, and D. Figure 17 illustrates these relationships, and Table 6 summarizes regression analysis results for estimating the Tex-120-E UCS based on the IDT strength for the different curing methods. The P-values of the coefficients in Table 6 show that none of the intercepts were statistically different from zero at the 95 percent confidence level. Conversely, each of the IDT test curing methods in Table 6 were deemed suitable for estimating UCS based on the low P-values (much less than 0.05) for the X-variable coefficients.



(a)

(b)

(c)

Figure 17. Tex-120-E UCS vs. IDT Strength for a Cross Section of Materials and Cure Durations: (a) 7-day Cure, (b) 72-hour Cure, and (c) 30-hour Cure.

Table 6. Regression Analysis for Estimating UCS from IDT Strength.

IDT Test Curing Method	Intercept		X-variable		R^2	Standard Error of the Estimate
	Coefficient	P-value	Coefficient	P-value		
A-Dry	87.1	0.25	4.504	9.93 E-05	0.67	106.7
A-Wet	80.5	0.30	5.100	0.000116	0.66	107.8
B-Dry	10.0	0.86	5.104	1.34 E-06	0.82	78.9
B-Wet	-37.5	0.53	5.581	4.96 E-07	0.84	73.6
D-Dry	116.3	0.079	5.695	3.78 E-05	0.71	99.8
D-Wet	123.1	0.067	4.985	5.02 E-05	0.70	101.8

Review of the fit (R^2) and the standard error of the estimate for each regression in Table 6 showed that curing method B represented the best approach to estimate UCS based on IDT strength. Specifically, curing method B-wet showed the highest R^2 and the lowest standard error among all the regression equations. Thus, these data suggested that the Tex-120-E UCS can be best estimated using an accelerated 72-hour cure, followed by a 24-hour moisture conditioning, using the following relationship:

$$UCS_7\ (psi)=5.19\ IDT_3 \qquad R^2=0.98,\ \text{standard error}=72.1 \tag{1}$$

where UCS_7 is the Tex-120-E unconfined compressive strength in psi, and IDT_3 is the indirect tensile strength in psi of specimens cured in sealed bags for 72 hours at 104°F, followed by a 24-hour water submersion at room temperature (~72°F).

4.3.2. Influence of Moisture Conditioning on IDT Strength

Researchers aimed to identify a test protocol that used moisture conditioning, with the goal of screening out materials that may lose strength when exposed to moisture ingress in a pavement service environment. Using paired t-tests, the data showed that IDT strength values were the same for dry and wet conditions for curing method B, as shown in Figure 18. Curing methods A and D did show moisture conditioning effects. With method A, moisture conditioning resulted in an average 8.1 psi decrease in IDT strength. With method D, moisture conditioning resulted in an average 6.5 psi increase in IDT strength. These results suggested that—among the curing methods examined in this research—the accelerated methods may not discern the potential moisture sensitivity of a material. Researchers hypothesized that the increase in IDT strength with moisture conditioning in curing method D could have resulted from significant amounts of unreacted cement remaining in the specimen after only 30 hours of curing; upon subjection to moisture, the water-cement reaction produced more reaction product and a strength gain compared to the nonmoisture conditioned specimens at such an early cure time.

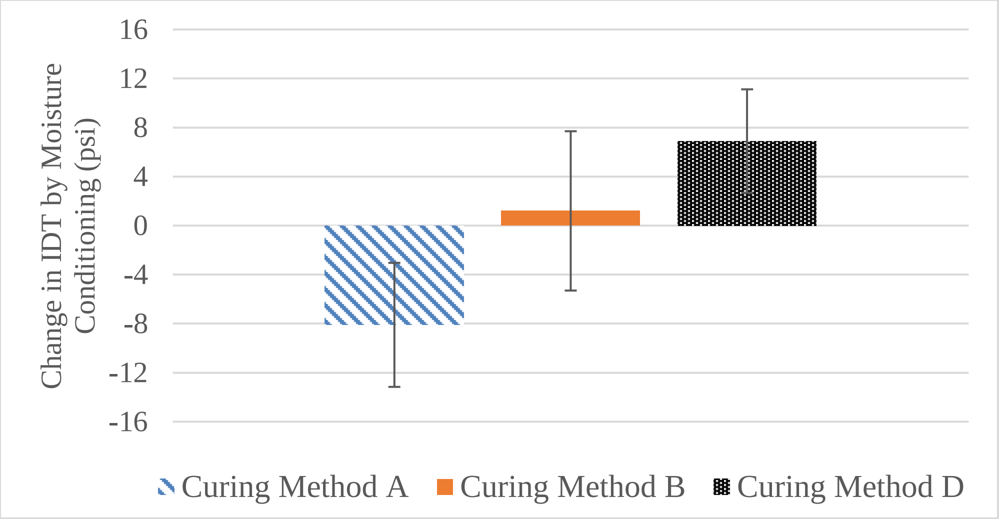


Figure 18. Mean Change in IDT Strength from Dry to Wet Test Conditions with 95 Percent Confidence Intervals.

4.3.3. Influence of Material-Specific Factors on UCS-IDT Strength Relationship

Researchers re-analyzed the data from Table 4 and Table 5 to include material-specific factors. Rather than simply use binary designators for a material, researchers performed multiple regression using quantifiable material properties including the plasticity index (PI), percent passing the #200 sieve (P200), and methylene blue value (MBV). Additionally, researchers explored inclusion of the percent cement (C) as a regressor variable. The initial multiple regression results showed that all coefficients were statistically significant at the 95 percent confidence level except for the MBV. Thus, researchers removed the MBV as a regressor variable and performed a new regression formulated in Equation 2 as follows:

$$UCS_7\ (psi)=-741+2.96\ IDT_3+38.7\ C+10.6\ P200+60.7\ PI \qquad (2)$$

$R^2=0.97$, standard error=37.8

In addition to cement content, Equation 2 demonstrated that material-specific properties could influence the relationship between IDT strength and UCS. Including those material-specific properties can improve the UCS-IDT strength model. While Equation 2 provided a similar fit as Equation 1 (measured by the R^2), the standard error of the estimate from Equation 2 substantially improved. Figure 19 compares the predicted UCS from Equation 2 and the actual (measured) UCS.

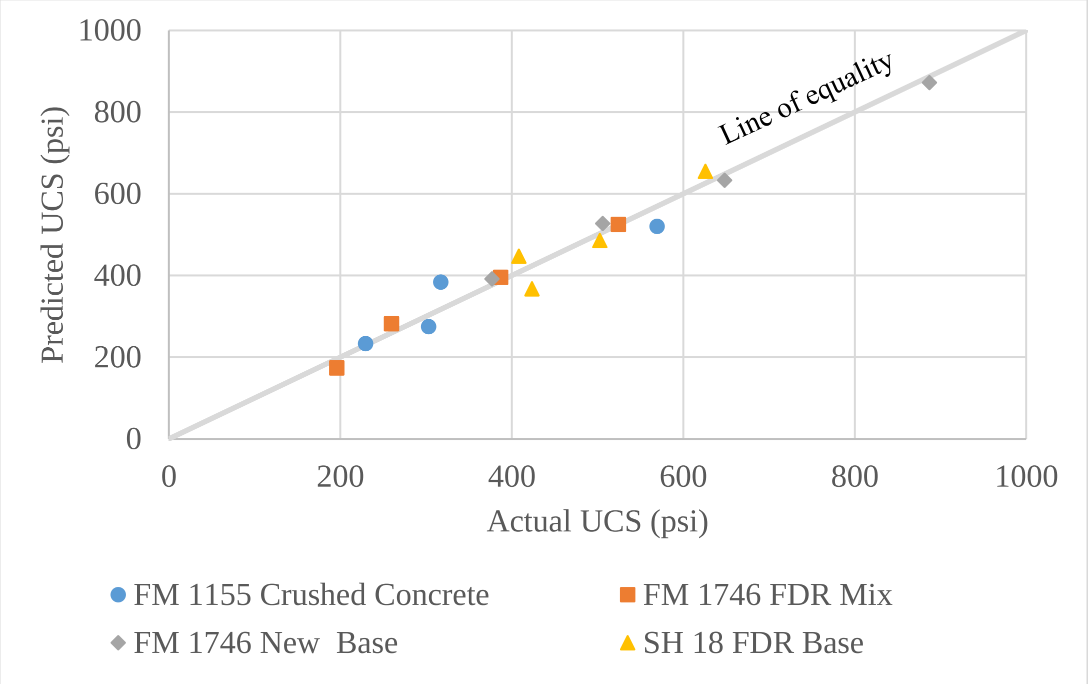


Figure 19. Actual vs. Predicted UCS from the UCS-IDT$_3$ Strength Model.

4.3.4. Precision of IDT Tests with Different Curing Methods

Researchers performed a preliminary in-lab precision analysis of the IDT tests with each of the different curing methods. Researchers determined the pooled coefficients of variation shown in Figure 20. Using F-ratio tests, the results showed the following:

- Method D-dry was more precise than methods A-dry and B-dry.
- Method D-wet was less precise than method D-dry.
- No significant differences existed across the methods for wet IDT strength precision.

- When pooling both wet and dry IDT strength values within each method, the methods were similar in precision.

Based on these findings, the data suggested that no curing method offered any distinct advantages in terms of test method precision.

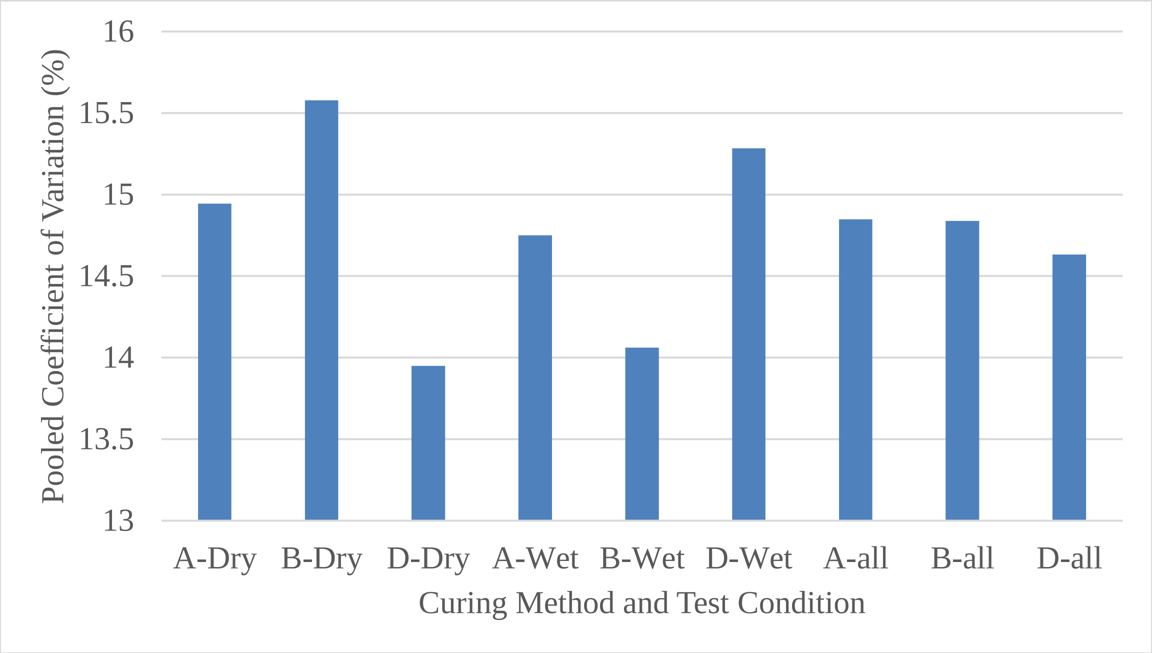


Figure 20. Pooled Coefficient of Variation for IDT Strength by Curing Method and Test Condition.

4.3.5. Estimation of the MoR using IDT Strength

Although not currently used within TxDOT, the modulus of rupture represents an accepted property for characterizing cement-treated bases and is a required input to evaluate crack life using the *Mechanistic Empirical Pavement Design Guide* (MEPDG) or methods outlined by the Portland Cement Association (PCA) (Applied Research Associates, Inc.-ERES Consultants Division, 2004; Scullion et al., 2008). Researchers analyzed whether the accelerated cure IDT test for mixture design could concurrently be used to estimate the MoR. Researchers also evaluated how the current lab study results compared with two other MoR prediction models identified in the literature.

4.3.5.1. Historical Context of the MoR Test

The MoR test requires much effort to perform, using 30 times as much material as an IDT test and offering a 28-day test turnaround time. Significant reductions in testing burden and turnaround time could be realized through alternative methods for determining a reasonable MoR design input. While the literature provided a basis for estimating the MoR from the UCS (Applied Research Associates, Inc.-ERES Consultants Division, 2004; Scullion et al., 2008), the failure modes of the UCS test are completely different from the MoR test. Compared to the UCS test, the failure modes of the IDT test better simulate the failure modes of the MoR test (Lee et al., 2017). Researchers identified two models in the literature that estimate the MoR using IDT tests (Lee et al., 2017; Wen et al., 2014). The first model is formulated as follows:

$$\mathrm{MoR}_{28}\ \text{(psi)}=1.742\ \mathrm{IDT}_7 \tag{3}$$

where MoR_{28} is the modulus of rupture in psi after 28 days of moist curing, and UCS_7 is the unconfined compressive strength in psi after 7 days of moist curing. It is important to note that researchers derived Equation 3 from the MoR-IDT strength and time-strength adjustment models previously developed by Wen et al. (2014).

Lee et al. (2017) sought to improve the MoR-IDT strength prediction model in Equation 3, by including an intercept value as follows:

$$\mathrm{MoR}_{28}\ \text{(psi)}=2.14\ \mathrm{IDT}_7–9.85 \tag{4}$$

4.3.5.2. *Relationship Between IDT and MoR Test/Prediction Methods*

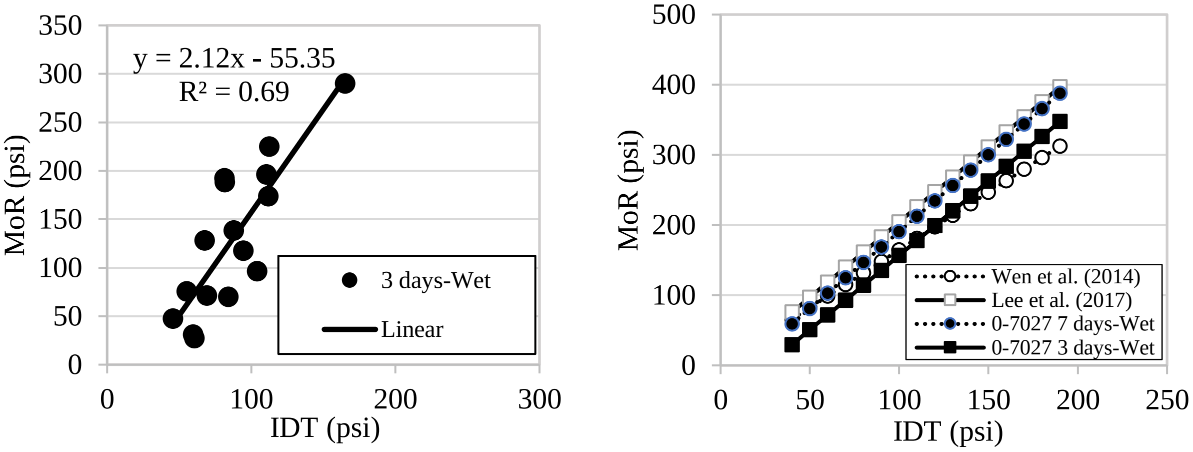
Figure 21(a) shows the relationship observed between the 28-day MoR and the wet IDT strength using curing method B. The data showed that the accelerated cure IDT test can be used to estimate the MoR as follows:

$$\mathrm{MoR}_{28}\ \text{(psi)}=2.12\ \mathrm{IDT}_3–55.35 \qquad R^2=0.69\text{, standard error}=43.9 \tag{5}$$

where IDT_3 is the indirect tensile strength in psi on specimens sealed in bags and cured for 72 hours at 104°F followed by a 24-hour water submersion at room temperature (~72 °F).

Figure 21(b) illustrates that the estimation of the MoR using the 7-day cure IDT test in this study agreed well with the prediction model (Equation 4) developed by Lee et al. (2017). Figure 21(b), along with Equations 3 and 4, also showed the following:

- The slope of the MoR-IDT strength relationship was similar regardless of whether the IDT strength was determined with curing methods A (7-day cure) or B (3-day wet cure).
- An offset (i.e., different intercept) exists between the 3-day IDT test and the 7-day MoR-IDT strength relationships. Because these underlying IDT strength data used different curing times and environmental conditions, it was not surprising to see a difference in this intercept value. Paired t-tests statistically confirmed that the 3-day wet cure IDT strength values were 15 psi higher than the 7-day wet IDT strengths. The resultant effect was that the model based on the 3-day IDT test was shifted to the right compared to the model based on the 7-day IDT test for a given MoR value.
- At high IDT strength values, the model developed by Wen et al. (2014) deviated significantly from the models developed in this study and the model developed by Lee et al. (2017). This deviation may be partly explained simply by differences in the materials represented in the underlying data. This study and the work of Lee et al. (2017) used materials exclusively from Texas and focused only on base materials.



(a) (b)

Figure 21. MoR vs. IDT Strength: (a) Regression Analysis Based on the Accelerated Cure IDT Test and (b) Comparison of Previous and Current Study MoR-IDT Strength Models.

4.3.6. Estimation of the Mr using IDT Strength

The resilient modulus is a fundamental parameter used in mechanistic-empirical pavement analysis and design. Figure 22 shows good correlation between the measured IDT_3 strength values and the lab-determined Mr values.

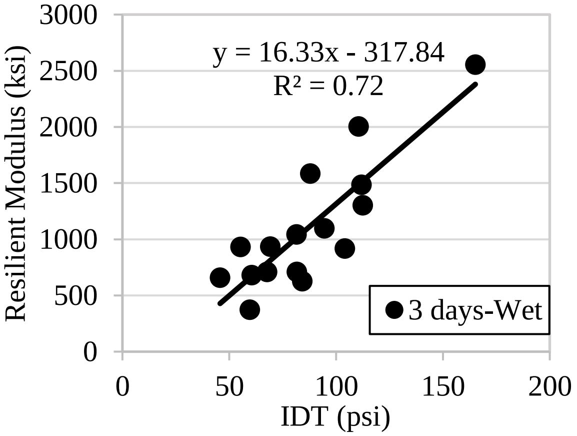
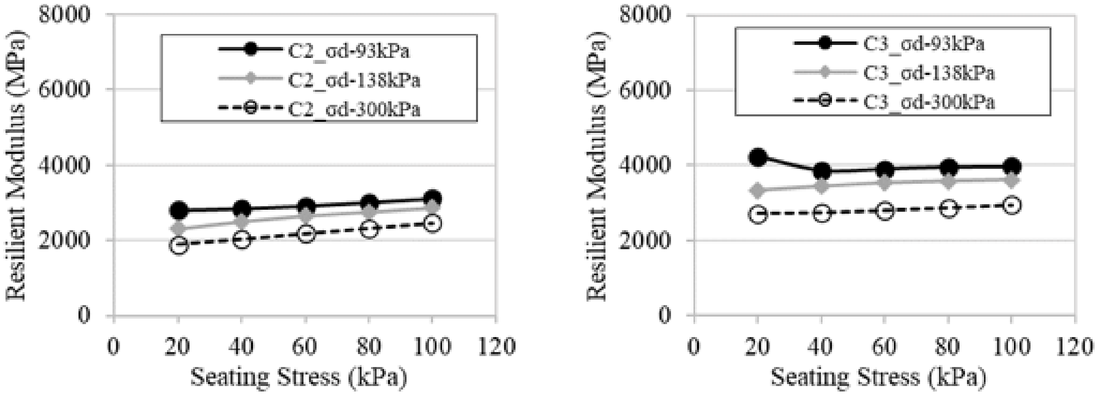


Figure 22. Correlation Between Mr and IDT Strength.

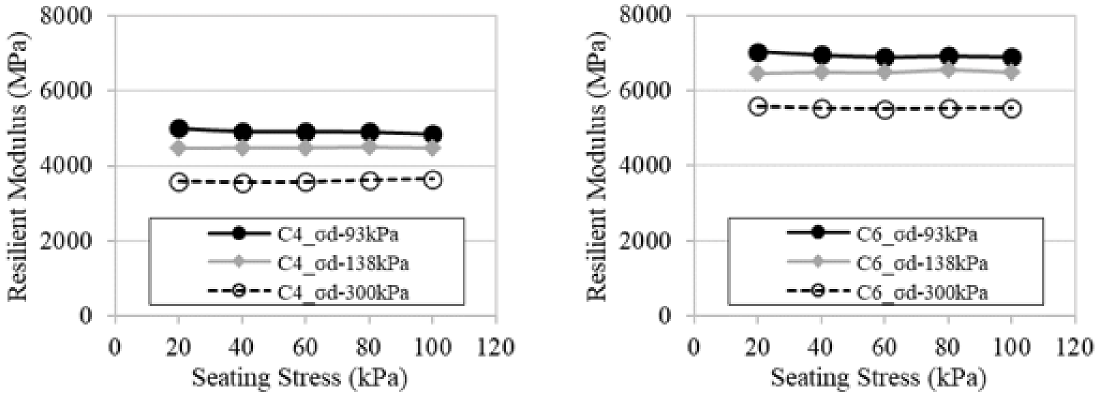
In practice, Louw et al. (2019) reported that Mr values measured in the lab corresponded directly with values backcalculated from falling weight deflectometer (FWD) measurements without the need for any shift factors or correlation models. However, some research has demonstrated conflicting results regarding the need for shift factors or correlation models to relate the lab to the field (Flintsch et al., 2003; Louw et al., 2019).

It is important to note that the lab Mr measurements do have certain limitations. The laboratory conditions may not be reflective of the in situ conditions (Mikhail et al., 1999). In the case of cement-treated bases, a lab test replicates ideal curing conditions, applies only a minimal number of load repetitions, and does not account for the potential influence of shrinkage cracking. Recognizing that some underlying assumptions and potential limitations do exist, the accelerated cure IDT test method from this study offers a scientifically correlated way to estimate the resilient modulus for pavement analysis and design that reduces materials, time, and complexity compared to conventional Mr testing.

While Figure 22 presented a simple linear model to estimate the Mr using IDT strength, Figure 23 illustrates that the Mr exhibited dependency on the deviator stress. This observation held true for almost all the materials and cement content levels tested.



(a) 2% cement treated (b) 3% cement treated



(c) 4% cement treated (d) 6% cement treated

Figure 23. Mr Dependency on Deviator Stress for FM 1155 Material.

Based on the results suggesting stress dependency, researchers explored the use of a resilient modulus linear or nonlinear model to fit the data. Equation 6 shows the model formulation as follows:

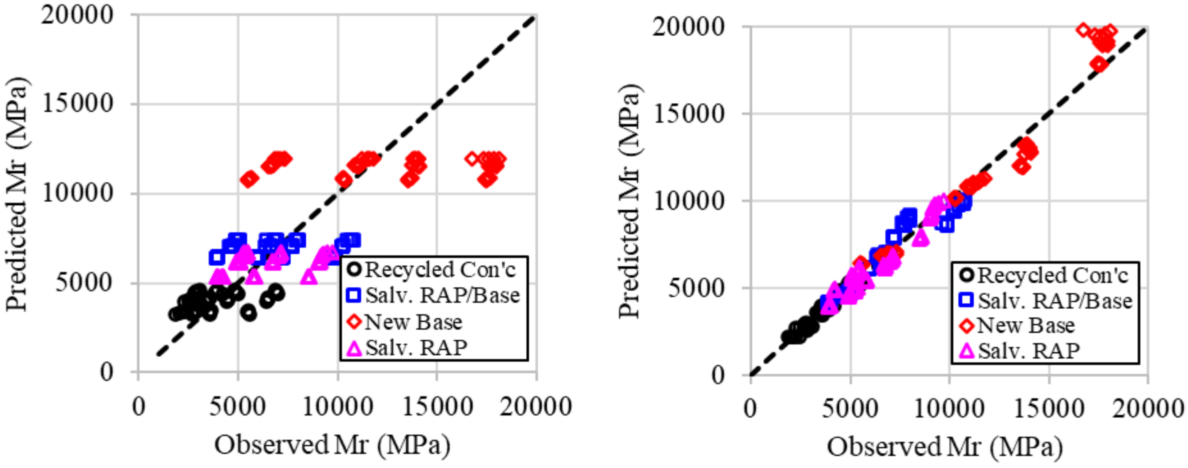
$$Mr = k_1 P_a \cdot \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \tag{6}$$

Figure 24(a) shows that this model could not provide accurate resilient modulus values across the full range of cement contents for a given material.

Researchers replaced the octahedral shear stress component in Equation 6 with IDT_3, producing the following formulation:

$$Mr = k_1 P_a \cdot IDT_3^{k_2} \left(\frac{\theta}{P_a} \right)^{k_3} \tag{7}$$

This change substantially improved the resilient modulus estimation, as shown in Figure 24(b). These results demonstrated the plausibility of relating the IDT strength to the resilient modulus behavior of cement-treated bases. Use of IDT strength would not only simplify the mix design procedure for cement-treated bases but could also offer a mechanism for performing design checks.



(a) Model requiring additional variables (b) Revised model using IDT_3 strength

Figure 24. Mr Regression Model Outputs.

4.4. CURING AND TESTING METHODS FOR ADDITIONAL MATERIALS

Based on the promising analysis results for the four initial materials, researchers subsequently coordinated with TxDOT districts to sample and test materials from US 259 (ATL), FM 2594 (ODA), and FM 205 (FTW). Each of these materials were candidates for cement treatment in upcoming construction projects. The FM 205 project included both roadway salvage and new flexible base from a stockpile; the new flexible base was used for widening.

Table 7 summarizes the materials and scope of lab work performed for each material. While the initial scope of this research project focused solely on base materials, many stakeholders expressed interest in learning whether the preliminary results would also apply to soils or soil/base blends. As such, two of the additional materials included the incorporation of subgrade into the cement-treated mixture.

Table 7. Additional Materials for Lab Testing.

Project	Material	Scope of Lab Work
US 259	50/50 RAP/salvage base blend	Analysis of UCS-IDT$_3$ strength relationship
FM 2594	Roadway salvage, 63/37 subgrade/salvage base	Analysis of UCS-IDT$_3$ strength relationship
FM 205	Roadway salvage from station 365+83 (8 inches) with an anticipated incorporated subgrade (1inch)	Full test plan including IDT (three different curing methods), UCS, MoR, and Mr testing Exploratory work to measure shrinkage on MoR beams during curing
FM 205	Type A, grade 1–2 flexible base	Full test plan including IDT (three different curing methods), UCS, MoR, and Mr testing Exploratory work to evaluate IDT testing with three different curing methods and two different cement sources. Exploratory work to measure shrinkage on MoR beams during curing

Researchers used cement contents of 2, 3, 4, and 6 percent Portland Type I/II cement for the IDT, UCS, MoR, and Mr tests. Unless otherwise indicated, researchers performed each test in triplicate at each cement content level for each material.

4.4.1. IDT Testing

Three curing methods for IDT strength determination were applied to the materials listed in Table 7 that were included in the full research test plan. These curing methods are described again below for reference. Prior results (Figure 13 through Figure 16) from this project showed that curing method C (immediate submersion in a 140°F water bath for 24 hours) was too harsh, so researchers eliminated this curing method when testing additional materials.

- **Curing Method A:** 7-day moist cure of specimens. This curing condition represented the standard curing time and environment used by TxDOT in the Tex-120-E test methods.
- **Curing Method B:** 72-hour cure at 104±0.5°F with specimens sealed in bags. This curing time and temperature harmonized the Tex-122-E and Tex-134-E draft test methods used for emulsion and foamed asphalt mixture design, respectively. For cement treatment, the curing condition included sealing specimens in bags to preserve molding moisture and allow for continued cement hydration and reaction product development during the cure time. This curing method produced the IDT$_3$ strength values.
- **Curing Method D:** 30-hour cure at 104±0.5°F with specimens sealed in bags. This curing method combined the most accelerated cure time found in the literature with the more accepted accelerated cure temperature of 104°F.

For IDT strength determination, researchers fabricated six IDT test specimens at each cement content level. They molded 4-inch diameter, 2-inch tall specimens in the SGC. Researchers weighed out and compacted specimens to height in the SGC to target the maximum dry density previously determined from the Tex-113-E test methods. This compaction method generally produced specimens with no less than 95 percent and no more than 100 percent of the maximum dry density, with actual molded densities generally measuring between 95 and 98 percent of the maximum.

After curing, researchers measured the IDT strengths of three specimens to determine their dry strengths. The remaining specimens received moisture conditioning after curing (full submersion in water for 24 hours at 72±4°F) before IDT testing to determine their wet strengths.

4.4.2. UCS Testing

For UCS testing, researchers fabricated three specimens at each desired cement content level in accordance with the Tex-120-E test methods. Figure 25 shows a representative batch of IDT test specimens in the foreground with a representative batch of Tex-120-E UCS test specimens in the background.

Figure 25. Representative IDT (Front) and UCS (Back) Test Specimens.

4.4.3. MoR Testing

Researchers performed MoR tests in accordance with the ASTM C78 standard. Figure 11(c) previously showed a MoR test in progress.

4.4.4. Mr Testing

Researchers performed Mr tests in accordance with the AASHTO T307 standard using deviator stresses of 93, 138, and 300 kPa and seating stresses of 20, 40, 60, 80, and 100 kPa. Researchers performed all resilient modulus tests unconfined. Figure 26 shows the preparation and test setup for the Mr test.

Figure 26. Preparation and Setup for Mr Testing.

4.4.5. Exploratory Shrinkage Measurements on MoR Specimens

Researchers also performed exploratory work to measure shrinkage on MoR beams. Using gauge studs, researchers installed measurement points with a 10-inch gauge length onto the top of each MoR specimen from FM 205. Researchers did not de-mold the specimens during curing because this could have potentially compromised the sample. Figure 27 shows the gauge studs installed on a batch of beams with zero bars. Figure 28 shows the measurement process using a strain gauge.

Figure 27. Gauge Studs with Zero Bars for Shrinkage Measurement.

Figure 28. Shrinkage Measurement on MoR Specimens.

Initially, researchers applied the gauge studs on premeasured positions marked on the final surface of each beam. After applying epoxy to the bottom of the gauge stud and the surface of the beam, researchers adjusted the final positions of the gauge studs while the epoxy was still workable using the zero bar. After the epoxy cured, researchers recorded these measurements using the strain gauge, providing the zero value for subsequent measurements. Researchers then conducted measurements with the strain gauge at various time intervals throughout the 28-day curing period.

4.5. LAB TEST RESULTS FOR ADDITIONAL MATERIALS

4.5.1. Material Characterization

Table 8 presents the key properties of each additional material. Three of the materials represented full depth recycling (FDR) mixtures, while one material represented a virgin flexible base for widening and subsequent cement treatment. For FM 205, material quantities were limited; adequate material to perform a full characterization of the roadway sample were available only from station 365+83 and from the Type A, Grade 1–2 stockpile.

Table 8. Basic Properties of Additional Materials.

Material	US 259 50/50 RAP/Salvage Base	FM 2594 63/37 Subgrade/Salvage Base	FM 205 Station 365+83 Roadway Salvage	FM 205 Type A, Grade 1–2 Flexible Base
AASHTO Soil Classification	A-2-4	A-6	A-2-6	A-2-4
Master Grading (Percent Passing)	*This space intentionally left blank*			
1¾ inch	100.0	100	100.0	100.0
1¼ inch	97.5	100	95.9	94.5
7/8 inch	93.3	97.1	85.8	85.3
5/8 inch	88.7	94.6	75.8	74.7
3/8 inch	73.9	88.2	59.1	55.7
#4	51.5	81.7	46.6	40.2
#40	17.2	73	25.8	22.2
#100	11.0	69.1	19.7	17.4
#200	7.9	59.3	15.4	14.5
Liquid Limit (%)	23	33	28	22
Plasticity Index (%)	10	17	17	9
Maximum Density (pcf)*	128.2	119.8	132.8	133.2
Optimum Moisture Content (%)*	7.8	10.5	6.7	8.0

*Determined with a 3 percent cement content except for US 259, which was determined with a 1 percent cement content.

4.5.2. Strength Results

Table 9 shows the results from the lab testing program for each material, cement type, cement source, and cement content level. Given the range of materials and cement contents used, measured UCS values ranged from about 150 to over 600 psi. Dry IDT strength measurements ranged from 21 to over 150 psi, while moisture conditioned IDT strengths ranged from 29 to over 150 psi. Researchers believed that these ranges of UCS and IDT strength values reasonably cover the range of interest. During testing, researchers also performed exploratory work using equivalent levels of Type IL Portland-limestone cement instead of Type I/II Portland cement for one of the materials.

Table 9. Lab Testing Results for Additional Materials.

Test		**Tex-120-E UCS (psi)**	**IDT (psi)**							**MoR (psi)**	**Mr (ksi)**
Curing Method		A	A		B		C	D		A	A
Conditioning		Dry	Dry	Wet	Dry	Wet	Wet	Dry	Wet	Dry	Dry
US 259 FDR Mixture w/Queen City RAP	2%	156	-	-	21	29	Curing method C eliminated from any further testing	-	-	-	-
	4%	296	-	-	48	63		-	-	-	-
	6%	458	-	-	65	100		-	-	-	-
FM 2594 63/37 Soil/Base	2%	159	-	-	93	69		-	-	-	-
	3%	221	-	-	120	100		-	-	-	-
	4%	283	-	-	134	127		-	-	-	-
	5%	-	-	-	152	146		-	-	-	-
FM 205 New Base-Cement from Site	2%	Not tested	42	35	38	35		26	24	-	-
	3%		73	60	53	55		38	37	-	-
	4%		101	96	75	83		58	61	-	-
	6%		145	161	112	118		86	97	-	-
FM 205 New Base-*House* Cement	2%	310	44	35	35	38		31	28	53	656
	3%	401	56	59	70	60		44	49	84	1002
	4%	527	107	90	86	82		67	63	128	1135
	6%	650	150	137	116	137		97	96	161	1428
FM 205 New Base-Type IL Cement	2%	272	38	31	37	32		28	19	-	-
	3%	304	53	49	46	52		31	29	-	-
	4%	377	65	63	59	64		45	42	-	-
	6%	405	117	107	86	104		57	64	-	-
FM 205 Station 365+83-*House* Cement	2%	200	47	41	56	48		37	37	68	367
	3%	259	57	54	61	57		42	37	94	616
	4%	288	82	63	80	68		50	49	114	867
	6%	356	99	94	93	97		65	77	153	1123

-Not tested due to insufficient quantity of material sample.

4.5.3. Shrinkage Results

Figure 29 and Figure 30 present the results from the exploratory work to measure shrinkage on the MoR beams for two different materials while curing. For reference, the PCA recommends that drying shrinkage should not exceed 310 microstrain for coarse-grained soils.

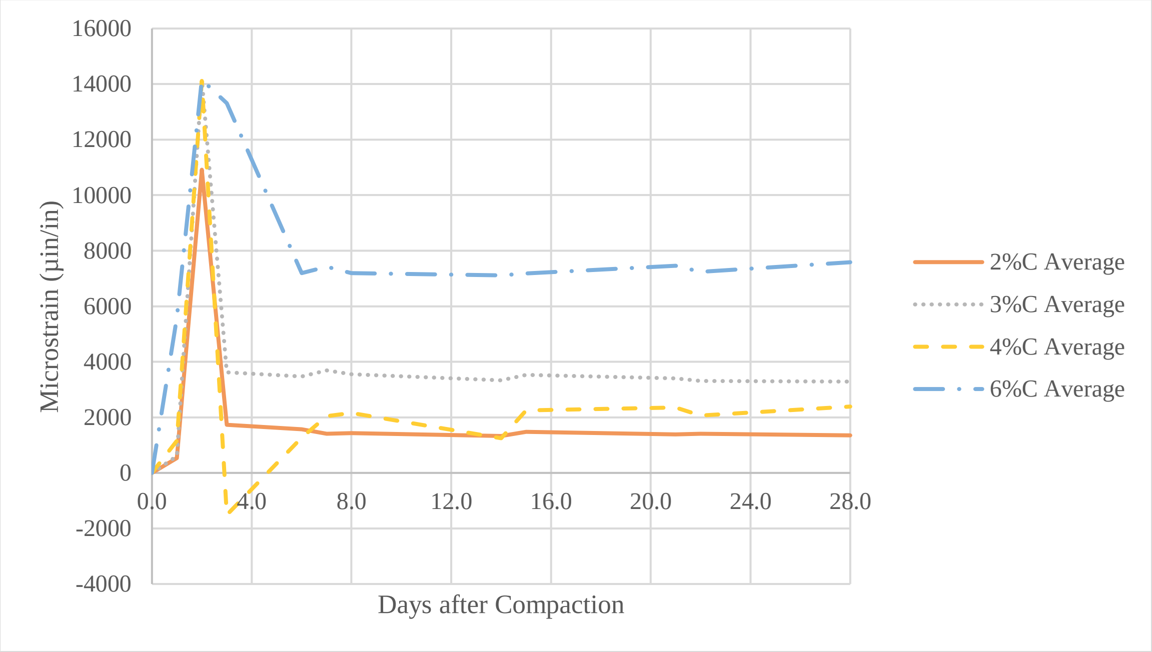


Figure 29. Shrinkage Results for the FM 205 Salvage Material.

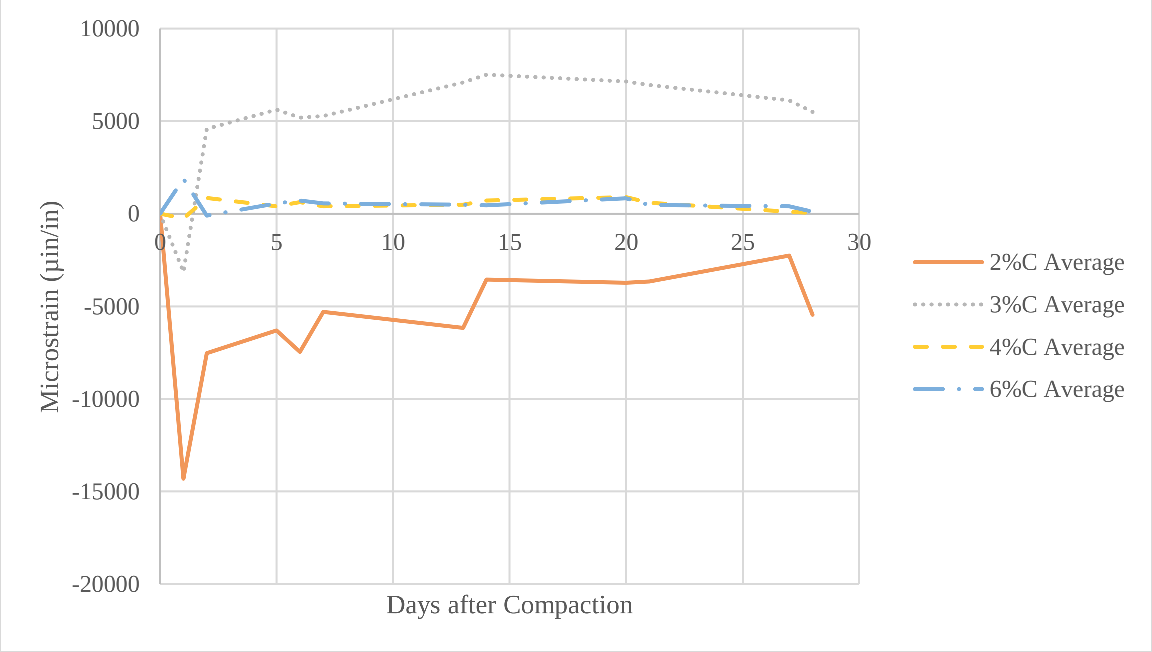


Figure 30. Shrinkage Results for the FM 205 New Base.

Researchers believed the results in Figure 29 and Figure 30 to be questionable. At a minimum, the specimens remaining in the molds during curing could have restricted movement, and the drastic spikes (and in some cases dips) in the data at the 2–3 day cure time seem suspect. Measurements from one of the specimens indicated expansion. While taking measurements, researchers also discovered that the bond between the gauge studs and specimens was unreliable. Based on these reasons for concern, researchers did not perform further analyses with these data and would not recommend attempting this test configuration again for shrinkage measurement.

4.6. ANALYSIS OF ADDITIONAL MATERIALS

Based on the test results for the additional materials, researchers focused on answering the following series of questions:

- How well does the IDT_3 strength correlate with the Tex-120-E UCS for the additional materials? (Researchers focused on the IDT_3 test method because curing method B was found to be most promising for accelerating the mixture design in the initial materials testing).
- Do the results for the additional materials agree with the UCS-IDT_3 prediction model developed in the initial materials testing?
- What other factors may exist for developing an accelerated cure IDT mix design method for cement-treated materials?
- What is the estimated precision of the IDT_3 test method?
- How well does the recommended cement content level in the IDT_3 test method agree with the level recommended in the Tex-120-E UCS test method?

4.6.1. Relationship Between IDT_3 and UCS Test Methods

Figure 31 presents the results of the Tex-120-E UCS and IDT_3 tests for each of the additional materials. The results showed strong correlations between IDT_3 strength and UCS. Thus, the results confirmed in principle that IDT tests could be a viable approach for mixture designs. The results also suggested the following:

- The slope of the relationship between UCS and IDT_3 strength was not equivalent across the three materials. The slope measured for the US 259 material was significantly higher than the slope measured for the other two materials. The slope for the FM 2594 material appeared lower than the slope for the other materials.
- The intercept in the relationship between UCS and IDT_3 strength was also not equivalent across the three materials. The intercept for the FM 205 material was higher than the intercept for the other two materials.

The next section of this report details the level of agreement between these results and findings from the initial materials tested in this research project.

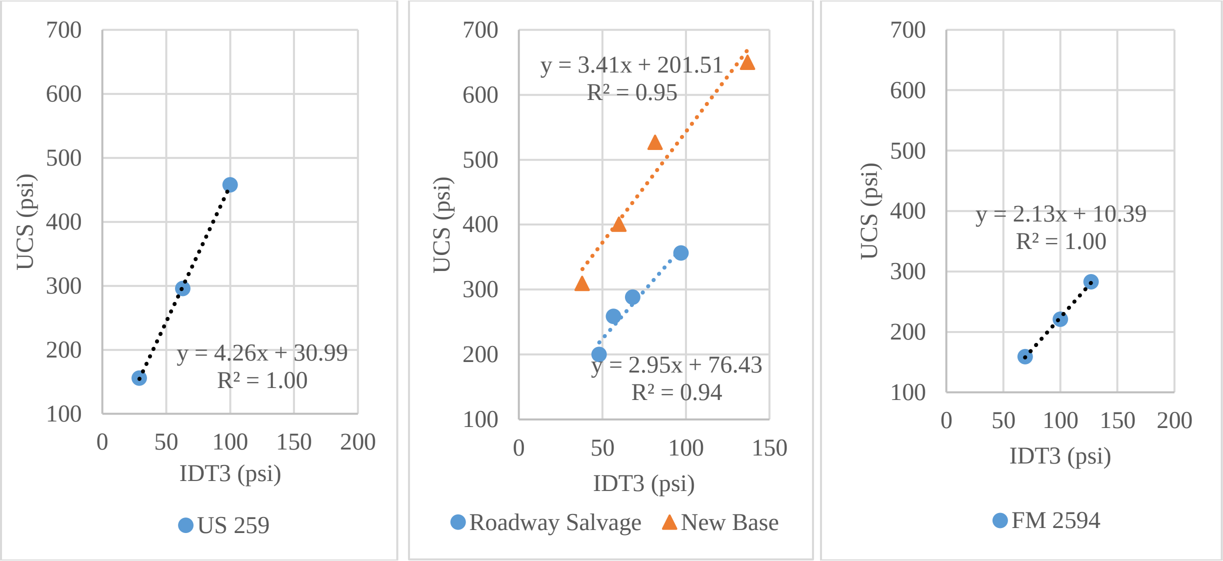


Figure 31. UCS vs. IDT_3 Strength for US 259 (Left), FM 205 (Center), and FM 2594 (Right).

4.6.2. Comparative Analysis of Additional Materials Results and Prior UCS-IDT_3 Strength Model

Equation 1 (UCS_7 [psi]=5.19 IDT_3) presented the generalized equation for estimating UCS based on IDT_3 strength based on an initial cross section of four different materials: two roadway salvage FDR materials; one type A, grade 1–2 flexible base from a stockpile; and one crushed concrete from a stockpile.

Figure 32 illustrates the results of additional material tests along with the predicted results from Equation 1. Reasonable agreement existed between the actual test data and the predicted UCS values for US 259. Results for FM 205 fell within two standard errors of Equation 1. For FM 2594, the actual UCS values were significantly lower than predicted from Equation 1. Thus, the data suggest that results for US 259 and FM 205 generally agreed with Equation 1, while the results for FM 2594 suggested that either Equation 1 was missing one or more parameters needed for a truly generalized model, or other test factors or conditions existed that contributed to the observed results.

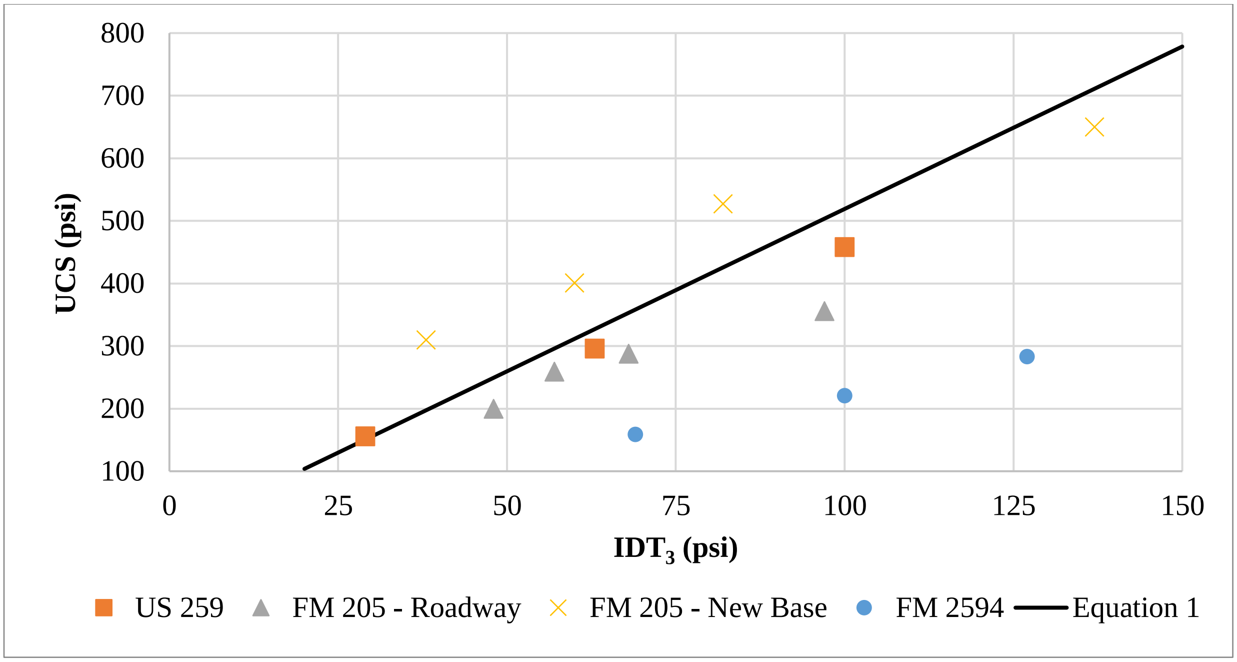


Figure 32. UCS-IDT$_3$ Strength Model Results for Additional Materials.

Researchers explored potential sources of test variability that may have helped to explain the discrepancy between Equation 1 and the actual test results for FM 2594 and identified the following issues:

- The FM 2594 material incorporated 63 percent subgrade in the mix and had almost 60 percent of material passing the #200 sieve. Other materials used in this project consisted of base material or, in the case of the FM 205 roadway salvage, primarily base material with a limited amount of subgrade incorporation. Other materials in this research had no more than 16 percent of material passing the #200 sieve.
- For the FM 2594 and FM 205 materials, the research laboratory was required to change to a different manufacturers' SGC due to nonrepairable issues with the unit that had been used to mold all prior IDT test specimens in this research.

Because the FM 2594 material was not representative of a base material due to the sizable proportion of incorporated subgrade, Figure 33 presents all results excluding FM 2594. The regression equation in Figure 33 had a standard error of 75 psi and agreed well with Equation 1.

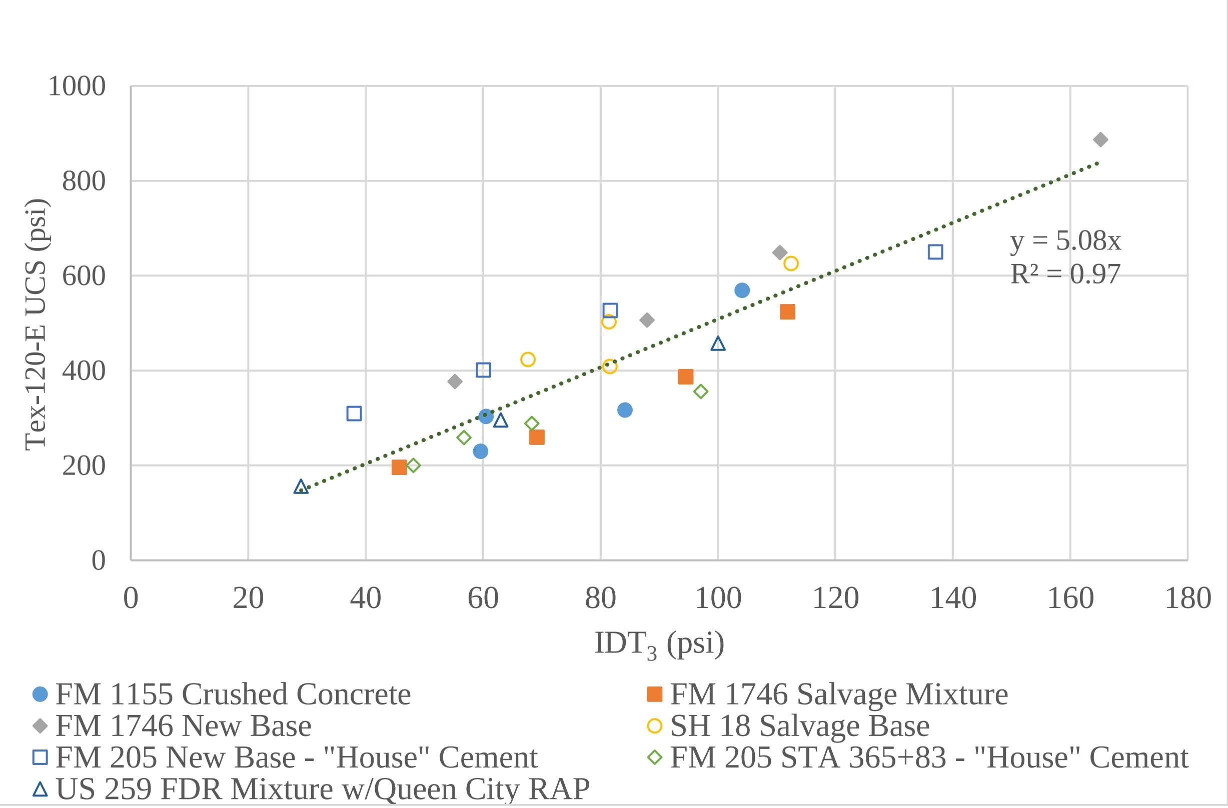


Figure 33. Pooled UCS-IDT$_3$ Strength Model Results for Additional Materials.

4.6.3. Other Factors for Developing Accelerated Mix Design

Figure 33 illustrated that material-specific factors influenced the UCS0-IDT$_3$ strength relationship, and inclusion of material-specific factors in the regression model reduced the standard error of the UCS estimate. This section explores other factors that may influence the development of an IDT-based accelerated mixture design. Factors explored by researchers included the potential influence of compaction method in the SGC, cement source, and cement type.

4.6.3.1. Influence of Compaction Method

The approach in this research project targeted the Tex-113-E maximum dry density when compacting IDT test specimens by specifying a target height of 2.0 inches in the SGC and allowing the number of gyrations (N) to vary. Feedback from stakeholders suggested that this method of allowing N to vary could be a barrier to implementation. Thus, researchers performed exploratory work to evaluate the potential influence of compaction method on the IDT$_3$ test results.

Because TxDOT’s pending methods for compacting mix design specimens for emulsified and foamed asphalt use a fixed 75 gyrations, researchers performed exploratory work to compare IDT$_3$ test results for cement-treated specimens compacted to fixed height and specimens of the same material compacted with 75 gyrations. Researchers fabricated and tested six replicates for each material/cement content/compaction method combination. Figure 37 and Table 10 summarize these results. Although exploratory in nature, the results showed no statistical differences in IDT_3 strength values between compaction methods. The data suggested, with further verification, that using a fixed 75 gyrations for compaction may be acceptable with an accelerated mix design procedure.

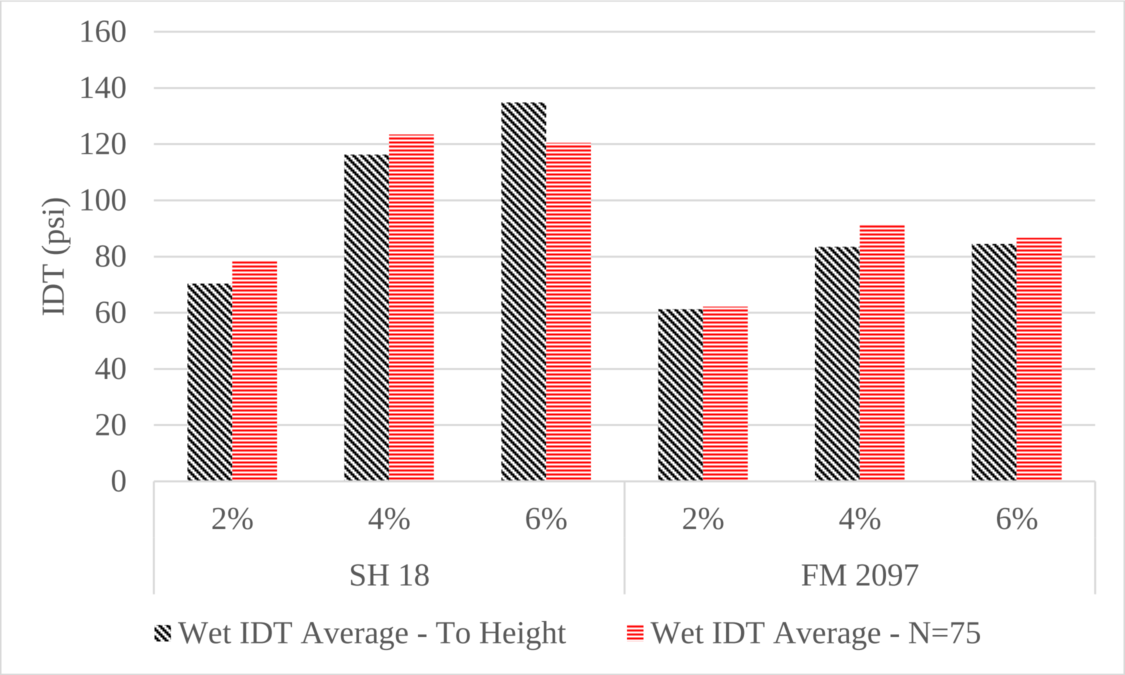


Figure 37. IDT Strengths for Specimens Compacted to Height vs. a Fixed 75 Gyrations.

Table 10. Influence of Compaction Method on IDT Strength.

Project	Cement Content (%)	To Height Average IDT (psi)	N=75 Average IDT (psi)	P-value
SH 18	2	70	78	0.06
SH 18	4	116	123	0.34
SH 18	6	135	120	0.16
FM 2097	2	61	62	0.77
FM 2097	4	83	91	0.13
FM 2097	6	84	87	0.67

4.6.3.2. Influence of Cement Source

Researchers performed additional exploratory work using two different sources of Type I/II cement for the FM 205 new base material. Researchers used cement sampled from the actual construction project and compared results to those attained from specimens prepared using the *house* cement source used throughout this research project. Figure 34 illustrates, and statistical tests confirmed, that no significant differences existed in IDT strengths based on cement source.

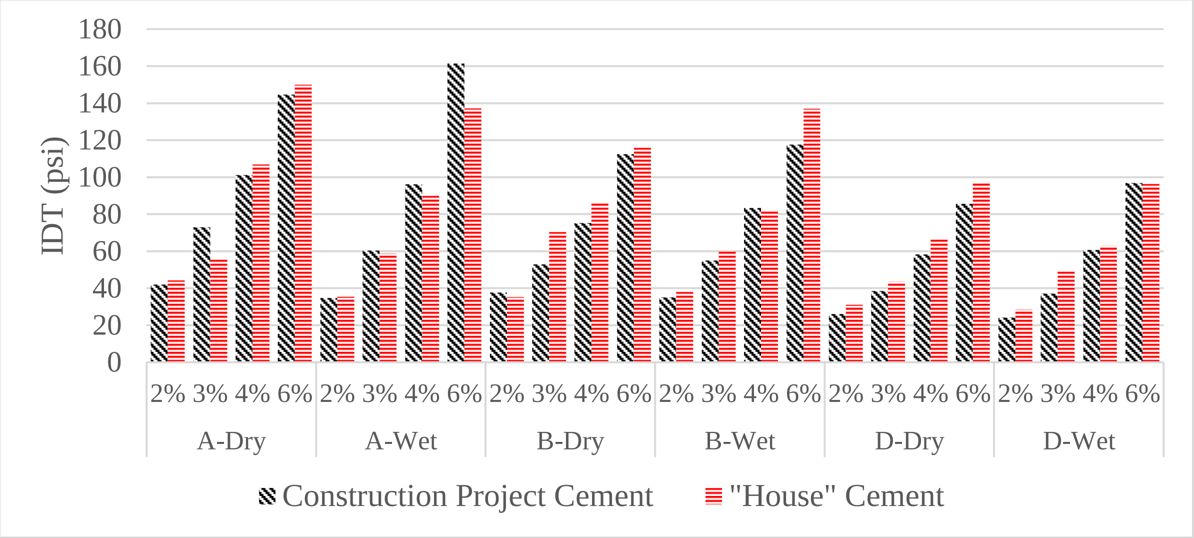


Figure 34. IDT Strengths by Type I/II Cement Source.

4.6.3.3. Influence of Cement Type

Researchers also performed exploratory work using Type IL cement for the FM 205 new base material. Researchers compared the results obtained from specimens prepared with the *house* Type I/II cement to those obtained using the Type IL cement. While there was limited data, researchers observed that—when treated with the same cement content levels—the UCS and IDT strengths behaved differently with the Type IL cement. Figure 35 indicates notable differences in the IDT test results based on the type of cement used. Paired t-tests confirmed that the differences in IDT strengths between the Type I/II and Type IL cements (with the same cement contents) were significant at the 90 percent confidence level for all IDT test methods considered, except for curing method A-dry.

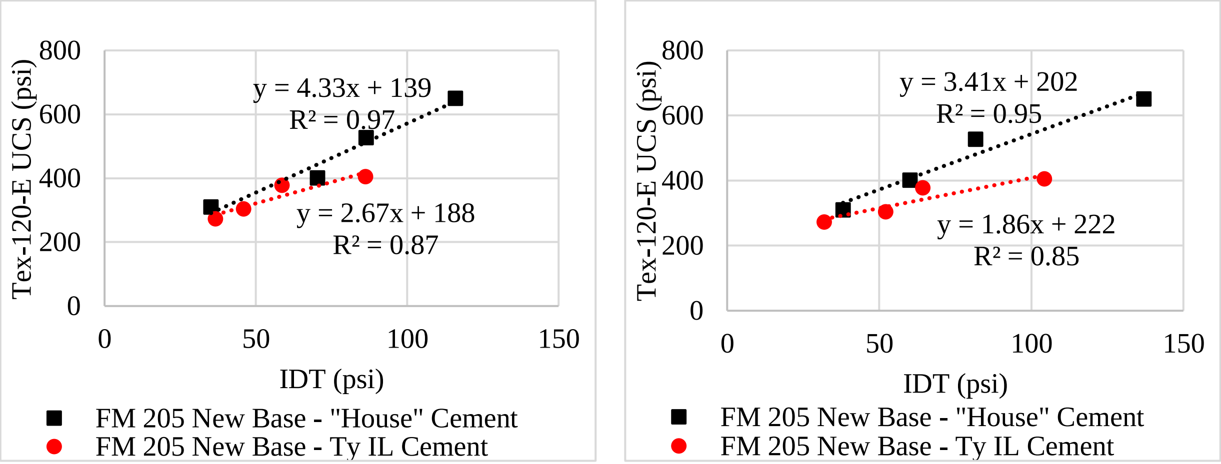


Figure 35. Example UCS vs. IDT Strength by Cement Type and Curing Method B-Dry (Left) and Curing Method B-Wet (Right).

To supplement the limited data in this study, researchers searched for further guidance in the literature. Tsivilis et al. (2000) conducted a study that investigated the effects of adding various percentages of limestone to cement pastes, as well as the concurrent effects of increasing fineness due to the limestone additions. Their findings indicated that as the limestone content increased (along with other additions), specimen strengths decreased, particularly after 28 days. Similar studies by Nehdi et al. (1996) and Marzouki (2013) also observed a notable decrease in compressive strength as limestone content increased.

Overall, these findings suggested that achieving a generalized accelerated mixing design approach using Type IL cement remains challenging based on the results obtained in this study. Caution should be exercised to only apply the findings from this research within the scope of material types used in the underlying data.

4.6.4. Precision of IDT_3 Test

A separate task of this research estimated the in-lab precision of the IDT_3 test. That work, summarized in Product 0-7027-P4, developed the in-lab precision estimates shown in Table 11.

Table 11. In-Lab Precision Estimates for the IDT_3 Test.

Cement Content (%)	Average IDT_3 (psi)	In-Lab Standard Deviation (psi)
2	46.2	4.0
4	81.2	7.3
6	108.8	15.9

4.6.5. Application of IDT_3 Strength for Setting Cement Rate

A key desired outcome from this project was a method to set cement content levels for cement-treated bases based on the IDT strength. Table 12 presents the recommended cement content levels for all the materials tested to date in this project based on specific criteria. More specifically, Table 12 presents the following information:

- The cement content levels required in the Tex-120-E test method to meet the minimum UCS.
- The cement content levels to meet the minimum UCS based on Equation 7 and the observed relationship between cement content and IDT_3 strength for that material.
- The cement content levels based on a material specific UCS-IDT_3 strength relationship. Establishing this cement content level requires two steps: (1) analyzing the UCS and IDT_3 strength relationship for a specific material to determine a material specific IDT_3 strength threshold and (2) analyzing the cement content and IDT_3 strength relationship to determine the cement content level required to meet the material specific IDT_3 strength minimum.

Table 12 presents these cement content levels for all materials included in this project.

Table 12. Cement Content Levels Based on Different Test Methods.

Material	Cement Content (%)		
	Tex-120-E and Minimum UCS Requirement*	**Generalized UCS-IDT$_3$ Relationship**	**Material-Specific UCS-IDT$_3$ Relationship**
FM 1155 Crushed Concrete	3.1	2.1	3.0
FM 1746 Salvage	3.3	2.4	3.2
FM 1746 New Base	1.4	2.0	1.4
SH 18 Salvage Base	0.3	1.2	0.09
US 259	4.0	3.7	3.9
FM 205 Salvage	3.1	2.2	3.0
FM 205 New base	1.2	2.5	1.1
FM 2594 soil/base	2.7	0.9	2.7

*300 psi minimum in all cases, except for FM 205 (250 psi) and FM 2594 (200 psi).

The results in Table 12 showed that, with the exception of the FM 2594 material, the generalized UCS-IDT$_3$ relationship (Equation 1) developed in this research project produced recommended cement content levels that were within 1.3 percentage points of the required cement content levels determined in accordance with the Tex-120-E test method. The FM 2594 material, which included 63 percent subgrade in the mix and had almost 60 percent of material passing the #200 sieve, was not consistent with the original scope of materials intended for inclusion in this research. As expected, Table 12 also showed that cement content levels based on a material specific UCS-IDT$_3$ relationship were in substantial agreement with the cement content levels determined by the Tex-120-E test method. This observation was particularly evident for the FM 2594 material that incorporated greater than 60 percent subgrade in its mix.

4.7. SUMMARY OF FINDINGS AND RECOMMENDATIONS FROM THE LAB STUDY

This laboratory research program systematically evaluated the use of IDT tests as a basis for the mixture design of cement-treated bases. Researchers used four different curing programs (specifically seeking to accelerate test turnaround times), along with standard 7-day moist cure UCS values for reference, to evaluate the relationship between IDT test results and compressive strengths.

The results showed that three of the four IDT test methods (based on the four different curing methods) could be used as a basis for mix design, as evidenced by their strong correlations to the reference UCS values. Specifically noteworthy is the fact that these data indicated that accelerated IDT tests with 72-hour cures and even 30-hour cures were viable. The lab study results supported the following conclusions:

- IDT test methods that included a 72-hour accelerated cure with molded specimens sealed in bags and maintained at 104°F, followed by a 24-hour moisture conditioning by water submersion, provided the best basis for mix design among all the IDT test methods analyzed in this research.

- Of the IDT test methods evaluated, only the 7-day cure showed a systematic drop in wet IDT strengths compared to dry IDT strengths. Researchers hypothesized that this observation may be due to the ongoing cement hydration and reaction kinetics occurring during an accelerated cure. Although mix design based on accelerated curing was proven feasible based on the data in this study, some risk exists that potential moisture sensitivity may not be detected within an accelerated cure time.
- For an accelerated cure, moisture conditioned IDT test method, the minimum IDT_3 strength thresholds can be related to historical minimum Tex-120-E UCS values (see Table 13).

Table 13. Tex-120-E UCS and IDT_3 Strength Target and Minimum Values.

Tex-120-E UCS Target (psi)	Accelerated Cure IDT_3 Minimum (psi)
175	34
220	43
300	59
500	98

- Recommended cement content levels from the accelerated cure IDT_3 approach agreed within 1.3 percentage points with the cement content levels determined in the Tex-120-E test method for all materials except one. This one material contained greater than 60 percent subgrade, and almost 60 percent of material passed the #200 sieve, which may or may not have contributed to this outcome.
- Results from this project also validated the prior MoR prediction model reported in the literature that was developed using Texas-based materials. Additionally, data from this study demonstrated that the accelerated cure IDT_3 strength values can be used to estimate the MoR and Mr.

Researchers recommend consideration of the accelerated mix design IDT test method as an option in the Tex-120-E procedures for cement-treated bases. This option would harmonize with methods currently used for emulsion or foamed asphalt treatments. However, in contrast to the current methods for asphalt treatments, researchers recommend fabricating and testing all six specimens using moisture conditioning. This approach would improve the confidence in the reported average IDT strength value by increasing the number of replicates and would also simplify the workflow. Product 0-7027-P2B presents a recommended test method.

Moreover, researchers recommend leveraging mix design data into pavement analysis and design. Results from this project showed that the accelerated cure IDT_3 strength values can be used to estimate the modulus of rupture and the resilient modulus. Chapter 6 of this report presents an approach that could synergize laboratory IDT_3 mix design tests with pavement design checks.

CHAPTER 5. DEMONSTRATION PROJECT RECOMMENDATIONS

Researchers coordinated with TxDOT districts for four demonstration projects. Two of the projects were constructed; post-construction FWD measurements were collected on the as-built typical sections.

5.1. US 180

5.1.1. Background

The US 180 project location, in Scurry County from US 84 to 0.3 miles east of CR 1121, includes an 8-inch cement treatment through full depth reclamation, followed by a 4-inch overlay. Figure 36 shows an example of the condition before the work and the collection of site materials for laboratory testing.

Figure 36. US 180 Initial Condition (Left) and Site Material Collection (Right).

5.1.2. Material Information

Using materials from the site, researchers reconstituted 75 percent salvage base with 25 percent salvage RAP to replicate the anticipated material combination and determined that either a 2 or 3 percent cement content level would be suitable for treatment of the material. Table 14 shows the lab strength results. The IDT strength values were generated using a 7-day cure in a moist room. The UCS was measured in accordance with the Tex-120-E test methods.

Table 14. Lab Strengths of Cement-Treated Materials from US 180.

Percent Cement	Dry IDT Strength (psi)	Wet IDT Strength (psi)	UCS (psi)
2	68	53	298
3	69	62	291
4	80	64	Not tested

5.1.3. Recommendations

Based on the results in Table 14, treatment with a 2 or 3 percent cement content level should be a suitable rate for the project materials. The district decided to treat with a 2.5 percent cement content.

5.1.4. Construction and Pavement Performance

The project was constructed in 2022, and researchers performed FWD tests on the completed project in March 2023. Figure 37 shows the completed project. Table 15 summarizes the FWD test results. No distresses were observed, and the measured field modulus well exceeds the value assumed in design.

Figure 37. Completed US 180 Project.

Table 15. FWD Test Results for the US 180 Constructed Project.

Average Normalized Deflection (mil)	5.90
Average Cement-Treated Base Modulus (ksi)	726
Adjusted Mean Cement-Treated Base Modulus (ksi)	454

5.2. FM 205

5.2.1. Background

The FM 205 project location, in Erath County from 0.456 miles northeast of CR 182 to FM 2870, consisted of widening the roadway with new flexible base and included 8 inches of road-mixed cement treatment and 3.5 inches of hot mix asphalt.

5.2.2. Material Information

Table 8 previously presented the lab results for the roadway salvage material and the new base used for the widening.

5.2.3. Recommendations

Table 9 previously indicated recommended cement content levels of 2.2 to 2.5 percent based on the IDT_3 strength. Figure 38 presents a test section layout that was determined and constructed in the field in March 2022, in coordination with the TxDOT district. The cement content levels in the westbound (WB) direction had already been determined by the TxDOT district based on material properties. The cement content levels in the eastbound (EB) direction were determined cooperatively by TxDOT district personnel and this project's researchers.

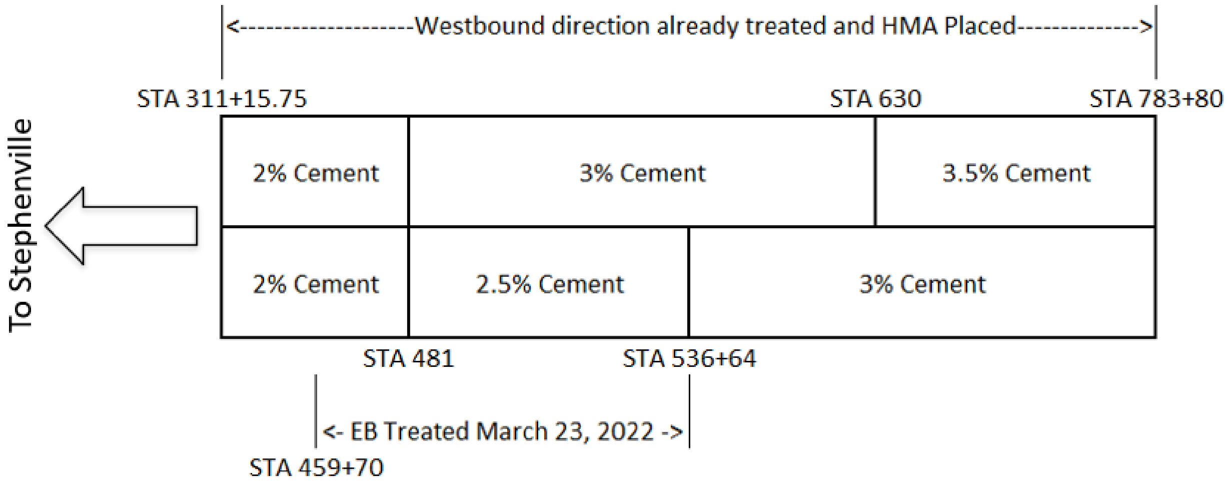


Figure 38. Test Section Layout on FM 205.

5.2.4. Construction and Pavement Performance

The general construction sequence for the cement treatment took place over 5 working days as follows:

Day 1	Prepulverize and correct cross slope.
Day 2	Treat with cement.
Day 3	Finish treated base.

Day 4 Place seal coat.
Day 5 Place first lift of hot mix asphalt.

Figure 39 illustrates the cement treatment operation on March 23, 2022.

Figure 39. Cement Treatment on FM 205.

Researchers collected FWD measurements on the completed project on August 2, 2022. Table 16 summarizes the results for the EB direction, where cement content levels were selected based on this research. The results showed almost identical average deflections throughout the project. Table 16 shows the lowest base modulus at the station treated with 2.5 percent cement; however, the average base moduli were not found to be statistically different after considering variability in the data. The results also showed that the average field modulus values measured by the FWD, which ranged from 377 to 538 ksi, were reasonably consistent with the lab results for the roadway material treated with 2 to 3 percent cement. The lab results (shown previously in Table 9) ranged from 367 to 616 ksi.

Table 16. FWD Test Results for the EB Direction of the FM 205 Constructed Project.

Starting Station	Ending Station	Cement Content (%)	Average Deflection (mil)	Average Base Modulus (ksi)
311.15	481	2	7.92	538
481	536.64	2.5	7.94	377
536.64	783.80	3.0	7.42	418

5.3. FM 1632

5.3.1. Background

The FM1632 project location, in Tyler County from FM 256 to US 69, will consist of widening the roadway with new flexible base and will include 8 inches of cement-treated material and 2 inches of HMA. This project has not yet been constructed.

Figure 40 shows an example of the ground penetrating radar (GPR) data collection process and the types of distresses observed. The GPR showed 1–4 inches of existing surfacing, some evidence of patching, and about 7–8 inches of total existing pavement. Existing distresses included cracking and wide, deep rutting in some locations.

Figure 40. FM 1632 GPR Data Collection (Left), Cracking (Center), and Rutting (Right).

Approximately 2.2 miles of the project have a flexible base, while the remaining 2.9 miles have a sand-oil base. Considering the new flexible base that will be used for widening, three different mixture designs were needed for this project.

5.3.2. Material Information and Recommendations

Table 17 presents the results for the three different material combinations. Due to material variability, along with different maximum material dry densities, the recommended uniform cement spread rate of 24.9 lb/yd^2 was selected by the TxDOT district for application over the entire project. The last row in Table 17 presents the equivalent cement content level as a percentage by weight for each material.

Table 17. Lab Strengths and Selected Cement Rate for FM 1632.

	38/62 RAP/Salvage Flexible Base	**38/62 RAP/Sand-Oil Base**	**New Type A, Grade 1–2 Flexible Base**
2% Cement IDT$_3$ Strength (psi)	42	36	51
2% Cement UCS (psi)	224	161	510
4% Cement IDT$_3$ Strength (psi)	80	70	104
4% Cement UCS (psi)	362	277	870
Selected Design Cement Content (%)[1]	3.4	3.4	2.8

[1] Based on a 24.9 lb/yd^2 cement spread rate and actual material densities.

5.4. FM 1745

5.4.1. Background

The FM1745 project location, in Tyler County from US 287 to FM 256, will consist of widening the roadway with new flexible base, placing 3 inches of new base over the newly widened road, and then treating 9 inches with cement. The final surface will be 2 inches of HMA. This project has not yet been constructed. Figure 41 shows two examples of current project conditions.

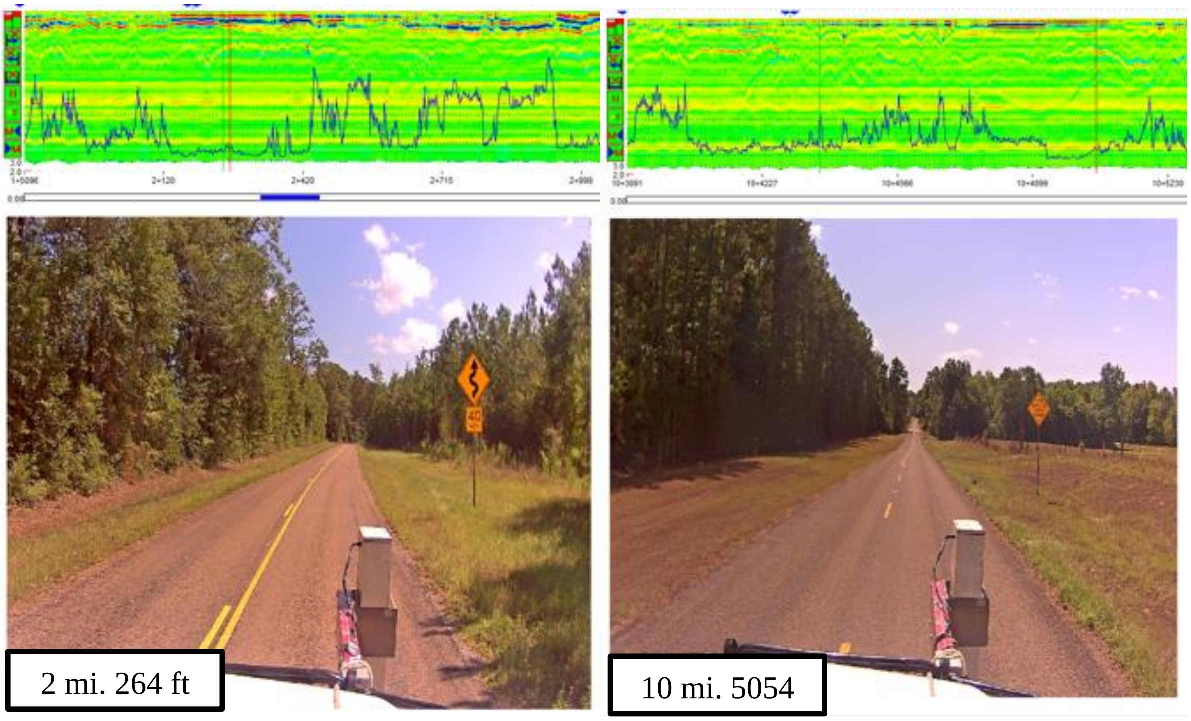


Figure 41. FM 1745 Initial Conditions with Sand-Oil Base (Left) and Iron Ore Base (Right).

Approximately 4.86 miles of the project have a soil-asphalt base, while the remaining 8.9 miles have an iron ore gravel base. Thus, mixture designs must include both material types. Additionally, a third mixture design was needed for the new flexible base material that will be used for widening.

5.4.2. Material Information and Recommendations

Table 18 presents the results for the three different material combinations. Due to material variability, along with different maximum material dry densities, the recommended uniform cement spread rate of 28.2 lb/yd^2 was selected by the TxDOT district for application over the entire project. The last row in Table 18 presents the equivalent cement content level as a percentage by weight for each material.

Table 18. Lab Strengths and Selected Cement Rate for FM 1745.

	33/33/34 New Flexible Base/RAP/Sand-Oil Base	33/67 New Flexible Base/Salvage Pavement	New Type A, Grade 1–2 Flexible Base
2% Cement IDT_3 Strength (psi)	54	39	51
2% Cement UCS (psi)	145	216	510
4% Cement IDT_3 Strength (psi)	92	48	104
4% Cement UCS (psi)	274	321	870
Selected Design Cement Content (%)[1]	3.3	3.2	2.8

[1] Based on a 28.2 lb/yd^2 cement spread rate and actual material densities.

5.5. CONCLUSIONS FROM DEMONSTRATION PROJECTS

The demonstration projects illustrated some of the potential advantages of small sample, rapid mix design for cement-treated bases. On three of the four projects, multiple materials and/or material combinations required evaluation. The small sample approach based on the accelerated cure IDT strength allowed these materials to be screened using significantly less material and with a faster test turnaround time.

Two demonstration projects had been constructed during this research, and FWD measurements on both completed construction projects showed adjusted mean base modulus values over 300 ksi. For the project where both field and lab base modulus measurements were available, the lab results agreed reasonably well with the field results for the range of cement contents considered. These construction projects should continue to be monitored over time. The sections that have not yet been constructed should also undergo performance monitoring to evaluate their field performance.

CHAPTER 6. DEVELOPMENT OF A CEMENT-TREATED BASE MECHANISTIC CHECK

6.1. BACKGROUND AND OBJECTIVES

The Flexible Pavement Design System 21 (FPS 21) is currently used to design the thickness of cement-treated base (CTB) layers in Texas. However, the FPS 21 training documentation acknowledges that stiff, stabilized bases are not modeled effectively in the FPS 21. When the current FPS 21 methods were developed, many TxDOT districts used high (~6 percent) cement contents in their pavements. The problem with these pavements was not rutting or cracking (as predicted by the FPS 21) but severe block cracking. This cracking allowed moisture to enter the pavement, weakening the base and subbase layer(s). The application of heavy truck loads subsequently led to base failures (Figure 42).

Figure 42. Early Severe Failures on Stiff CTB Layers with High Cement Contents.

To minimize the risk of failures due to thin, stiff CTB layers, TxDOT adopted design values between 80 and 150 ksi for CTB layers used in the FPS 21. These values were obtained through backcalculation of FWD data for pavements with CTB layers that had developed severe cracks. The FWD was positioned with the crack between the W1 and W2 sensors.

Currently, the failure mechanisms shown in Figure 42 are not common in TxDOT roadways, because most districts have adopted practices that generally result in around 3 and usually no more than 4 percent cement. In the current design of CTB layers, the FPS 21 needs to be updated to include a mechanistic design check for stabilized layers. A similar check is currently included in the FPS 21 for asphalt fatigue cracking and subgrade rutting; a similar fatigue cracking check of CTB layers needs to be developed and implemented. The purpose of this check is to ensure that a base layer will not crack under a relatively low number of heavy truck traffic loads.

This chapter outlines a feasible approach for implementing a mechanistic check into TxDOT's design procedure for CTB layers that synergizes the accelerated cure mix design developed in this research project with mechanistic-empirical pavement analysis tools.

6.2. MECHANISTIC CHECK APPROACH

Two methods for estimating cement-treated base fatigue life exist in the literature (Scullion et al., 2008). The basis of all CTB thickness design methods is to restrict the stress ratio at the bottom of the stabilized layer (i.e., the ratio of the load-induced tensile stress to the modulus of rupture of the material). It is assumed that if the tensile stress is less than 45 percent of the MoR, then the fatigue life of the CTB layer will be infinite (i.e., no fatigue damage will occur).

6.2.1. CTB Fatigue Models

In the National Cooperative Highway Research Program's *Mechanistic Empirical Pavement Design Guide* (NCHRP 1-37A), computed stresses for CTB layers are not adjusted to factor in shrinkage cracking, and layer moduli are assumed constant throughout the pavement life (Applied Research Associates, Inc.-ERES Consultants Division, 2004). The performance criterion for fatigue cracking is defined in terms of a damage index that reflects the amount of computed fatigue life used up by each axle group.

Scullion et al. (2008) proposed a mechanistic check for CTB layers. For this check, the design limit for accumulative fatigue damage is set to 25 percent (0.25) of the total fatigue life. Design modifications may entail increasing layer thicknesses until fatigue life usage falls below 25 percent. This 25 percent damage threshold is established to accommodate uncertainties in performance, including shrinkage cracks. The fatigue relationship is contingent on the stress ratio as follows:

$$\log N_f = \frac{(0.972\beta_{c1} - (\frac{\sigma_t}{MR})}{0.0825 * \beta_{c2}} \tag{8}$$

where N_f is the number of repetitions to fatigue cracking of the stabilized layer, σ_t is the maximum traffic induced tensile stress at the bottom of the stabilized layer (psi), Mr is the 28-day modulus of rupture (psi), and β_{c1} and β_{c2} are field calibration factors.

Packard (1970) had proposed an alternate mechanistic check for CTB layers in which the fatigue relationship was inspired by the PCA design approach used for soil-cement bases. This relationship is expressed exponentially as follows:

$$N_f = \left(\frac{\beta_{c4}}{\sigma_t / MR} \right)^{\beta_{c3} \cdot 20} \tag{9}$$

where β_{c3} and β_{c4} are field calibration factors.

Scullion et al. (2008) developed field calibration factors for both models in Equation 8 and Equation 9. Researchers concluded that the best experimental data was developed by Larsen et al. (1969). Table 19 presents the calibration factors developed by Scullion et al. (2008), and Figure 43 compares model predictions with actual stress ratio measurements.

Table 19. CTB Fatigue Model Calibration Factors (Scullion et al., 2008).

β_{c1}	β_{c2}	β_{c3}	β_{c4}
1.0645	0.9003	1.0259	1.1368

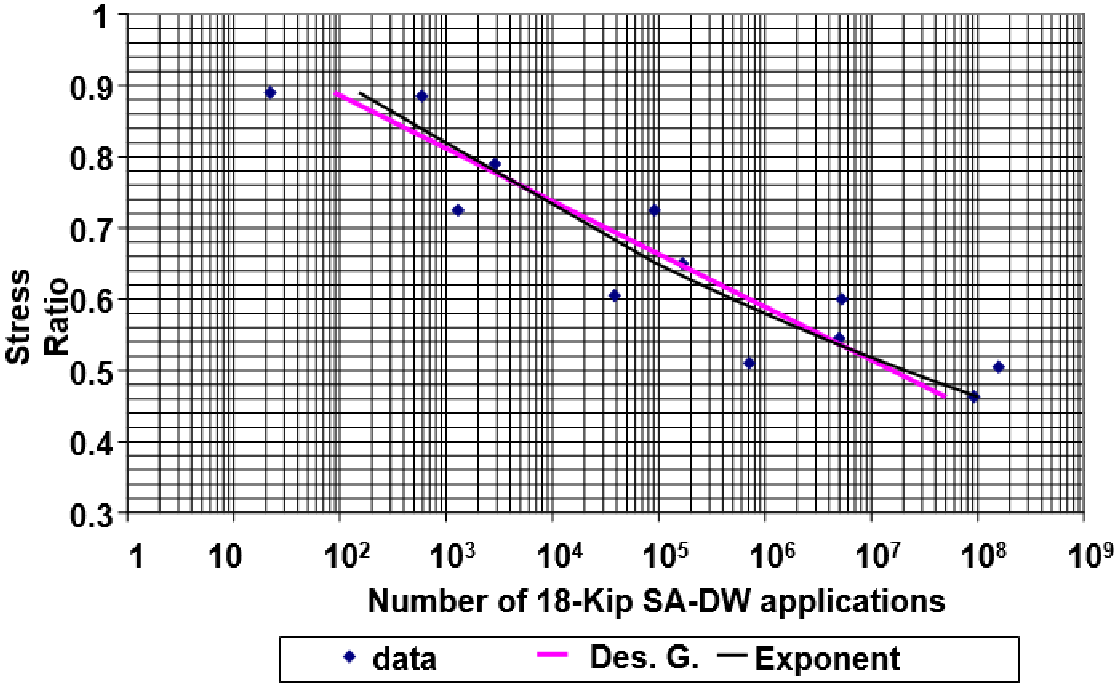


Figure 43. Actual vs. Predicted Stress Ratios from the CTB Fatigue Model (Scullion et al., 2008).

6.2.2. Other Inputs for a CTB Mechanistic Check

Mechanistic check approaches require axle load and tire configuration inputs, pavement section thicknesses, and pavement layer properties. Specific to cement-treated base layers, values for the MoR, Mr, and Poisson's ratio are required.

The most reliable approach for determining these CTB material properties would be to use field-measured Mr values from the FWD and lab-measured MoR values collected according to the ASTM C78 standard; however, obtaining such values for every material would require substantial time, effort, and cost (Figure 44).

Figure 44. Most Reliable Inputs for CTB Mechanistic Check Include Lab-Measured MoR Values (Left) and Field-Measured FWD Mr Values (Right).

6.2.2.1. Estimating CTB MoR for Mechanistic Check

The lab results in this research showed that the IDT$_3$ test method developed for accelerating the mixture design of cement-treated bases could be used to estimate the MoR. Additionally, results in this research project showed that the fit of the IDT$_3$ strength-MoR relationship was nearly equivalent to the fit of the UCS-MoR relationship (Figure 45).

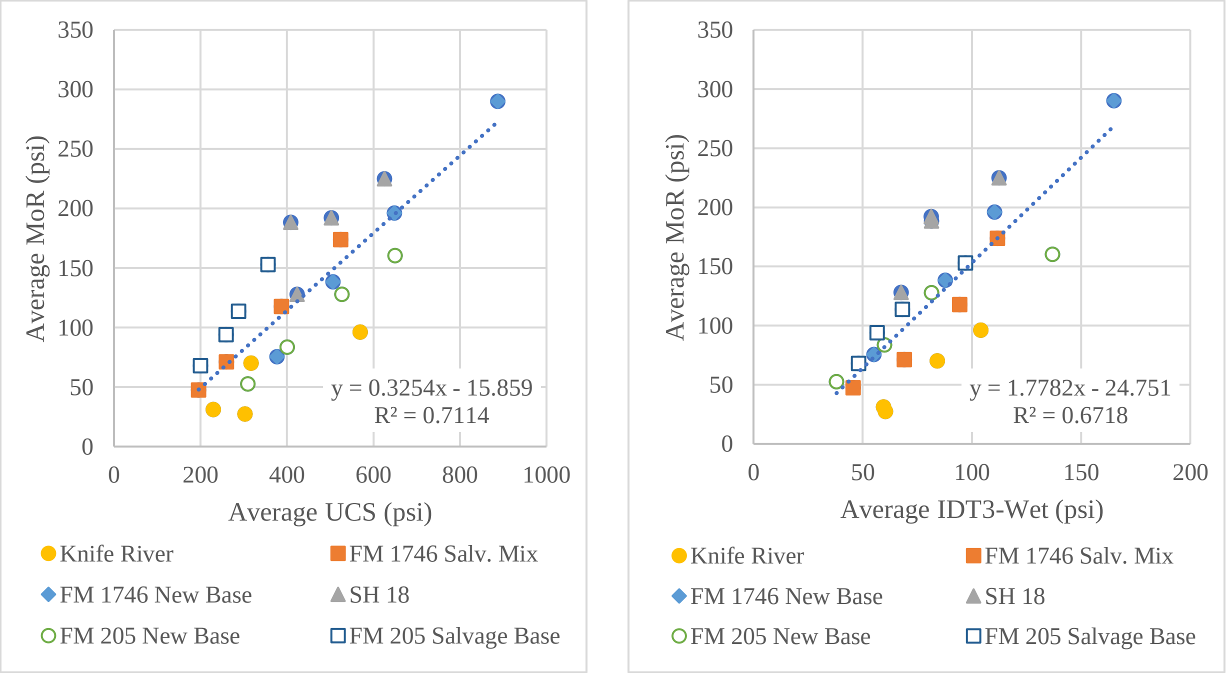


Figure 45. MoR vs. UCS (Left) and IDT$_3$ Strength (Right).

Thus, the data from this research suggested that the IDT$_3$ strength from an accelerated mix design was suitable for estimating the 28-day MoR using the following formulation:

$$\text{28-day MoR (psi)} = 1.778\ \text{IDT}_3 - 24.7 \tag{10}$$

6.2.2.2. Estimating CTB Mr for Mechanistic Check

To develop an estimated resilient modulus value for the CTB layer, researchers similarly considered the fit of the IDT$_3$ strength-Mr and UCS-Mr relationships. Figure 46 shows a reasonable fit between the UCS and Mr and the IDT$_3$ strength and Mr.

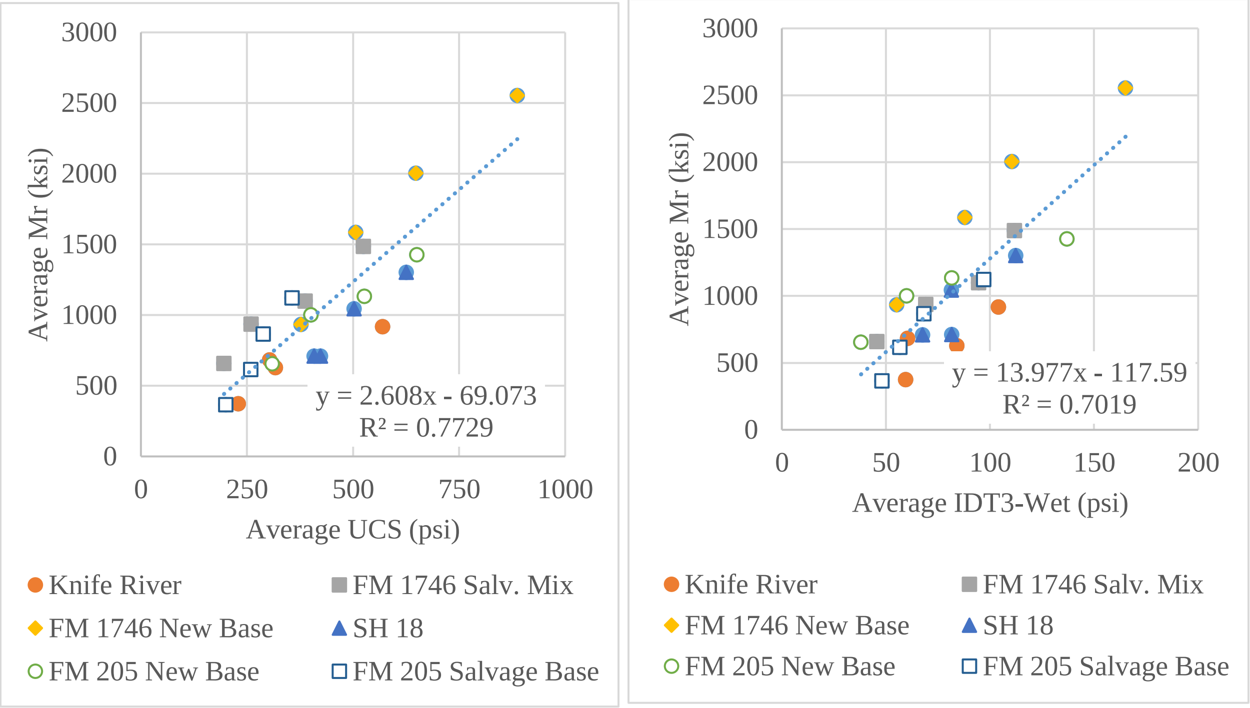


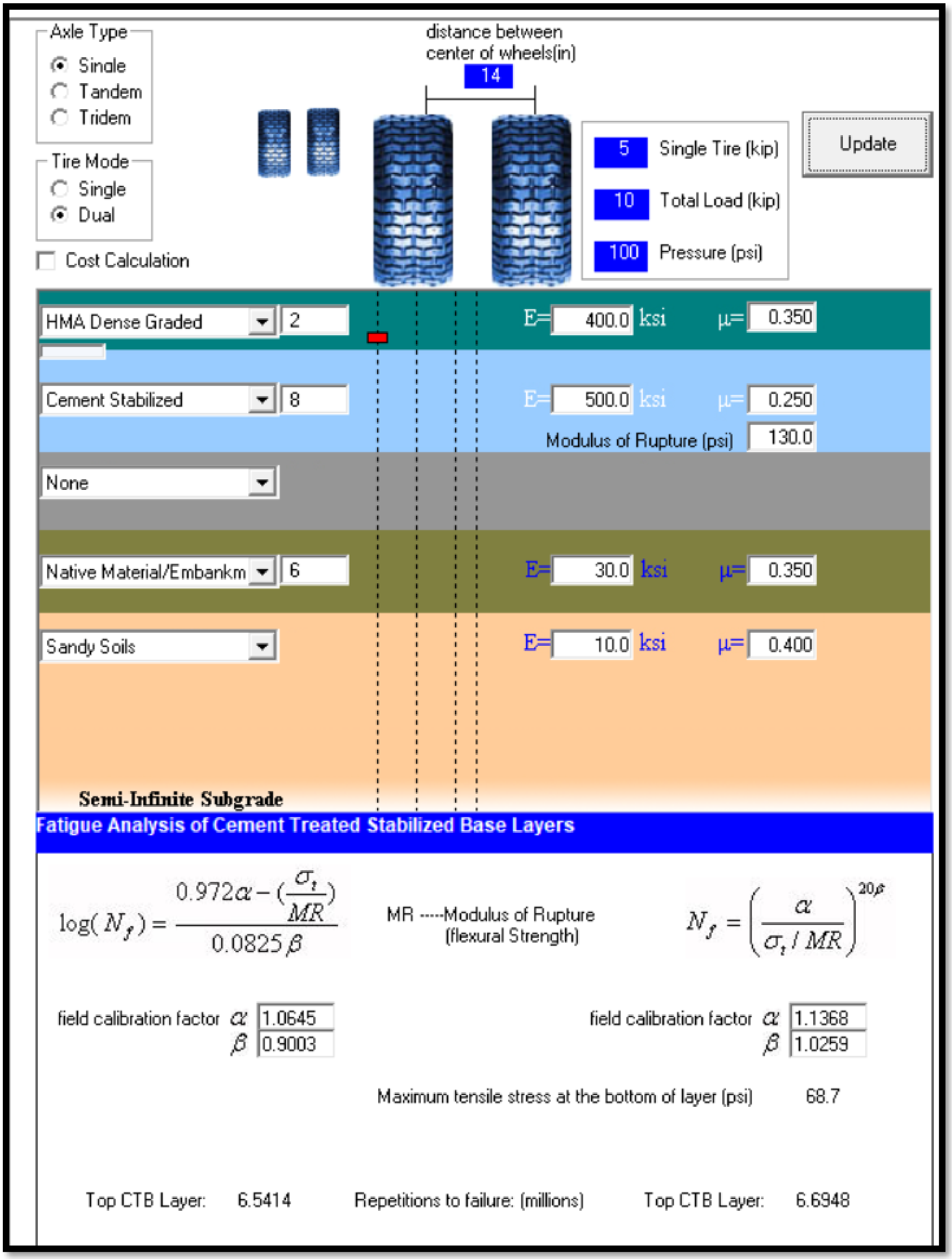
Figure 46. Mr vs. UCS (Left) and IDT$_3$ Strength (Right).

Although Figure 46 suggests a slightly better fit using the UCS, researchers believed that the IDT$_3$ strength remained suitable for use in estimating the Mr using the following formulation:

$$\text{Mr (ksi)} = 13.98\ \text{IDT}_3 - 117.6 \tag{11}$$

6.2.3. Integration of Mechanistic Check into Pavement Analysis

The models and calibration factors from Equation 8, Equation 9, and Table 19 were incorporated into a pavement analysis and design tool. Figure 47 shows the outputs from one run. The CTB design modulus and MoR can be predicted using the relationships developed in this study (Figure 45 and Figure 46). The preliminary design thickness and support conditions are shown in the upper portion of Figure 47. The maximum tensile stress and predicted load applications to failure for both models according to Equation 8 and Equation 9 are shown in the lower portion of Figure 47; in this example the average number of loads to failure is about 6.6 million.



Axle Type

● Single
○ Tandem
○ Tridem

Tire Mode

○ Single
● Dual

☐ Cost Calculation

distance between center of wheels(in): 14

5 Single Tire (kip)
10 Total Load (kip)
100 Pressure (psi)

HMA Dense Graded: 2, E= 400.0 ksi, μ= 0.350
Cement Stabilized: 8, E= 500.0 ksi, μ= 0.250
Modulus of Rupture (psi): 130.0
None
Native Material/Embankm: 6, E= 30.0 ksi, μ= 0.350
Sandy Soils: E= 10.0 ksi, μ= 0.400

Semi-Infinite Subgrade

Fatigue Analysis of Cement Treated Stabilized Base Layers

$$\log(N_f) = \frac{0.972\alpha - (\frac{\sigma_t}{MR})}{0.0825\beta}$$

MR -----Modulus of Rupture (flexural Strength)

$$N_f = \left(\frac{\alpha}{\sigma_t / MR}\right)^{20\beta}$$

field calibration factor α: 1.0645
β: 0.9003

field calibration factor α: 1.1368
β: 1.0259

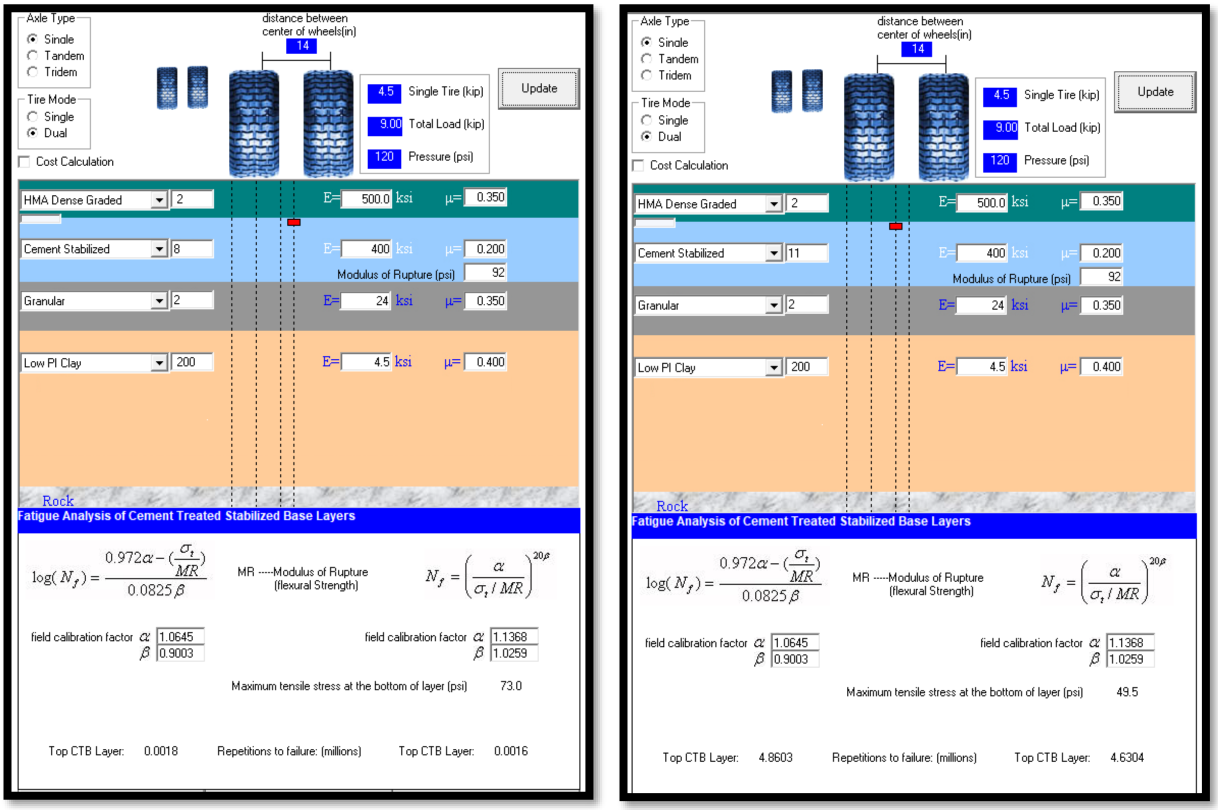
Maximum tensile stress at the bottom of layer (psi): 68.7

Repetitions to failure: (millions)
Top CTB Layer: 6.5414
Top CTB Layer: 6.6948

Figure 47. CTB Mechanistic Check.

6.3. MECHANISTIC CHECK CASE STUDY

Figure 48 presents the mechanistic check results for a case study project where the FWD detected a localized 0.6 mile long section with an extremely low subgrade modulus of 4.5 ksi. The initial pavement strategy called for 8 inches of cement treatment and then a 2-inch asphalt mixture overlay. Based on the expected traffic and site conditions, the mechanistic check showed that the CTB layer would fail prematurely—after exposure to less than 0.01 million equivalent single axle loads (M ESALs) (Figure 48 [left]). By adding additional flexible base prior to cement treatment and increasing the CTB thickness to 11 inches, the mechanistic check showed that the CTB fatigue life would increase to exceed the design ESALs. Thus, Figure 48 suggests that this mechanistic check could be a valuable tool for designers to assess the risk of CTB cracking, as long as reasonable input values are available.



Axle Type: ● Single ○ Tandem ○ Tridem
Tire Mode: ○ Single ● Dual
☐ Cost Calculation
distance between center of wheels(in): 14
4.5 Single Tire (kip)
9.00 Total Load (kip)
120 Pressure (psi)
HMA Dense Graded 2 E= 500.0 ksi μ= 0.350
Cement Stabilized 8 E= 400 ksi μ= 0.200
Modulus of Rupture (psi) 92
Granular 2 E= 24 ksi μ= 0.350
Low PI Clay 200 E= 4.5 ksi μ= 0.400
Rock
Fatigue Analysis of Cement Treated Stabilized Base Layers

$$\log(N_f) = \frac{0.972\alpha - (\frac{\sigma_t}{MR})}{0.0825\beta}$$

MR -----Modulus of Rupture (flexural Strength)

$$N_f = \left(\frac{\alpha}{\sigma_t / MR}\right)^{20\beta}$$

field calibration factor α 1.0645 β 0.9003
field calibration factor α 1.1368 β 1.0259
Maximum tensile stress at the bottom of layer (psi) 73.0
Top CTB Layer: 0.0018 Repetitions to failure: (millions) Top CTB Layer: 0.0016

Axle Type: ● Single ○ Tandem ○ Tridem
Tire Mode: ○ Single ● Dual
☐ Cost Calculation
distance between center of wheels(in): 14
4.5 Single Tire (kip)
9.00 Total Load (kip)
120 Pressure (psi)
HMA Dense Graded 2 E= 500.0 ksi μ= 0.350
Cement Stabilized 11 E= 400 ksi μ= 0.200
Modulus of Rupture (psi) 92
Granular 2 E= 24 ksi μ= 0.350
Low PI Clay 200 E= 4.5 ksi μ= 0.400
Rock
Fatigue Analysis of Cement Treated Stabilized Base Layers

$$\log(N_f) = \frac{0.972\alpha - (\frac{\sigma_t}{MR})}{0.0825\beta}$$

MR -----Modulus of Rupture (flexural Strength)

$$N_f = \left(\frac{\alpha}{\sigma_t / MR}\right)^{20\beta}$$

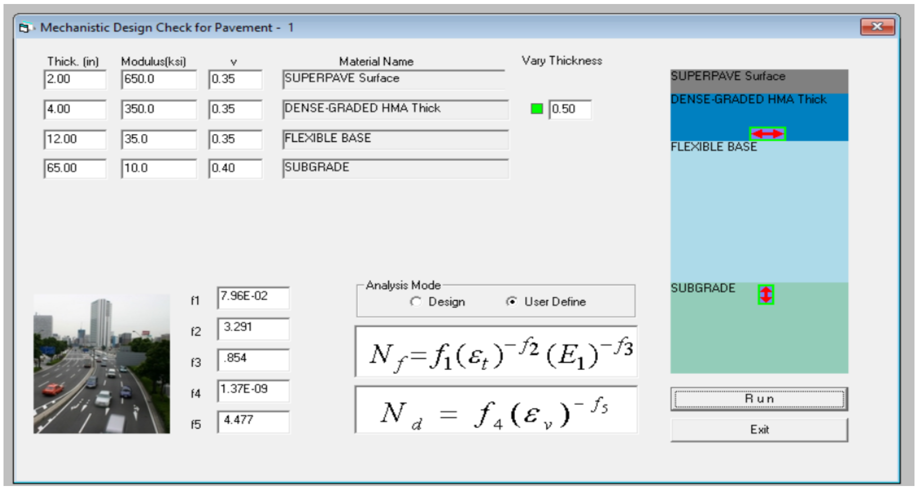
field calibration factor α 1.0645 β 0.9003
field calibration factor α 1.1368 β 1.0259
Maximum tensile stress at the bottom of layer (psi) 49.5
Top CTB Layer: 4.8603 Repetitions to failure: (millions) Top CTB Layer: 4.6304

Figure 48. Mechanistic Check Showing Risk of Premature CTB Cracking (Left), and a Revised Design to Meet Design Life Requirements (Right).

6.4. HOW TO IMPLEMENT CTB MECHANISTIC CHECK

This chapter presented a framework whereby the accelerated mix design procedure using the IDT_3 strength of a cement-treated base could synergize with mechanistic-empirical pavement analysis and design tools to provide a mechanistic check for cement-treated bases. The purpose of this check is to evaluate the risk of premature cracking in the CTB layer. Most inputs required for this mechanistic check (i.e., pavement layer thicknesses, asphalt layer and subgrade modulus values, and traffic information) are already used in the Texas FPS 21. The key properties of the cement-treated base field modulus and modulus of rupture can be estimated using Equation 10 and Equation 11 with a user input of the lab-measured IDT_3 strength.

The CTB mechanistic check would be relatively simple to incorporate into the FPS 21. Figure 49 and Figure 50 show the current system's input and output screens for both HMA fatigue cracking and subgrade rutting. One interesting and useful feature of the current checks is the automatic computation of the design life for a layer of interest. The CTB mechanistic check could be similarly incorporated into the FPS 21, allowing designers to see the impact of changing CTB layer thickness on the predicted CTB cracking life. Such information would allow designers to make more informed decisions on minimum acceptable CTB layer thicknesses.



Thick. (in)	Modulus(ksi)	v	Material Name	Vary Thickness
2.00	650.0	0.35	SUPERPAVE Surface	
4.00	350.0	0.35	DENSE-GRADED HMA Thick	🟩 0.50
12.00	35.0	0.35	FLEXIBLE BASE	
65.00	10.0	0.40	SUBGRADE	

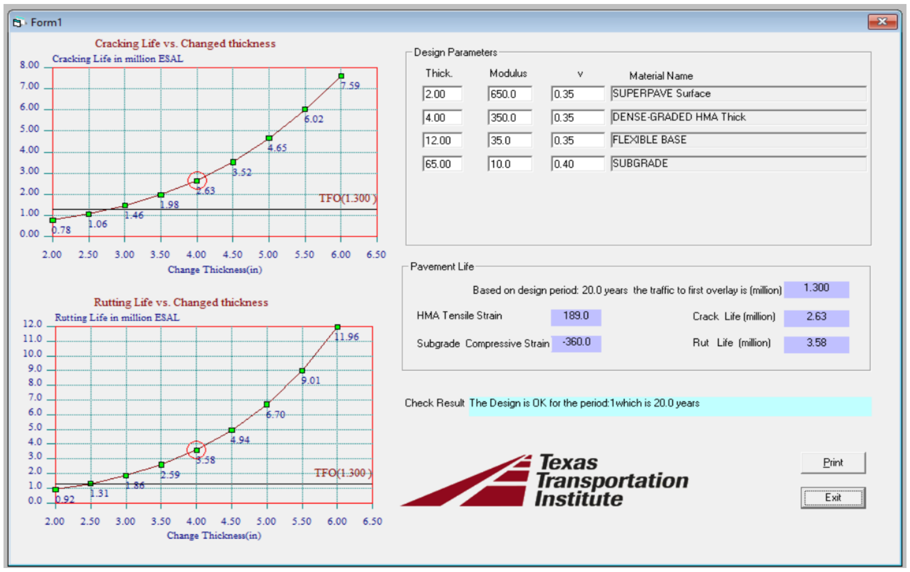
f1 7.96E-02
f2 3.291
f3 .854
f4 1.37E-09
f5 4.477

Analysis Mode: ○ Design ● User Define

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3}$$

$$N_d = f_4(\varepsilon_v)^{-f_5}$$

Figure 49. Current FPS 21 Mechanistic Check Input Screen.



Design Parameters

Thick.	Modulus	v	Material Name
2.00	650.0	0.35	SUPERPAVE Surface
4.00	350.0	0.35	DENSE-GRADED HMA Thick
12.00	35.0	0.35	FLEXIBLE BASE
65.00	10.0	0.40	SUBGRADE

Pavement Life

Based on design period: 20.0 years the traffic to first overlay is (million) 1.300

HMA Tensile Strain	189.0	Crack Life (million)	2.63
Subgrade Compressive Strain	-360.0	Rut Life (million)	3.58

Check Result The Design is OK for the period:1which is 20.0 years

Figure 50. Current FPS 21 Mechanistic Check Output Screen.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Cement treatment of roadway or stockpile materials remains the most common approach for enhancing the strength and stiffness properties of pavement base layers. Cement-treated base mixture design criteria have historically relied on compressive strength test results; depending on the treatment and exact test method used, tests could take nearly a month to complete. Adequately capturing site variability in mixture design can require significant material quantities and result in a substantial testing burden. In this project, researchers developed a rapid mix design procedure for CTB layers with a focus on rapid test turnaround times, lab curing techniques that quickly simulate cured field conditions, inclusion of moisture susceptibility in the mix design, and performance-related design criteria. This project also explored opportunities to synergize the rapid mix design procedure with mechanistic properties that could serve as a basis for performing CTB mechanistic design checks.

7.1. CONCLUSIONS

The results from this project showed that three of the four IDT test methods investigated could be used as a basis for mix design, as evidenced by their strong correlation to the reference UCS values. The results showed that the IDT_3 test method using a 72-hour accelerated cure with specimens sealed in bags and maintained at 104°F, followed by a 24-hour moisture conditioning by water submersion, provided the best basis for mix design among all IDT test methods analyzed in this research (Figure 51).

Figure 51. IDT_3 Test Specimens Curing (Left) and being Tested (Right) for Rapid CTB Mix Design.

Compared to the Tex-120-E test method, this approach reduces the test turnaround time for strength results from 7 to 4 days, and the required material quantity (for the strength phase of the mix design) from 180 to less than 60 lb.

The results from this project showed that IDT_3 strength can be used to estimate the MoR and Mr of the cement-treated base. These estimates could be used with fatigue life models to synergize mix design with pavement analysis to perform a mechanistic check of the CTB layer in the pavement design process.

Findings in this project focused on base materials treated with Type I/II Portland cement. The IDT test specimens were compacted in a SGC targeting the material maximum densities. All materials tested in this research project were classified under AASHTO A-2, except for one exploratory material that contained over 60 percent subgrade soil and was classified as AASHTO A-6. Exploratory work suggested that changing to fixed 75 gyrations was probably viable without influencing the results. However, the exploratory work suggested additional investigation was needed to confirm whether the use of Type IL cement influenced the results and recommendations from this research. Furthermore, the AASHTO A-6 material did not follow the same trends as observed with the other materials tested in this project.

7.2. RECOMMENDATIONS

The rapid mix design method developed in this project should be considered for inclusion as Part III in the Tex-120-E test method. Product 0-7027-P2B presents the recommended test method. Based on the data in this project, Table 13 presented recommended IDT_3 strength minimums; these minimums relate to the common historical UCS values used by TxDOT. Most TxDOT districts are currently using 300 psi minimum UCS, which would require a minimum IDT_3 strength of 59 psi according to Table 13. Consistent with the scope and underlying data from this project, the developed test procedure should only be used with road-mixed or stockpiled base materials.

The mechanistic check developed in this project should be considered for inclusion in the Texas FPS 21. The best option for implementing this check would be to allow users to enter the IDT_3 strength value from mixture design. The mechanistic check would then automatically populate the MoR and Mr values for the CTB layer based on the relationships developed in this research, thus linking the lab to expected field performance. Other approaches could be viable, such as providing default values for the MoR and Mr in the absence of lab data or allowing the user to directly enter the MoR and Mr values for the CTB.

Multiple opportunities for future work exist to better the state-of-the practice. Implementation efforts should deploy the rapid mix design procedures on upcoming construction projects. Constructed projects should be monitored for visual condition and with a FWD over time to determine whether shrinkage cracks are occurring with current mix designs and construction practices and whether in-service CTB moduli remain stable or change over time. Additionally, recent designs for cement-treated bases are trending toward thicker layers with reduced cement contents. Efforts should explore this design philosophy to determine if the aims of reduced shrinkage cracking and risk of fatigue cracking are attained with the lower cement content/thicker treated layer design approach.

Feedback from stakeholders suggested significant interest in extending the rapid mix design approach from this research to other materials. Efforts should take place to evaluate the utility of this rapid mix design procedure with cement-treated subgrades and subbases. Finally, TxDOT's mix design methods for lime treatment still require a 7-day curing period plus an additional 10-day capillary rise period; efforts need to take place to develop a rapid mix design procedure for lime-treated materials.

CHAPTER 8. VALUE OF RESEARCH

Table 20 presents value areas and a description of these value areas in context to the project.

Table 20. Benefit Areas of Research.

Value Area	Description
Level of Knowledge	The project developed viable methods for rapid mixture design of cement treated base. The project demonstrated how this mix design method could be used for performing a mechanistic check. The project demonstrated that cement treated materials may exhibit stress dependency.
Environmental Sustainability	The project developed a method that reduces the amount of material and time needed to complete the mixture design. This reduced testing burden could foster more use of cold recycling with cement treatment.
System Reliability and Service Life	The project developed a mechanistic check framework that can reduce risk of premature pavement distress.
Materials and Pavements	The project developed a method to expedite testing using less material. The project developed relationships to link lab testing to performance-related properties.
Engineering Design improvement	The project demonstrated a method that can expedite mixture design, allow more verification testing, and allow faster adjustment as unforeseen materials are encountered. The method cuts 4 days off the amount of time required for strength testing, and, in conjunction with the mechanistic check, can reduce overall project risk.

The economic benefits from this project are driven by the following:

- Reduced testing burden: The economic value is estimated as a reduction in time and effort developing mixture designs. Over 12 months, TxDOT let about 120 projects using cement. If only 10 percent of these projects used the mix design method developed in this project, and the method produces results 4 days faster, valued at $6,000 per day, the yearly value is $288,000.
- Reduced change orders from more thorough evaluation and verification testing of materials: Cases have been documented where one change order costed $1M. The value is estimated as preventing one such change order every 5 years, or $200,000 per year.
- Reduced project delays from faster turnaround time when unforeseen materials are encountered: If 5 situations per year arise where unforeseen materials are encountered, 20 days of delay would be avoided yearly. The economic value is estimated as $6,000 per day, or $120,000 per year.
- Reduced project risk: Over 12 months TxDOT let about $45M of work using cement treatment. If only 10 percent of this work benefitted from reduced risk, and that risk reduction is valued at 5% of project costs, the annual value is $225,000.

The combined annual value is $833,000. Over 10 years the value is about $7.6M.

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