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16. Abstract

Rehabilitating an old pavement by pulverizing and stabilizing the existing pavement is a process referred to as Full Depth Reclamation (FDR). The stabilized layer becomes either the base or sub-base of the new pavement structure. This process has been used widely for over 20 years in Texas to strengthen and widen structurally inadequate pavement sections. This project developed guidelines on successful FDR practices, developed training materials, and identified areas where improvements to current practices are required. To improve the FDR process, this report includes the following enhancements:

- Current laboratory testing to select the optimal type and amount of stabilizer takes too long and requires too much material. Continue to run parallel testing with the small sample test protocols proposed in this report.
- Use the falling weight deflectometer (FWD) during construction to validate that the design assumptions are being met.
- Implement the proposed bond test to select the optimum prime material and amount needed to effectively bond the base to the surfacing materials.
- Modify the specifications to avoid working in freezing conditions.
- Consider implementing the other modifications to specifications proposed in this report.

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# FULL-DEPTH RECLAMATION: NEW TEST PROCEDURES AND RECOMMENDED UPDATES TO SPECIFICATIONS

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

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# EXECUTIVE SUMMARY

Rehabilitating an old pavement by pulverizing and stabilizing the existing pavement is a process referred to as Full Depth Reclamation (FDR). This process shows great potential as an economical rehabilitation alternative that provides deep structural benefit, conserves highway construction raw materials, and quickly returns the section to service. The stabilized layer becomes either the base or sub-base of the new pavement structure. In the early 1990s, the Bryan and Lubbock Districts constructed their first few projects on low volume roadways. Their initial experiences were positive, and both districts have now recycled close to 1000 miles of low volume roadways. Although the FDR process is widely used in several districts, others are just getting started.

Project 0-6271's purpose was to work with experienced districts to identify all of the key steps in the design, construction, and monitoring of the FDR process so that districts just getting started can build upon the lessons learned from earlier projects. The project also identified areas where improvements are needed to design practices and/or construction specifications. In this study the Texas Transportation Institute's (TTI's) research team has completed the following:

- Submitted Research Report 0-6271-1, which presented recommended protocols for project evaluation and mixture design. This report also described five case studies that the research team conducted to test and design FDR projects in the Austin and Dallas Districts.
- Developed and submitted to TxDOT a set of training materials together with the associated PowerPoint slides for a comprehensive FDR workshop.
- Conducted two one-day workshops for District personnel in March 2011: one in the Dallas District office and one in the Bryan District office.
- Delivered to TxDOT a professional-quality DVD of the key steps in the FDR process for the purpose of supplying video clips for use in future training schools.

The objectives of this final report are to present the work conducted in the final year of Project 0-6271, to address key issues identified, and to make suggested changes to both test protocols and specifications. This report is broken down as follows:

- Chapter 2 and Appendix A present TTI's efforts to simplify and accelerate the laboratory procedures. Current procedures require sampling several hundred pounds of material from existing roadways to complete a single design. Also, moisture susceptibility testing increases the total time required to close to three weeks. Chapter 2 describes efforts to move to smaller sample sizes and to accelerate testing so that a design can be completed in less than one week.
- Chapter 3 presents ideas on how to improve construction control and explores techniques for checking the uniformity of stabilizer distribution. The chapter also includes examples of deflection testing of projects under way or recently completed to ensure the section was constructed as designed.

- Chapter 4 and Appendix B provide an update on the recommendations for selecting the optimum type and amount of prime material for a stabilized layer. Ensuring that the surfacing layer adequately bonds to the base is still a major concern on FDR projects.
- Chapter 5 presents a summary of troubleshooting forensic investigations completed to investigate premature distresses in FDR studies.
- Chapter 6 provides recommended changes to construction specifications.

# CHAPTER 1
# EVALUATION OF REDUCED SAMPLE SIZES FOR SELECTING OPTIMUM STABILIZER CONTENT

To select the optimum stabilizer content for FDR base-course mix design, specimens are prepared in accordance with Texas Department of Transportation (TxDOT) guidelines. The laboratory testing protocol includes the determination of gradation, Atterberg limits, optimum moisture content, unconfined compressive strength, evaluation of the moisture susceptibility using the tube suction test (TST), and seismic properties. The determination of the optimal FDR mix design includes consideration of what percentage reclaimed asphalt pavement (RAP) to allow, what pretreatments are required, and what level of stabilizer to use. For cement designs the following design criteria are often used. Similar criteria are available for the other commonly used stabilizers (lime and asphalt).

- Unconfined compressive strength (UCS) after seven-day moist-curing: Cement-stabilized: ≥ 175 psi (minimum).
- Retained UCS after TST: ≥ 100% seven-day UCS.

These engineering properties are obtained from laboratory tests using 6-in. by 8-in. specimens. Traditionally, approximately 300 lb of materials are required to complete a single set of laboratory evaluations for FDR mix design. As shown in Figure 1.1, a single FDR design requires large quantities of material for completion.

**Figure 1.1. Sampling Highways for FDR Work.**

A highway under design with numerous different pavement structures further complicates the process. These instances require the addition of new sampling locations to be included in the laboratory test program. Furthermore, in several instances the district may want to investigate either using different levels of RAP in the design (say, 25 percent and 50 percent) or in the case

of asphalt stabilization, perhaps a pretreatment with lime before adding the asphalt emulsion. Handling these variations in the laboratory means that massive amounts of materials will be required, and the complete design process will not be possible.

In addition to the amount of material required, another concern with the 10-day capillary rise test is the amount of time required to complete a full design. A full design can take close to one month from start to finish. Measuring the engineering properties of strength and moisture susceptibility takes close to 20 days. This duration is problematic if the design criteria are not met and a redesign is required. Often, designs are prepared under tight deadlines, and waiting one month is a real concern.

This chapter explores preliminary ideas to use much smaller samples and accelerated moisture conditioning. These concepts are based on the procedures that Wirtgen, Inc. (Marshall 2010) had recommended. Figure 1.2 below shows the basic concept, where the current Texas Gyratory press is used to mold 4-in. diameter by 2-in. high samples to a required density. These samplers then cure for seven days (in the case of cement) and are then tested in the indirect tension test. For a typical test sequence, six samples are prepared and cured for seven days and three samples are submerged in water for four hours prior to testing so a wet versus dry indirect tension (IDT) strength can be measured. Appendix A contains complete details of the sample preparation procedures and a draft test procedure for running the IDT test on these samples.

**Figure 1.2. Use of the Texas Gyratory Compactor and IDT Test for FDR Design.**

## EXPERIMENTAL PROGRAM

### Experimental Scope

To determine the feasibility of running the small samples to select the optimum stabilizer content, parallel tests were conducted on three FDR designs. Samples were made using traditional TxDOT 6-in. by 8-in. samples, and the obtained unconfined compressive strengths were compared with the IDT strength obtained on the smaller samples. Figure 1.3 illustrates the procedure used to study the UCS in parallel with the IDT for each mixture.

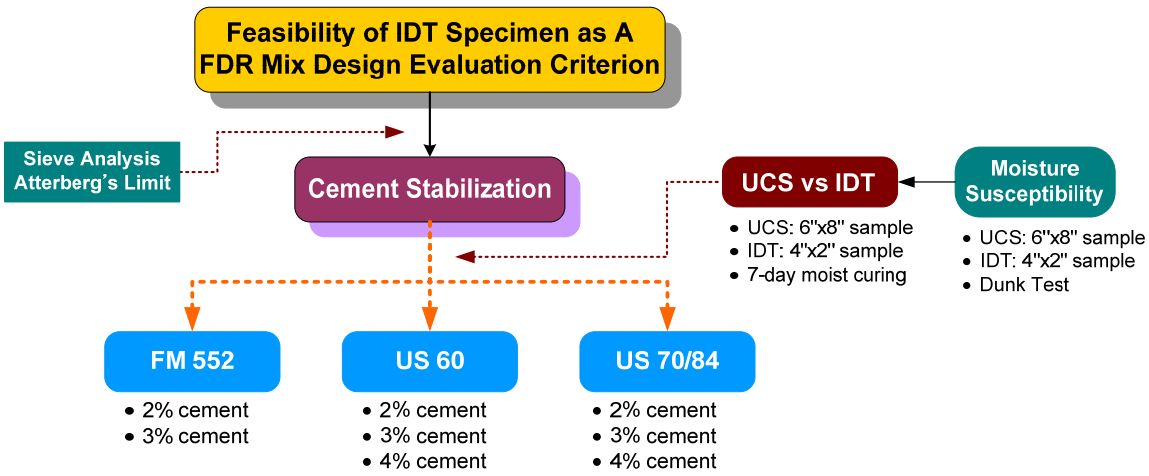



**Figure 1.3. Experimental Program.**

### Materials and Specimen Preparation

Recycled asphalt pavement materials and existing base materials were collected from three different locations, namely US 60, US 70/80, and FM 552. Gradation analysis and Atterberg's limit tests were conducted. As all of these highways had four or more inches of existing HMA, a 50/50 combination of RAP and flexible based materials was selected to prepare the FDR base-course specimen. Cement was also selected as a stabilizer and cement replacement levels were 2 percent, 3 percent, and 4 percent by mass of dry solid material.

A set of cement-treated specimens with a diameter of 6 in. and a height of 8 in. was prepared at optimum moisture content using 10 lb hammer drops at 18 in. in height at 50 blows/layer (a total of four layers) for UCS testing. Test specimens with a diameter of 4 in. and a height of 2 in. were also molded using the Texas Gyratory Compactor for IDT testing. Appendix A describes the IDT specimen preparation procedure in more detail.

For moisture conditioning, TTI developed a "dunk test," used for both the 6-in. by 8-in and 4-in. by 2-in. samples. The dunk test is an accelerated test procedure to assess moisture susceptibility of the stabilized mixture. The test consists of full submergence of test specimens for four hours at room temperature (77°F) and conducting the UCS or IDT test at the end of the term. The residual retained compressive strength, which represents an indicator of the moisture susceptibility of mixture was determined on the basis of dry UCS.

## TEST RESULTS AND DISCUSSION

### Material Gradation Analysis

Figures 1.4 through 1.6 show material gradation analyses of RAP, existing flexible base materials, and blend of these materials for US 60 (Lubbock), US 70/84 (Lubbock), and FM 552 (Dallas) roadways. For US 60, flexible base material belongs to Grade 1, while the RAP material is affiliated with Grade 3, as TxDOT Item 247 specified. A gradation analysis of US 70/84 is the complete opposite of US 60. The flexible base material of FM 552 is not affiliated with any categories of Grade 1 though Grade 3 because the material retained 90 percent on the No. 40 sieve; the specification maximum is 85 percent cumulative retained on the No. 40 sieve. However, the RAP material complies with the Grade 2 gradation band.

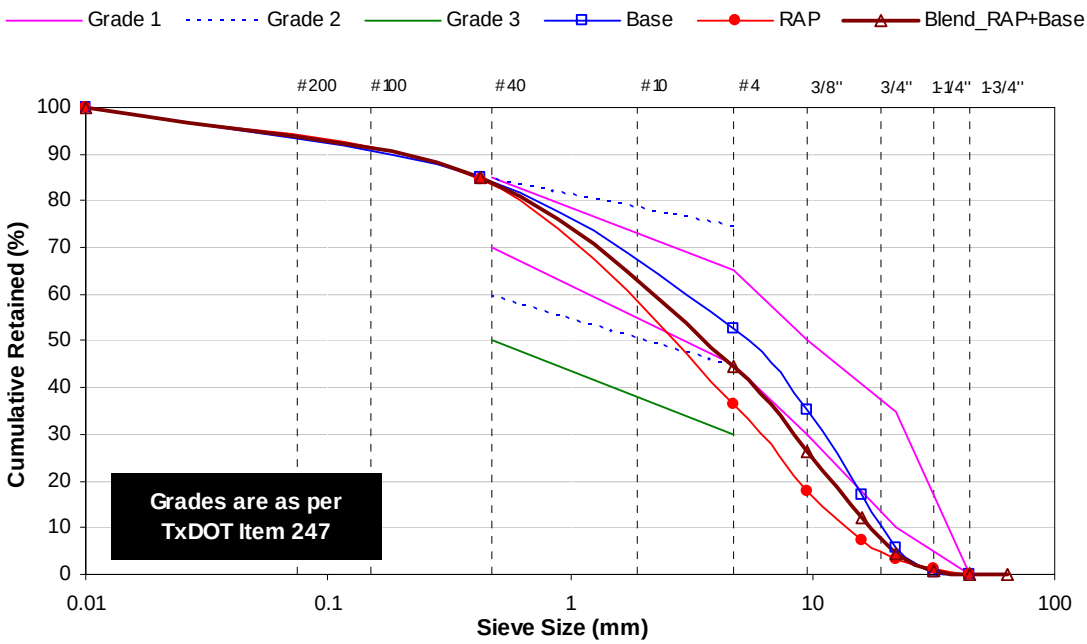



**Figure 1.4. Gradation Analysis of US 60.**

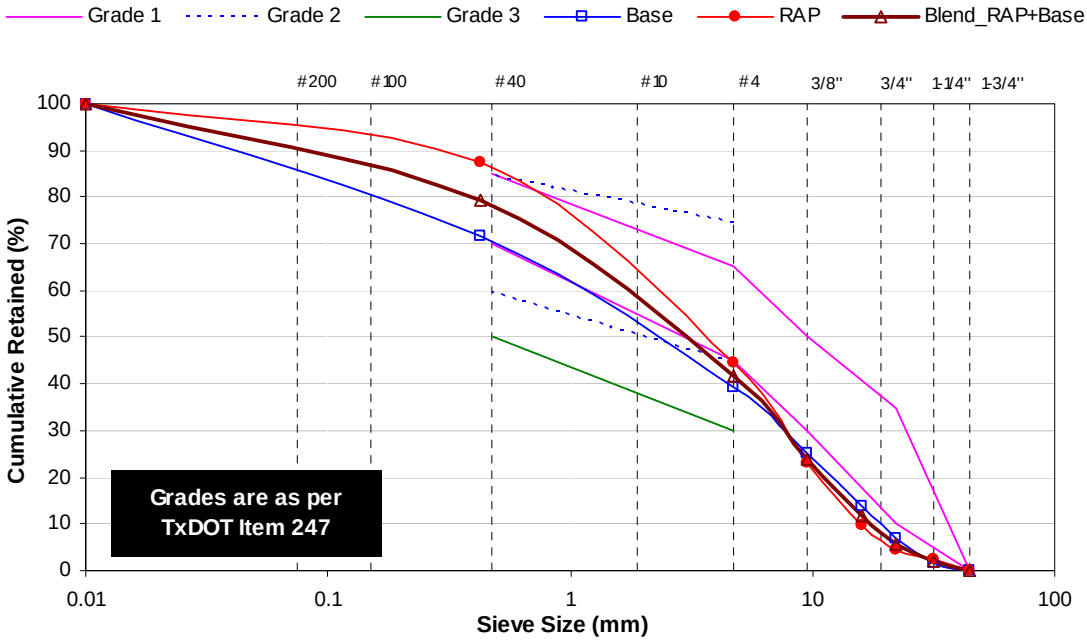



**Figure 1.5. Gradation Analysis of US 70/84.**

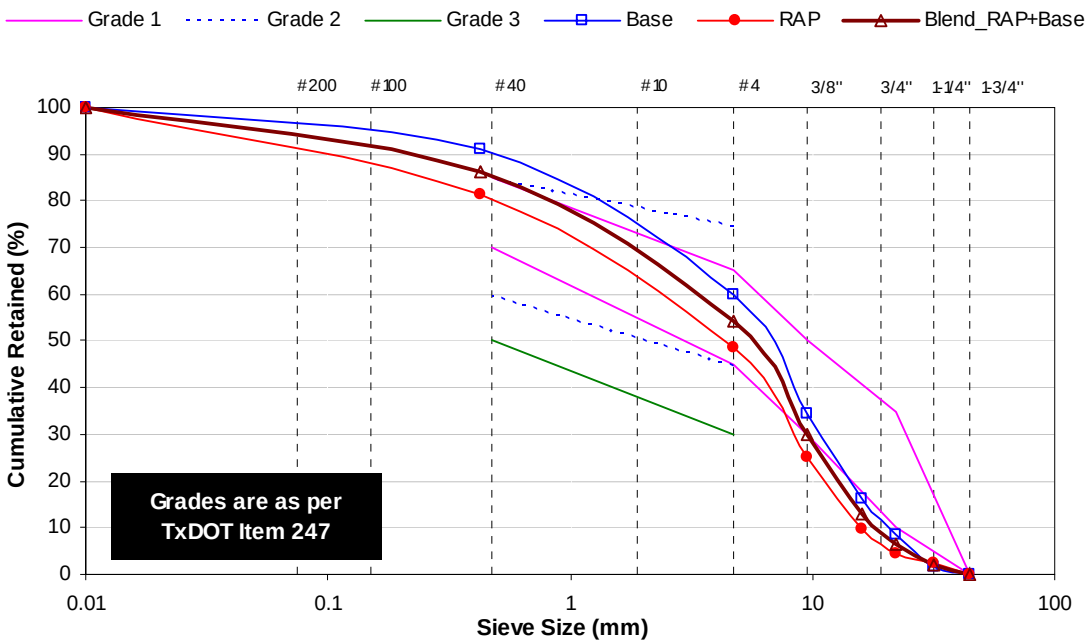



**Figure 1.6. Gradation Analysis of FM 552.**

Based on the gradation analyses of each material, the blend of 50 percent flexible base and 50 percent RAP materials was selected for the FDR base mixture. This blend meets TxDOT's current Grade 2 gradation for flexible base.

### Atterberg Limits

Table 1.1 presents the Atterberg limits results. The PI values of base materials for US 60, US 70/84, and FM 552 were determined to be 3.3, 7.8, and 15.4, respectively. In spite of different PI values for each road, cement was selected as the stabilizer for FDR base-course application.

**Table 1.1. Atterberg's Limits of Base and Subgrade Materials.**

| Property | Flexible Base | | | Subgrade | | |
|---|---|---|---|---|---|---|
| | US 60 | US 70/82 | FM 552 | US 60 | US 70/82 | FM 552 |
| Liquid Limit (LL) | 20 | 21.4 | 29.2 | 35.0 | 15.2 | - |
| Plastic Limit (PL) | 17.3 | 13.6 | 13.8 | 15.1 | 11.8 | - |
| Plasticity Index (PI) | 3.3 | 7.8 | 15.4 | 19.9 | 3.4 | - |

*(The base material for FM 552 was a fine sandy clay material, more like a select fill than base. Under normal requirements, other stabilizers [lime] would be recommended. As will be shown below, the cement strengths for these materials did not meet the required targets. Consequently, the researchers created an additional design with lime, which proved to be satisfactory, and lime was recommended as the required stabilizer for this FDR project.)*

**Moisture Density Relationship**

Figure 1.7 illustrates the moisture-density curve. The moisture-density relationship revealed the following characteristics of the 50%/50% combination of flexible base and RAP materials treated with 3 percent cement:

- Optimum moisture content ($W_{opt}$) = 7.6% and maximum dry density ($\gamma_{d-max}$) = 119.8 lb/ft$^3$ for US 60.
- $W_{opt}$ = 8.0% and $\gamma_{d-max}$ = 120.2 lb/ft$^3$ for US 70/82.
- $W_{opt}$ = 8.8% and $\gamma_{d-max}$ = 128.2 lb/ft$^3$ for FM 552.
- Moisture contents were adjusted for each of the remaining cement contents (2 and 4 percent) at .25 percent moisture per 1 percent cement.

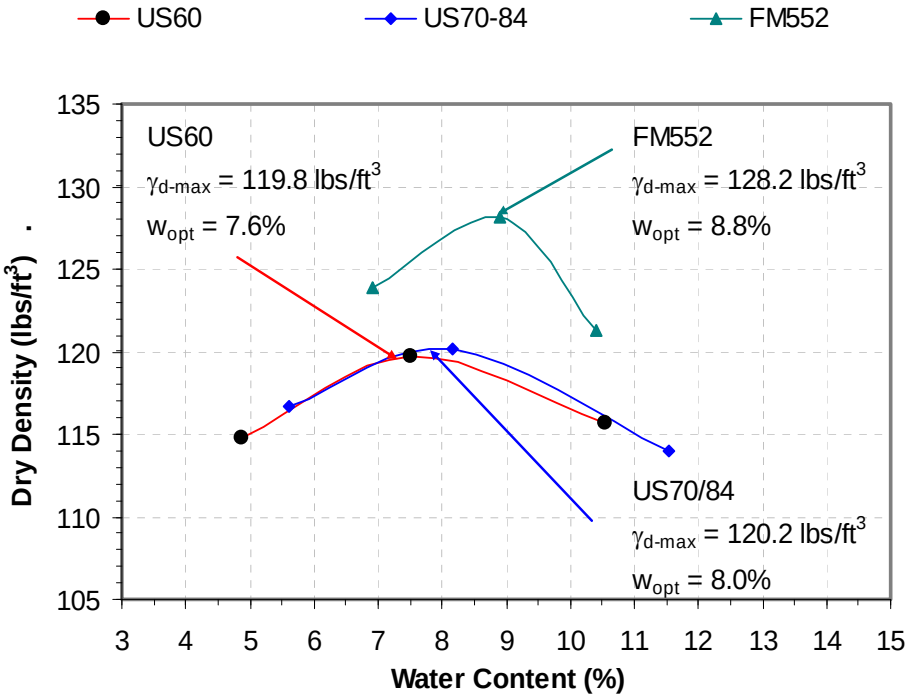



**Figure 1.7. Moisture-Density Relationship of 3 Percent Cement-Treated Specimen.**

**Comparison of UCS and IDT Strength**

Researchers compared the unconfined compressive strength and the indirect tensile strength. Figure 1.8 presents the relationship between UCS and IDT for each road mixture. The correlation coefficient ($R^2$ value) between UCS and IDT varies for each road mixture. While there is little correlation for FM552 primarily because only low strength gains were obtained on this high PI material, there is good correlation for US 60 and US 70/84. However, the $R^2$ value of the best-fit curve through all points is 0.7955 (see Figure 1.9). The trend line of the data points (solid) is very close to the line of equality (dashed). This indicates that there is a strong relationship between UCS and IDT.

Figure 1.10 shows the comparison between wet/dry strengths for a range of moisture conditioning. TxDOT procedures currently use the TST wet/dry, where the wet strength is the UCS measured after the 10-day capillary rise in the Tube Suction Test. The IDT and UCS wet strengths are measured after the samples were submerged for four hours. For all of the TST results, the wet strengths are always substantially higher than the dry strengths (this is the TTI researchers' experience from other work; this criteria very rarely fails with cement). The 4-hr dunk test appears to give similar results, and seems more severe from this data set. No criteria are currently established for the 4-hr dunk and more data should be collected, but a retained strength of 80 percent of dry strength seems reasonable.

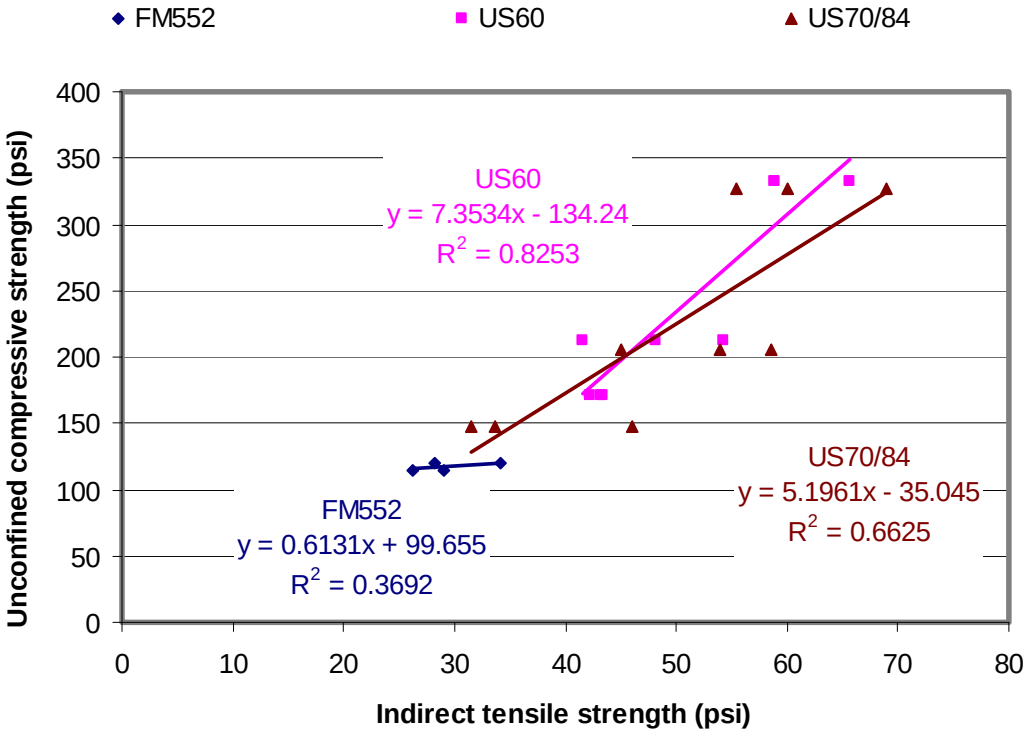



**Figure 1.8. Comparison of UCS and IDT for Each Road Mixture.**

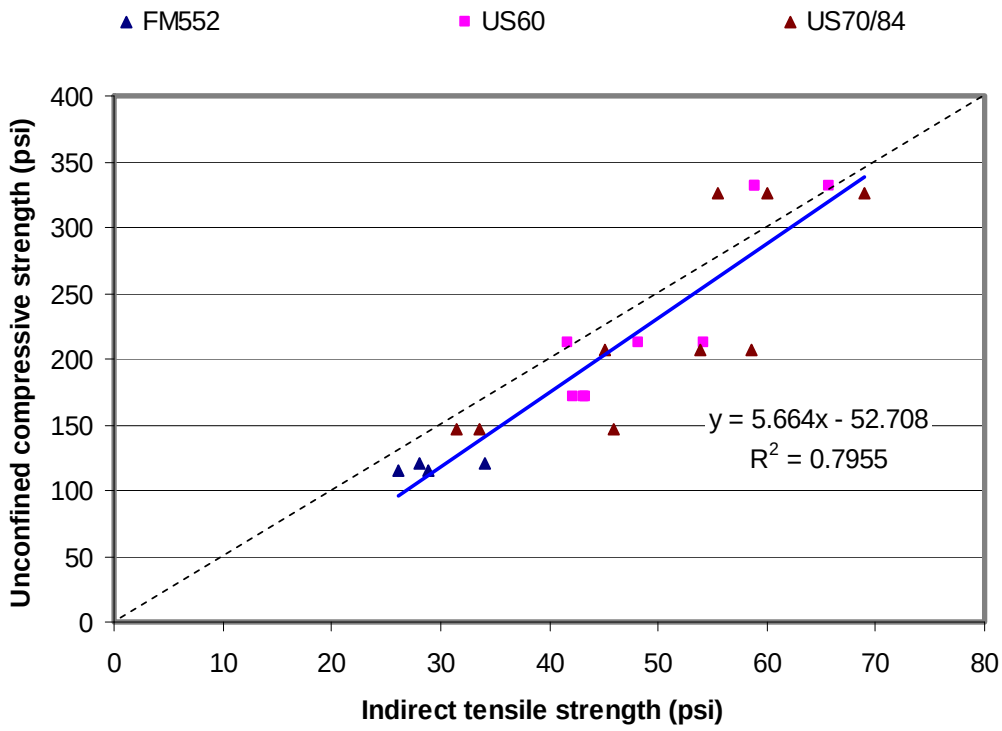



**Figure 1.9. Relationship between UCS and IDT through All Points.**

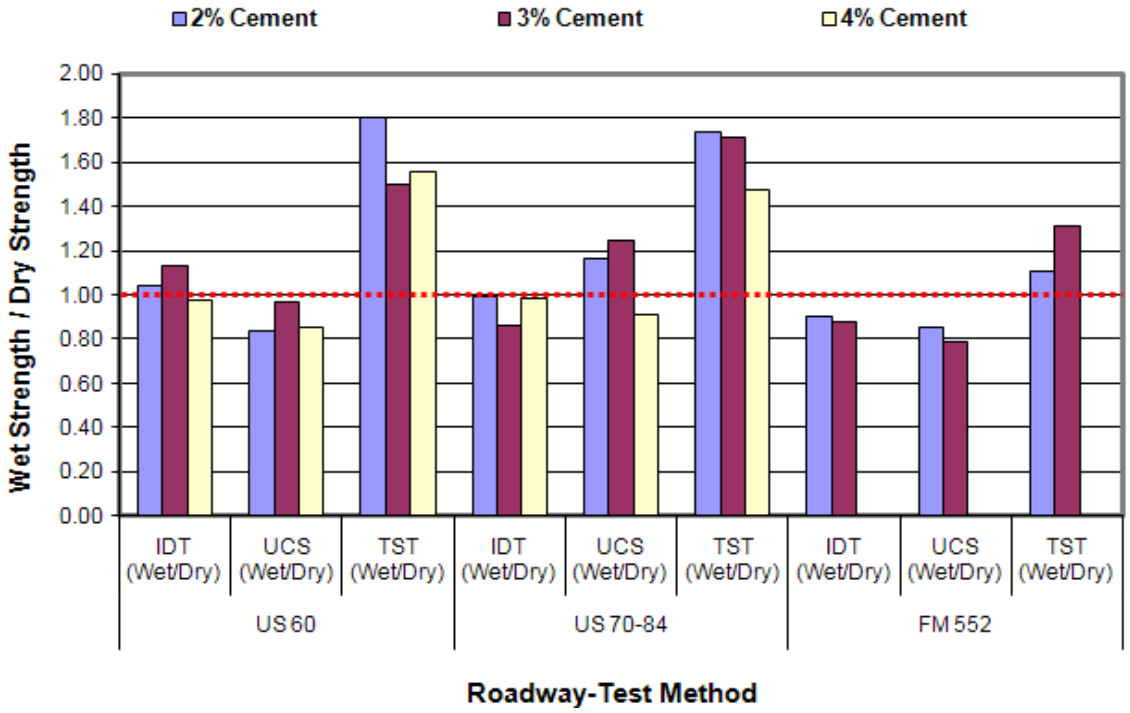



**Figure 1.10. Relationship between UCS and IDT through All Points after Dunk Test.**

Figure 1.9 shows a reasonable correlation between UCS as per Tx-Method 120E with 6-in. by 8-in. samples compared to the IDT results on 2-in. by 4-in. samples. Using this regression equation, the following strengths in Table 1.2 would be required to meet the current UCS strengths:

**Table 1.2. Proposed IDT Criteria Based on Current TxDOT UCS Requirements.**

| UCS Tex-120-E | IDT |
|---|---|
| 175 psi | 40 psi |
| 220 psi | 48 psi |
| 300 psi | 62 psi |

Further implementing this test requires more work with stabilizers other than cement. The test has been conducted on lime stabilizer FDR samples, and it appears that IDT strengths around 20 psi would be required to meet the strength requirements obtained in Tex-121-E. The next section describes the work performed on asphalt stabilized samples.

**Use of Small Sample Size with Foamed Asphalt FDR Design**

TTI researchers were asked to assist Bill Pierce, P.E., the TxDOT Area Engineer in Waxahachie (Dallas District) who was considering the use of foamed asphalt for a possible FDR project on the frontage roads of IH 35. As shown in Figure 1.11, these roadways are in very poor condition and are subjected to heavy truck traffic. Figure 1.12 shows TTI's laboratory foaming system. For this evaluation, the Wirtgen representative visited TTI to demonstrate their FDR process of using the small samples.


**Figure 1.11. Distressed Condition of IH 35 Frontage Road in Dallas District.**


**Figure 1.12. TTI's Foaming Equipment.**

TxDOT has little experience with foamed asphalt, so for this evaluation the Wirtgen design protocols and criteria were applied. The Wirtgen process for doing FDR designs with foamed asphalt is highly accelerated. The molded samples are placed in an oven at 104°F and dried for three days. Unlike curing when cement or lime stabilizers are used, the goal of the foamed curing is to get the water out of the sample. For a typical design at a single asphalt content, six samples are made. After the three-day cure the samples are submerged for 24 hours prior to running the IDT test. The one concern with this project was the very low quality of the caliche base on the IH 35 frontage road, which was a soft friable limestone with a PI of around 15. After a few initial attempts the researchers decided to use lime as a pretreatment for this material. In this case the lime was added to the RAP/base blend and the sample left overnight prior to starting the normal Wirtgen design sequence. Table 1.3 contains the results from this entire process.

**Table 1.3. Test Result for Foamed Asphalt Stabilization on the IH 35 Project.**

| Base type used | % Lime | % Foam Asphalt | Dry UCS (psi) (>32 psi) | Wet UCS (psi) (> 22 psi) | TSR (%) (>50) |
|---|---|---|---|---|---|
| Existing | 0 | 2.5 | 56.5 | 13.1 | 23 |
| Existing | 0 | 3.5 | 44.0 | 20.3 | 46 |
| Existing | 2 | 2.5 | 42.0 | 20.5 | 48 |
| Existing | 2 | 3.5 | 47.8 | 29.3 | 61 |
| New Grade 2 | 0 | 2.5 | 62.5 | 7.2 | 11 |
| New Grade 2 | 0 | 3.5 | 53.5 | 10.2 | 19 |

In Table 1.3 the specified Wirtgen design criteria for foamed asphalt with their lab curing conditions are shown in green as Dry (32 psi), wet > 22 psi and a retained strength ratio >50 percent. No pretreatment results failed the TSR requirement. The only combination that passed these criteria was the 2 percent lime pretreatment with 3.5 percent foamed asphalt. As part of this study, researchers tried a new local base instead of the existing base. The new base was mixed with the existing RAP, but it failed to meet the TSR requirement.

The purpose behind this example is not to promote the Wirtgen criteria or foamed asphalt (although this technique does have much potential especially in West Texas); rather, it is to demonstrate the flexibility of the design process. Note the following:

- The six designs shown in Table 1.3 were all completed in seven working days.
- The total amount of material used was around 200 lb.
- To complete this design with TxDOT procedures would require about 2000 lb of material and take approximately one month.

## SUMMARY

Based on these results, the researchers recommend that TxDOT initiate an implementation project to further evaluate this small sample concept on upcoming FDR design projects. The amount of samples and time required is a major limitation with current design procedures. If these techniques can be used to rapidly arrive at a potential stabilizer type and content, the full size sample can then be made to validate the small sample design strengths.

The proposed future work should perform duplicate designs on a number of upcoming projects using the full Tex-120-E and Tex-121-E strengths in parallel with the strengths obtained in the proposed IDT design procedure. This approach allows a more thorough study of the correlations between the large and reduced sample size test methods, and allows for further evaluating whether both techniques produce the same recommended stabilizer content.

# CHAPTER 2
# CONSTRUCTION CONTROL IN FDR

## INTRODUCTION

Even with a proper mixture and pavement design, the successful completion of an FDR project requires proper construction control. During the construction phase, the following factors exist that can impede successful FDR, particularly when stabilization or chemical treatment is used:

- Obtaining the proper field gradation.
- Processing the material to the proper water content.
- Identifying environmental conditions that may impede stabilization.
- Verifying that the proper quantity of stabilizer is added.
- Heterogeneity in the FDR mixture (particularly varying RAP percentages).

Additionally, although acceptance testing currently relies solely on in-place field density, hindrances may exist that impede the stabilization reaction. For this reason, some consideration was given in this project to validating the construction through field modulus measurements. This chapter presents a summary of methods to control or accommodate these factors during the course of construction on an FDR project.

- Attainment of proper gradation is easily verified in the field. Using up-front testing to achieve proper gradation assists in the consistent attainment of the relatively homogenous structure.
- Thus far, rapid, non-nuclear methods for measuring moisture content content in the field have provided mixed results. The Vertek SMR probe may be suitable for rapidly measuring windrows or loose material. However, some initial calibrations between the SMR and the true oven-dry gravimetric water content should be performed prior to placing this non-nuclear device in service on a project.
- Although TxDOT specifications currently allow application of stabilizer when the air temperature is at least 35°F and rising or at least 40°F, field reports indicate a requirement for overnight temperatures is needed. Consideration should be given to modifying TxDOT specifications to not allow application of stabilizer if the overnight air temperature is forecast to be below 32°F.
- This project included much work on verifying the quantity of stabilizer using X-Ray Fluorescence (XRF). While XRF can work to develop a calibration curve for the stabilizer content, more research is needed to see if the approach could be developed into a practical field method. The following major hurdles exist:
    - The XRF approach works best on fine-grained materials, such as passing the No. 40 sieve or finer. Obtaining a representative sample of passing No. 40 materials from a wetted FDR mixture is difficult.
    - The “background” level of calcium seems to vary significantly even among “replicate” samples.

- After determining the calibration curve between the XRF and stabilizer content, the standard error of the estimate may be quite large, resulting in wide confidence intervals for the true mean stabilizer content.
- In some cases, the relationship between XRF and the stabilizer content was non-linear.

- RAP percentages should continue to be restricted to 50 percent or less.
- Existing physical or chemical barriers can impede successful stabilization. The laboratory testing phase is the best stage to catch symptoms of these problems.
- Portable stiffness devices are best used to easily verify techniques such as microcracking; the rapidly changing nature of stiffness during the curing stage makes the stiffness values a moving target. Stiffness or modulus-based acceptance of stabilized mixtures seems best approached with an FWD after completion of curing; in this manner the field values can be compared to the as-designed values from FPS.

Figure 2.1 presents an overview of the FDR process. The remainder of this chapter discusses approaches and findings for the major steps and QC areas of the FDR process up through compaction acceptance.

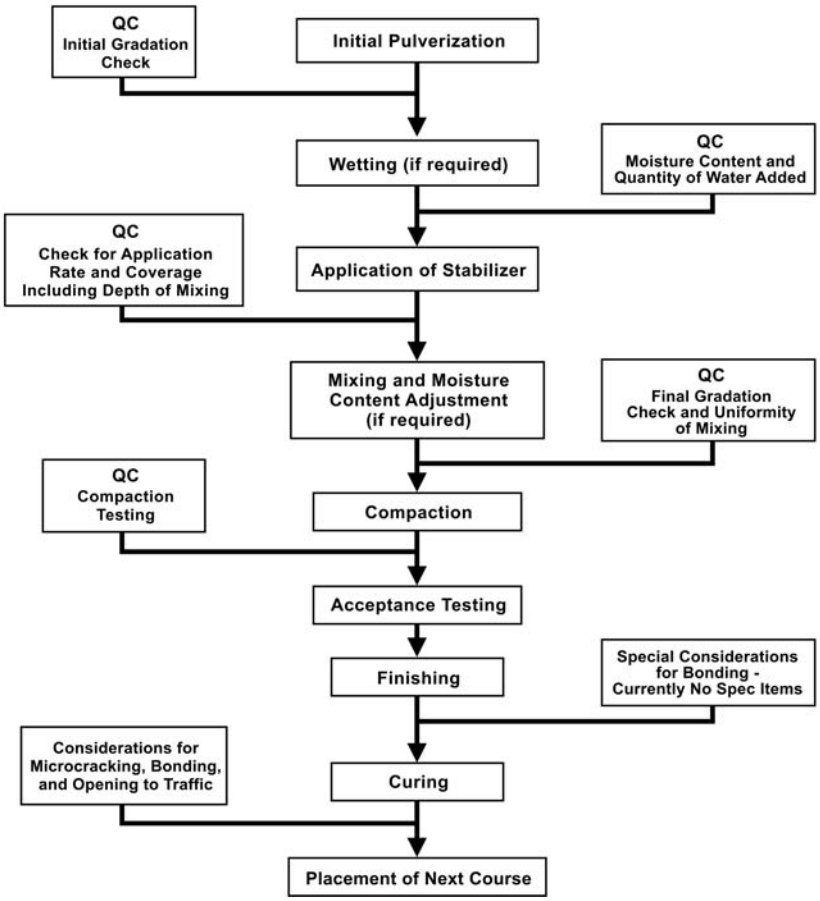



**Figure 2.1. Major Sequences in FDR.**

## CHECKING GRADATION

When the project employs road-mixed stabilization, TxDOT specifications require a certain level of field pulverization. Several factors can influence the ability to pulverize the material:

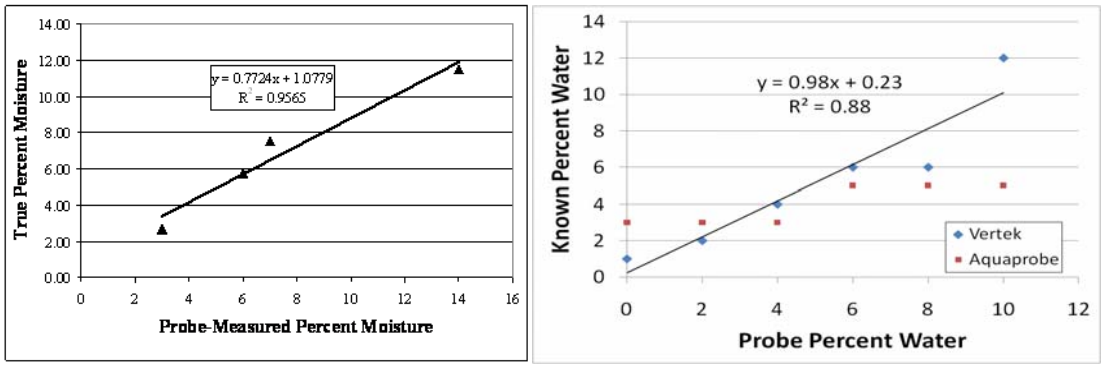
- The thickness of the surface layer.
- The temperature of the surface layer.
- The type of base material.
- The variability of the pavement structure.

By performing thorough up-front testing and planning the project in a manner to produce a relatively homogenous pavement structure as described in Product 0-6271-P2, the thickness and variability of the pavement structure can be controlled. Once in the field, attainment of the proper pulverization can be checked simply by sieving as Figure 2.2. shows.

**Figure 2.2. Checking Field Pulverization by Sieving.**

## CHECKING FIELD MOISTURE

Field moisture control is critical for proper compaction and to promote the stabilization reaction. In this project, two non-nuclear moisture probes were evaluated: the Aquaprobe and Vertek SMR. Limited tests as illustrated in Figure 2.3 indicated the Vertek probe may be promising. An upcoming TxDOT project will specifically investigate non-nuclear water content measurement in soils and base materials.




Vertek SMR in Sandy Subgrade  Both probes in FDR Mixture

**Figure 2.3. Test Results from Spear-Type Moisture Probes.**

## TEMPERATURE RESTRICTIONS

TxDOT specifications allow application and mixing of stabilizers when the air temperature is at least 35°F and rising or is at least 40°F. Several TxDOT field personnel report surface problems with fly-ash mixtures when the air temperature falls below freezing overnight. Although the current specifications require the contractor to suspend operations when the Engineer determines that weather conditions are unsuitable, specific wording should be considered for inclusion in the specification to disallow application and mixing of stabilizers if the air temperature is expected to fall below 32°F within 24 hours.

## EVALUATING STABILIZER CONTENT IN FDR MIXTURES USING XRF

The amount of stabilizer and how uniformly the stabilizer is mixed into the soil or base material will affect stabilization. Being able to validate the amount of stabilizer added to a project is therefore an important quality control measure in ensuring effective stabilization. The researchers tested portable X-ray Fluorescence technology as a potential non-destructive approach for determining the amount of lime and cement added to stabilized soils or bases. The approach is based on the premise that application of lime, cement, or any other calcium-based stabilizers to a soil or base material will result in an increase in calcium (Ca) concentration proportional to the stabilizer content. By using a portable handheld XRF instrument to quickly measure the change in Ca concentration with known additions of stabilizer, a calibration curve can be developed and used to validate the amount of stabilizer at different locations.

X-ray Fluorescence, as the name suggests, uses x-rays to bombard the sample. Because each element in the sample is unique, a characteristic response (fluorescence) to the bombardment is obtained. For example, calcium will have a different response signature than say, iron (Fe), aluminum (Al), or zinc (Zn). The intensity of the response is proportional to the concentration of the element and therefore enables direct quantification of a specific element in a given sample. Traditionally, XRF is considered to be more suitable for quantifying heavier elements (atomic number > 20). However, new advances in XRF technologies now allow for the quantification of much lighter elements.

**Materials and Methods**

The study was carried out in three phases, using a portable handheld Niton XL3 XRF analyzer. Figure 2.4 shows a photograph of the instrument. Details of the instrument operation and capabilities are outlined on the manufacturer's website (www.Niton.com).

The first phase of the study evaluated the instrument's response to calcium from different sources. Instrument response to two Ca-based stabilizers (lime and cement) and two sources of soil calcium (Gypsum-$CaSO_4.2H_2O$ and Calcite-$CaCO_3$) were evaluated. Samples were prepared by mixing each Ca-based material with bentonite clay (in a 1L Ziploc® bag) to produce mixtures containing 1–8 percent lime, cement, gypsum, or calcite. After thorough mixing, samples were analyzed for calcium (Soils mode) at five random locations across each Ziploc bag (Figure 2.5). Analysis time was 2 min per location for a total of 10 min per sample.


**Figure 2.4. Portable Handheld XRF Analyzer and a Soil Sample Used in Study.**

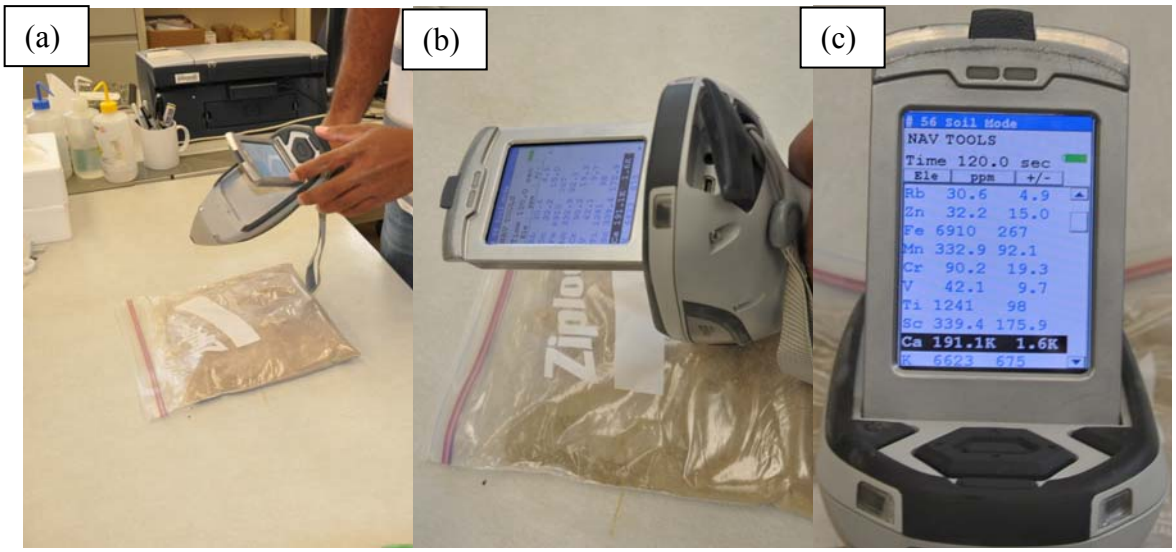



**Figure 2.5. Analyzing Samples for Calcium Using Handheld XRF Analyzer. (a) Select "Soil Mode," (b) Analyze Five Random Locations across Sample, (c) Record Results for Each Analysis Location.**

The second phase of the study evaluated (1) the performance of handheld XRF analyzer to measure stabilizer content in actual base or soil and (2) the influence of particle size on XRF measurements. Two recombined base materials (Oklahoma and FM 957) and one soil (SH6) were studied. Samples were prepared by mixing lime and cement with base materials or soil at concentrations ranging between 2–10 percent stabilizer.

To evaluate the effect of particle size on XRF measurements, samples (base+stabilizer and soil+stabilizer) were initially sieved through a #10 sieve and the calcium content of −10 fraction measured as described earlier (Figure 2.2). The −10 mixtures were then sieved through a #40 sieve and the calcium content of −40 fraction measured.

The third phase of the study was a case study of an actual cement stabilization project along FM 1696. Samples of calcium analysis were located in the eastbound lane of FM 1696 between Stations 159 and 161 (Figure 2.6). Prior to analyzing the cemented-treated samples, the researchers developed a calibration curve for predicting cement content using untreated material and cement collected from the project site (on the day of stabilization). In developing the calibration curve the untreated material and cement were mixed to achieve stabilizer contents of 0, 2, 4, and 6 percent. After mixing, each calibration sample was passed through a #40 sieve and the −40 fraction analyzed for calcium using the XRFanalyzer as in Figure 2.5. The cement-treated samples collected from the stabilization project were also passed through a #40 sieve and the −40 fraction analyzed for calcium as the calibration samples. Parameters from the calibration curve were combined with calcium data from the cement-treated samples to predict cement content at each sampling location.

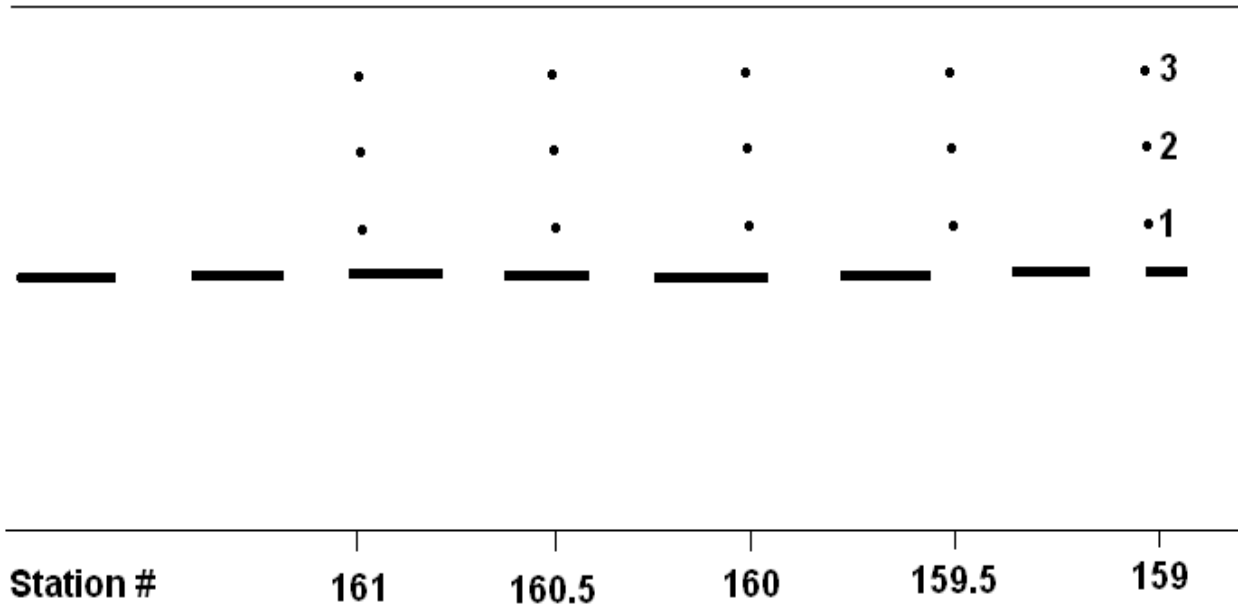



**Figure 2.6. Sampling Scheme for Cement-Stabilization Project along FM 1696.**

## Results and Discussion

*Phase 1: XRF Response to Different Calcium Sources*

Figure 2.7 shows the results when the handheld XRF analyzer was used to measure calcium concentration in laboratory-prepared clay mixes containing 1–8 percent of different Ca-based materials (lime, cement, calcite, and gypsum). Lime and cement represented Ca-based stabilizers while calcite and gypsum represented naturally occurring Ca-bearing minerals likely to be present in soils and/or base materials. In all cases, the correlation coefficient ($r^2$) for XRF-Ca as a function of the amount of Ca-based material exceeded 0.99. Such strong linear relationships indicates the effectiveness of the handheld XRF analyzer in measuring differences in calcium concentration in different materials. This also bodes well for the potential use of XRF technology for measuring stabilizer content in soils and base material, since in most cases the amount of stabilizer added to a project is usually within the 1–8 percent range (used in our experiments).

The slope of the regression lines in Figure 2.7 also provide evidence to support the effectiveness of the handheld XRF analyzer in measuring calcium concentrations in soils and base materials. For example, the slope of the regression lines suggest that the lime, calcite, and gypsum used in the experiments contained approximately 75, 46, and 25 percent calcium, respectively. These values are in close agreement with theoretical values for calcium content (lime = 69 percent, calcite = 40 percent, and gypsum = 23 percent) in these materials. By using a similar approach with cement, the slope of the cement regression line suggests a 73 percent calcium content.

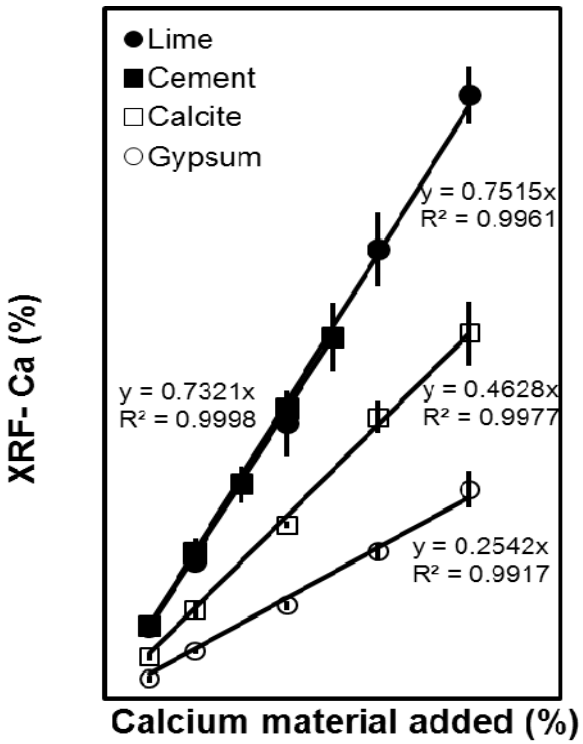



**Figure 2.7. Correlation between Calcium Concentration Measured by XRFAnalyzer (XRF-Ca) and the Amount of Lime, Cement, Calcite ($CaCO_3$), or Gypsum ($CaSO_4 \cdot 2H_2O$) Added.**

*Phase 2: XRF Measurement of Stabilizer Content in Soil or Base Material and the Influence of Particle Size*

Figures 2.8, 2.9, and 2.10 show the relatonship between calcium measured by XRF analyzer (XRF-Ca) and lime or cement content in two base materials (Oklahoma and FM 967) and a subgrade soil (SH 6). The XRF-Ca measurements were carried out after passing the stabilizer treated material through a #10 sieve and then through a #40 sieve.

Strong linear correlations ($R^2$>0.98) were observed between XRF-Ca and stabilizer content in all cases, except in the cement-treated FM 967 base material and the cement-treated −10 fraction of the SH 6 subgrade soil. The reason(s) for the non-responsiveness and non-linearity in these samples are currently unknown. The strong linear relationships obtained in the other samples were consistent with those obtained in Phase 1 and provides further proof of the ability of the handheld XRF analyzer to differentiate between samples containing varying amounts of stabilizer.

Besides non-responsiveness and non-linearity, Figures 2.8, 2.9, and 2.10 highlight several issues that may arise in using XRF to measure stabilizer content. These issues are significant and will need to be addressed before XRF can be considered feasible for estimating stabilizer content.

The first issue is the high variability in XRF-Ca measured for some samples. In some cases (particularly in the SH 6 sample), the standard deviation exceeded 50 percent of the mean value. Typically, variability less than 10 percent is required for quantitative methods while less than 15 percent is required for semi-quantitative methods. Based on the data obtained from the two base materials and the soil, at present XRF can only be considered a qualitative approach for estimating

stabilizer content, which would have significant implications for the enforcement of quality control standards.

The second issue is the apparent effect of particle size on XRF measurements. Similarity between results for the −10 and −40 fraction of the respective Oklahoma and FM 967 bases suggested that particle size had no influence on XRF-Ca in these materials. On the other hand, a significant difference was observed in XRF-Ca for −10 and −40 fractions of the SH 6 soil. Although the actual reason for this discrepancy is not currently fully understood, the type of material and preparation will clearly have a significant effect on results obtained. For example, the lack of a significant effect of particle size on XRF-Ca in the Oklahoma and FM 967 materials, compared to the soil, could be explained by the fact that the base materials were recombined materials rather than natural materials. Irrespective of the reason for the discrepancy in particle size effect, a rigorous sample preparation protocol will need to be developed.

The third issue is discrepancies in regression parameters for XRF-Ca versus stabilizer content relationships, specifically the y-intercepts and slopes. The y-intercepts indicate the background concentration of calcium in the base or soil, prior to stabilization. What this then means is that the y-intercept for a given soil or base should be similar across all types, irrespective of the type of stabilizer added. However, with the exception of the FM 967 base material, this was not the case. For example, the y-intercept for the lime-treated Oklahoma base (Figure 2.8) was 9.14, suggesting that the background concentration of calcium in the material was 9 percent, which was twice the amount suggested from the cement-treated samples.

As shown earlier, the slope for the plot of XRF-Ca as a function stabilizer content is indicative of the Ca content of the stabilizer. Hence, for a given stabilizer and particle size, this value should be the same irrespective of the material being stabilized. From Figures 2.8, 2.9, and 2.10 the slopes for the −10 fraction when 2–10 percent of lime were added to the Oklahoma base, FM 967 base, and SH 6 soil were 2.79, 1.8, and 3.23, respectively. Besides the fact that these values are different, they suggest unrealistically high Ca content (279, 180, and 323 percent) for the stabilizer.

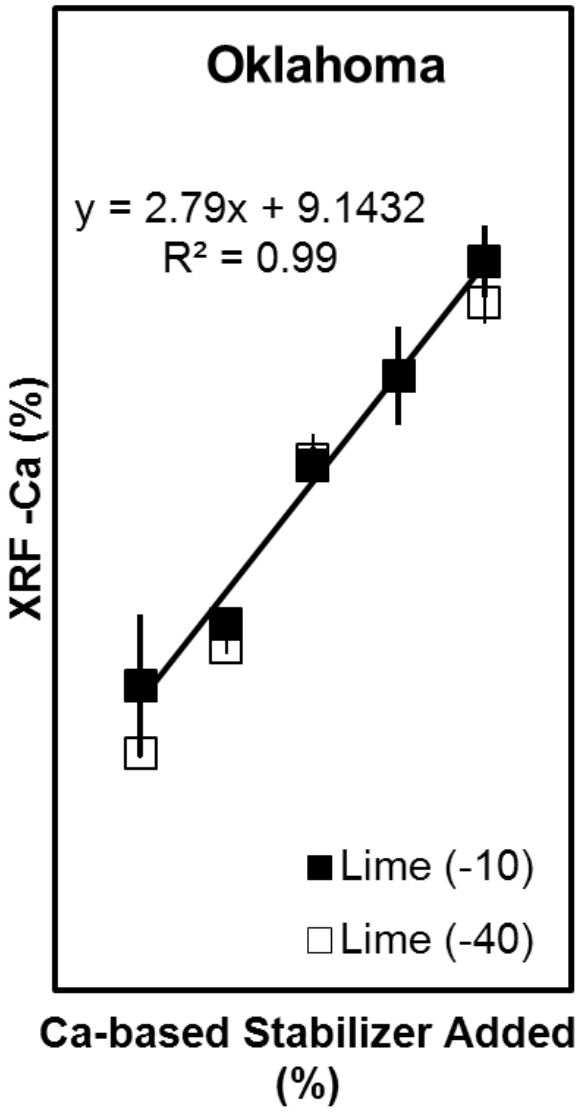



**Figure 2.8. Relationship between XRF-Ca and Stabilizer Content for the −10 and −40 Fractions of Oklahoma Base Material.**

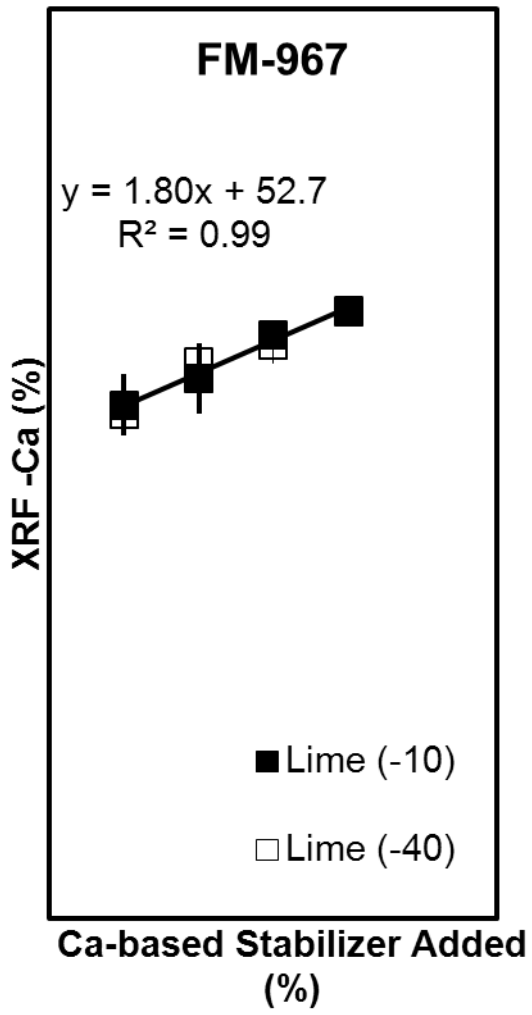



**Figure 2.9. Relationship between XRF-Ca and Stabilizer Content for the −10 and −40 Fractions of FM 967 Base Material.**

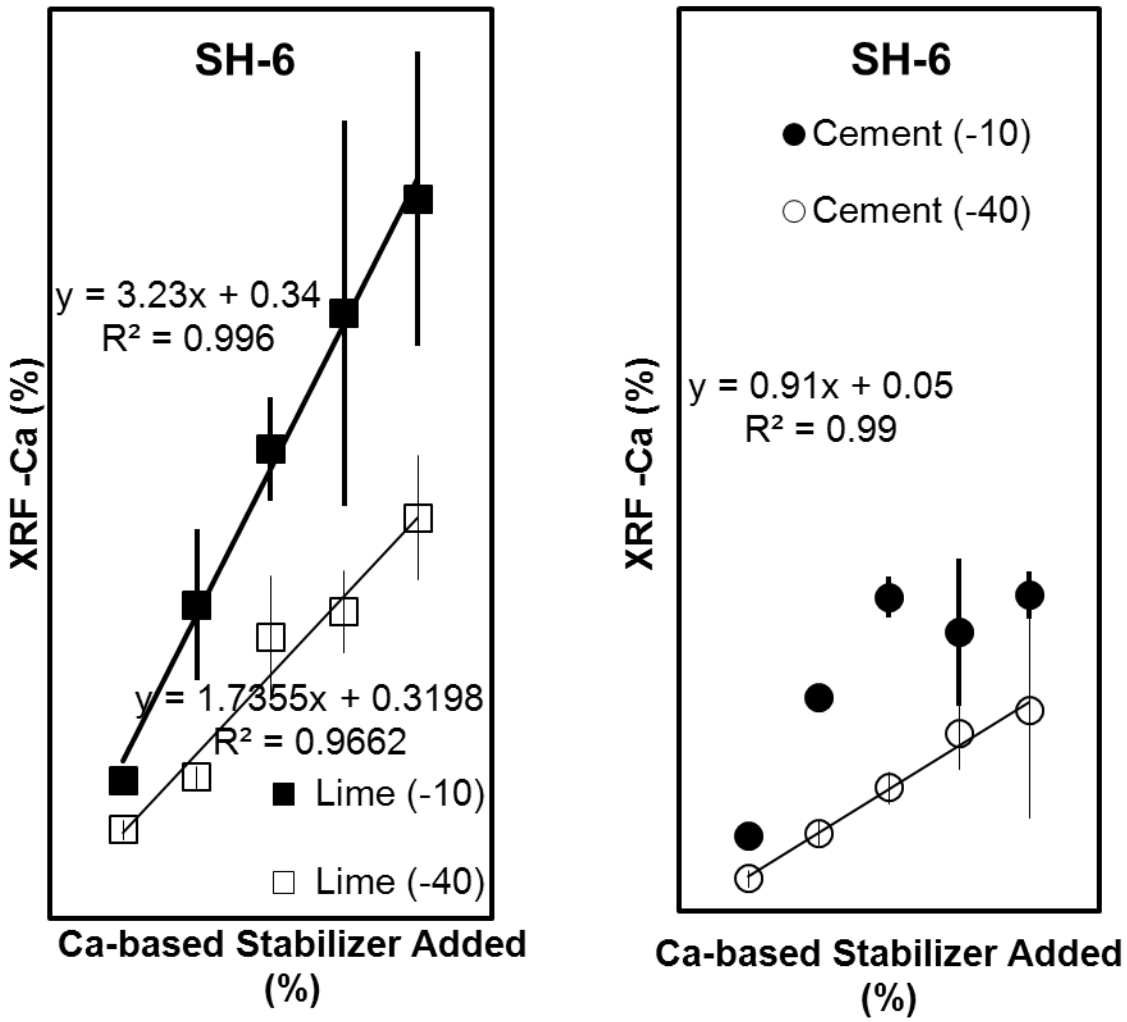



**Figure 2.10. Relationship between XRF-Ca and Stabilizer Content for −10 and −40 Fractions of SH 6 Study Soil.**

*Phase 3: FM 1696 Case Study*

Figure 2.11 shows the calibration curve obtained by mixing cement and untreated material (collected from project site). In addition to a strong linear relationship ($R^2 = 0.95$) between XRF-Ca and stabilizer content, the standard deviation was reasonably low (< 11 percent). The slope suggests that the calcium content of the cement was about 76 percent, which was consistent with the 73 percent estimated for the cement used in Phase 1 of this study.

Table 2.1 shows the XRF-Ca and estimated stabilizer content of the cemented treated samples (collected at the project site). Estimated stabilizer contents were obtained by using XRF-Ca for each location as the x-value in the calibration equation shown in Figure 2.11. Values for stabilizer content (Table 2.1) suggest some spatial variability in cement application across the sampled area. However, the standard deviations about the mean estimated cement content were extremely high (exceeding 20 percent variability in most cases). Such uncertainity in stabilizer

content would make it difficult for the enforcement of any quality control standards. For example, let us consider the case of sample location 160.5-2 (Table 2.1) with estimated cement content of 3.8 ± 1.4 percent or a 37 percent variability. In reality the "true" cement content could be anywhere between 2.4 and 5.2 percent. Making a quality control call on whether a project meets the minimum stabilizer requirement of 4 percent based on 37 percent variability becomes very difficult, compared to, say, a 15 percent variability, which would have a range of between 3.2 and 4.4 percent.

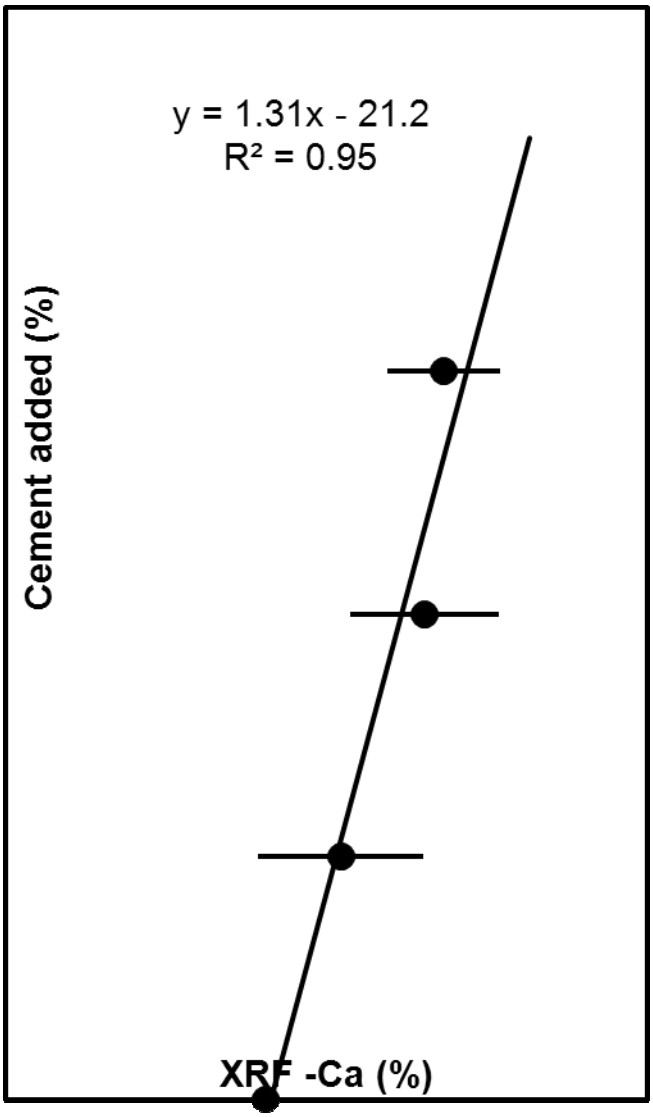



**Figure 2.11. Calibration Curve when 0, 2, 4, and 6 Percent of Cement Was Added to Untreated Material from the FM 1696 Project.**

**Table 2.1. Calcium Measured by X-Ray Fluorescence and Estimated Cement Content at Several Locations along the FM 1696 Project.**

| | ----------XRF Calcium (%)---------- | | | | | Estimated Cement Content (%) | |
|---|---|---|---|---|---|---|---|
| Station 159 | 1 | 2 | 3 | 4 | 5 | Average | stdev |
| 159-1 | 18.7 | 19.4 | 19.5 | 19.2 | 19.8 | **4.1** | 0.5 |
| 159-2 | 16.4 | 17.5 | 17.0 | 16.8 | 17.1 | **1.0** | 0.5 |
| 159-3 | 16.6 | 13.9 | 15.7 | 16.2 | 15.0 | **−0.9** | 1.4 |
| Station 159.5 | | | | | | | |
| 159.5-1 | 18.8 | 17.1 | 18.4 | 17.8 | 18.0 | **2.4** | 0.8 |
| 159.5-2 | 16.8 | 15.9 | 17.3 | 16.9 | 17.3 | **0.9** | 0.8 |
| 159.5-3 | 21.0 | 21.5 | 21.3 | 20.2 | 21.4 | **6.4** | 0.7 |
| Station 160 | | | | | | | |
| 160-1 | 21.9 | 21.0 | 19.9 | 12.7 | 20.4 | **3.9** | 4.8 |
| 160-2 | 17.8 | 18.6 | 18.5 | 17.2 | 18.2 | **2.5** | 0.7 |
| 160-3 | 18.9 | 20.3 | 20.1 | 19.3 | 20.1 | **4.7** | 0.8 |
| Station 160.5 | | | | | | | |
| 160.5-1 | 19.6 | 18.4 | 18.8 | 19.4 | 18.1 | **3.5** | 0.9 |
| 160.5-2 | 20.3 | 17.6 | 19.8 | 18.4 | 19.5 | **3.8** | 1.4 |
| 160.5-3 | 15.8 | 19.1 | 20.5 | 19.4 | 18.7 | **3.3** | 2.3 |
| Station 161 | | | | | | | |
| 161-1 | 18.4 | 17.9 | 18.3 | 18.6 | 18.0 | **2.7** | 0.4 |
| 161-2 | 19.4 | 19.3 | 18.5 | 19.3 | 18.4 | **3.7** | 0.6 |
| 161-3 | 22.0 | 18.8 | 19.2 | 18.3 | 15.9 | **3.5** | 2.9 |

**Conclusions from XRF Evaluation**

Preliminary investigations using the XRF analyzer to estimate Ca-based stabilizer content in soils and base material show some promise. However, it is important to emphasize that the data presented are only preliminary. Before the technique can even be considered for implementation/adaptation, a significant amount of research is required to address a number of issues that this study highlighted. Paramount among the issues needing to be addressed are:

- The high variability in XRF-Ca measurements in a given sample.
- The non-responsiveness or non-linearity of XRF-Ca with increasing stabilizer content in some cases.
- The large differences between measured background Ca (y-intercept values) for the same soil or base when lime versus cement is added.

- Discrepancy in slope (apparent Ca content of stabilizer) for a given stabilizer added to different soils or base material.
- Why particle size (−10 versus −40) had no apparent effect on XRF-Ca for bases but had such a large effect on XRF-Ca in soils.
- Given that current analysis time is approximately 10 minutes/sample, what is the optimal analysis time required for accurate and precise measurement while enabling rapid determination of stabilizer content.

## EVALUATING STABILIZER CONTENT IN FDR USING INDICATOR TESTS

There is still an urgent need for a simple field technique that can be used to at least determine if the stabilizer is adequately spread and mixed to the required depth. As described below, a laboratory study was undertaken to determine if a simple phenolphthalein test could be run to estimate the amount of stabilizer within an FDR base.

### Indicator and pH Tests

Aim: To produce a quick field procedure using phenolphthalein to indicate the amount of lime or cement stabilizer present. A reaction that produces a fuchsia color would show the presence of lime or cement, and the intensity of this color would show the amount. With further work, a scale would be developed against which samples would be compared in order to assess the stabilizer amount present.

### Indicator Test

1. Several bags of a 50/50 mixture of reclaimed asphalt pavement (RAP) and base were obtained.
2. Five 50 g samples of this 50/50 material were weighed out. (Note that these were "dry samples," maintained at the same water content that they had when taken from the field).
3. No lime (0 percent) was added to one sample while 2, 4, 6, and 8 percent lime, respectively, was added to the remaining four samples.
4. 500 ml of water were added to each sample.
5. The 50/50 material, lime, and water mixtures were shaken for 5 min and allowed to stand for 10 min. (Solutions with a 1:10 concentration were produced.)
6. The supernatant was poured into 250 ml bottles.
7. The supernatant was then filtered (using 0.45 μm filters) into centrifuge tubes for subsequent analysis.
8. The same procedure from steps 1 through 7 was followed to obtain four cement treated materials that had 0, 1, 3, and 5 percent cement. (Note that these were also dry samples.)
9. In addition to the dry samples, one more set of five 50 g wet samples containing lime and five 50 g wet samples containing cement was obtained by adding water to the Optimum Moisture Content (adjusting for water based on stabilizer amount). The wet samples were put through the same procedure described in steps 1 to 7 above.

**Dilution of Solutions and Addition of Phenolphthalein**

When phenolphthalein was added to samples of the four different sets (i.e., dry and wet containing lime, dry, and wet containing cement) of 1:10 solutions, there were no visible differences in shading between those that contained 2, 4, 6 and 8 percent lime and 1, 3, and 5 percent cement. The solutions that did not contain lime and cement remained colorless. As a result, different dilutions were investigated for each of the four different sets of solutions. This process was repeated until an appropriate dilution was obtained where there were visible differences in shading between the samples that had different lime and cement contents.

The 1:95 dilution containing lime seemed to work best for the dry and wet solutions. The 1:95 solutions were made by taking 1 ml of the 1:10 solution and making it up to 95 ml (the same as taking 0.5 ml and making it up to 47.5 ml) with double distilled water. Subsequently, 0.25 ml drops each of the 1:95 solutions were pipetted onto a spot plate, followed by a 0.01 ml drop of 0.1 percent phenolphthalein (Figure 2.12).

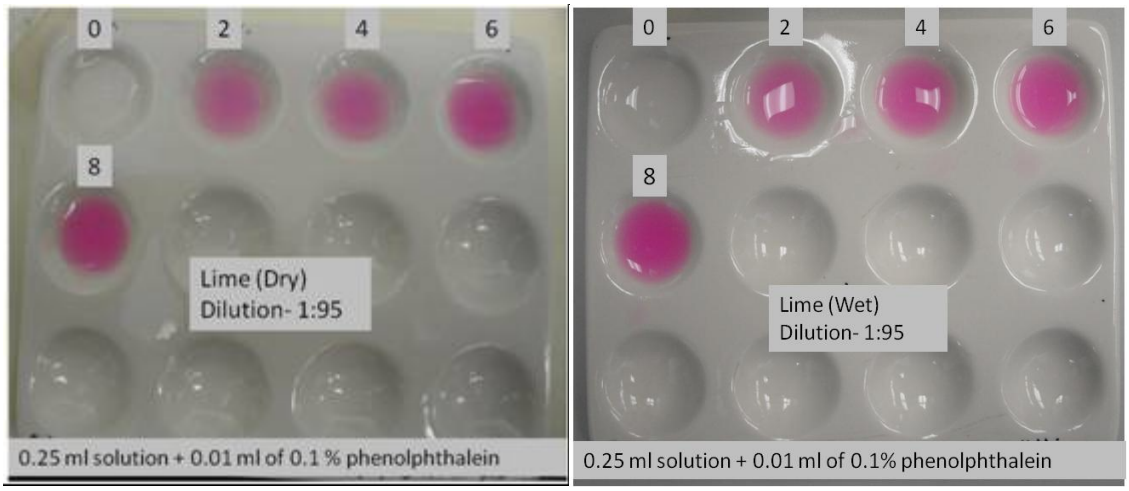



**Figure 2.12. Different Amounts of Lime Are Differentiated by Shades of Fuchsia.**

The spot plate on the left has solutions made from the dry samples containing lime. The spot plate on the right contains solutions that were made from a wet sample containing lime. Note that the 0 percent lime solution remains uncolored, but it appears that the shade of fuchsia increases with the lime content.

The dilution used for the wet solution containing cement was 1:20, and for the dry one, 1:30 (Figure 2.13). Using the same procedure as with the samples that contain lime, researchers placed 0.25 ml drops on a spot plate followed by 0.01 ml drops of 0.1 percent phenolphthalein.

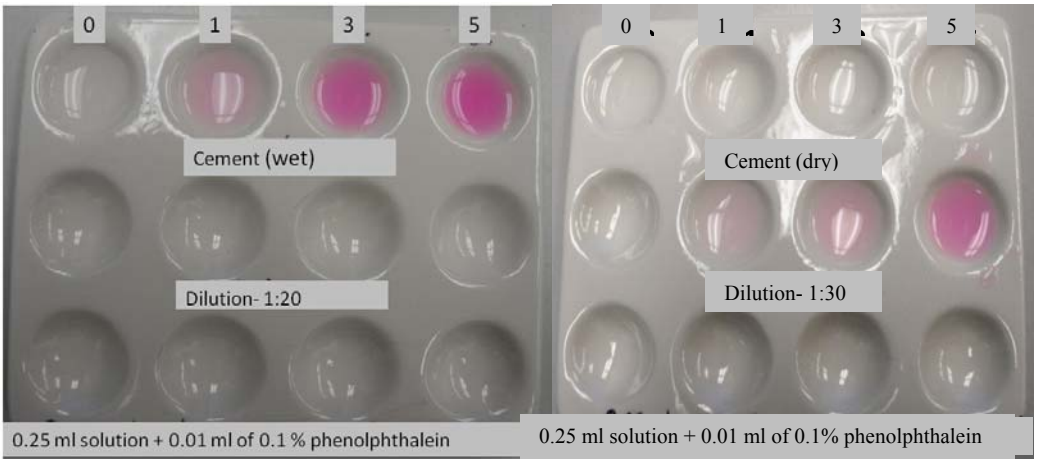



**Figure 2.13. Different Amounts of Cement Are Differentiated by Shades of Fuchsia.**

The spot plate on the left has solutions made from the wet samples containing cement. The spot plate on the right contains solutions that were made from dry samples containing cement.

**Limitations**

The researchers observed several clear limitations as the test method was followed. One of the most striking was the quick disappearance of coloration after the addition of phenolphthalein. Within a few seconds (approximately 10) after its addition, the color started to disappear and the sample would become totally colorless within 5–10 minutes. It would then be safe to say that any observations on color should be made within the first 15 seconds after phenolphthalein addition.

Additionally, it is apparent at this time that different scales would have to be developed for wet and dry samples. The intensity of the shade was different for wet and dry samples having the same stabilizer content. As seen in Figure 2.12, even though there is an increase in shading for both the wet and dry samples, it would be difficult to tell the difference between those of higher pH, for example between 6 and 8 percent lime. It would be easier to differentiate between a 2 and 8 percent lime content. Currently, the method is subjective at best. It provides only a potential qualitative assessment but not a quantitative one.

The work presented above found that the phenolphthalein test was not feasible to be a definite indicator of the amount of stabilizer used in an FDR project. Phenolphthalein remains a useful go/no-go indicator (see Figure 2.14). The best use is in auger holes to determine if the stabilizer is mixed to the depth required in the pavement design.


**Figure 2.14. Using Phenolphthalein to Check Depth of Stabilization.**

## INFLUENCE OF VARYING RAP PERCENTAGES

Determining how varying RAP percentages impact the strength that the FDR mixture achieves remains a topic of concern during construction. Variability in the bituminous surface layer thickness will result in the RAP percantage changing. The best method for controlling this variability is by planning for it through the up-front testing and design stages of the FDR project. However, even with careful planning, some variability will be encountered.

TxDOT specifications currently limit RAP content to 50 percent. To investigate whether this limit should be changed, the research team used the FDR materials from FM 969 and systematically varied the RAP percentage, while maintaining the design cement content, to evaluate at what RAP content the mixture failed to meet the minimum strength criterion. Figure 2.15 presents the mixture design, which called for 3 percent cement with 50 percent RAP. Figure 2.16 illustrates that while keeping the treatment level constant, the RAP percentage could reach up to 63 percent and still meet the minimum strength criterion of 175 psi.

Project location – FM 969 Travis Co., TX
Project # - n/a
Contractor – n/a
Date Completed – 06/25/09

TTI
Lab Technician –
Phone # -
Design Engineer –

| Design Blend Percentages | |
|---|---|
| Existing RAP | ~50% |
| Existing Base | ~50% |
| Add Rock | 0% |

| Compaction Properties | |
|---|---|
| Required Moisture | 6.6 |
| Max Dry Density | 133.5 |

| Subgrade Sulfate Content |
|---|
| 160 ppm |

| Sieve Analysis of Aggregate Base | |
|---|---|
| Sieve Size | % Passing |
| 1 ¾ | 100 |
| 1 ¼ | 94.3 |
| 7/8 | 88.9 |
| 5/8 | 81.5 |
| 3/8 | 66.5 |
| #4 | 48.5 |
| #10 | 35.6 |
| #40 | 18.9 |
| #100 | 10.4 |
| #200 | 8.3 |

| Performance Criteria | | | | |
|---|---|---|---|---|
| | 2% | 3% | 4% | Spec Limits |
| Unconfined Compressive Strength (psi) @ 25°C (Tex-120-E) | 166 | 247 | 327 | 175 psi min |
| Retained UCS (psi) @ 25°C after Tube Suction Test | 193 | 304 | 359 | 80% min |
| Retained UCS (psi) after 7-day cure and 4 hour submersion | 162 | 222 | 263 | For Information Only |
| Tube Suction Test Final Dielectric (Er) and moisture content (%) (Tex-144-E) | 13.5 | 13.1 | 11.3 | For Information Only |
| Unconditioned Seismic Modulus (ksi) (ASTM D 4123) | 957 | 1314 | 1512 | For Information Only<br>Tested at 7 days |

| Recommendations | |
|---|---|
| Cement Content | 3 |
| Optimum Moisture Content | 6.6 |

**Figure 2.15. FM 969 Mixture Design.**

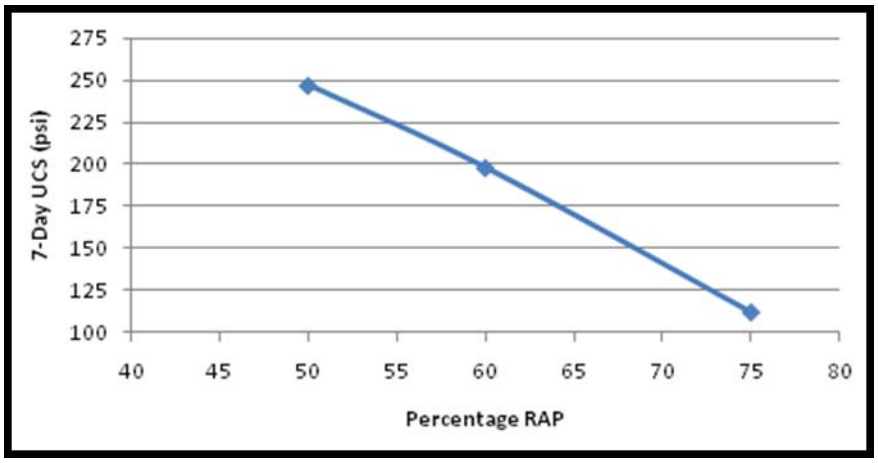



**Figure 2.16. Influence of RAP Content on UCS for FM 969.**

Next, the research team prepared test samples with 75 percent RAP and investigated how much the cement content would need to be increased to still meet minimum design strengths. Figure 2.17 presents the results, which show the cement content must increase from 3 to approximately 4.5 percent to still meet the minimum strength criterion with this material at 75 percent RAP.

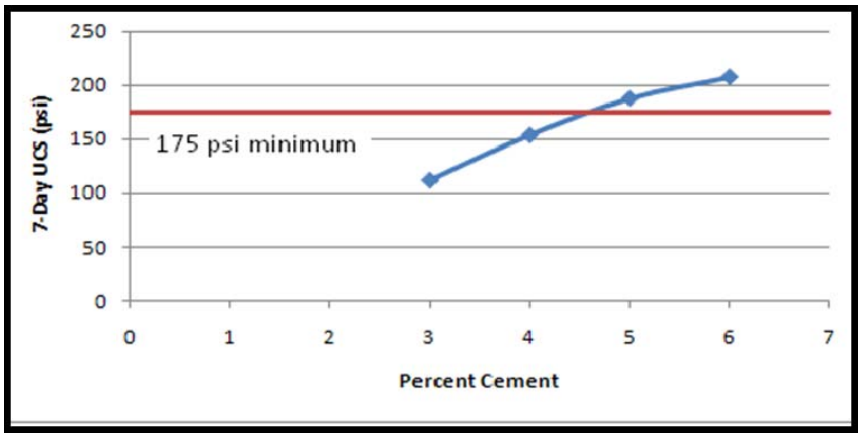



**Figure 2.17. Strength of FM 969 Mixture with 75 Percent RAP.**

The results suggest that no incentive exists to raise the allowable percentage RAP in FDR mixtures. The highest economic value with RAP is generally in bituminous mixtures (due to the asphalt cement content); additionally, the results suggest that strength rapidly declines as the percentage RAP increases. To account for significant increases in RAP percentage, the FDR mixture requires additional stabilizer. While this can be performed through a redesign, the best approach is to retain the maximum percentage RAP at 50 percent and use thorough up-front testing to design the project in a manner that minimizes variability.

## POTENTIAL HINDRANCES TO EFFECTIVE STABILIZATION

Some TxDOT offices have reported problems with stabilization taking place, even when relatively high amounts of stabilizer are added. Both physical and chemical mechanisms can interfere with and/or retard effective stabilization. Table 2.2 presents some examples of each type of interference.

**Table 2.2. Physical and Chemical Interferences with Stabilization.**

| Mechanism | Example |
|---|---|
| Physical properties of material:<br>• Roundness<br>• Sorting<br>• Sphericity | Muscovite<br><br>Rounded sands |
| Chemical:<br>• Reactivity/Retardents | Sulfates<br>Organics<br>Iron Oxides (anecdotal evidence) |

## CHECKING FIELD MODULUS

While TxDOT uses field density measurements for compaction testing and acceptance, limited work in this project was conducted employing a PFWD and PSPA for tests on FDR layers after compaction. Since the stiffness and modulus values of stabilized layers are constantly changing during the curing period, the research team concluded that identifying target values for compaction of stabilized layers was impractical. Additionally, even if the "true" target could be identified, few practical options exist for reworking stabilized layers. Also, under normal curing operations the surface is kept moist during the first three days. Stiffness needs to be checked during this time. Other concerns were also raised about the poor repeatability of measurements with the coarse textured surface. Figure 2.18 shows the grid arrangement used on FM 2502 to check the different NDT devices shown in Figure 2.19.

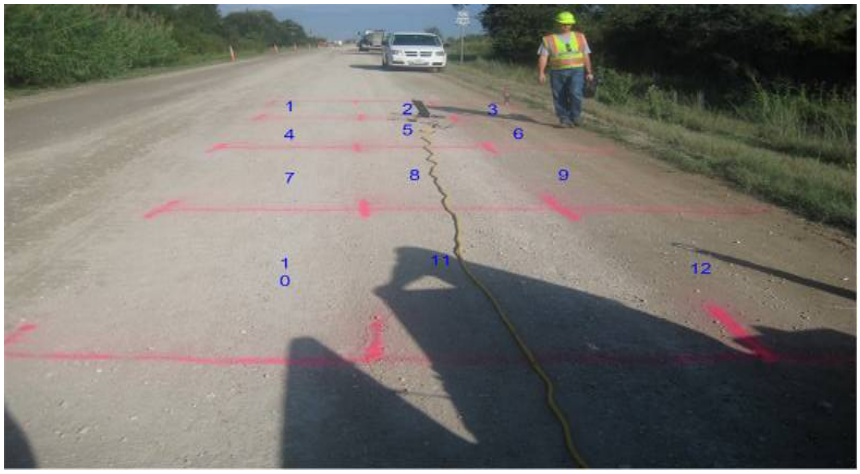



**Figure 2.18. NDT Testing Arrangement on FM 2502.**

**Figure 2.19. Portable FWD and Seismic Test Equipment.**

Table 2.3 shows the two highest and two lowest modulus locations from the test conducted on FM 2502 two days after compaction. Each value is an average of three readings taken at each location. The DCP modulus was obtained from the standard Corps of Engineers CBR equation. The seismic modulus values are substantially less than those measured in the lab during design, which were around 600 ksi at two days. The most promising use of portable stiffness or modulus devices in FDR currently is for evaluating effectiveness (or uniformity) of microcracking of cement-treated materials. Product 0-4502-P4 contains guidelines for such use.

**Table 2.3. Correlation of Stiffness Values Obtained on an FDR Project in the Bryan District.**

| Location | PFWD (ksi) (subgrade ksi) | Seismic (ksi) | DCP (ksi) |
|---|---|---|---|
| 2 | 92 ( 11ksi) | 145 | 65 |
| 7 | 90 ( 12 ksi) | 120 | 73 |
| 9 | 31 ( 6 ksi) | 84 | 43 |
| 12 | 15 (4.5 ksi) | 52 | 30 |

## USE OF THE FWD FOR DESIGN VALIDATION

In several of the recently completed FDR projects, the research group collected FWD data to verify the uniformity of stabilization and to check that pavement design assumptions have been met. This section presents the method used to set target deflection values and shows case studies of good and poor results. These studies support the following conclusions:

- FWD data should be collected during construction of the FDR project.
- Acceptable limits should be based on maximum deflection under 9000 lb load level.
- This use of the FWD should be implemented by plan note on all FDR projects, with testing conducted as soon as possible after compaction.
- The data should be presented to TxDOT area office personnel in the graphical format shown below.
- Provide guidelines on an action plan if unsatisfactory results are obtained.

Implementing this approach is very simple and can be used to avoid major failures, which have and still continue to occur. The first step is to set the target deflection level in mils for the highway under construction. This will require the designer to select the pavement layer where the FWD data will be taken. This level could be on top of the underseal prior to placement of the final HMA surface or directly on top of the stabilized layer. Both of these placements have been performed in the field, and both work well. The important issue is to collect FWD data as soon as the first section (for example, 1000 ft) has been completed so that modifications to the process can be made before the construction is finalized.

The process requires the designer to know the layer thicknesses and the layer moduli and Poisson's ratio. The values shown below in Table 2.4 can be used for this purpose. These are the values used in the FPS design process, and they are known to be very conservative (low). The values measured in the field should be higher than these numbers.

**Table 2.4. Modulus Values to Be Used to Calculate Target Deflections.**

| Materials Description | FPS Design Modulus Values | Poisson's Ratio |
|---|---|---|
| Existing Subgrade | Backcalculated from FWD | 0.40 |
| Existing Pavement Scarified, Reshaped | 3 Times Subgrade Modulus | 0.35 |
| Stabilized Existing/Subbase | | |
| • Most Granular Base (75% more base) | 100 ksi | 0.30 |
| • Blend Subgrade & Base (50–75% base) | 65 ksi | 0.30 |
| • Mostly Subgrade (< 50% base) | 35 ksi | 0.35 |
| Stabilized RAP/Existing Base; Max 50/50 Blend | | |
| • Cement | 150 ksi | 0.25 |
| • Lime | 75 ksi | 0.30 |
| • Emulsion | 100 ksi | 0.30 |
| • Fly Ash | 75 ksi | 0.30 |
| New Flexible Base over Stabilized Layer | 70 ksi | 0.35 |

Values for the subgrade should be known from district experience; values for all other layers can be assumed as shown below:

- Subgrade if unknown: 6 ksi and Poisson's ratio 0.4.
- Surface treatment assume thickness of 0.5 in. and modulus of 200 ksi.
- Hot Mix asphalt: 500 ksi.

The values from Table 2.4 and other layers are then input into the Stress Analysis Tool of the FPS21 software. Figure 2.20 shows the screen from the FPS stress analysis software. The layer thicknesses and moduli are entered in the structure on the left of the figure, the 9000 lb FWD load pulse is applied to this pavement, and the predicted FWD deflection bowl is graphed and displayed numerically in the deflections versus sensor location graph. The researchers propose that the computed maximum deflection value (29.4 mils in this example) will be used for strength validation.

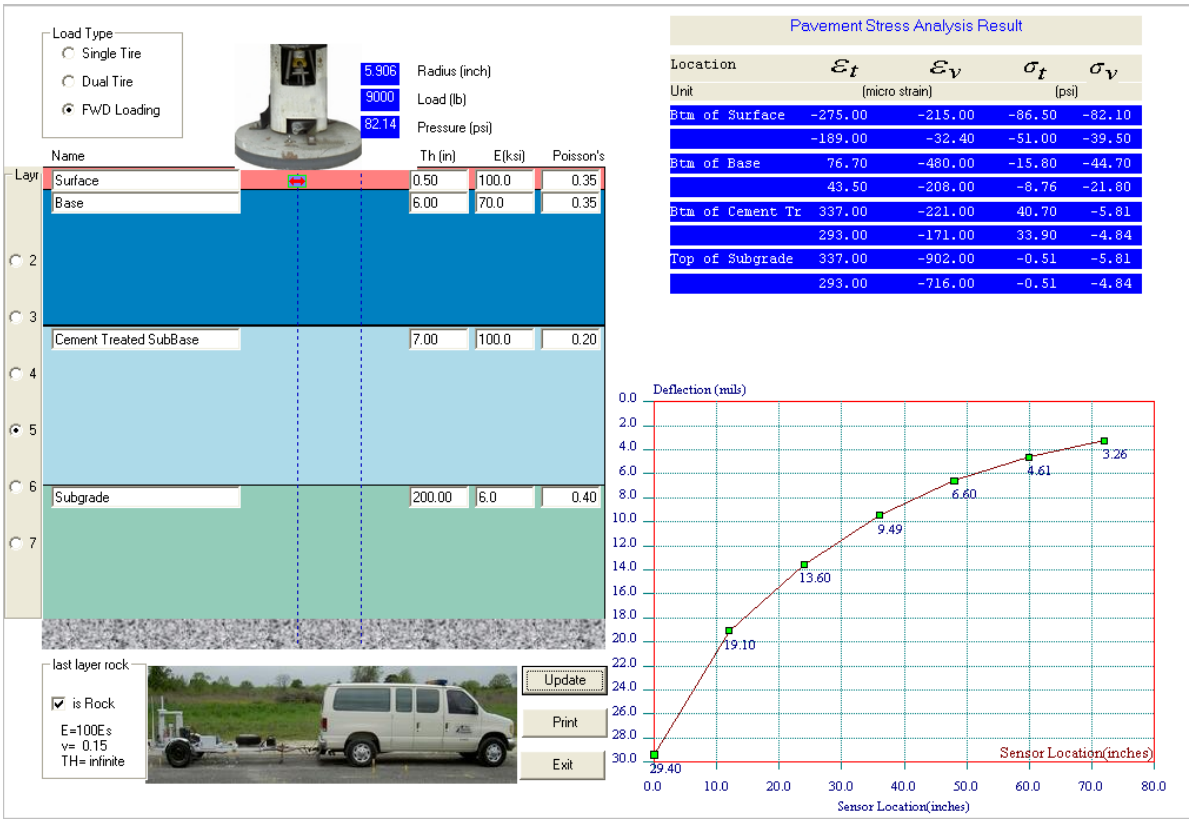



**Figure 2.20. Application of Stress Analysis Tool in FPS21 to Predict Target Maximum FWD Deflection for an FDR Project.**

Figure 2.21 shows the prediction for the FDR project completed in Dallas on FM 148. The FWD testing was to be completed on top of the flexible base layer on the underseal, but before the final HMA surfacing was placed. In the graph shown in Figure 2.20 the maximum deflection allowable should be 31 mils. The FWD data can be collected and compared with this value.

**Figure 2.21. Partially Completed FM 148 Verification Testing of First 1.1 Mile.**

The FWD data for FM 148 are shown below as the blue line in Figure 2.22, the target from the pavement design is shown as the red line, and the average deflection prior to the FDR work is shown as the green line. The measured deflections all fall below the value predicted from design, which indicates a strong pavement structure.

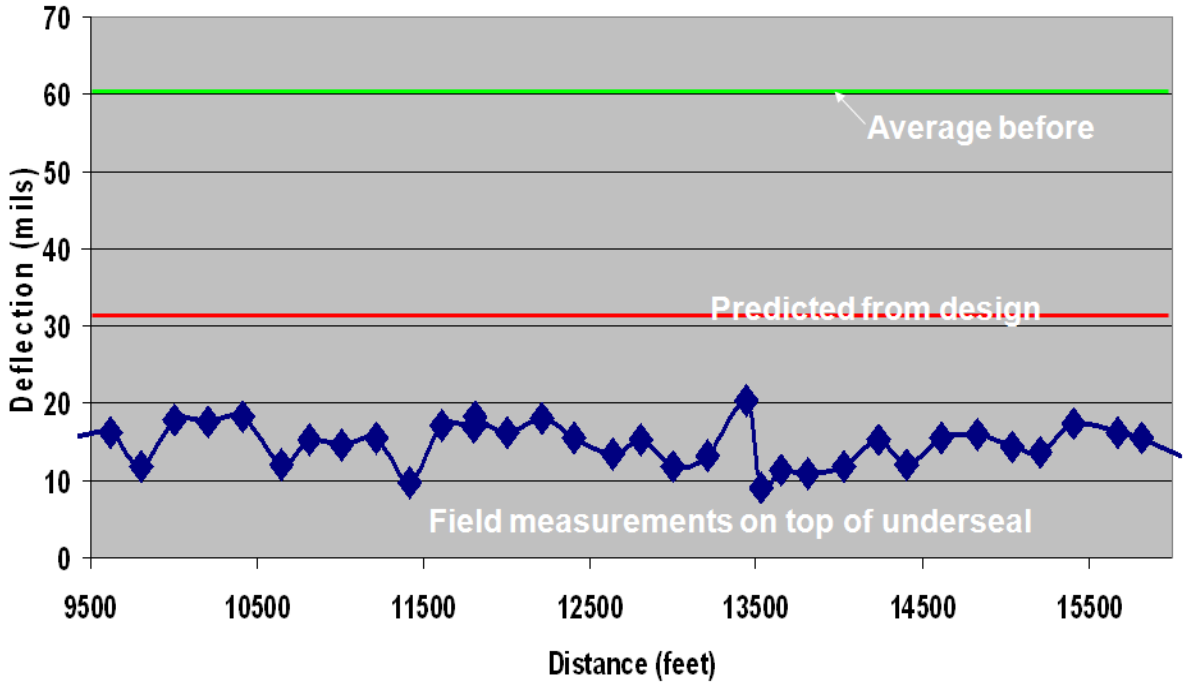



**Figure 2.22. Validation Testing Results for FM 148 (Good Design and Good Construction).**

The satisfactory results from FM 148 have not been found on all projects tested. Figures 2.23 and 2.24 show both a marginal and a poor project. In Figure 2.23, poor results were found in the first 200 ft of the project. This result was related to construction problems where the application of water to the cement treatment was delayed because of equipment failure.

Figure 2.24 shows data collected as part of a forensics evaluation that was conducted when the pavement started to fail no more than two months after construction. The deflections should have been below the yellow line, which is based on having a properly stabilized layer. In this case, many problems were found, with the selection of the wrong stabilizer and very wet weather during construction. Unfortunately, researchers performed this testing after construction was completed. Clearly the whole project is bad, and this could easily have been mitigated if the section was tested when the first 0.5 miles was completed. This case study clearly shows the benefits of early FWD validation testing. The FWD equipment is widely available around Texas, and it should be used for this purpose.

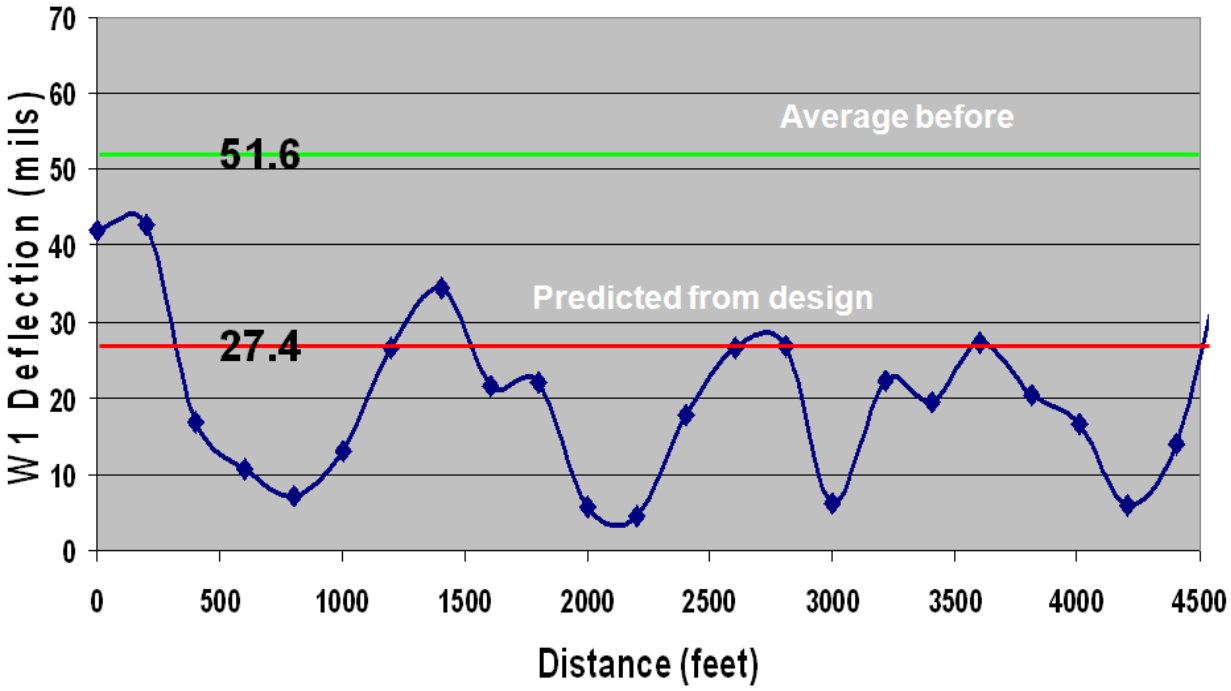



**Figure 2.23. Validation Test Results from a Marginal Project (Equipment Problems).**

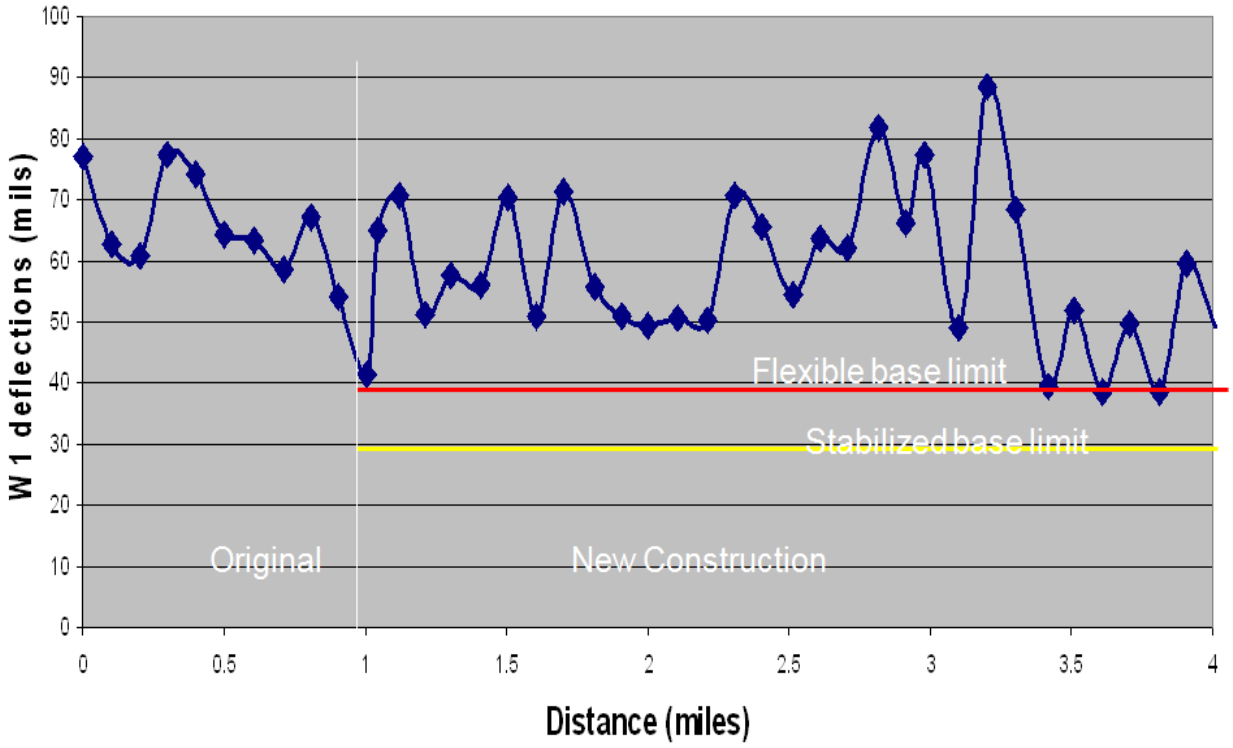



**Figure 2.24. Validation Results from a Section that Failed Two Months after Completion.**

# CHAPTER 3
# EVALUATING SURFACE TREATMENT BONDING ON FDR MIXTURES

## BACKGROUND

The common practice in Texas is to pave most low-volume FDR roadways with a surface treatment. After the recycled base has been stabilized and compacted to density and grade, a prime material is applied. The prime material will usually be a spray-on application of one of the following products (Spec Item 300):

- MC-30 (medium cure cutback asphalt).
- AE-P (asphalt emulsion prime).

Application rates range from 0.1 to 0.2 gal/sy, depending on the tightness of the base finish and whether construction traffic has to be allowed on the primed surface. If the base must carry traffic until the surface treatment is applied, then a "covered prime" may be used. A covered prime is an RC-250 with an application of Grade 5 (Spec Item 302) seal coat aggregate. This type of prime can provide two to three months of satisfactory service as a temporary wearing course.

A few districts have used a worked-in or cut-in prime though it is more common on flexible base construction rather than FDR. Diluted asphalt emulsion (such as SS-1, CSS-1h, and MS-2) is sprayed onto the base and mixed into the top 1–2 inches of the base course as it is being constructed. A total application rate of 0.2 gal/sy is usually targeted.

The purpose of the prime coat for FDR roadways is to (1) maintain the moisture content of the base while it cures, and (2) bond the surface treatment to the base. Given the array of FDR stabilizers, types of base materials, types of prime materials, base finishing techniques, construction techniques, and traffic handling situations, one recurring problem statewide is achieving an adequate bond of the surface treatment to the base course.

## SURFACE TREATMENT BOND TEST

The researchers developed a test procedure in this study to assess the bond of the surface treatment to FDR base material. Most of the work has been directed toward adapting the test for laboratory evaluation so that optimization of materials and quantities may be achieved prior to field application. This test was also performed in the field using a fast-setting, underwater epoxy called WaterWeld™. However, additional research is needed to standardize this test for field use. It is a modification of the Direct Tensile Bond Test (ASTM C 1583), which is a test used to measure the bond strength of concrete repair and overlay materials. The test is performed on a compacted, recycled base sample that has been primed and topped with a surface treatment. The procedure includes gluing a steel disk with epoxy to the surface treatment and applying a tensile load perpendicular to the surface. Table 3.1 provides a summary of the test procedure. The measured strength is controlled by one of four failure mechanisms requiring the least stress: (1) failure within the base layer; (2) bond failure at the interface between the surface treatment and the base; (3) failure within the surface treatment binder; or (4) bond failure at the epoxy interface. Figure 3.1 shows the equipment and a sample after testing where the failure has occurred within the base layer.

This test may seem similar to a current TxDOT test: Tex-243-F "Tack Coat Adhesion" (Figure 3.2). The tack coat adhesion test measures the adhesive properties (or "stickiness") of a tack coat that is used to bond asphalt concrete to an existing paved surface. This test could not be

used to assess a prime coat, which is placed prior to the surface treatment, because a good prime coat completely penetrates into the surface of the base with no sticky residue remaining at the time of the surface treatment binder application. The researchers polled the districts but did not find anyone using Tex-243-F for evaluating primed base courses.

**Figure 3.1. Surface Treatment Bond Test Equipment and Tested Lab Specimen.**

**Figure 3.2. Tack Coat Adhesion Tester (Tex-243-F).**

**Table 3.1. Summary of Test Procedure to Evaluate Surface Treatment Bond.**

| | |
|---|---|
| Determine optimum moisture content according to Tex-113-E for recycled base material. Compact 6 replicate 6-in. diameter by 2-in. high samples in a single lift. Cover sample with plastic wrap for 1 hr. After 1 hr, trim plastic wrap from the surface of sample. |  |
| Apply prime material at predetermined application rate to specimen surface. Place sample in 110°F oven to cure for three days. |  |
| Apply Grade 5 surface treatment to samples and place in 110°F oven overnight. |  |
| Remove samples from oven and allow to cool for 1 hr. Apply epoxy glue to the metal disk and place on to specimen surface. Allow glue to dry overnight. |  |
| Test sample in Direct Tension Bond Test apparatus and record the ultimate breaking strength in lb and identify the plane where the failure occurred:<br>• In the surface treatment.<br>• Interface between prime and surface treatment.<br>• Within the penetrated portion of the prime.<br>• Beneath the prime.<br>• Into the base. |  |

## LABORATORY TEST RESULTS

The previous project report (0-6271-1) presents early laboratory trials and preliminary test development results. Subsequent test results are presented here. Appendix B includes the draft laboratory test protocol.

A laboratory test program was implemented to further evaluate the test procedure and bond strength of surface treatments fabricated under different conditions. The following variables were examined in a limited laboratory study:

- Type of prime material.
- Prime material application rate.
- Type of base material.
- Effects of coring into the base sample prior to testing.
- Type of stabilizer used.
- Moisture content of base material.

### Effect of Prime Material Type on Surface Treatment Bond

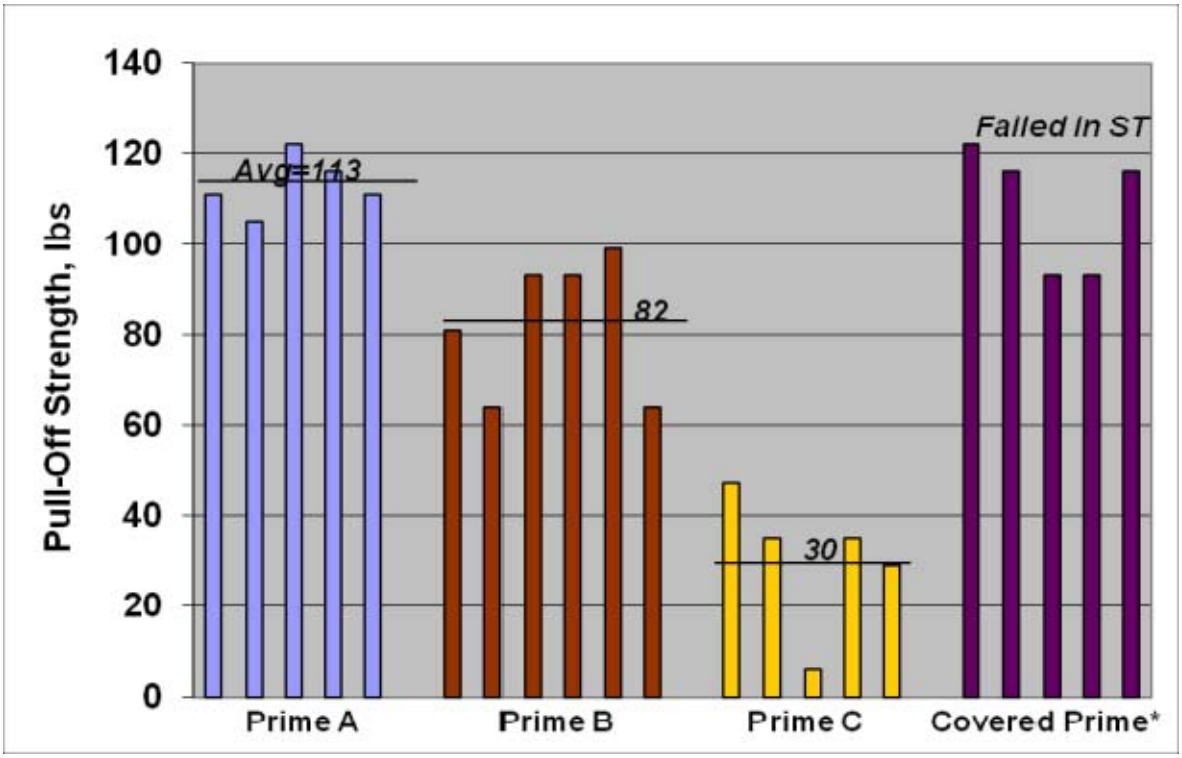
To evaluate the effect of prime type, researchers prepared and treated 24 base samples with 0.1 gal/sy of different prime types as follows:

- Six samples treated with prime material A.
- Six samples treated with prime material B.
- Six samples treated with prime material C.
- Six samples treated with a covered prime (RC-250/Grade 5 Aggregate).

The base course was from the Frost Pit in the Bryan District and was treated with 3 percent cement. After the specimens were primed and cured, the researchers applied a surface treatment using AC-20-5TR and Grade 5 lightweight aggregate. Figure 3.3 presents the pull-off strength results. Figure 3.4 shows photos of the primed specimens prior to application of the surface treatment.

For Primes A and B, the pull-off tensile failure occurred beneath the prime and into the base course. This failure indicates that the surface treatment was well bonded to the base course. Figure 3.5 shows the prime coat well penetrated into the base. On the other hand, prime coat C was not well penetrated (Figure 3.6), and the failure occurred just at the surface of the base course, indicating the surface treatment was not well bonded to the base.

On the specimens where the covered prime was used, the surface treatment was so well bonded to the base course that the failure occurred within the surface treatment binder as shown in Figure 3.7. These results indicate that some types of primes are more effective than others at ensuring a good bond of the surface treatment to the base course and that the bond test developed in this study can distinguish between different types of prime materials.




*RC-250 with Grade 5 Aggregate

**Figure 3.3. Effect of Different Primes on Surface Treatment Pull-Off Strength.**

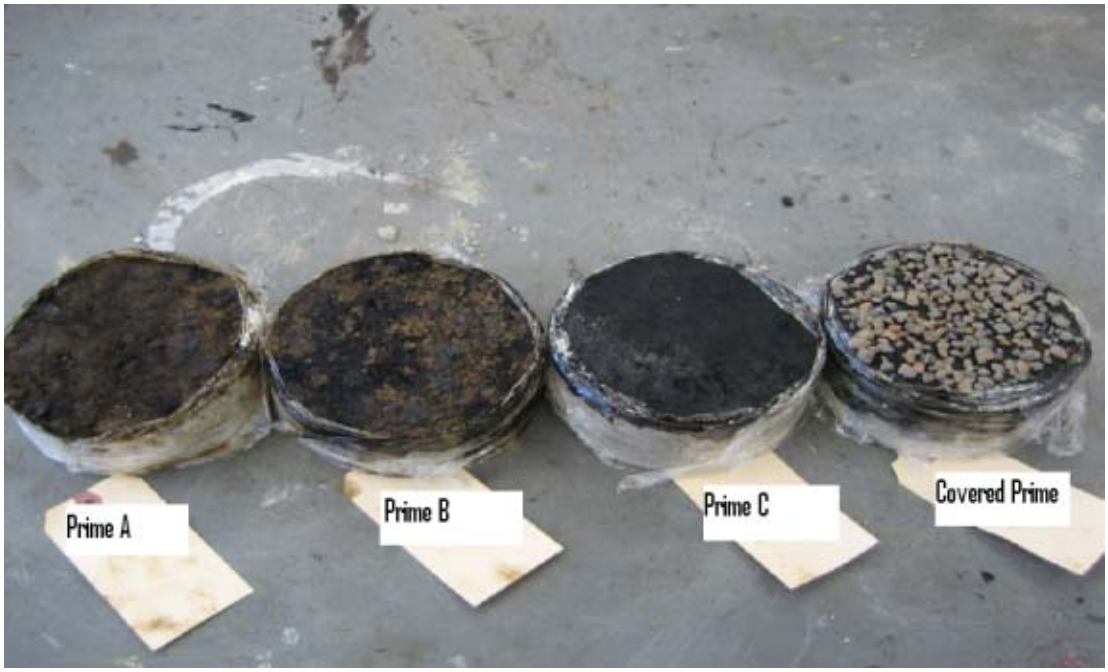



**Figure 3.4. Base Course Specimens after Prime Coat Has Cured and Just prior to Surface Treatment Application.**


**Figure 3.5. Failure Plane of Surface Treatment Bond Test when Prime Coat A Material Was Used (Good Penetration of the Prime, Failure in Base Course).**


**Figure 3.6. Failure Plane of Surface Treatment Bond Test when Prime Coat C Material Was Used (Poor Penetration of the Prime, Failure at Surface Treatment/Base Interface).**


**Figure 3.7. Failure Plane of Surface Treatment Bond Test when Covered Prime Was Used (Failure within Surface Treatment Binder Indicating Good Bond to Base Course).**

**Effect of Prime Material Application Rate on Surface Treatment Bond**

To evaluate the effect of prime coat application rate, base course specimens were treated with different quantities of MC-30 and cured prior to application of a surface treatment. For this experiment, the same base course material was used (Frost base with 3 percent cement). The surface treatment was also the same as in the previous experiment (AC-20-5TR with Grade 5 lightweight aggregate). Samples were treated as follows:

- Six samples treated with no prime.
- Six samples treated with 0.05 gal/sy of MC-30.
- Six samples treated with 0.10 gal/sy of MC-30.

Figure 3.8 illustrates these results. The samples prepared with no prime had the lowest strength averaging 43 lb, and the failure occurred at the top of the base course at the interface of the surface treatment as shown in Figure 3.9. The primed samples all failed within the base course, indicating the surface treatment was bonded to the base. The 0.05 gal/sy prime application rate had the highest pull-off strength averaging 134 lb followed by the 0.1 gal/sy prime application rate, which had an average pull-off strength of 82 lb. This result is surprising because it is common in the field to apply as much prime as will penetrate the base course within a reasonable amount of time (one to two days) and is usually about 0.1 to 0.2 gal/sy. A rate as low as 0.05 gal/sy is seldom used in the field, and yet these data (though limited) would indicate that this amount may be sufficient to achieve adequate bond of the surface treatment to the base course. Additional research would be needed to validate these findings prior to implementation.

To verify these results, the researchers repeated the entire experiment with additional samples to include an prime application rate of 0.15 gal/sy as shown in Figure 3.10. Similar results were achieved as in the previous experiment with the worst condition being that of no prime and the best being a prime application rate of 0.05 gal/sy. The results of Figures 3.8 and 3.10 were combined and plotted in Figure 3.11. Each data point in Figure 3.11 represents the average of the six specimens shown in Figures 3.8 and 3.10.

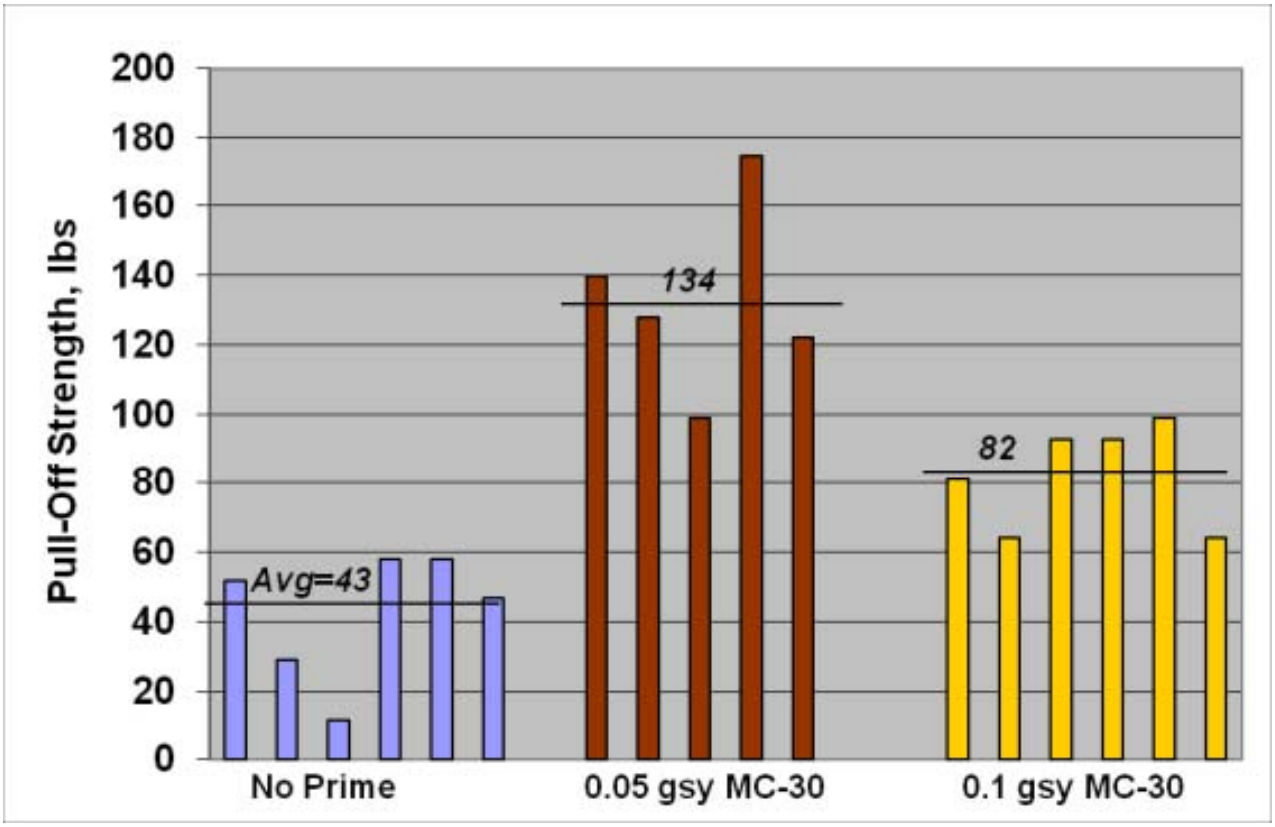



**Figure 3.8. Effect of Prime Application Rate on Surface Treatment Pull-Off Strength – Experiment I.**


**Figure 3.9. Failure Plane of Surface Treatment Bond Test when No Prime Was Used (Failure at Surface Treatment/Base Interface).**

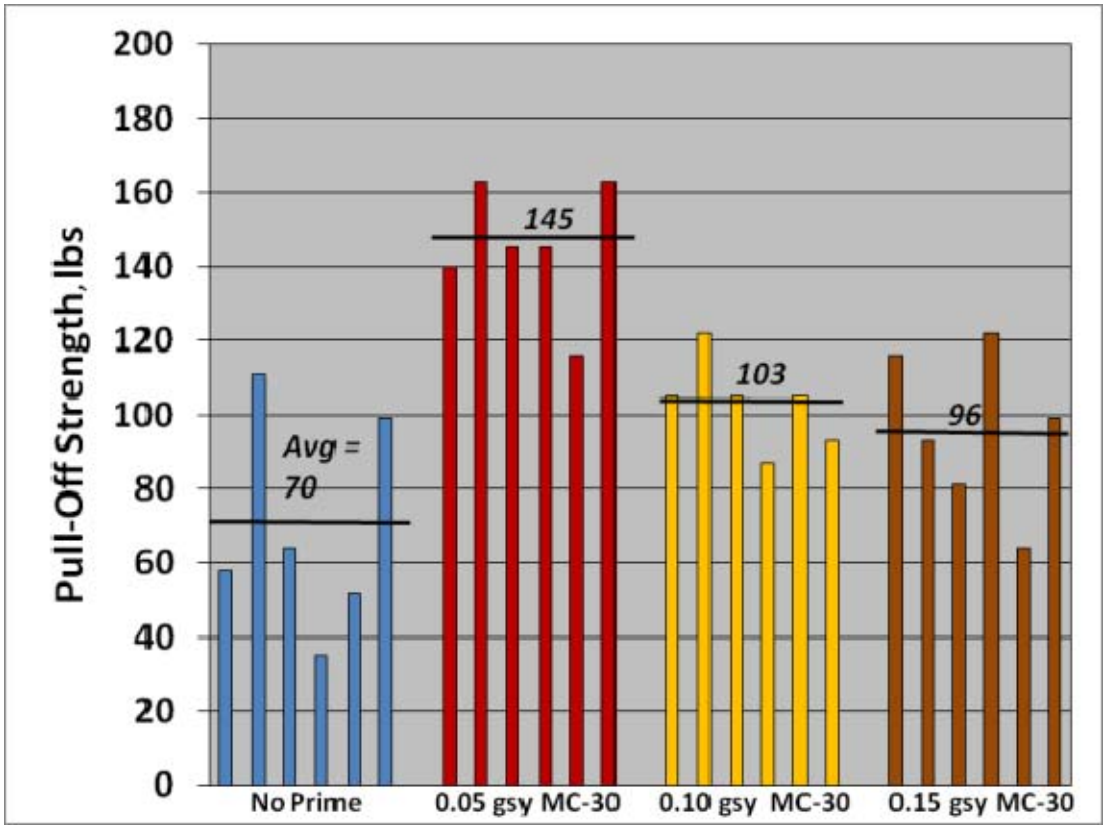



**Figure 3.10. Effect of Prime Application Rate on Surface Treatment Pull-Off Strength – Experiment II.**

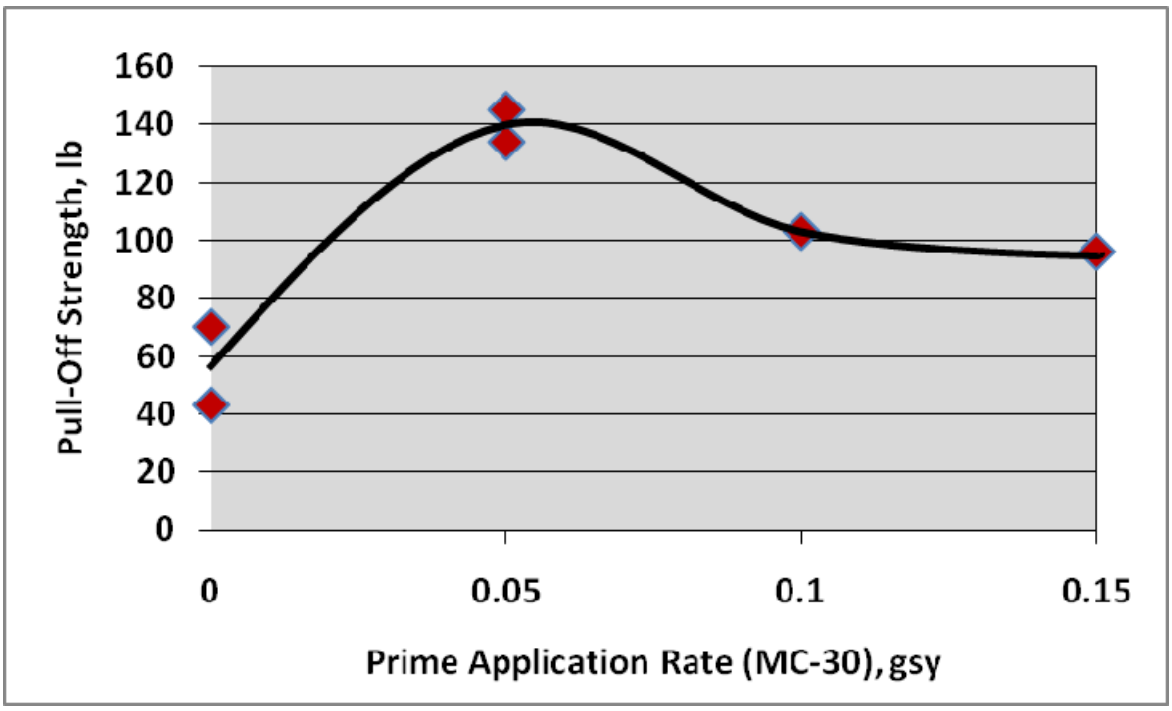



**Figure 3.11. Pull-Off Strength versus Prime Application Rate (Summary of Data from Figures 3.8 and 3.10).**

**Effect of Coring Laboratory Specimens**

All of the results discussed previously were performed on laboratory molded samples that had been cut using a 2-in. core barrel to a depth of 0.5 in. prior to gluing the steel disk to the specimens. Figure 3.12 shows a photo of specimens after coring. All specimens were cored without water to minimize damage to the base course.

Previous laboratory tests were performed using a single base material type from the Frost Pit. When such tests were performed using a different base material, the specimens broke during the coring process. The original ASTM C 1583 procedure called for cutting the test area with a core barrel prior to testing. However, the original procedure was developed for materials that are bonded to portland cement concrete and not likely susceptible to damage during the coring process. To evaluate the need for coring the specimens prior to testing the bond of surface treatments to stabilized bases, the researchers prepared 12 samples: six were cored and six were not. Samples were treated with 0.1 gal/sy of an MC-30 prime prior to application of a Grade 5 surface treatment. Figure 3.13 shows pull-off strength results. Mean pull-off strengths for the cored specimens was significantly lower than the strength for the uncored specimens. This result indicates that the coring process is damaging the base course. By coring the specimen, the failure-surface area will be well-defined and of the same diameter as the steel test disk. However, for the uncored FDR specimens, the failure area was very nearly the same diameter as that of the steel test disk. Therefore, the coring process was eliminated from the test procedure and all subsequent results were performed without coring the specimen prior to testing.

**Figure 3.12. Laboratory Specimens Cut Using 2-In. Core Barrel prior to Bond Strength Testing.**

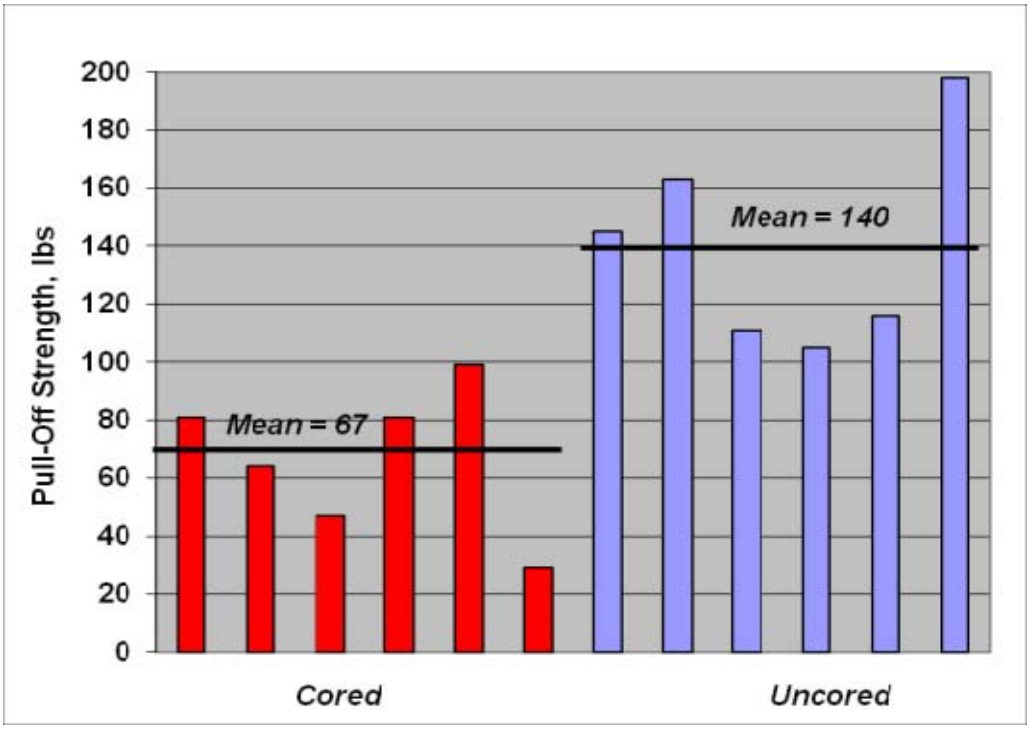



**Figure 3.13. Pull-Off Strength Results for Cored versus Uncored Specimens.**

**Effect of Two Different AEP Sources on Surface Treatment Bond**

Some districts occasionally dilute AEP when applying as a prime coat. Though most emulsions can be diluted with water, this does not always apply to AEP. One of the suppliers in Texas for AEP, Ergon Asphalt and Emulsions reports that AEP from their Waco plant can be diluted with water but AEP from their Austin plant cannot. This information led researchers to believe that the chemistry of the two different AEPs might significantly affect their performance. Researchers obtained samples from both plants to see if the materials performed differently in the surface treatment bond test. Twelve specimens were prepared using the Frost base material treated with 3 percent cement. The specimens were primed using 0.1 gal/sy of the AEP from each plant. A Grade 5 surface treatment was applied and the results of the surface treatment bond test are shown in Figure 3.14. Though the chemistry of the two AEP emulsions is different, the pull-off strength results are very similar. All of the samples failed under the prime within the base course, indicating a good surface treatment bond was achieved.

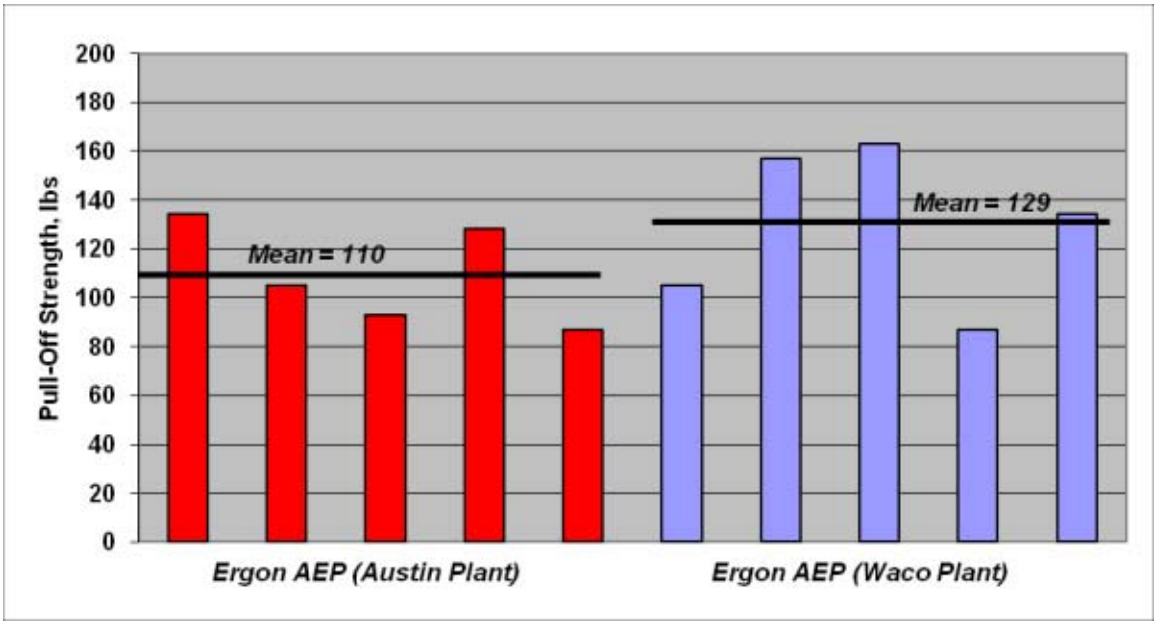



**Figure 3.14. Pull-Off Strength Results for Two Different AEP Sources.**

**Tensile Strength Bond Test on Fly-Ash Stabilized Base**

All previous tests were performed on base samples, which were stabilized with 3 percent cement. Using the same base material (Frost), the researchers stabilized a set of samples with 7 percent fly ash. Half of the specimens were primed with AEP and half with MC-30 at a rate of 0.1 gal/sy. A Grade 5 surface treatment was applied and the pull-off bond strength was measured. Figure 3.15 presents these results. The samples primed with the AEP averaged a pull-off strength of 81 lb, which was similar to the samples primed with the MC-30 that averaged a strength of 76 lb. All of the specimens failed within the base course underneath the prime as shown in Figure 3.15. The pull-off strengths were less than those reported in Figure 3.14 for samples stabilized with cement. This difference is likely due to the effect of the stabilizer since the failure occurred within the base course.

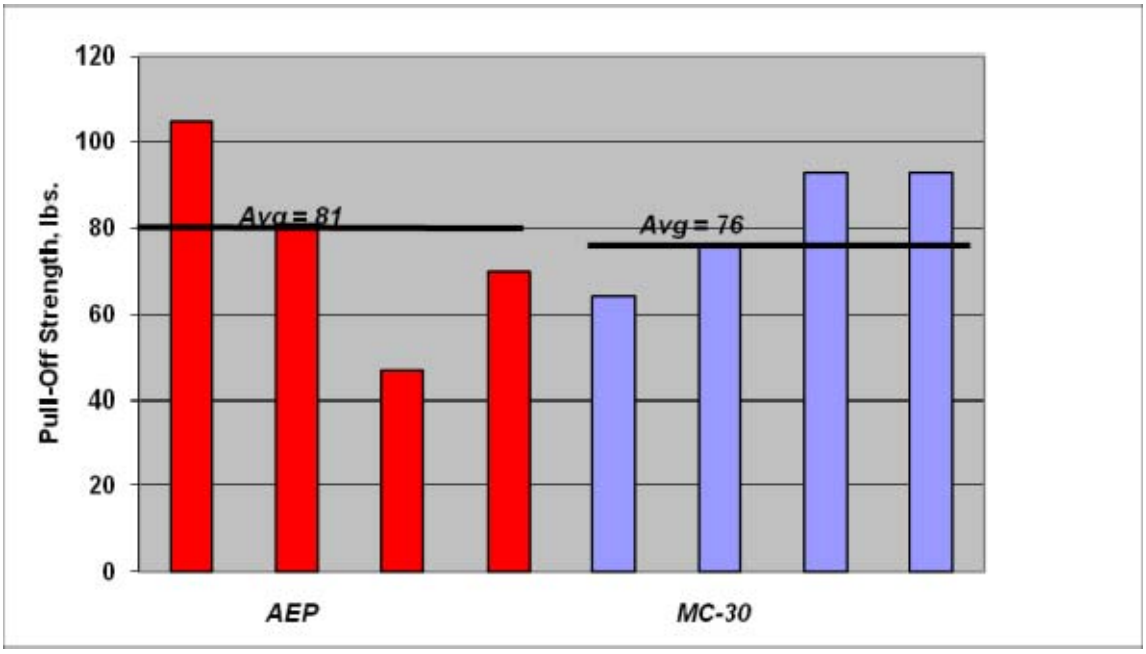



**Figure 3.15. Pull-Off Strength Results for Fly-Ash Stabilized Base Specimens.**

**Figure 3.16. Failure Plane of Surface Treatment Bond Test on Fly Ash Stabilized Specimen (Failure within Base Layer).**

**Effect of Base Moisture Content on Pull-Off Strength**

Using the Frost base stabilized with 3 percent cement, researchers prepared base specimens at moisture contents five percentage points above optimum. Specimens were primed with the following products at a rate of 0.1 gal/sy:

- No prime.
- AEP from Ergon Austin Plant.
- AEP from Ergon Waco Plant.
- MC-30.

Grade 5 surface treatments were applied and tested for bond strength. Average results are shown in Figure 3.17 and compared to specimens compacted at optimum moisture content. A significant drop in pull-off strength was observed in the primed specimens compacted with excess moisture. However, the failure occurred within the base course, indicating that the surface treatment was bonded to the base. The base course layer was apparently weaker in the wet specimens. For both the wet and dry specimens where no prime was used, the failure occurred at the interface between the surface treatment and the base due to lack of bond.

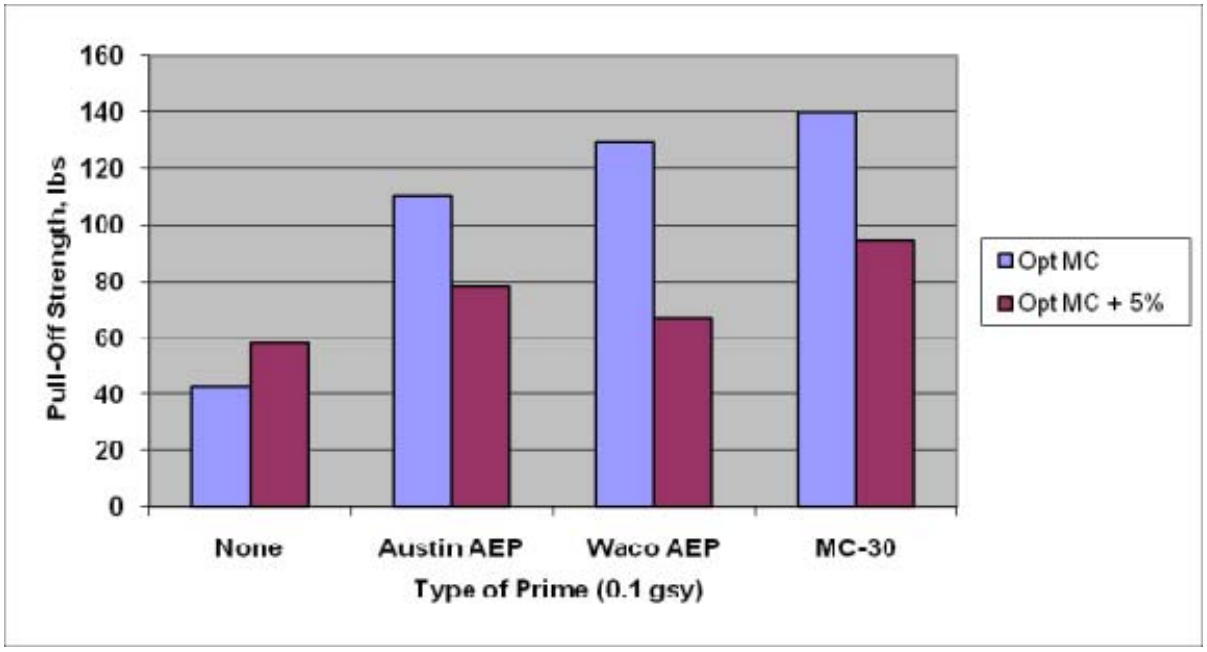



**Figure 3.17. Effect of Base Moisture Content (MC) on Pull-Off Strength.**

## FIELD EVALUATION OF SURFACE TREATMENT BOND TEST

The researchers evaluated the surface treatment bond test on two projects. These projects are described below.

**SH 6 FR at Graham Road**
Grade 4 Surface Treatment
Prime Coat MC 30
Limestone Flexible Base
Age of Surface Treatment at Time of Testing: ~ 1 month
Date of Test: July 2010
Notes: New construction, not under traffic, final surface will be an AC overlay.

**FM 2502**
Grade 4 Surface Treatment
Prime Coat
FDR Base with 4 in. of added flex base stabilized with cement
Age of Surface Treatment at Time of Testing: ~ 3 months
Date of Test: October 2010

Table 3.2 contains the pull-off strength results from the field tests. The surface treatment was not bonded to the base course for either of these two roadways. This is reflected in the pull-off data and can also be seen in Figures 3.18 and 3.19. Further performance of SH 6 could not be observed since it was covered with an asphalt concrete overlay. As shown in Figure 3.20, FM 2502 has performed well in spite of the lack of bond for the surface treatment. This performance is attributed to the very low traffic volume on this roadway.

**Table 3.2. Pull-Off Strength Results on Field Projects.**

| Test No. | Pull-Off Strength, lb | |
|---|---|---|
| | SH 6 | FM 2502 |
| 1 | 6 | 23 |
| 2 | 3 | 23 |
| 3 | 6 | 23 |
| 4 | 10 | 17 |
| 5 | 17 | 17 |
| 6 | 12 | 23 |

**Figure 3.18. Surface Treatment Bond Testing on SH 6.**

**Figure 3.19. Surface Treatment Bond Testing on FM 2502.**

**Figure 3.20. FM 2502 after 3 Months of Service.**

## SUMMARY

A surface treatment is commonly used as the final riding surface on low-volume FDR roadways in Texas. Achieving adequate bond of the surface treatment to the recycled base course has been a recurring problem due to one or more factors:

- Construction techniques.
- Base finishing techniques.
- Moisture.
- Type and amount of prime material.
- Traffic.

Figure 3.21 shows a typical example of a surface treatment, which is not bonded well to the base course. This surface treatment was constructed in the winter months and performed well until the first day of hot weather. With the hot weather, however, the surface treatment started to bleed and stick to the tires of traffic, pulling off the surface treatment. Numerous unsuccessful maintenance techniques (limewater, crusher fines) were used to mitigate the problem.

**Figure 3.21. Debonded Surface Treatment (FM 2154).**

A surface treatment bond test protocol was developed in this study to assess the bond of a surface treatment to FDR base material. The test seems best suited for laboratory evaluation so that optimization of prime materials and quantities may be achieved prior to field application. The test may also be performed on field projects; however, it may be of little practical value to assess the bond of a surface treatment to a primed base course once it has been constructed. The research effort in this task:

- Developed a test method to measure surface treatment bond.
- Refined the test protocol.
- Evaluated effects of prime type, application rate, base stabilizer, and base moisture content on the surface treatment bond.

Results of the laboratory study indicated that a prime coat is necessary to achieve a good bond of the surface treatment to the base. Researchers also found that some types of prime materials are more effective than others, and the test developed in this study can distinguish between different types of primes. A surprising finding was that a prime application rate as low as 0.05 gal/sy may be more effective than a rate more typical of that used in the field: 0.15 gal/sy. While these data are based on limited tests and materials, the results warrant further testing in both the field and laboratory. Selecting a prime material, which provides the best surface treatment bond for a given base, is important. If further testing can support the use of lower prime coat application rates as seen in the laboratory testing, then the following benefits are significant:

- Lower cost due to less material use.
- Shorter prime coat curing times.
- Lower use of materials with high volatiles (lower environmental effect).
- Longer pavement life due to improved surface treatment bond.

Implementation of the surface treatment bond test method developed in this study should be supported by additional field validation and extended for application to flexible base courses. This work should focus on several carefully controlled field experiments around the state on both stabilized and flexible bases to validate the findings of this study. The field studies should focus on varying the prime material type as well as the application rate. Corresponding laboratory testing should accompany the field study.

# CHAPTER 4
# TROUBLESHOOTING FDR PROJECTS

The vast majority of the FDR projects are performing well, and more and more districts are using the process. However, as with all paving projects, performance problems can occur. When they do, it is recommended that a forensic study be initiated to identify the cause, corrective action options, and steps needed to minimize recurrence on future projects. The six examples shown in Figures 4.1–4.6 below highlight what can go wrong and what recommendations are made to avoid this in the future.

## 1) LONGITUDINAL CRACKING

Longitudinal cracking is by far the most common problem associated with FDR projects in East Texas.

**Figure 4.1. Longitudinal Cracking on FDR Projects.**

The causes of this distress are associated with:

- Highly plastic subgrade soils (PI > 35), which shrink excessively during summer.
- Side slopes failure.
- Trees down the sides of road, which cause additional soil drying.
- Stiff stabilized bases—the stiffer the base, the more severe the cracking.

In the late 1990s, the Bryan District initiated a design modification in these problematic areas by incorporating a layer of geo-grid over the treated base, on top of which they placed at least 6 inches of flexible base and a thin surface layer. The geo-grid acted as a slip plane and greatly minimized this problem. For any project the soil survey maps are reviewed, and the design engineer drives the project to note the location of trees and existing pavement failures.

Auger samples of the project soils are taken and PI values measured in the laboratory. Where the conditions noted above are detected, the geo-grid is incorporated into the pavement design. Figure 4.2 shows the placement of localized geo-grid over a stabilized layer.

**Figure 4.2. Localized Geo-Grid in Potential Problem Location.**

The longitudinal cracking problem was also more severe when higher cement contents were used—the stiffer the base, the worse the cracks. The use of the 175 psi design criterion to select cement content and the use of micro-cracking has helped minimize the severity of these cracks. Darlene Goehl in the Bryan District is the expert in this treatment, and successful applications have been placed in other districts including Dallas and Austin.

**2) INADEQUATE STABILIZATION**

The failure below is a result of adding insufficient cement during construction; the design called for 3 percent, but upon checking only 1 percent was added. Compounding this problem is the presence of a longitudinal joint close to the edge of the wheel path, which is probably allowing water into the base layer.

**Figure 4.3. Under-Stabilization.**

It is critical that construction personnel check the application rate of stabilizers. Simple spreadsheets are available based on unit weights, application rates, etc. to compute the length of application for one ton of cement. This construction problem is fairly simple to solve.

### 3) BONDING FAILURE

This failure is found with all stabilizer types and can be slippage failures (where the final surface is HMA), or pop-out failures (when the final surface is a seal coat). Chapter 3 described the failures associated with seal coat surfaces.

**Figure 4.4. HMA Bonding Problems and Seal Coat Pop-Outs over Stabilizer Base.**

Bonding failures often relate to:

- Ineffective prime coat, which lacks penetration.
- Dirty or unstable stabilized layer surface.
- Surface bleeding of seal coats (tires pull out the surface).

Districts with a persistent history of these failures should conduct a lab study using the pull-off device described in Chapter 3 is recommended to select the best prime coat material and the optimal amount.

### 4) SHRINKAGE CRACKING FROM CTB LAYERS

This was a common problem several years ago, and it is caused by adding too much cement. During curing, the base shrinks and cracks typically in block patterns. This problem has been greatly reduced in recent years with the changes to the specifications and construction practices. Several years ago the target CTB strength was 500 psi; in recent years this target CTB strength has been reduced to 300 psi or 175 psi in the 2004 specifications book. Also, current construction practices sometimes perform microcracking or apply early trafficking; both of these construction practices can help reduce the cracking problem in CTB layers.

**Figure 4.5. Block Cracking.**

**5) NON UNIFORM DISTRIBUTION OF STABILIZERS**

Extreme failures of the type shown in Figure 4.6 are very rare, but they have occurred. This is largely due to constructing FDR projects on narrow roadways under traffic, where one lane has to continually be in operation and barriers are used to protect construction workers. In these rare instances, a strip of roadway never gets full treatment with the stabilizer of choice. The situation is compounded by having a longitudinal construction joint in the HMA layer directly over the untreated base.

**Figure 4.6. Failure in One Wheel-Path Only.**

This situation can be avoided by modifying the specifications to mandate a minimum 2 in. overlap on longitudinal joints. Pre-marked cut lines should be marked on the pavement and the recycling machine steered so as to accurately follow them. The overlap cut width should be confirmed before starting a new cut sequence.

**6) VERY EARLY LOAD ASSOCIATED DISTRESSES**

The situation shown in Figure 4.7 can occur if TxDOT's stabilization guidelines are not followed. In some cases where the existing materials are clay contaminated, some type of lime treatment will be required to attain the required laboratory strengths. In the case shown below, an asphalt emulsion treatment was applied to a roadway with little base. No effective stabilization occurred, and the heavy rainfall during construction added to the problem. The base did not dry out before sealing. The FWD deflections were found to be very high, and roadway cores disintegrated.

**Figure 4.7. Alligator Cracking and Rutting a Few Months after Construction.**

# CHAPTER 5
# POTENTIAL SPECIFICATION REVISIONS

As part of this study, the researchers polled experienced districts to identify what changes need to be made to current TxDOT specifications. The current FDR work is specified under Item 260 (Lime), Item 265 (Fly Ash), Special Spec 3066 (Asphalt Emulsion) and Item 275 (Cement). The bulk of the work in Texas either uses cement or lime, and these are broad specifications that do not specifically focus on FDR but also on lime stabilization of soils, etc.

The first question to the districts was "Should we develop a new FDR specification?" The unanimous response was "No" because:

- The treatments are all different, requiring different design, curing and acceptance criteria.
- The current specifications are viewed as good "with a little tweaking."

The districts polled identified the following six areas where they thought changes should be made to specifications.

## ACTION ITEM 1: CHANGE TEMPERATURE SPECIFICATION FOR ALL STABILIZER TYPES

The Lubbock District stated this as their top priority; the current spec calls for temperatures of 35°F and rising. Lubbock's concern is that if the temperature falls below zero on the first or second night after placing the stabilizer then they have a major issue with finishing the section. They thought this gave them major bonding and base stability problems.

Researchers suggest general wording such as "Suspend operations when the engineer determines that the weather conditions are unsuitable" be added to the spec. Similar wording should be added to all stabilization specifications.

## ACTION ITEM 2: ADD INSTRUCTIONS ON HOW TO PROMOTE BONDING TO TREATED BASE

Four separate items were requested to assist in promoting bond:

- Mandate sweeping and skeeting of base before priming as covered in Item 310.4.b.
- Mandate the use of a cut finish (fill finishes always lead to bonding problems).
- Always apply the prime at optimum moisture content.
- Follow Item 247 specification on when to place a seal or hot mix; that is, specify that the base has to be at least 2 percent below optimum moisture content.

## ACTION ITEM 3: NEED FOR PROOF ROLLING

Mandate the use of proof rolling before buying the job. The proof roller will find weak spots and also find "scabs" that must be removed before priming. The proof rolling specification may need to be expanded to cover the needs of FDR, such as where and when to test.

## ACTION ITEM 4: MICROCRACKING

Permit the use of microcracking under item 275 and 276.

## ACTION ITEM 5: ENCOURAGE THE USE OF UP-FRONT TESTING

Both the Lubbock and Bryan Districts strongly support the need for up-front pavement testing and feel this must be strongly suggested to districts that are just getting started in this area. Both districts make strong use of coring, soil sampling, DCP testing, GPR, FWD and lab testing. They recommend that a pavement design report be completed for every project. Both districts felt that this is where the big savings occur, and TxDOT has all of the tools to do this up-front work.

The Lubbock District also felt strongly that in several instances, chemical stabilization is not required and base reworking and perhaps base thickening is required. These items would require the mandating of a pavement design report with the minimum items.

- Coring/auger and/or GPR data to document existing pavement structure.
- Lab testing results.
- Pavement design report using FPS.
- Identification of non-uniform areas where pretreatments or changes to design will be required.

## ACTION ITEM 6: ALLOW VARIATIONS IN COMPACTION TIME FOR PROBLEM BASES

The Bryan District reported that with some bases (especially Iron Ore) there is a delayed reaction, which can be observed in the laboratory. This could be related to organics or other components in the base. The current cement specs mandate the compaction within two hours. Bryan prefers to wait that long before starting compaction for these bases. Wording should be added to permit this.

# CHAPTER 6
# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

The vast majority of the FDR projects in Texas are performing well**.** TxDOT has available the required pavement testing tools, lab test protocols, and good specifications to ensure a successful project. Very few problems were identified in the districts when good pavement testing and existing TxDOT design protocols were used. FDR can be highly cost-effective if executed properly. However, lack of guidance in the overall design and construction process, including formulating a mixture design for the reclaimed materials, controlling the construction process, performing quality assurance of the in-place product, and bonding the surface layer to the finished base led to construction delays and poor performance on several projects. Designing and constructing good performing FDR projects in Texas is challenging for several reasons, including:

- Existing hot mix thickness often varies, especially if substantial maintenance has been performed. This variability must be measured and accounted for in the pavement design process. TxDOT has little success incorporating more than 50 percent RAP in typical FDR design, so approaches to dealing with thick localized HMA layers must be developed.
- Problems have been encountered with pavements built on expansive clays (most of east Texas). Edge drying and trees down the sides of roadways are a problem when brittle stabilized layers are placed over them. When severe longitudinal cracks exist, the use of the DCP should be encouraged to identify the depth of slip planes and to aid in designing the appropriate edge support.
- Old base materials are often contaminated and sometimes weak. TxDOT guidelines based on plasticity index to select the appropriate stabilizer appear reasonable. High PI bases require the use of lime, and asphalt is only recommended if the PI of the existing base is less than six.
- Many low-volume roadways are narrow, and widening must be part of the FDR process.
- Often the process is conducted on two-lane highways, so traffic handling is a major concern. When performing construction under traffic, it is critical to ensure that the middle portion of the roadway receives the correct amount of stabilizer.

## RECOMMENDATIONS

Based on the findings presented in this report the following major recommendations are made to improve the existing TxDOT FDR process:

- TxDOT should initiate and implement projects to further develop the small sample design procedure described in Chapter 2 of this report. The current laboratory test procedures work well, but they require too much material and take too long to complete. The proposed procedure uses less than 25 percent of the material currently required. It is proposed that on upcoming jobs the two procedures be run in parallel to determine if the criteria proposed in this report are reasonable.
- TxDOT should require by plan note FWD testing be conducted as early as possible on all upcoming FDR projects. The procedures described in this report should be used to compare the measured FWD deflections with the target generated during the pavement design process. Each project should produce graphs similar to Figures 2.22–2.24. Guidelines should be developed to aid Area Office personnel to interpret and develop action plans based on these graphs.
- The pull-off test described in Chapter 3 should be considered for an implementation project. The test provides potential for selecting the optimal prime type and application rate to be used with any stabilized base. The big unknown to date is why the limited number of field projects tested so far have all exhibited low bond strength. A lab and field study should be initiated to compare laboratory results to field bonding strengths. This can best be achieved by constructing a range of small test strips with the different primes used in the laboratory.
- The districts suggested six items for incorporation into existing specifications. The most urgent of these suggestions was to modify the temperature requirement to avoid the possibility of the stabilized base experiencing freezing conditions in the first or second day after treatment.

The researchers expended a substantial effort to attempt to determine if XRF technology could be used to measure the actual content of either cement or lime in FDR applications. This was found not feasible with the limestone aggregates commonly found throughout Texas. However, the researchers found the technique useful for measuring the cement or lime content of stabilized soils. Consideration should be given to continue to explore the use of this new technology in the soil stabilization area.

As part of Project 6271, two FDR workshops were taught to district staff. There was great interest in this topic, and more classes are required. It was also reported that the future direction of TxDOT will potentially be to do more of this work with in-house maintenance forces rather than with contractors. If this is the case then a second hands-on workshop will need to be developed focusing on equipment selection, operator training, project scheduling, and management.

# REFERENCES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# APPENDIX A

# DRAFT TEST PROCEDURE FOR MIXTURE DESIGN WITH TEXAS GYRATORY COMPACTOR

**Test Procedure for**

# INDIRECT TENSILE STRENGTH TEST FOR FULL DEPTH RECLAMATION MIXTURE USING THE TEXAS GYRATORY COMPACTOR (TGC)

**TxDOT Designation: Tex-XXX**
***Effective Date: April 2011***

## 1. SCOPE

1.1 This method determines the indirect tensile strength of full depth reclamation (FDR) mixtures compacted by using the Texas gyratory compactor (TGC).

1.2 This method consists of two parts.

1.3 Part I describes the test procedure for preparing 4 in. by 2 in. FDR flexible base samples using TGC.

1.4 Part II describes the test method to determine the tensile strength of TGC-compacted FDR flexible base samples.

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

## PART I − COMPACTING SPECIMEN USING THE TGC

## 2. SCOPE

2.1 Use this procedure to properly compact specimens of FDR mixtures using the TGC.

## 3. APPARATUS

3.1 Motorized gyratory-shear molding press, calibrated in accordance with Tex-914-K (See Figure 1).

3.2 Molding assembly, consisting of gyratory-shear mold, base plate, and wide-mouthed funnel.

3.3 A balance readable to 0.1 g and accurate to 0.5 g with a minimum capacity of 10,000 g.

3.4 Sieve, ¾″ (19 mm), when required.

3.5 Flexible spatula, with a blade 4 in. (100 mm) long and 0.75 in. (20 mm) wide.

3.6 Micrometer dial assembly or calipers, capable of measuring a height of at least 2 ± 0.06 in. (50.8 ± 1.5 mm)

3.7 Non-porous paper gaskets, 4 in. (100 mm) in diameter.

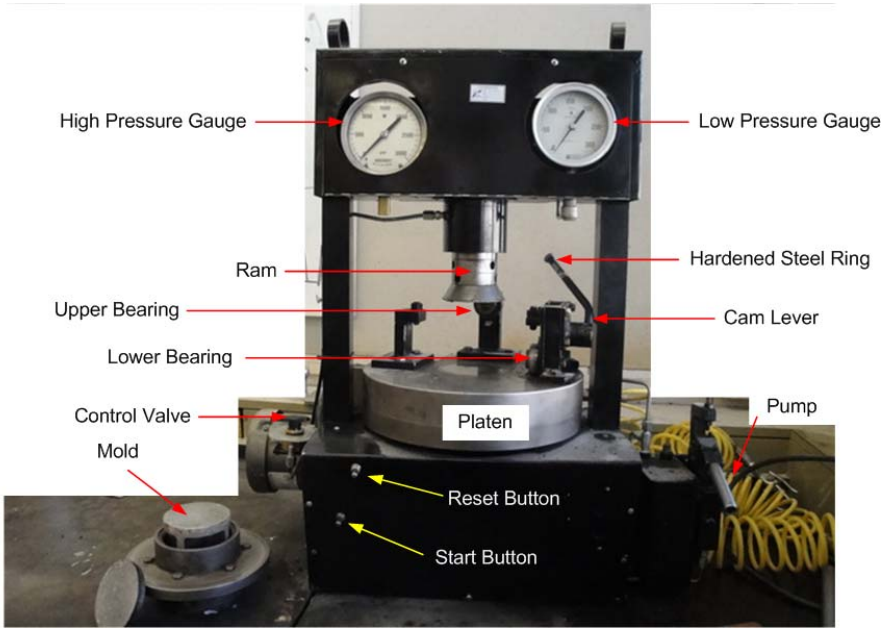


**Figure 1. Gyratory Shear Molding Press.**

## 4. MIXTURE PREPARATION

4.1 Obtain a representative sample in accordance with Tex-400-A. Prepare the material in accordance with Tex-101-E, Part II.

4.2 For stabilized materials, see appropriate test method for preparation procedure for specification compliance and density:

- Cement Stabilization: Tex-120-E.
- Lime Stabilization: Tex-121-E.
- Lime-Fly Ash Stabilization: Tex-127-E.

4.3 Take care to properly label specimens according to their material characteristics to avoid confusion later (when testing especially).

## 5. PROCEDURE

5.1 Obtain a representative sample of flexible base and recycled asphalt pavement (RAP) materials prepared in accordance with Tex-101-E, Part II.

5.2 Combined flexible base and RAP material on the basis of combination ratio (e.g., 50/50 flexible base/RAP).

5.3 Estimate the mass of air-dry material that will fill the mold to the maximum density when wetted and compacted at the optimum moisture content (OMC).

5.4 Determine the OMC and dry density in accordance with Tex-113-E.

5.4.2. For stabilized material, see appropriate test method for preparation procedure:

- Cement Stabilization: Tex-120-E.
- Lime Stabilization: Tex-121-E.
- Lime-Fly Ash Stabilization: Tex-127-E.

5.5 Prepare the FDR base materials batch using the determined OMC.

5.6 Estimate the mass of air-dry FDR materials that will fill the 2-in. height by 4 in. diameter mold when wetted and compacted.

5.6.1 If the mixture contains aggregate larger than ¾″ (19 mm), remove the large aggregate using a ¾″ sieve.

5.7 Calculate the desired amount of stabilizer, defined as a percent of the total dry soil:

$$\text{amount stabilizer} = (\text{percent stabilizer}/100) \times \text{mass dry soil}$$

5.8 Weigh out stabilizer and thoroughly mix it into the wetted FDR base materials (Figure 2).

**Figure 2. Mixing FDR Materials and a Stabilizer.**

5.9 Insert base plate into TGC mold with large diameter up, and place a paper gasket (such as the Gilson MSA-120 or equivalent) over the base plate (Figure 3).


**Figure 3. Set-Up for Texas Gyratory Compactor Mold.**

5.10 Use the wide-mouthed funnel to transfer the mixed and wetted FDR mixture into the mold, taking care to spread out uniformly (Figure 4). Press the material down slightly using a spatula.

**Figure 4. Placement of the Material into the Mold Using the Wide-Mouthed Funnel.**

5.11 Place a paper gasket on top of the mixture. Avoid loss of material while placing the mixture into the mold (Figure 5).


**Figure 5. Placement of a Paper Gasket on Top of the Mixture.**

5.12 Transfer the mold to the platen of the TGC and start to gyrate the mold in accordance with Tex-206-F, compaction procedure (Figure 6).

**Figure 6. Compaction of Mold Using the TGC.**

5.13 Extrude the compacted sample from the mold. Wrap the specimens into plastic bags and place them in the curing room for seven days (Figure 7).

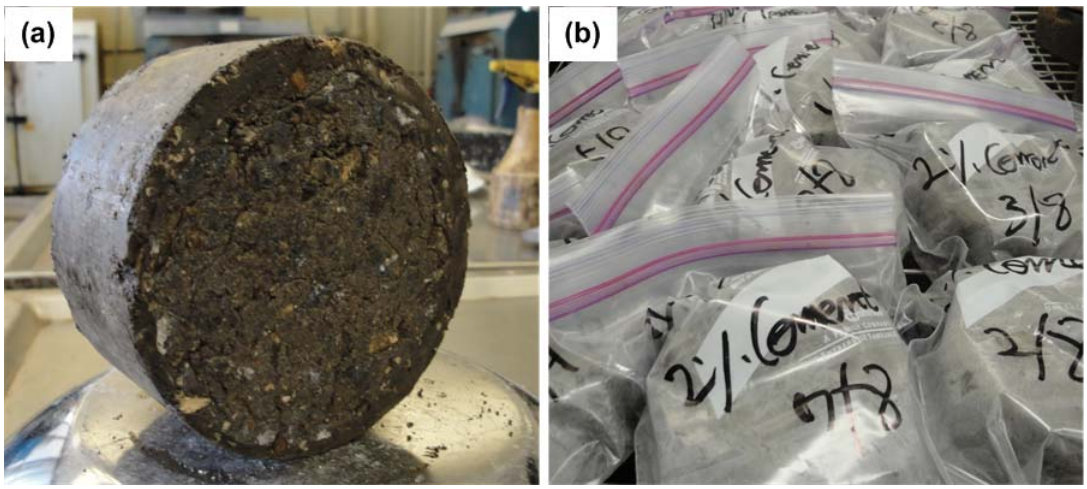


**Figure 7. Extruded and Cured Specimens.**

## PART II − INDIRECT TENSILE STRENGTH TEST

### 6. SCOPE

6.1 Use this test method to determine the tensile strength of compacted FDR mixtures.

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

### 7. APPARATUS

7.1 Loading press, capable of applying a compressive load at a controlled deformation rate of 2 in. per minute.

7.2 Loading strip, consisting of 0.5 in. by 0.5 in. square steel bars for 4-in. diameter specimens. Machine the surface that contacts the specimen to the curvature of the test specimen.

### 8. SPECIMEN

8.1 Laboratory-molded specimen with a diameter of 4 in. and a height of 2 ± 0.06 in., prepared in accordance with Part I, Section 5.

### 9. PROCEDURE

9.1 Combine aggregates and prepare laboratory mixture as described in Part I, Section 5.

9.2 Mold three specimens in accordance with Part I, Section 5 with the Texas Gyratory Compactor.

9.3 Place the specimens in the constant temperature apparatus for 15 minutes to attain a consistent temperature of 77 ± 2°F (25 ± 1°C) throughout the specimens.

9.4 Set the loading press to utilize a deformation rate of 2 in. per minute.

9.5 Carefully place the specimen on the lower loading strip.

9.6 Slowly lower top loading strip into light contact (approximately 2 lb) with the specimen.

9.7 Ensure the two loading strips remain parallel to each other during testing.

9.8 Apply the load at a controlled deformation rate of 2 in. per minute and determine the total vertical load at failure of the specimen (Figure 8). Record the total vertical load at failure.

9.9 Repeat steps 9.5 through 9.8 for each test specimen.

**Figure 8. Indirect Tensile Strength Test**.

## 10. CALCULATIONS

10.1 Calculate the tensile strength of the compacted FDR mixture:

$$S_T = \frac{2F}{3.14 \times (hd)}$$

Where:
$S_T$ = Indirect tensile strength, psi
$F$ = Total applied vertical load at failure, lb
$h$ = Height of specimen, in.
$d$ = Diameter of specimen, in.

## 11. REPORT

11.1 Report the following for each specimen:

- Height and diameter of each specimen.
- Total vertical load at failure of each specimen.
- Indirect tensile strength, psi.

# APPENDIX B

# DRAFT TEST PROCEDURE FOR PULL-OFF TEST

Test Procedure for

# SURFACE TREATMENT BOND TEST

TxDOT Designation: Tex-XXX
*Effective Date: March 2011*
*Revised: June 2011*

## 1. SCOPE

1.1 This test procedure is used to determine the bond strength characteristics of the interfaces between the surface of a stabilized base layer, prime coat, and surface treatment.

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

## 2. APPARATUS

2.1 Forced draft oven, capable of attaining a temperature of at least 325°F± 5°F (163 ± 3°C).

2.2 Pull-Off Tester with 50 mm diameter × 25 mm aluminum caps, draw bolts (Refer to Figure 1).

2.3 Spacers (maximum diameter 1 in., maximum thickness ⅛ in.), and base plate. (Refer to Figure 2).

2.4 Balance, readable to 0.1 g and accurate to 0.5 g.

## 3. MATERIALS

3.1 Plumber's putty.

3.2 Plastic wrap.

3.3 2″ painter's masking tape.

3.4 Two-part epoxy with a minimum 24-hr tensile strength of 4.1 MPa (600 psi) and 24 hr shear strength of 13.8 MPa (2,000 psi) in accordance with Tex-614-J.

3.5 10 lb (4.5 kg) weight less than 6 in. in diameter or dimension.

3.6 Box cutter or razor blade.

3.7 12-in. wooden rolling pin.

3.8 Air compressor.

3.9 Paint marker.

3.10 Foam brushes.

3.11 Tongue depressors.

3.12 Standard handheld brush.

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## 4. SPECIMEN

4.1 Prepare a minimum of 4 2-in. tall by 6-in. diameter base specimens using one lift applying 50 blows of the hammer in accordance with the procedure and apparatus described in Tex-113-E.

Note 1 – If adding cement stabilizer, refer to Tex-120-E, Steps 5.1 to 5.2.3.
If adding lime stabilizer, refer to Tex -121-E, Steps 5.1. to 5.3.4.
If adding lime-fly ash stabilizer, refer to Tex-127-E, Steps 5.1. to 5.1.4.

Note 2 – Take care to properly label specimens according to their material characteristics so as to avoid confusion later (when testing especially).

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## 5. PROCEDURE

5.1 Sample Preparation.

5.1.1 Use four cylindrically molded specimens in accordance with section four.

5.1.2 Immediately after compacting each individual specimen, seal the sample with plastic wrap.

5.1.3 Using the painter's masking tape, apply to the circumference of the specimen, leaving a minimum of a ⅛-in. lip above the surface that will be tested (to retain the prime/seal coat).

5.1.4 60±5 minutes after compacting the specimens, use the box cutter or razor blade to remove the plastic covering from the top of the specimen (i.e., the surface to be tested).

5.1.5 If applying a prime coat, use the design-specified application rate and evenly distribute the prime coat over the exposed specimen surface using the foam brush. Refer to section 6.1 to determine the correct weight of prime to apply in grams.

Note 1 – Place specimen on scale, tare the balance, then add material until the desired weight of prime is reached. Take care to apply the appropriate weight as the foam brush tends to absorb some of the material.

5.1.6 After completing step 5.1.4, place the specimen in the oven to cure at 110°F ± 2°F for 72±4 hr.

5.1.7 After the three-day cure, remove the specimen from the oven to ambient temperature.

5.1.8 Evenly distribute 30 g of the asphalt cement binder (40 g if using asphalt emulsion) required for the seal coat design to the primed specimen surface using the tongue depressor or foam brush. This is the amount of asphalt needed for a Grade 5 seal coat aggregate. Even if the proposed field surface treatment is not a Grade 5, it is recommended that a Grade 5 be used for the laboratory evaluation to allow for more aggregate surface area to glue to the test cap. A Grade 5 aggregate also enables the test cap to be glued in a more level position than if a coarser aggregate grade is used.

Note 1 – Foam brushes are used when applying non-heated materials, and tongue depressors are used when applying heated materials.

5.1.9 Place the specified aggregate onto the binder immediately, in order to ensure proper seating of the aggregate (if using emulsion or cutback, place aggregate on binder after the appropriate setting or curing time).

Note 1 – Washed Grade 5 aggregate is recommended as the extra dust particles can produce erroneous test results.

5.1.10 Gently roll the rolling pin over the aggregate to apply pressure in order to properly seat the aggregate into the asphalt binder, taking care not to force the binder out from underneath the aggregate.

Note 1 – Proper seating generally occurs after 10–20 passes with the rolling pin.
Note 2 – Be sure to roll in the perpendicular direction as well.

5.1.11 Place the specimens back into the oven to cure at 110±2°F for an additional 24±1 hr.

5.1.12 After the 24-hr cure, remove the specimens from the oven to ambient temperature.

5.1.13 Brush the specimen gently to remove the loose aggregate. Using compressed air, remove all remaining loose particles from the surface of the specimens (with particular attention to the remaining dust particles). This will help the bonding between the epoxy and the seal coat.

5.1.14 Place a pull-off tester test disc on the center of the specimen and trace the circumference of the test disc onto the surface of the specimen using the paint marker.

5.1.15 Place the plumber's putty around the traced circle such that the inner circumference of the putty is touching the circle. Apply pressure to the putty to ensure that it fills any gaps in the surface of the seal coat to prevent epoxy from seeping outside the circle.

5.1.16 Note 1 – Mold the putty to a height that will prevent overflow of epoxy to the outside of the putty.

5.1.17 Prepare epoxy following manufacturer's instructions.

5.1.18 Place enough epoxy inside the ring of putty to ensure that the tallest rock within the ring is completely submerged.

5.1.19 Gently place the pull-off tester test disc onto the epoxy. Rotate the test disc at least 90° clockwise and counterclockwise to ensure proper distribution of the epoxy onto the test disc.

5.1.20 Place the 10-lb weight directly on top of the pull-off tester test disc to ensure that the test disc adheres properly to the specimen.

5.1.21 Allow the epoxy to cure for the time recommended by the manufacturer. Remove the weight from the specimen after the epoxy has cured.

5.2 Testing Specimen (Refer to Figure 3).

5.2.1 Refer to the manufacturer's operating instruction manual to properly prepare the pull-off tester. This includes setting the machine to display the correct units and correct data collection rate.

5.2.2 Install the draw bolt into the test disc.

5.2.3 Place the base plate onto the sample such that the test disc is centered within the inner diameter of the base plate.

Note 1 – Position the base plate in such a way that the tensile force is applied perpendicular to the surface of the specimen. This can be accomplished by placing spacers between the specimen surface and the base plate such that the base plate becomes level or by adjusting the height of the legs of the pull-off tester.

5.2.4 With the machine disconnected from the specimen, turn the crank back to its initial position in a counterclockwise direction until slight resistance is encountered.

5.2.5 Turn the crank once in the clockwise direction to relieve the hydraulic system.

5.2.6 Connect the coupling of the draw spindle to the draw bolt of the test disc.

5.2.7 Zero the maximum load.

5.2.8 Turn the wheel clockwise until slight resistance is encountered.

5.2.9 Turn the crank steadily clockwise until specimen failure has occurred. Specimen failure is defined as a 50 percent reduction in the maximum observed load. Record the maximum load.

5.2.10 After specimen failure, turn the wheel in the clockwise direction until the test disc can be easily removed from the specimen by hand. Record the location of failure (i.e., which layer bond failed). If a single layer failure is not clear, record an estimated percentage of failure in each layer (e.g., failure occurred in 50 percent of the base layer and 50 percent of the prime coat).

## 6. CALCULATIONS

6.1 Calculate the weight of prime to be applied to each specimen given the application rate in gallons per square yard:

$$SG \times AR \times 82.51 = Wb$$

Where:
SG = specific gravity of the prime coat.
AR = application rate of the prime coat, gal/sq. yd.
Wb = weight of binder to be applied to each specimen, g.

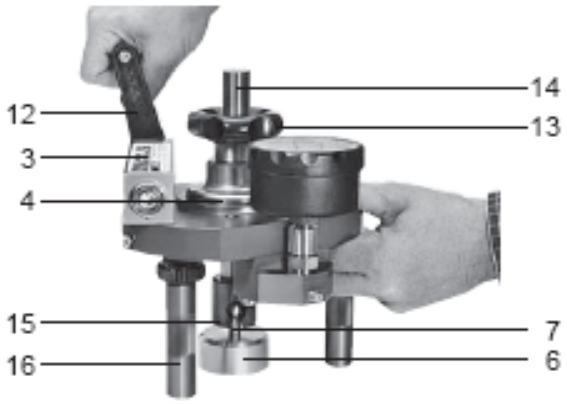
## 7. REPORT

7.1 Report the following for each specimen:

- Maximum load.
- Failure location.

## 8. FIGURES


1 Pull-off tester
2 Digital manometer
3 Hydraulic pump
4 Piston
5 Device plate
6 Test disc
7 Draw bolts




3 Hydraulic pump
4 Piston
6 Test disc
7 Draw bolt
12 Crank
13 Wheel
14 Draw spindle
15 Coupling
16 Legs

**Figure 1. DYNA Z Pull-Off Tester and Digital Manometer.**

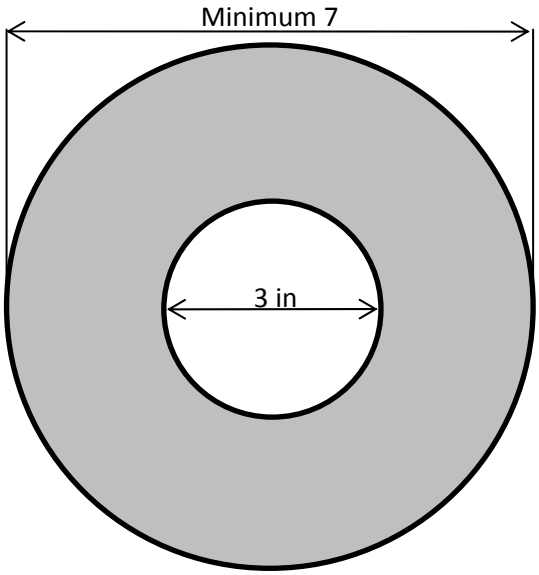



**Figure 2. Base Plate.**

**Figure 3. Surface Treatment Bond Test Equipment Set-Up and Tested Lab Specimen.**